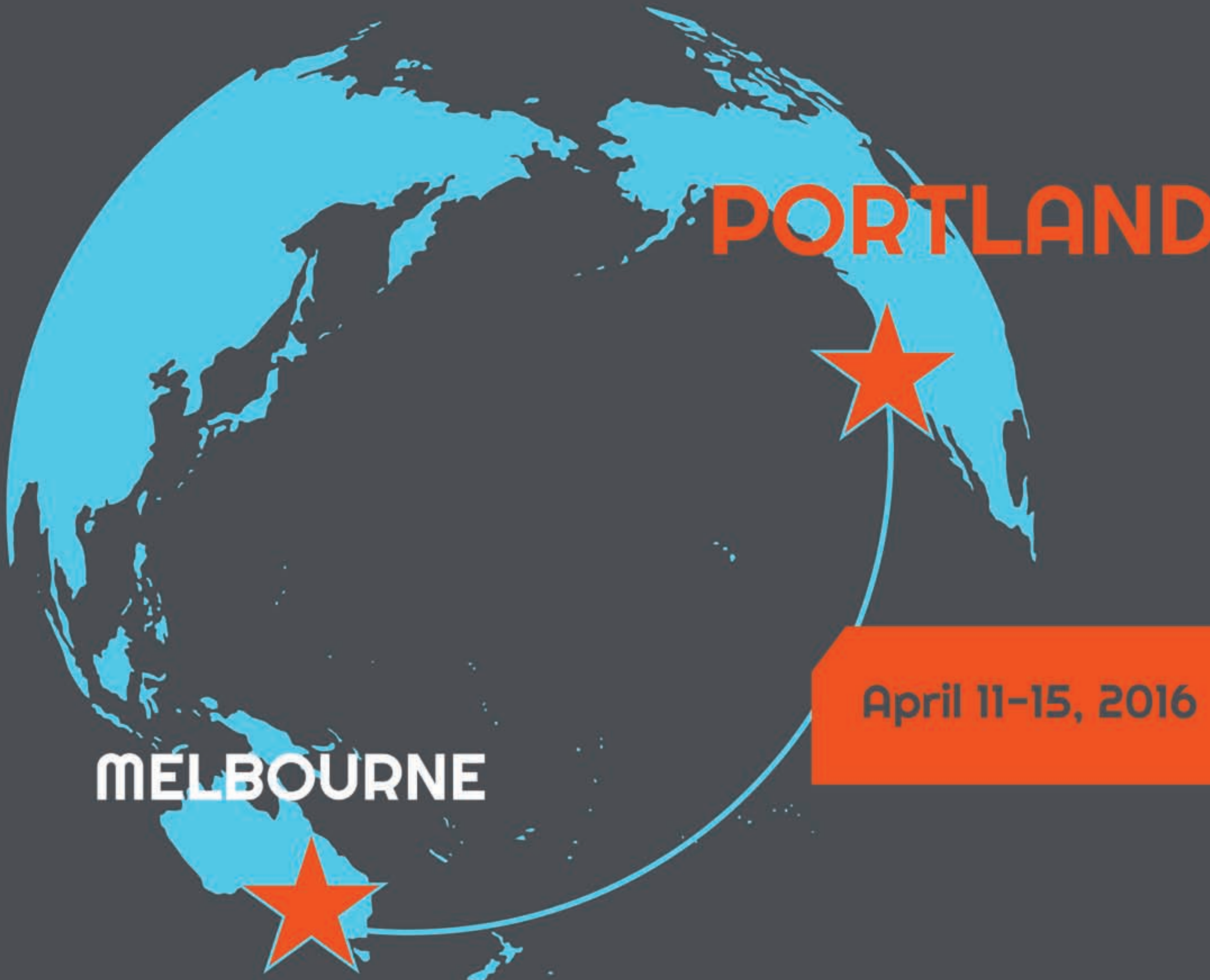

April 11-15, 2016

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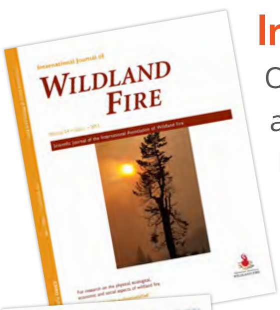
The IAWF is uniquely positioned as an independent organization whose membership includes experts in all aspects of wildland fire management. IAWF's independence and breadth of global membership expertise allows it to offer a neutral forum for the consideration of important and at times controversial, wildland fire issues. Our unique membership base and organizational structure allow the IAWF to creatively apply a full range of wildland fire knowledge to accomplishing its stated mission.

Vision: To be an acknowledged resource, from the local to global scale, of scientific and technical knowledge, education, networking and professional development that is depended on by members and partners in the international wildland fire community.



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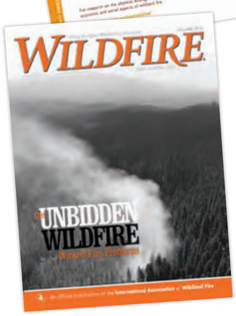

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WELCOME

International Association of Wildland Fire (IAWF) is extremely proud to present the 5th International Fire Behavior + Fuels Conference, co-sponsored by IAWF and Bushfire and Natural Hazards CRC of Australia and held concurrently in Portland, OR, USA, and Melbourne, Australia. This conference is being presented to bring focus to the many issues associated with fuels, fire behavior, large wildfires, and the future of fire management.

Much attention is being given to wildland fire management. It seems with each passing year we recognize escalating complexity, increasing risk, and mounting challenges. Wildland fire management cannot respond to current and future challenges without actively enlarging its body of knowledge, experience, and capabilities. Changing situations, what many would characterize as worsening situations, must be anticipated and responded to. Predictive entities continue to forecast worsening fire seasons and continued droughts leading to expectations of increasing numbers of fires, area burned, burning intensities, and duration of wildfire activity.

As all of these elements of wildland fire are manifested, we see that simply put, this is a wicked problem. How this occurred, and what can be done about it are important considerations for future strategic planning and operational management. A significant number of research reports, national leader presentations, political hearings, accountability reports, strategic plans, and forward-looking plans state the problem and actions for the future. It is commonly reported that the most extensive and serious problem related to the health of wildland areas is the over-accumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable and destructive wildfires.

Significant issues abound. New solutions are needed. Obvious targets like increased funding exist, but it is important to realize that short-term fixes are less likely to have success and long-term commitments, strategies, and actions are necessary. Management of fuel complexes; accelerated fuel treatments; preparation of communities to withstand wildfire; incorporation of learning, experience, emerging science and technology; as well as sustainable funding for wildfire suppression and fuel treatments are vital for success.

The International Association of Wildland Fire (IAWF) Bushfire and Natural Hazards CRC recognize these needs. We have an unwavering commitment to promote increased involvement, improved communication, escalated research, focused education and training, and active management support to help, promote success in wildland fire management.

This conference is designed to be innovative, revolutionary, and provocative. It will provide a forum to facilitate discussion of the latest relevant research findings, information dissemination about management treatments, stimulation of policy discussions, and inspire global fire management interaction. Both venues will provide a stage having hundreds of oral and poster presentations of new research information, practical experience lessons, and case studies; numerous knowledge and skill building workshops; on-the-ground learning field trips and tours; keynote and plenary presentations; and panel discussions by leading experts in the field. Conference participants will be able to share what is known, what needs to be learned, how to advance knowledge, and how to use this knowledge to effectively respond to increasing concerns.

On behalf of the International Association of Wildland Fire, all conference sponsors and partners, I welcome all participants and hope that this conference will meet, and even exceed your expectations of increasing awareness, knowledge, and capability in this important field in addition to networking with peers to establish future avenues of discovery. We hope that you will enjoy attending and gain significant information from what promises to be the most informative, enlightening, and powerful conference to date on fire behavior and fuels in wildland fire management.

If you were not previously a member of the IAWF, you are receiving a one-year membership in the association included in your registration. By participating as an active IAWF member you can help to improve communication between firefighting organizations, enhance firefighter and public safety, increase our understanding of wildland fire science, and improve our ability to manage fire. Your membership in the IAWF provides you with a connection to other wildland fire professionals from across the world. Our membership, which is truly international, includes professionals from the fields of fire ecology, suppression, planning, contracting, fire use, research, and prescribed fire. Our members are scientists, firefighters, mangers, contractors, and policy makers. As an association, we are unique in that we represent all areas of wildland fire management. Membership benefits include, but are not limited, to the following:

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INTERNATIONAL JOURNAL OF WILDLAND FIRE – Our other official publication of the IAWF, published by CSIRO, is dedicated to the advancement of basic and applied research covering wildland fire and is available as an additional membership option. A discounted rate of US$225 for a 1-year subscription of eight issues is offered to IAWF members; this includes a 1-year membership and a subscription to Wildfire magazine – AND free e-access to the "Journal's" abstracts and articles.

On behalf of the Board of Directors of the IAWF, thank you for your support of our association.

Thomas Zimmerman

Tom Zimmerman
IAWF President

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Proceedings for the 5th International Fire Behavior and Fuels Conference
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A 72-day Probabilistic Fire Growth Simulation used for Decision Support on a Large Mountain Fire in Alberta, Canada

Neal McLoughlin*
Alberta Agriculture and Forestry, Edmonton, Alberta, CA, neal.mcloughlin@gov.ab.ca

Kelsy Gibos
Alberta Agriculture and Forestry, Edson, Alberta, CA, kelsy.gibos@gov.ab.ca

Introduction

Lightning ignited the Spreading Creek fire in the Rocky Mountain front ranges of west-central Alberta on 3 July 2014. The ignition was in close proximity to an approved prescribed burn planned for the Upper North Saskatchewan River valley. The prescribed burn was to contribute to a 10-year disturbance target for the R11 Forest Management Unit. An overarching forest management plan supported the use of prescribed fire to reduce the threat of large-scale wildfire and create resilient forest ecosystems (Alberta Sustainable Resource Development 2007).

The fire was situated in a complex mountain environment with poor firefighter access. Predominate vegetation included Lodgepole pine (*Pinus contorta*) in valley bottoms, and Engelmann spruce (*Picea engelmannii*) and Subalpine fir (*Abies lasiocarpa*) on steep north-facing slopes. Critically dry fuel moisture conditions contributed to several high-intensity crown fire runs beyond the control of suppression resources. The fire spread east towards the Kootenay Plains Ecological Reserve, south into the Siffleur Wilderness Area, and west into Banff National Park. Incident command had the challenging task of balancing the merits of prescribed fire with aggressive suppression.

The incident command team managing the fire requested a long-range assessment of potential fire spread on 18 July. The team recognized that residual burning left on the landscape could result in additional fire spread. The authors completed a 72-day probabilistic fire growth simulation for the period 21 July to 30 September and presented their results to the incident command team on 22 July. Simulation outputs quantified the likelihood of additional fire spread and supported a strategic fire management plan for the remainder of the fire season.

We discuss our methodology used to assess long-range fire spread potential and present the results of three retrospective analyses. First we evaluated the accuracy of our original modeling approach. Next we investigated what the Spreading Creek fire might have burned in the absence of suppression. Finally, we explored how our long-range assessment may have supported initial response decisions had we completed it on the first day of the fire.

Methods

The Prometheus fire growth simulation model (Tymstra *et al*. 2010) was used to produce deterministic and probabilistic fire growth approximations for the 2014 Spreading Creek fire. All fire growth simulations used noon weather records from the Kootenay Plains automatic weather station (R4) located 18.5 km northeast of the fire's point of origin. The Prometheus model

* 9th Floor, 9920 - 108 Street, Great West Life Building
Edmonton, Alberta, CA T5K 2M4
neal.mcloughlin@gov.ab.ca

requires hourly weather inputs. Noon weather records and FWI System values were therefore replicated 24 times for each historical day.

Deterministic fire growth simulations were based on weather and Canadian Fire Weather Index (FWI) System values (Van Wagner 1987) from 2014. The last organized fire runs were observed on 16 July, and a fire boundary captured during the afternoon of 17 July was within 48 ha of the final area burned (8,961 ha). We therefore simulated fire growth for the period 3 to 17 July to evaluate the accuracy of our modeling approach against observed fire growth. A simulation for the period 3 July to 30 September was used to investigate what the Spreading Creek fire might have burned in the absence of suppression.

Probabilistic fire growth was modeled using weather records from the years 1994 to 2013. Missing records were filled using archived records from weather stations located within a 100 km radius and +/- 400 m elevation of R4. We recalculated FWI System values for each historical weather year using R4 moisture codes reported on 2 July 2014 as starting values (Table 1).

Table 1. Starting moisture codes used to recalculate FWI System values for each historical year of weather from station R4.

Moisture Code	Starting Value
Fine Fuel Moisture Code (FFMC)	93.5
Duff Moisture Code (DMC)	67.5
Drought Code (DC)	561.5

Separate fire growth outputs were generated for each historical weather year. Burn probability was calculated by dividing the number of simulations that resulted in a cell burning by the total number of simulations.

Static Inputs

Fuel data were clipped from the Government of Alberta's 2014 provincial fuel type grid classified according to the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The primary sources of vegetation information used to create the fuel type grid include the Alberta Vegetation Inventory and Alberta Ground Cover Classification. Several areas of NoData were reclassified based on underlying natural subregion classifications (Natural Regions Committee 2006). NoData values were classified as non-fuel within the Alpine subregion, and as the C-3 fuel type within the Montane and Subalpine subregions. The grass curing parameter for the O-1b fuel type was set at 40 %. A green-up setting was applied to mixedwood and deciduous fuel types to account for deciduous leaf-out.

Elevation data were clipped from Shuttle Radar Topography Mission (SRTM) digital elevation models. Prometheus generated slope and aspect grids from the elevation data provided. WindNinja version 2.5.4 software (Forthofer 2007) was used to approximate the effect of local topography on wind flow based on point initialization inputs for the R4 station location. Wind direction and wind speed grids were provided for each of the eight main cardinal directions.

The starting ignition for all simulations used the discovery time (3 July 21:18) and initial assessment location (51.988983° N, -116.656067° W) for the Spreading Creek fire. Highways 11 and 93 were used as 15 m wide fuel breaks.

Model Parameterization and Calibration
Simulations were limited to four hours of burning per day to compensate for daily FWI System values used throughout each 24-hour period. Daily FWI System values represent peak burning conditions (Van Wagner 1987). We assumed four hours of burning under peak burning conditions equivalent to a day of burning given typical diurnal weather and fuel moisture trends.

Fire growth was additionally constrained to days when station R4 reported a FWI > 29. Podur and Wotton (2011) recommended a threshold of FWI > 19 for modeling the growth of large fire over a multi-day period. However, their study focused on fires that occurred in the boreal regions of Ontario and Alberta. Fire behavior observations validated that a threshold of FWI > 19 was too low for predicting the difference between spread and non-spread days for this mountain fire. Fire growth predictions during the incident were more reasonable using the FWI > 29 threshold.

Prometheus does not model fire extinguishment. Xianli *et al*. (2014) used Duff Moisture Code (DMC) < 20 to identify substantial rain events (eg. 10-20 + mm) that effectively extinguish a fire. We used this DMC threshold to specify the earliest end date for each simulation.

Breaching was applied to all simulations. This parameter allows a simulated fire to cross a vector fuel break or non-fuel grid cell whenever the width is less than 1.5x flame length. Fire control lines and air tanker drops that took place during the Spreading Creek fire were not incorporated into any of the simulations. However, we ended the deterministic simulation used to evaluate accuracy of our modeling approach on 17 July to account for suppression activities prematurely extinguishing portions of the fire perimeter.

Results

Evaluation of Modeling Approach
The Spreading Creek fire burned 8,961 ha. Our modeling approach which used daily fire weather inputs and several fire spread thresholds over predicted fire growth by 6,798 ha on the east and west ends of the fire (Figure 1a). The simulation did not predict the 200 ha excursion that occurred on the north side of Highway 11.

Potential Area Burned in the Absence of Suppression
Deterministic simulation outputs for the period 3 July to 30 September suggest the Spreading Creek fire might have burned 112,778 ha in the absence of suppression. The irregular fire shape in Figure 1a highlights strong topographic channeling on fire spread.

Probabilistic Assessment of Long-Range Fire Spread
Fire growth simulations for 20 years of weather records produced fire sizes from 0 to 129,795 ha. Burn probabilities from 0.51 to 0.90 aligned best with the final fire perimeter (Figure 1b). Burn probabilities from 0.05 to 0.10 aligned best with our 2014 simulation that assumed no suppression. The simulation that used weather records from 2003 produced the largest area

burned and accounts for the 0.5 to 0.10 probability contour . The 2003 simulation was most similar to our 2014 simulation with respect to fire size, shape, and extent. A repeating 8 to 10 year gap was observed between R4 weather records conducive to large fire growth.

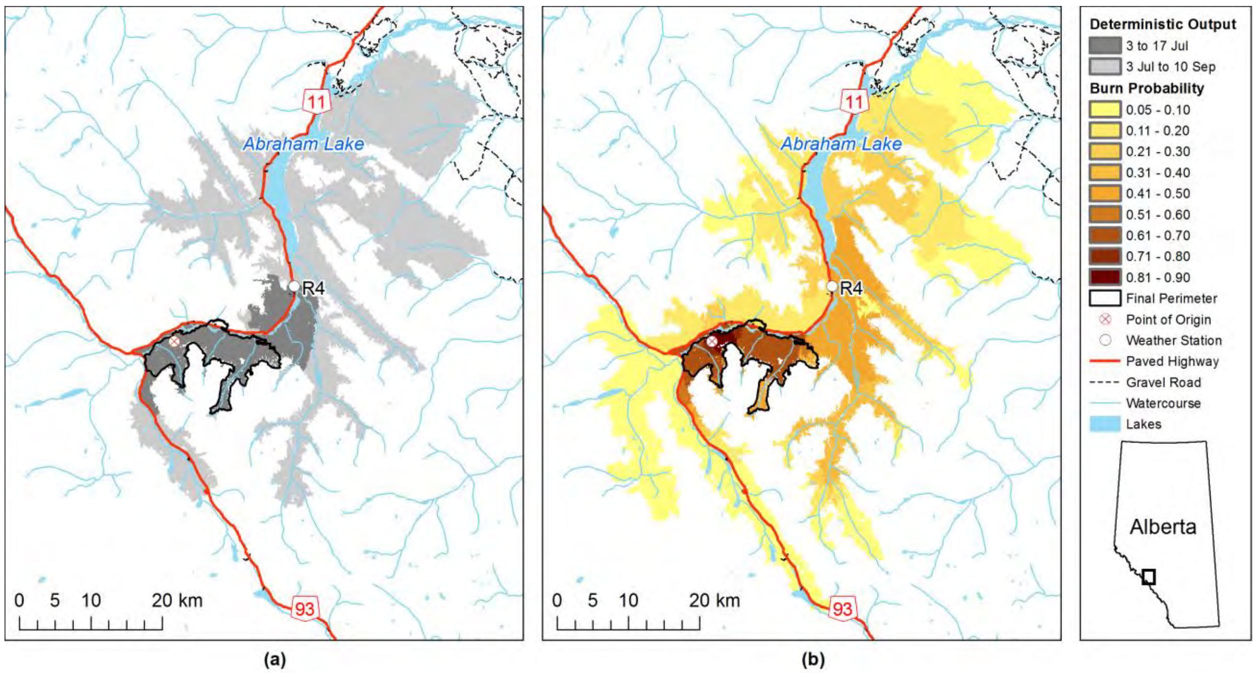

Figure 1: Deterministic (a) and probabilistic (b) fire simulation outputs for the 2014 Spreading Creek fire.

Potential fire spread days (FWI > 29) that occurred in the 20 historical weather years were summarized by month to provide insight as to when large fire growth is more likely. The greatest number of potential spread days were expected in July, and the least in September (Figure 2a). The number of potential spread days in 2014 were above average in both July and August. The distribution of potential spread days suggests there are typically 0 to 10 days conducive to large fire growth between 3 July and 30 September (Figure 2b). Station R4 reported 34 potential spread days in 2014.

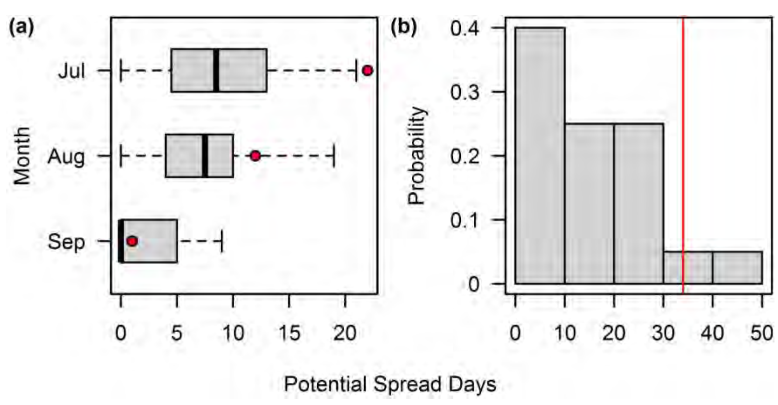

Figure 2: Monthly box and whisker plots (a) and distribution (b) of potential fire spread days (FWI > 29) for the period 3 July to 30 September based on 20 years of weather records from station R4. The red dots and vertical line show the number of potential spread days reported in 2014.

The median date of fire-ending events (DMC < 20) used in our analysis was 17 Aug (Figure 3). The first fire-ending event reported by station R4 in 2014 did not occur until 10 September.

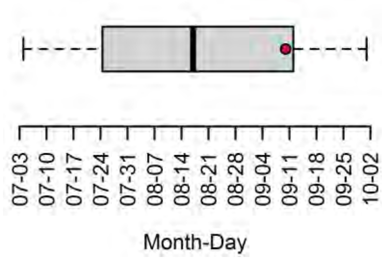

Figure 3: Box and whisker plot of fire-ending events applied to probabilistic fire growth simulations. The red dot is the expected date of extinguishment for the 2014 Spreading Creek fire in the absence of suppression.

Discussion

Deterministic simulation outputs suggest that our modeling approach overestimates area burned. There are several factors that likely explain this result. First, we did not account for suppression activities that slowed or extinguished parts of the fire perimeter. Second, we did not account for minimal fire growth from 11 to 15 July due to heavy smoke trapped in the valley. Finally, aerial ignition operations conducted in Banff National Park on 9 July created a large smoke column that shaded and calmed fire behavior at the east end of the fire. We suggest that our modeling approach provides realistic predictions of fire spread direction. Area burned predictions are more likely representative of a free burning fire with no suppression influence. Assuming no suppression, the 2014 Spreading Creek fire had potential to burn 112,778 ha. A fire of this magnitude would have impacted numerous values located along Highways 11 and 93. Yet our results suggest a low probability (0.05 to 0.10) of fire growth > 100,000 ha.

Original model outputs were presented to the incident management team 19 days after the fire was detected, and six days after the last organized fire run. Strategic fire management decisions were supported by nearly one month of fire behavior observations, model outputs, and certainty in established control lines. What if model outputs were available on the date of detection when little was known about the fire? Maguire and Albright (2005) describe mental shortcuts that commonly lead to overly risk-averse fire management decisions that appear inconsistent with an organization's stated goals. We speculate that incident management would have focused on worst case outputs despite their low probability of occurrence resulting in a similar initial response. However, this information may have also supported the early formation of a strategic suppression response by drawing attention to locations well ahead of the active fire perimeter.

There are no standards or guidelines regarding how best to incorporate probabilistic model outputs into real-time fire management decisions. The best way to develop such standards or guidelines is regularly provide probabilistic model outputs to incident management shortly after fires are detected. This statement is perhaps most relevant to escape fires located in areas with prescribed fire objectives. Mountain fires are rare in Alberta. Organization knowledge and experience to effectively manage infrequent mountain fire regimes is difficult to obtain. Alexander and Thomas (2003) describe case studies, field experience, and computer modeling as the best learning combination for fire practitioners. We hope this retrospective analysis contributes to your learning.

Acknowledgments
We thank Bernie Schmidt and Dave Finn for providing guidance and a unique challenge to model long-range spread potential on a mountain fire deployment. We recognize Connor Wollis and Mike Milner for incorporating our original outputs into the strategic management plan for the 2014 Spreading Creek fire.

References

Alberta Sustainable Resource Development (2007) R11 forest management plan. Forestry Division, Clearwater Forest Area. (Rocky Mountain House, AB)

Alexander ME, Thomas DA (2003) Wildland fire behaviour case studies and analyses: value, approach, and practical uses. *Fire Management Today* **63(3)**, 4-8.

Forestry Canada Fire Danger Group (1992) Development and Structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Information Report ST-X-3. (Ottawa, ON)

Forthofer, JM (2007) Modeling wind in complex terrain for use in fire spread prediction. MSc Thesis, Colorado State University, Fort Collins, CO.

Maguire LA, Albright EA (2005) Can behavioral decision theory explain risk-averse fire management decisions. *Forest Ecology and Management* **211,** 47-58.

Natural Regions Committee (2006) Natural Regions and Subregions of Alberta. Compiled by Downing DJ and Pettapiece WW. Government of Alberta. Publication Number T/852.

Podur JJ, Wotton BM (2011) Defining fire spread event days for fire growth modeling. *International Journal of Wildland Fire* **20**, 497-507.

Tymstra C, Bryce RW, Wotton BM, Taylor SW, Armitage OB (2010) Development and structure of Prometheus: the Canadian Wildland Fire Growth Simulation Model. Natural Resource Canada, Canadian Forest Service, Northern Forestry Centre, Information Report NOR-X-417. (Edmonton, AB)

Van Wagner CE (1987) Development and Structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Forestry Technical Report 35. (Ottawa, ON)

Xianli W, Parisien M-A, Flannigan MD, Parks SA, Anderson KR, Little JM, Taylor SW (2014) The potential and realized spread of wildfire across Canada. *Global Change Biology* **20**, 2518-2530.

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A Fire History Map of the White Cap Creek Watershed in the Selway-Bitterroot Wilderness in Idaho

Valentijn Hoff*
National Center for Landscape Fire Analysis, Missoula, Montana, USA,
valentijn.hoff@firecenter.umt.edu

Introduction

Fire is a powerful process in many ecosystems in the Northern Rocky Mountains. Remote areas provide opportunities for fires to burn without suppression, while not endangering human life and threatening infrastructure. Fire consumes organic matter, thus changing the structure and composition of the vegetation with great spatial and temporal variation. When looking at the White Cap Creek watershed between 1889 and 2013, the resulting mosaic, although unique to this place and time, can be an example for fire management in many other areas. This map displays the mosaic of fire history and aims to inspire a conversation on the role of fire in a wilderness area.

Area Description

The White Cap Creek drainage is a remote area in the 485,600-hectare Selway-Bitterroot Wilderness, bordered by the Selway River in the west and the Idaho-Montana border in the east (Figure 1). The Bitterroot National Forest West Fork Ranger District manages this part of the Wilderness. The watershed is on the west slope of the Bitterroot Mountains. The elevation ranges from a low of 930m at the confluence of White Cap Creek and the Selway River, up to 2680m at the summit of Vance Mountain. Located just south of the 46th parallel in the Northern Rocky Mountains, where the maritime influence of the Pacific starts to give way to a more continental climate, the area contains large gradients of temperature and moisture. This creates a variety of vegetation types, leading to a variety of fuel types, fire return intervals and thus spatial and temporal fire interactions. Coniferous forests dominate the area, with Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasiocarpa) dominating higher elevations, Douglas-fir (Pseudotsuga menziesii), and ponderosa pine (Pinus ponderosa) forests in the lower elevations and on south facing slopes. Smaller areas consisting of meadows, sub-alpine woodlands, lodgepole pine (Pinus contorta) forests and deciduous shrubs are also present. At the higher elevations, snow lingers into late spring and early summer. Fire growth is sometimes limited by rocky areas on ridgelines. The only infrastructure in the area is the Paradise Guard Station with a log cabin and campground, located at the confluence of White Cap Creek and the Selway River.

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

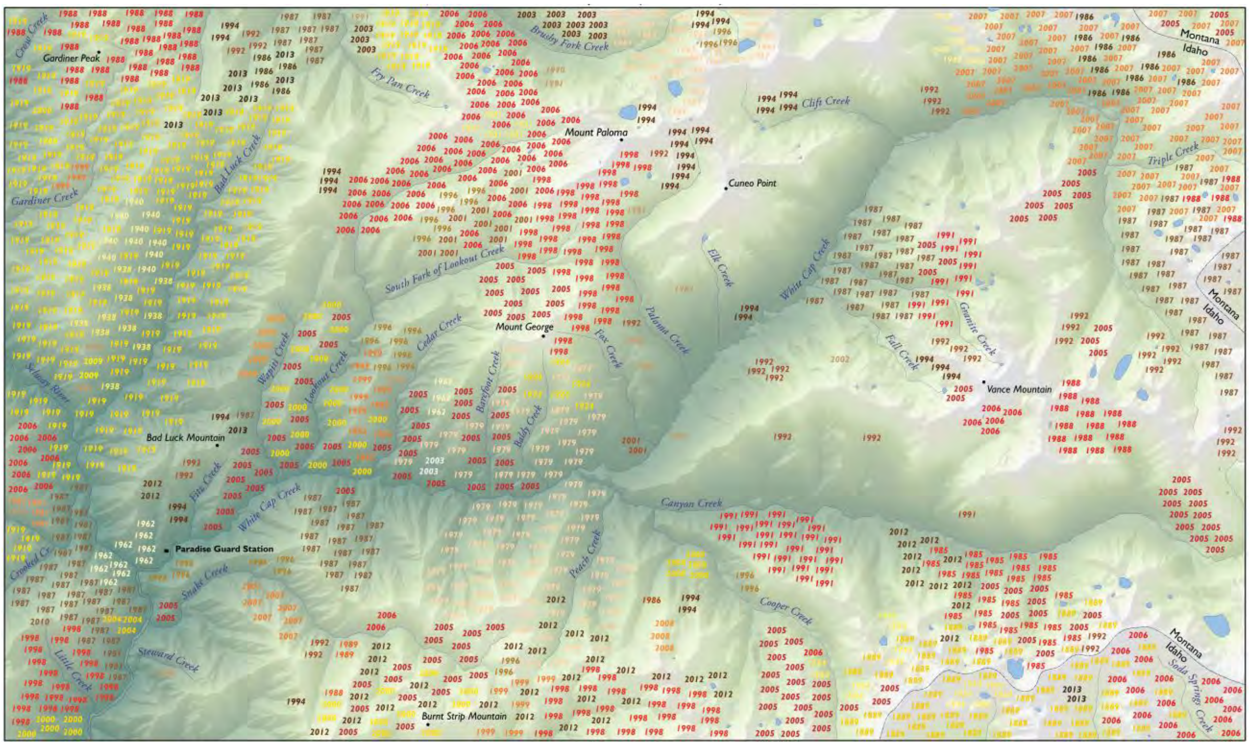

Figure 1: The fire history map of the White-Cap Creek watershed in Idaho. The original size of this map is 27" by 46".

Fire History

In 1970, the White Cap Creek area became home to a radical experiment: letting fires burn. In 1972, the lightning caused Bad Luck Creek fire burned for 4 days, the first time a fire ran its course since aggressive suppression began in the aftermath of the 1910 fires. It grew to only 24 x 24 feet (Smith, 2014). Fire control efforts in the middle of the twentieth century were very effective and did reduce the number of acres burned (Habeck and Mutch, 1973). Many fires have burned since in this area, creating the burn mosaic of a natural fire regime. Fires are sometimes limited in growth by previous fires, and sometimes burn on previous fires; indicating a complex relationship between time-since-fire, previous fire severity and fuel conditions (Teske *et al*, 2012). The prescribed natural fire program in the Selway Bitterroot Wilderness has been successful in returning fire as a natural process, but there has been a decrease in low severity fires in recent times, compared to pre-settlement (Brown *et al*, 1994).

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

Cartography

Typography lends itself well for displaying fires on a map. Spatial features displayed using typography lack the hard lines of the usual fire perimeter polygons. Because, especially in fires that burned a long time ago, the exact location of perimeters is unknown; these perimeters do not have a false level of precision. Each fire is approximately covered by one to many 'years' on the map. Typography also allows for easy display of fires burning in the same area, but years apart (Figure 2). The various burn years comingle, allowing for quick visual confirmation of the spatial and temporal mosaic. The cool color gradient used to display relief contrasts with the warm colors used for the fires. The darker blue-green at the lower elevations leading to the white on the highest ridgetops coincides with the vegetation gradient. Typography also alleviates the need for a legend, as the text on the map indicates the year when a fire burned in conjunction with the area affected by the fire. The fonts used on the map complement each other. The text is set in Adobe Garamond Pro, the title is set in Franklin Gothic Medium. Fire years are set in Gill Sans MT, mountain names are in italic Gill Sans MT, streams are in Adobe Garamond Pro. The author used ESRI ArcGIS (ESRI Inc.) for spatial data processing and analysis, and Adobe Illustrator (Adobe Systems Inc.) for map production.

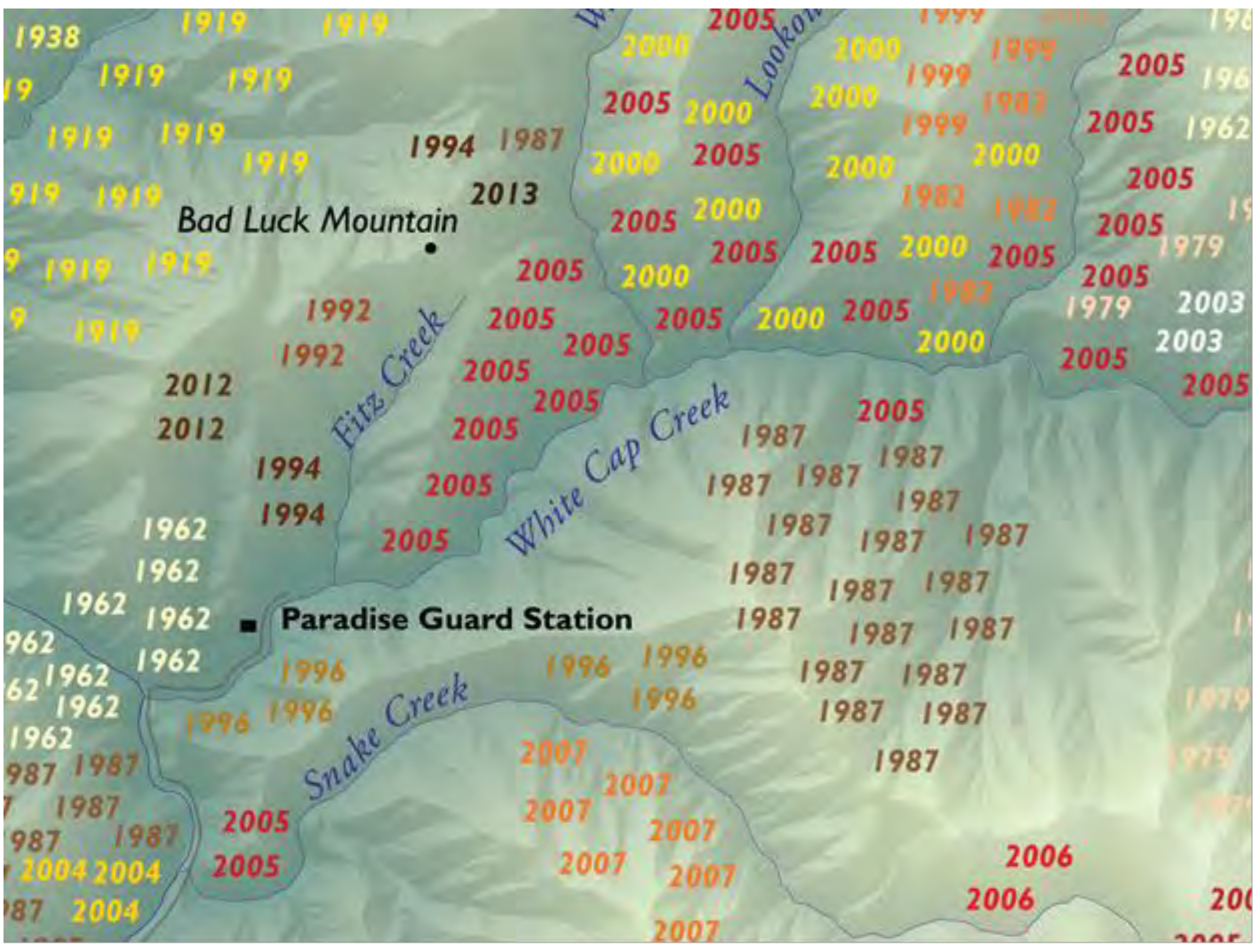

Figure 2: This is a portion of the map showing the area around Paradise Guard Station in detail. Typography shows the interactions between fires over many decades.

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

References

Adobe Systems Incorporated, 345 Park Avenue, San Jose, California 95110-2704

Brown, J.K., Arno, S.F., Barrett, S.W. and Menakis, J.P., 1994. Comparing the prescribed natural fire program with pre-settlement fires in the Selway-Bitterroot Wilderness. *International Journal of Wildland Fire*, *4*(3), pp.157-168.

Environmental Systems Research Institute Incorporated (ESRI), (2014). ArcGIS Desktop 10.1

Habeck, J.R. and Mutch, R.W., 1973. Fire-dependent forests in the northern Rocky Mountains. *Quaternary Research*, *3*(3), pp.408-424.

Smith, D., 2014. From Research to Policy, The White Cap Wilderness Fire Study. *Forest History Today*, page 4.

Teske, C.C., Seielstad, C.A. and Queen, L.P., 2012. Characterizing fire-on-fire interactions in three large wilderness areas. *Fire Ecology*, *8*(2), pp.82-106.

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Valentijn.hoff@firecenter.umt.edu

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A Novel Forest Fire Prediction Tool Utilizing Fire Weather and Machine Learning Methods

Leo Deng*
Portland State University, Portland, Oregon, USA, leodeng5@gmail.com
Marek Perkowski
Portland State University, Portland, Oregon, USA, h8mp@pdx.edu
John Saltenberger
Northwest Interagency Coordination Center, Portland, Oregon, USA, jsaltenb@blm.gov

Introduction

Wildfires are an essential and natural part of ecosystems that help restore them. Many species of plants rely on such fires to cleanse the environment for better regeneration and growth. Additionally, they have the potential to support the growth of thriving native species while eliminating invasive species. The result is most often a newly created ground perfect for the future plants that still live. It is a catalyst for promoting biological diversity and keeping ecosystems healthy. Despite their integral contributions to the environment, wildfires also threaten people and property, especially when they are unable to be contained (Fried *et al.* 2004). We have been able to keep the advantages of wildfires much greater than its disadvantages, but due to climate change, fire seasons are becoming uncontrollable, and there is a need for a more efficient management system. Better fire forecasting becomes more and more crucial to retain a balanced relationship between wildfires, humans, and the environment. The purpose of this work is to aid these management agencies on planning and strategy to efficiently manage wildfires and being prepared to contain hazardous, unwanted fires.

There has been a spark of interest in the use of data mining in the field of wildfire management. Many techniques have been developed in attempt to increase fire awareness (Lee *et al.* 2002; Cruz *et al.* 2005; Alonso-Betanzos *et al.* 2003; Vega-Garcia *et al.* 1996; Hsu *et al.* 2002; Stojanova *et al* 2006; Sitanggang *et al.* 2013). In Portugal, an attempt was made to predict the number of acres future wildfires would burn using machine learning methods combined with regression techniques, based on weather attributes and the Fire Weather Index (FWI) for wildfires. The method is unique in that it takes advantage of easily obtainable fire and weather information from existing local sensors. However, this model used a continuous method which resulted in relatively poor prediction accuracy (Cortez *et al.* 2007). In addition, the database used was limited to the Fire Weather Index and basic meteorological variables, and a limited range of time. The machine learning methods used included Decision Trees, Random Forests, SVM, Neural Networks and Naïve Bayes. The best configuration developed utilized the SVM method. In contrast to these previous works, this work introduces improved novel Machine Learning (ML) methods, where the emphasis is on predicting future forest fire intensities with the use of real-time and easily-obtained meteorological data from existing local sensors. This work is demonstrated on a complete database with an optimized training set of historical weather attributes, and optimized machine learning methods. The result of the prediction will be discretized in the terms of the magnitude of the fire, as needed by fire management agencies.

*1924 NW Norfolk Ct. Portland, OR 97229
leodeng5@gmail.com,

Materials and Methods

Fire weather database

The data collected from local sensors by the Northwest Interagency Coordination Center was used for testing and developing the tools in this work. The data includes the monthly averages of ten different relevant fire weather attributes including National Fire Danger Rating System (NFDRS) indices.

The attributes are: 100 hour dead fuel moisture (F100), 1000 hour dead fuel moisture (F1000), Live Fuel Index 1-100 (LFI), Sum of Rain Duration in hours (RainDur), Sum of Rain Amount in inches (RainAmt), Average Temperature in °F (Temp), Maximum Temperature in °F (Max Temp), Minimum Relative Humidity % (MinRH), Wind Speed in mph (Wind), and Duff Moisture Code (DuffMC)

Each of these attributes of the fires in the database is multiple-valued, and this data was integrated from the 12 predictive service areas in Oregon and Washington States over a time period of 32 years. Each of the 1443 instances includes the number of acres burnt by the fire.

Machine learning methods

Six different machine learning methods were selected and used in the Orange Machine Learning software suite on the fire weather data. Three are based on multiple-valued logic: a Disjunctive Normal Form (DNF) rule based method, Decision Trees, and Naïve Bayes (Barber 2012; Alpaydin 2014). The other three are based on continuous representation: the Support Vector Machine (SVM) along with the radial basis and polynomial kernel functions. As a result of the varying concepts these methods are based on, one cannot be absolutely named better than another; their ability to optimize with precision is dependent on the type of data that is being tested. We intentionally selected different types of methods and different representations, with the intent to find the best method with the data (Zupan *et al.* 2007).

Strategically testing and selecting the attributes

For each of the 7 intensity levels, the machine classifies the fire into one of two categories – less than or greater than a specific number of acres burnt. This is done multiple times as shown in Fig. 1 resulting in the discovery of the final intensity of the fire. The 10 fire weather attributes utilized in this work were tested in different combinations to confirm their relevance to the intensity of a wildfire. The Support Vector Machine and rbf kernel were used on each attribute individually to identify their individual potential for predicting the intensity of a fire. The 10 attributes are ranked from the highest to the lowest average accuracy.

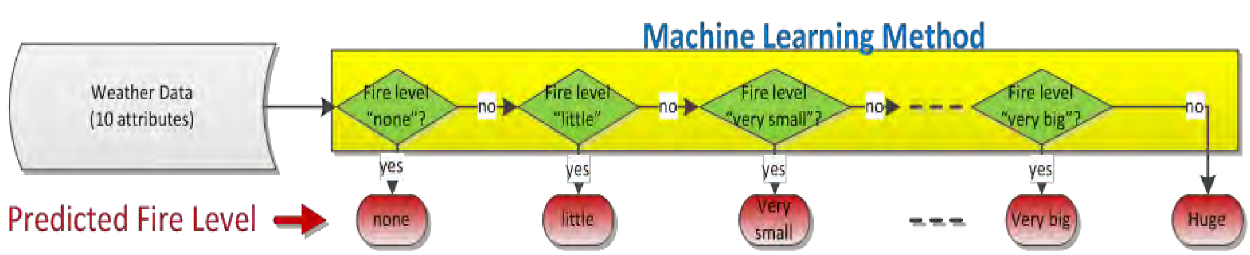

Fig. 1. Final FFPT illustration

Fig. 2 illustrates how the best set of input data is determined using the two support vector machine methods. The "4 best attributes" and "7 best attributes" are determined from the previous step; individual accuracies are used to rank them by importance. The “Medians of attributes” option takes the median value of each of the 10 attributes and uses those single values to train on the data. These four training set options are used to train a linear SVM as well as the radial basis function (RBF) kernel SVM using a 97%/3% training/testing set on randomly selected data. This is repeated 5 times for each method to see which preprocessing option gives the highest accuracy and ultimately the optimal training set that will be used to test each of the six different machine learning methods later.

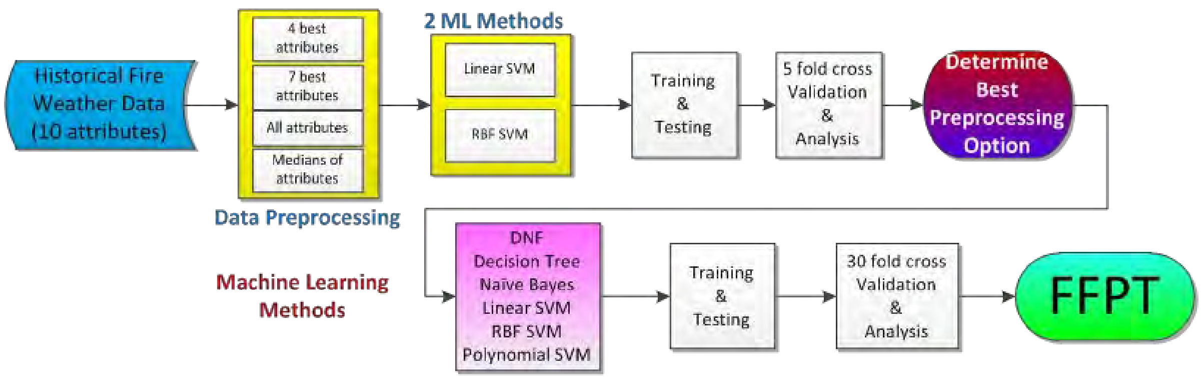

Fig. 2. Determining best set of input data and applying to 6 ML Methods to develop FFPT

Applying six methods on selected attributes to optimize FFPT

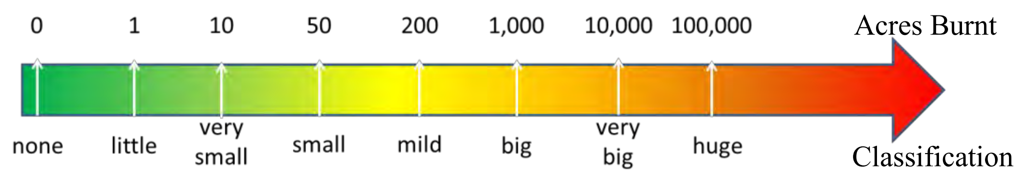

Fig. 3. Classification levels used by FFPT

Once the most optimal training set was determined, this set of data was used to train on all 6 different machine learning methods using the same 97%/3% training/testing method repeating on each intensity/method combination 36 times using randomly selected data each time. The tool was made to classify fires into one of 6 specific intensity levels as shown in Fig. 3 where intensity levels 0 and 1 – none and very small – were combined together in the testing. For each of the 1443 instances used in this work, the machine must perform as many as 6 different separations between the two adjacent intensity levels, varying depending on its specific fire intensity level. For example, for the “huge” fire, all six separations must be done, as the tool will keep asking if the fire is smaller than a certain number of acres until it reaches the final stage of classification. However, for fire level “none”, only the first separation is necessary, as the tool simply asks if there is a fire or not, and if not, then the tool reaches the conclusion “none”. This process is illustrated in Fig. 1. Six different machine learning methods and six different intensity separations result in a total of 36 accuracies. These values are the result of the mean of the accuracies from the 30 random trials in previous step. Finally, each of the six machine learning methods was given an overall average accuracy.

Results and Discussion

Fig. 5-7 show the accuracy results of each of the 10 attributes tested individually with the support vector machine, the 6 ML methods accuracy for each of the 7 intensity levels, and the final master average accuracies of each version of the FFPT respectively.

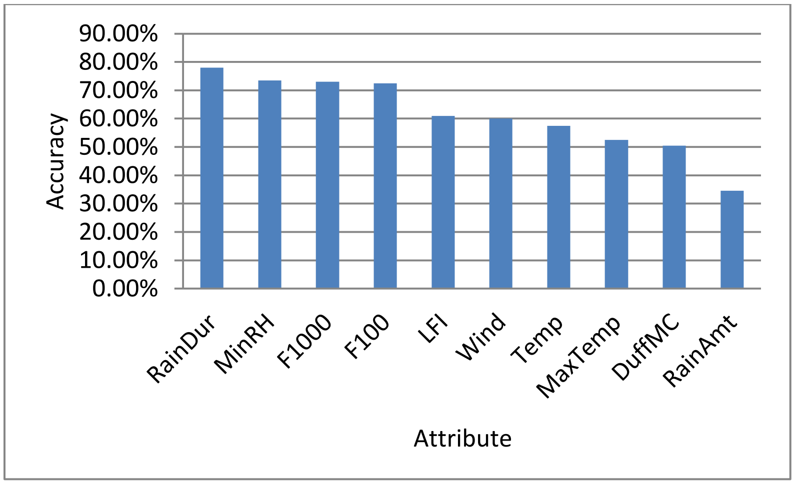

Fig. 5. Accuracy of each individual attribute using SVM

The results in Fig. 5 show each of the 10 attributes' individual accuracies when tested with a 97%/3% training/testing set. Clearly the top 4 attributes are Rain Duration, Minimum Relative Humidity, F1000, and F100. The top 7 attributes additionally include the LFI, Wind, and Temperature. These two sets of attributes, along with the set of all attributes and the set of all attributes' median values, are tested with 2 machine learning methods in the next step to determine which of these sets of attributes is the optimal training set.

Using 7 attributes with the rbf Kernel SVM gave a much higher accuracy than when using 4 attributes. The least optimal training set was the one that was using median values. Rbf Kernel SVM is almost always better than the Linear SVM. These results determine that in all future steps, all attributes – as opposed to a select few – are used to train the 6 machine learning methods, as they all have a significant role to play in the intensity of a fire.

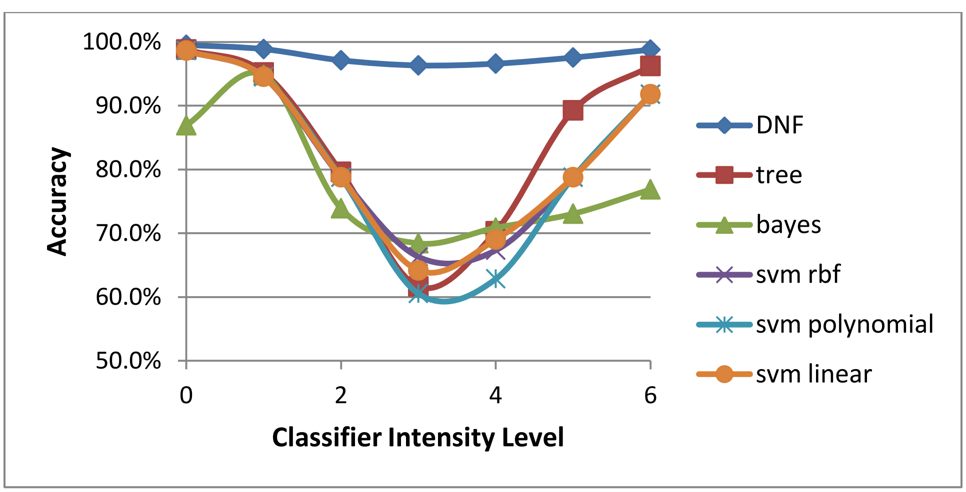

Fig. 6. Accuracy of each machine learning method for predicting each of the 7 intensity levels of wildfires

The trend seen in Fig. 6 for all 6 methods shows that this tool is most accurate at predicting very small fires or very huge fires, and the accuracy drops by some margin as the intensity level nears the center of the pool of data. This can be explained, because for classifying mild fires, the machine learning process has to deal with an equal amount of data on both sides of the separation. Looking at whether a fire is huge or not, on the other hand, is much easier with almost all of the data being less intense than "huge" and only a small portion of months with extreme weather conditions that resulted in the burning of more than 100000 acres of land.

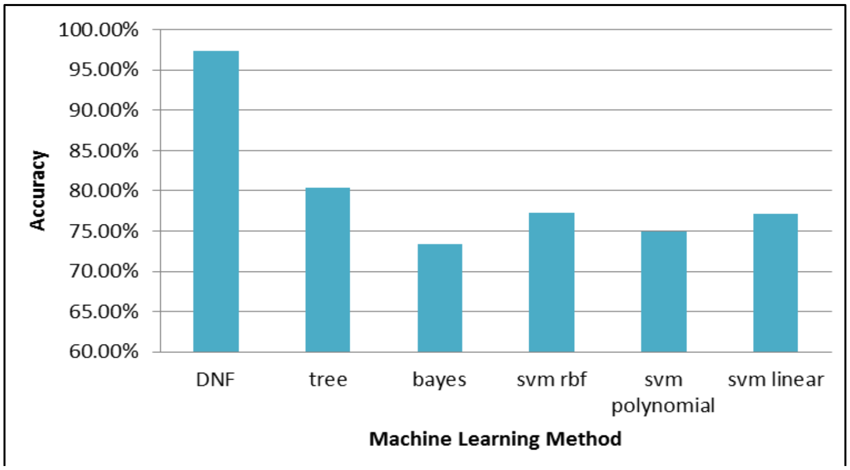

Fig. 7. Average accuracy for each machine learning method

Fig. 7 gives the final average accuracies of each machine learning method when tested on all attributes with a 97%/3% training/testing set. The DNF rule based method gives the highest average accuracy at 97.8%, and a maximum accuracy of 98.8% when predicting huge fires. With so much data from the past 32 years – 1443 months of fires – the DNF method shows the best ability to optimize the large data set with precision. Its lowest accuracy when classifying fires into very small vs. mild fires stayed very high at 96.3% unlike the other 5 methods whose accuracies all dropped significantly by at least 25%.

In this work a novel tool for forecasting wildfires was developed, providing a specific intensity level for a given fire based on the amount of land it would burn. Forecasting of wildfire intensity levels is dependent on the accuracy of weather attribute forecasts. An important factor to consider is that despite the rain duration's high impact on the intensity of a fire, methods to predict this variable are much less accurate than others such as rain amount. The importance of this prediction tool lies with the wildfire management agencies' need to increase awareness of burning wildfires in order to make an educated decision as to which events require the most or least attention.

Conclusion

Our results support the expectation that the newly developed tool will perform with highly accurate information, ultimately benefitting fire managers in their preparations, resource allocation, and minimizing additional assistance for unexpected intense wildfires. A novel Forest Fire Prediction Tool (FFPT) utilizing a disjunctive normal form (DNF) based method was developed and used for wildfire prediction for the Pacific Northwest United States. This method was the best chosen out of six different machine learning methods all tested with random selected data from the historical fire weather database of the past 32 years. In contrast to previous methods of fast fire detection, this tool makes it possible to enable proactive resource management for firefighting response teams, promoting the conservation of valuable resources. This will inevitably result in a significantly higher control and balance of large fires as well as lowered costs for land restoration.

Results showed that of the six machine learning methods used, given a 97%/3% training/testing combination, DNF rule based method, used with all 10 fire weather attributes gave the highest average accuracy of 97.8%, the highest accuracy reported for forest fire intensity prediction in literature. The prediction accuracy is higher for small and large scale fires. This tool will result in a much greater awareness for wildfire management, allowing response teams to conduct accurate planning and decision making.

REFERENCES

Alpaydin, Ethem. Introduction To Machine Learning. Cambridge, MA: MIT Press, 2014.

Alonso-Betanzos, Amparo, et al. "An intelligent system for forest fire risk prediction and fire fighting management in Galicia." *Expert Systems with Applications* 25.4 (2003): 545-554.

Barber David. *Bayesian Reasoning and Machine Learning*. Cambridge University Press, 2012. 203-213.

Cortez Paulo and Anibal de Jesus Raimundo Morais. "A Data Mining Approach to Predict Forest Fires Using Meteorological Data." (2007).

Cruz, Miguel G., Martin E. Alexander, and Ronald H. Wakimoto. "Development and testing of models for predicting crown fire rate of spread in conifer forest stands." *Canadian Journal of Forest Research* 35.7 (2005): 1626-1639.

Fried, Jeremy S., Margaret S. Torn, and Evan Mills. "The impact of climate change on wildfire severity: a regional forecast for northern California." *Climatic change* 64.1-2 (2004): 169-191.

Hsu, Wynne, Mong Li Lee, and Ji Zhang. "Image mining: Trends and developments." *Journal of intelligent information systems* 19.1 (2002): 7-23.

Lee, B. S., et al. "Information systems in support of wildland fire management decision making in Canada." *Computers and Electronics in Agriculture* 37.1 (2002): 185-198.

Lee, B. S., P. M. Woodard, and S. J. Titus. "Applying neural network technology to human-caused wildfire occurrence prediction." *AI applications* (1996).

Sitanggang, Imas Sukaesih, et al. "Predictive Models for Hotspots Occurrence using Decision Tree Algorithms and Logistic Regression." Journal of Applied Sciences, 13.2, 252-261.

Stojanova Daniela, et al. "Learning to Predict Forest Fires with Different Data Mining Techniques." *Conference on Data Mining and Data Warehouses (SiKDD 2006), Ljubljana, Slovenia*. 2006.

Zupan, Blaz, et al. "Orange and decisions-at-hand: Bridging predictive data mining and decision support." *Proceedings of the ECML/PKDD Workshop on Integrating Aspects of Data Mining, Decision Support and Meta-Learning, Freiburg, Germany*. 2001.

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Assimilation of Satellite Active Fires Detection Into a Coupled Weather-Fire Model

Jan Mandel*
University of Colorado Denver, Denver, Colorado, USA, jan.mandel@gmail.com

Aimé Fournier
University of Colorado Denver, Denver, Colorado, USA, aime.fournier@ucdenver.edu

Mary Ann Jenkins
York University, Toronto, Ontario, Canada, maj@yorku.ca

Adam K. Kochanski
University of Utah, Salt Lake City, Utah, USA, adam.kochanski@utah.edu

Sher Schranz
Colorado State University and NOAA, Boulder, Colorado, USA, sher.schranz@noaa.gov

Martin Vejmelka
AVAST Software s.r.o., Prague, Czech Republic, vejmelkam@gmail.com

Introduction

Active fire detection products from the VIIRS and MODIS instruments on polar-orbiting satellites provide planet-wide fire detection at resolutions from 375 m to 1.1 km, every 6 to 12 hours. Because the data products are continuously available online, they present an attractive data source for automated fire behavior simulations and forecasts. Active fire detection was used to initialize simulations previously (Coen and Schroeder, 2013). However, the scale of fire simulation is typically finer (30m-200m) than the scale of the satellite fire detection, there are false positive and false negative errors as well as geolocation errors, and there is no detection under clouds (Hawbaker *et al.*, 2008, Schroeder *et al.,* 2014). For these reasons, we use satellite detection to improve fire simulation in a statistical sense only, rather than as a direct input.

Level 3 products, used in in Mandel *et al.* (2014b), are already fused from multiple satellite sources as detection squares in arbitrary locations, which provides convenience but loses information. Consequently, they are not recommended for science use (Giglio, 2015). Level 2 products, used here, are grid based, and provide cloud information and confidence levels of detections. Unfortunately, no confidence level is available for water or ground detection with no fire. Level 2 active fires data come as granules, which are areas under the satellite path over about 5 minutes of flight (Fig. 1). A granule may or may not contain the area of interest, or it may intersect it only partially (Fig. 2).

* Department of Mathematical and Statistical Sciences, University of Colorado Denver, Denver, CO 80217-3364.

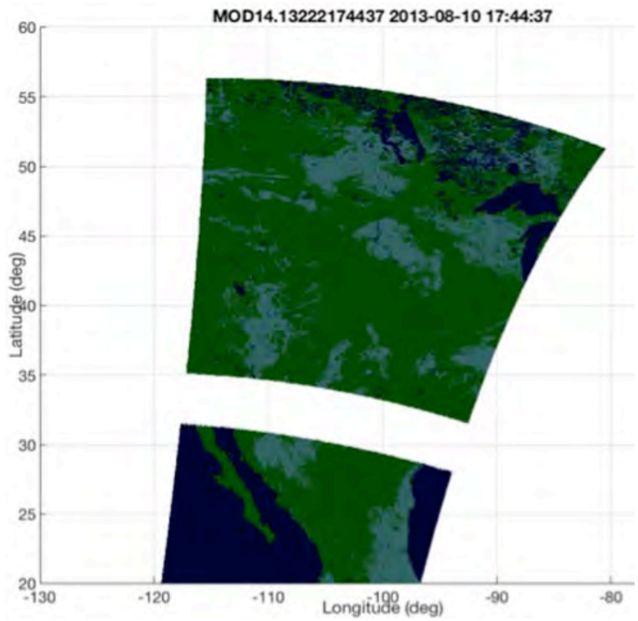

Figure 1. A MODIS Active Fires detection granule in false colors: blue=water, green = groud, grey= cloud, red = fire, white = no data. The fire pixels are too small to see on this scale.

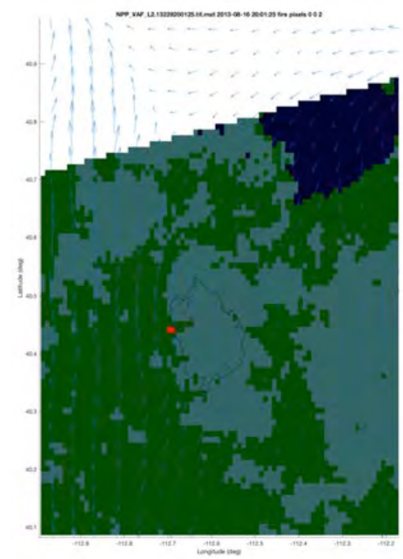

Figure 2. VIIRS Active Fires detection in false colors same as in Fig. 1, shown with the fire perimeter and ground wind field from WRF-SFIRE simulation of 2013 Patch Springs fire, UT. The granule only partially intersects the area of interest, and there is a significant cloud cover.

Methods

Model

We are using the coupled atmosphere-fire model WRF-SFIRE (Mandel *et al*., 2009; 2011; 2014a), which combines the community WRF model (Skamarock *et al*., 2008) with the fire spread implemented by the level set method. A limited version of the software from 2010 is contained in WRF release as WRF-Fire (Coen *et al.*, 2013). For data assimilation, the fire state in WRF- SFIRE was encoded as fire arrival time *T*, with a value given at every node in a grid on the surface of the Earth. The fire arrival time can be modified and inserted back into the model. The atmosphere model is then restarted from a checkpoint at a time in the past and driven by fire heat fluxes generated by the modified fire arrival time, which allows the proper atmospheric circulation to develop. At the time of the observation, the fire model and the two-way coupling with the atmosphere takes over again. This technique was originally developed in the context of ignition from a given fire perimeter (Mandel *et al*., 2012; Kochanski *et al*., 2016), and it allows multiple cycles of the model advancing in time and of new data being assimilated.

Data assimilation

The satellite data are assimilated in the fire arrival time using the Maximum Aposteriori Probability (MAP) estimator (e.g., Stuart, 2010) from Bayesian statistics. Given forecast fire arrival time $T^{\mathrm{f}} = T^{\mathrm{f}}(x,y)$ on the simulation domain, we maximize the aposteriori probability density

$$p^{\mathrm{a}}\left(T\right) = \text{const}\, e^{\sum_G \sum_{(x,y)\in G} c_G(x,y) f_{G,x,y}(T-t_G,x,y)} e^{-\frac{\alpha}{2}\left\|T-T^{\mathrm{f}}\right\|_A^2} \rightarrow \max_T,$$

which is equivalent to the penalized optimization problem for the log likelihood,

$$-\sum_{G}\sum_{(x,y)\in G} c_G(x,y) f_{G,x,y}(T-t_G,x,y)+\frac{\alpha}{2}\left\|T-T^{\mathrm{f}}\right\|_A^2 \rightarrow \min_T .$$

Here, the first sum is over the granules G being assimilated, the second sum is over the grid nodes (x,y) in the intersection of the granule G and the simulation domain, and $c_G(x,y)$ is the confidence level of the granule G data at the location (x,y). When no data are available for the location, e.g., because of a cloud, $c_G(x,y)$ is taken to be zero. The quantity $f_{G,x,y}$ is the log likelihood – the natural logarithm of the conditional probability of the observed value (fire detection or non-detection) given the fire arrival time. The probabilities of fire detection in MODIS and VIIRS pixels are available from statistical assessment of active fires detection by comparison with high-resolution limited-area satellite imagery (Schroeder *et al*., 2008, 2014) and logistic regression, as a function of the fraction of the sensor pixel on fire and of the largest contiguous fire in the pixel. These are really a proxy for the fire intensity, which could not be directly measured. We use the fire heat flux, which is available in the model, substituted in the logistic function (Fig. 3), which results the shape of the fire detection log likelihood as a function

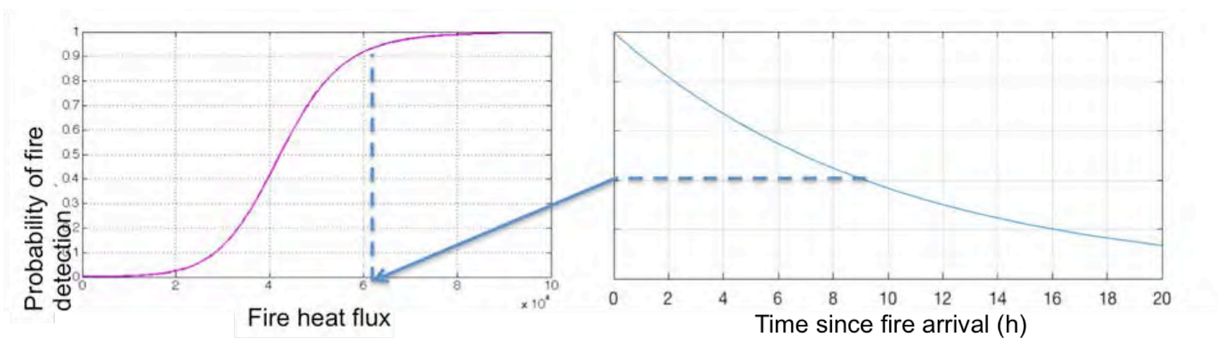

Figure 3. Derivation of the likelihood of detection as a function of the fire arrival time, by composition of the heat release as a function of time (right), and the probability of detection as a function of the heat release (left).

of the time elapsed since the fire arrived at the location (Fig. 4) as in Mandel *et al*. (2014b); the tails model geolocation uncertainty. The likelihood of a land/water pixel (i.e., no fire) is determined from the property that the probabilities of positive and negative outcomes add up to one. In the second term, $\alpha > 0$ is the penalty parameter, and the squared norm in the penalty term is defined as

$$\left\|u\right\|_A^2 \approx \int u\left(-\frac{\partial^2}{\partial x^2}-\frac{\partial^2}{\partial y^2}\right)^a u\,dx\,dy,\ a>1,$$

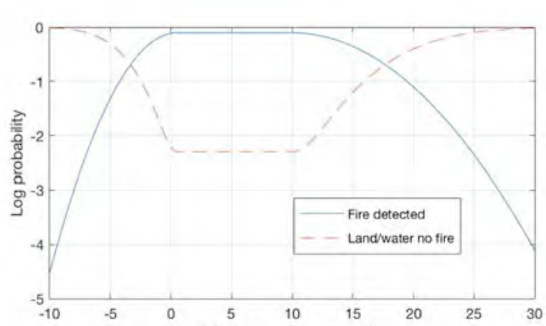

Figure 4. Log likelihood of positive and negative detection as a function of time since fire arrival.

where the fractional power of the Laplace operator is implemented efficiently by Fast Fourier Transform (FFT). The penalty term results in a preference for smooth changes in the fire arrival time *T*, and it prevents overfitting the estimate to uncertain and sparse data. The minimization method is done by gradient descent preconditioned by A^{-1}, which results in spatially smooth search directions. Ignition is treated as a constraint that the fire arrival time is fixed at the point of ignition. One or two iterations are sufficient for acceptable results. See Mandel *et al.* (2014b) for further details of the computational method.

Results

The method was tested on the 2013 Patch Springs fire. The simulation was done at a relatively coarse resolution, 200m fire grid and 4000m atmospheric grid, thus mimicking the situation

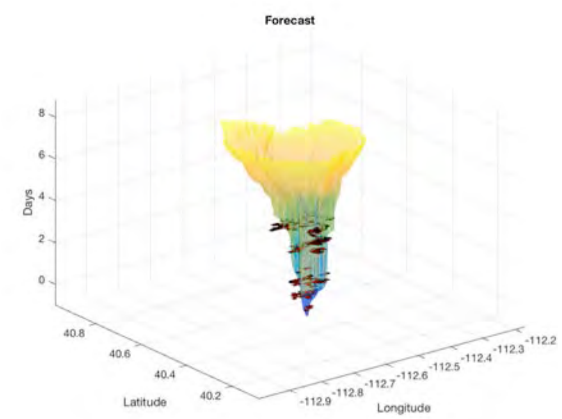

Figure 5. Fire arrival time before the assimilation (the forecast), with MODIS and VIIRS Active Fires detections. Fire detections in a horizontal plane are from one satellite overpass. There are many detections outside of the fire, indicating the need for an adjustment of the model state.

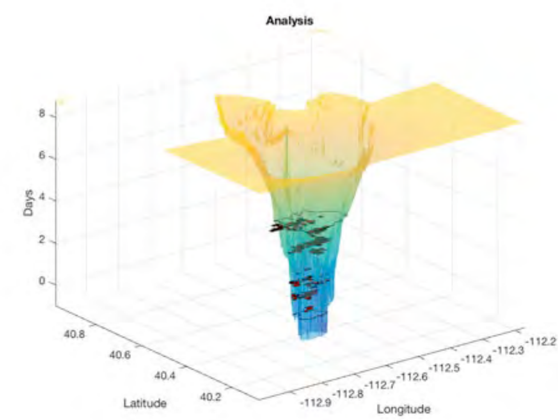

Figure 6. Analysis fire arrival time, with the MODIS and VIIRS Active Fires detections assimilated. The fire detections tend to be more on the inside of the fire shape, which is rendered as transparent. The fire state has changed by data assimilation so almost all detections are now inside the fire.

when the simulation needs to run much faster than real time. The 9 days simulation period started at 00:00 Aug11, 2013 GMT, and the fire ignited 2 hours into the simulation. The forecast state, i.e., the result of the simulation, is shown in Fig. 5. Fig. 6 shows the analysis state, i.e., the simulated fire arrival time with the fire detections taken into account.

Conclusion

We have presented a data assimilation technique, which modifies the state of the fire spread model from Level 2 Active Fires MODIS and VIIRS data. The method incorporates confidence levels and cloud mask, which are present in Level 2 active fires products, and it allows data granules which intersect the simulation area only partially. The method can naturally use data detection from multiple sources with different resolutions and detection characteristics.

Several improvements of the method are in progress. In preliminary experiments, the method has shown to be stable in cycling mode, when observations are assimilated in batches and the simulation continues. Detailed description will be presented elsewhere. Next, the likelihood of detection depends on the brightness in the whole MODIS or VIIRS pixel, as used in the statistical assessments of the active fires detection (Morisette *et al.*, 2005; Schroeder *et al*., 2008, 2014). This approach follows the properties of the hardware (Cao *et al.*, 2014) and the software (Schroeder *et al.*, 2014) stack, in particular the discrete nature of the rows of the CCD sensors in the imager hardware, which effectively integrate the signal over their pixels. Our calculation of data likelihood currently does not follow these physical characteristics of the instrument; rather, the data likelihood is evaluated at nodes of the fire simulation grid, which is much simpler. While the actual scanning by the MODIS and VIIRS instruments is aligned with the flight path of the satellite, we are using more convenient product resampled into GeoTIFF, with the grid aligned with the latitude and longitude. Even if reasonable results were obtained, it might be more accurate to compute the data likelihood from the actual Level 2 data pixels.

More realistic data likelihood should be developed. The current version of the method assumes that the error in the fire arrival time is smooth, which is suitable for global changes. A more sophisticated model of the state uncertainty might allow, e.g., easier change in the state in locations where fire suppression activities are known to exist. With the increasing role of Information Technology (IT) in fire management, this may become possible in near future.

Finally, our current method assumes a given fixed location of the ignition point. Work on estimating the ignition point from uncertain and sparse detections is in progress (James Haley) and it should eventually become a part of the optimization process.

The ultimate goal is a completely autonomous simulation of a wildland fire with no other fire data than satellite sensing.

Acknowledgements

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References

Cao C, Luccia FJD, Xiong X, Wolfe R, Weng, F (2014) Early on-orbit performance of the Visible Infrared Imaging Radiometer Suite onboard the Suomi National Polar-Orbiting Partnership (S-NPP) satellite. *IEEE Transactions on Geoscience and Remote Sensing* **52**, 1142–1156, doi:10.1109/TGRS.2013.2247768.

Coen JL, Cameron M, Michalakes J, Patton EG, Riggan PJ, Yedinak, K (2013) WRF-Fire: Coupled weather-wildland fire modeling with the Weather Research and Forecasting model. *Journal of Applied Meteorology and Climatology* **52**, 16–38, doi:10.1175/JAMC-D-12-023.1.

Coen JL, Schroeder W (2013) Use of spatially refined satellite remote sensing fire detection data to initialize and evaluate coupled weather-wildfire growth model simulations. *Geophysical Research Letters* **40**, 1–6, doi:10.1002/2013GL057868.

Giglio L (2015) MODIS collection 6 active fire product user's guide version 2.6. Department of Geographical Sciences, University of Maryland, available at http://modis-fire.umd.edu/files/MODIS_C6_Fire_User_ Guide_A.pdf, accessed March 2015.

Hawbaker TJ, Radeloff VC, Syphard AD, Zhu Z, Stewart SI (2008) Detection rates of the MODIS active fire product in the United States, *Remote Sensing of Environment* **112**, 2656–2664. doi:10.1016/j.rse.2007.12.008

Kochanski AK, Jenkins MA, Kondratenko VY, Schranz S, Vejmelka M, Clements CB, Davis B (2016) Ignition from fire perimeter and assimilation into a coupled fire-atmosphere model. In Proceedings for the 5th International Fire Behavior and Fuels Conference April 11-15, 2016, Portland, Oregon, USA.

Mandel J, Beezley JD, Coen JL, Kim M (2009) Data assimilation for wildland fires: Ensemble Kalman filters in coupled atmosphere-surface models. *IEEE Control Systems Magazine* **29**, 47–65, doi:10.1109/MCS.2009.932224.

Mandel J, Beezley JD, Kochanski AK (2011) Coupled atmosphere-wildland fire modeling with WRF 3.3 and SFIRE 2011. *Geoscientific Model Development* **4**, 591–610, doi:10.5194/gmd-4-591-2011.

Mandel J, Beezley JD, Kochanski AK, Kondratenko VY, Kim M (2012) Assimilation of perimeter data and coupling with fuel moisture in a wildland fire – atmosphere DDDAS. *Procedia Computer Science* **9**, 1100–1109, doi:10.1016/j.procs.2012.04.119.

Mandel J, Amram S, Beezley JD, Kelman G, Kochanski AK, Kondratenko VY, Lynn BH, Regev B, Vejmelka M (2014a): Recent advances and applications of WRF-SFIRE. *Natural Hazards and Earth System Science* **14**, 2829–2845, doi:10.5194/nhess-14-2829-2014.

Mandel J, Kochanski AK, Vejmelka M, Beezley JD (2014b) Data assimilation of satellite fire detection in coupled atmosphere-fire simulations by WRF-SFIRE. In Advances in Forest Fire Research (Ed DX Viegas), pp. 716–724 (Coimbra University Press)

Morisette JT, Giglio L, Csiszar I, Setzer A, Schroeder W, Morton D, Justice CO (2005) Validation of MODIS active fire detection products derived from two algorithms. *Earth Interactions* **9**, 1–25, doi:10.1175/EI141.1.

Schroeder W, Prins E, Giglio L, Csiszar I, Schmidt C, Morisette J, Morton D (2008) Validation of GOES and MODIS active fire detection products using ASTER and ETM+ data. *Remote Sensing of Environment* **112**, 2711–2726, doi:10.1016/j.rse.2008.01.005.

Schroeder W, Oliva P, Giglio L, Csiszar IA (2014) The New VIIRS 375 m active fire detection data product: Algorithm description and initial assessment. *Remote Sensing of Environment* **143**, 85– 96, doi:10.1016/j.rse.2013.12.008.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG (2008) A description of the Advanced Research WRF version 3. NCAR Technical Note 475, http://www.mmm.ucar.edu/wrf/users/docs/arw_v3.pdf, retrieved December 2011.

Stuart AM (2010) Inverse problems: a Bayesian perspective. *Acta Numerica* **19**, 451– 559, doi:10.1017/S0962492910000061.

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Benefits and Incentives for Fuels Treatment in the Mokelumne Basin, CA

Mark Buckley - ECONorthwest, 222 SW Columbia St. Suite 1600, Portland, OR, buckley@econw.com

Keywords: economics; costs; treatment; incentives; property value; infrastructure; carbon

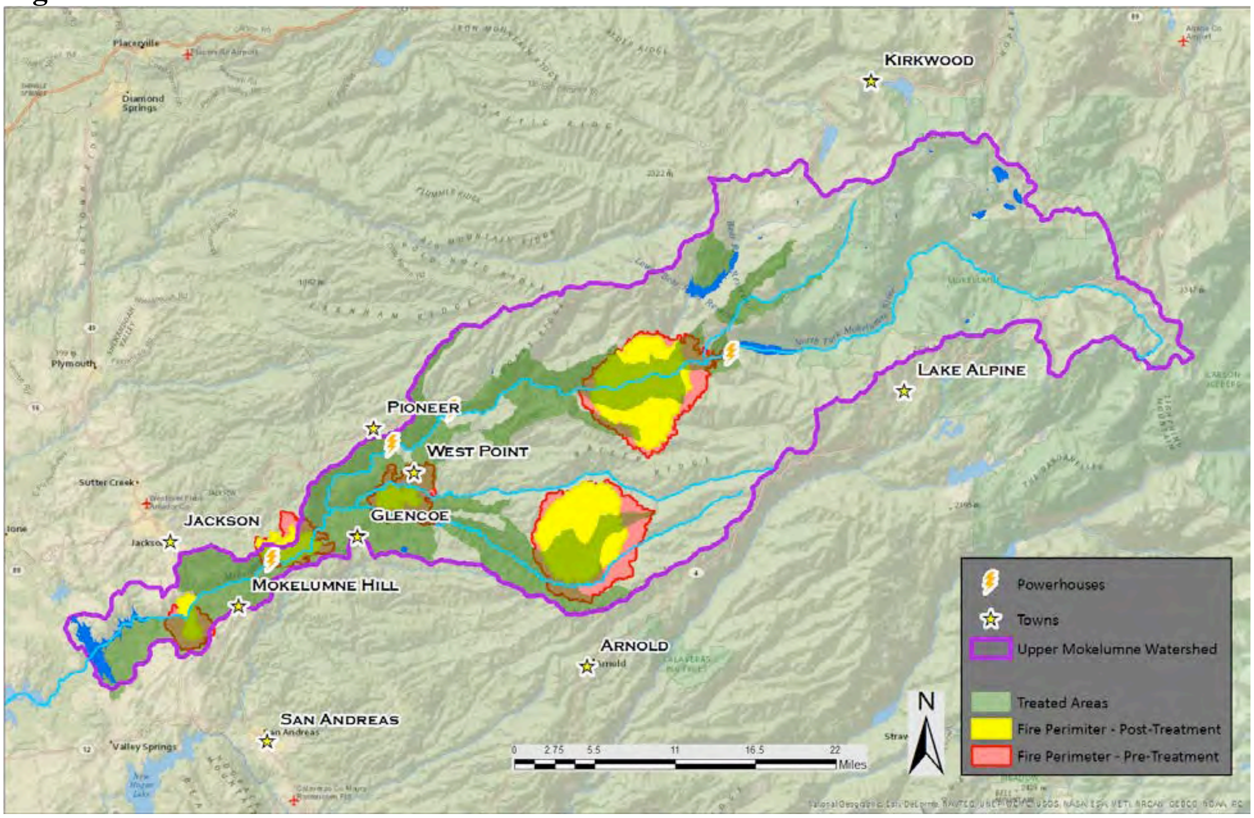
Introduction

The purpose of this analysis is to evaluate the costs and consequences of wildfire in the upper Mokelumne River watershed in the Sierra Nevada, California with and without fuel reduction treatments. Results show that by thinning the forests and reducing hazardous fuels, the probability, extent, and intensity of wildfire in the watershed are substantially reduced, leading to quantifiable cost savings. In short, strategic fuels reduction treatments are a good investment and produce multiple benefits to landowners, residents, and watershed interests and beneficiaries. This treatment strategy for the project area is based on treatments commonly applied by local public land managers. We used the fire model FSim to predict future wildfires in the watershed based on historical patterns and subsequently applied the fuel treatment scenario to the model in order to identify how wildfire characteristics would change in response. We then quantified the financial costs and benefits, including biomass, carbon, and job impacts. It is important to note that because our fire modeling was based on historic fire trends (last 30 years), our conclusions may underestimate the costs and benefits associated with larger, more destructive fires that have become more common in the Sierra Nevada over the last decade and are projected to increase with climate change.

We used the fire simulations to identify the effects of fire directly on assets, including homes, roads, transmission lines, and timber resources. We also estimated the fire suppression costs and carbon emissions, both with and without fuel treatment. We utilized the GeoWEPP and Debris Flow erosion models to evaluate the effects of fire on sediment erosion, and modeled the transport and impact of that sediment on water storage, diversion, and conveyance infrastructure for the utilities in the watershed.

This study shows that the total quantified benefits of fuel treatment in this basin would far exceed the costs of treatment if fires would occur over the next few decades after treatment. The benefits accrue to a wide range of land and water managers and owners, public and private entities, and taxpayers and electric and water utility ratepayers in general. Figure 1 shows that not all fuel treatments were within the vicinity of the five fires. This demonstrates that we include costs for fuel treatments that did not directly provide fire protection in our modeled scenario, just as the reality that not every area treated will experience wildfire. All told, the benefits we accounted for in this study due to fuel treatments total between \$116 and \$211 million (Table 1). If the fires were to occur one year after the treatments were implemented, the benefits would be pushed back by one year, leading to discounting (3 percent) and a shift in the benefit range down to \$113 to \$205 million. Under either case, the quantified benefits are 2 to 4 times the costs (Figure 2).

Figure 1: Locations of Fuel Treatments and Simulated Fires



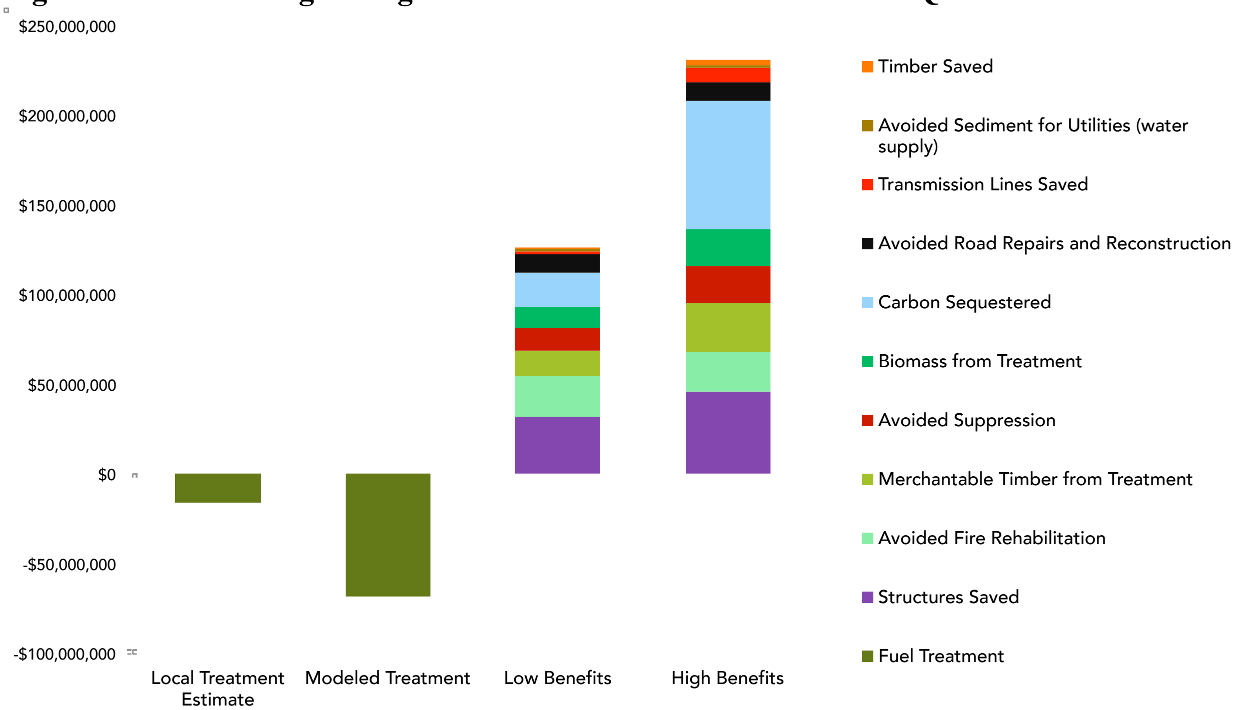
Summary of Fuel Treatment Costs and Benefits

As a first step towards determining the potential costs and benefits, we first defined a potential fuel treatment scenario, which was reviewed and refined by local land managers so that techniques and costs were consistent with local practices. While a literature review suggests a wide potential range of costs ($17-160 million) for our treatment scenario of 99,894 acres, based on local information we estimate a one-time cost of implementing this scenario of approximately $46 million.

Based on consultation with local BLM and USFS staff and prevailing market conditions, we estimate the potential revenue from merchantable timber associated with the fuel treatment efforts would be between $14-27 million under a 1-year treatment plan. Biomass chip revenue, with sufficient demand, regional bioenergy generation capacity, and value added manufacturing, could reach $12-21 million under the 1-year treatment plan.

The modeled wildfires would immediately damage and destroy infrastructure and assets. Homes, businesses, and other public and private structures would be lost. Not including roads or utility infrastructure, the structures in the areas that would have burned in the fire scenario without treatments are worth $46 million. The change in the value of structures in high and medium severity areas of the fires equates to $32 million, providing the range of structural values. While some structures might maintain residual value and only require repairs, others requiring total demolition would have costs greater than simply the replacement construction costs because of cleanup. It is also important to note that these costs are based on county assessor data, where values are constrained by Proposition 13, not replacement cost values from insurance companies, which could significantly increase the value of the structures saved compared with the constrained assessor data.

Figure 2: Low and High Range of Fuel Treatment Costs and Total Quantified Benefits



For private landowners, parcels zoned for timber that do not burn as a result of treatment have assessed value of $1.2 million. Public lands are managed for different objectives than private timber parcels and as a result it is common to use half of the average hectare value of these parcels to estimate the timber value on public lands. When applied to this study, the result is that treatments helped to protect $1.9 million in public timber values, bringing the total of protected timber resources to $3.1 million. Because the timber on public lands may or may not have ever been removed from the forest, we apply its value only to the high benefit side of the avoided costs, while protected private timber values are placed in both the low and high benefit categories. We estimate road repair and reconstruction costs avoided to be $8.6 million. Additionally, the cost savings from avoiding the repair and reconstruction of transmission lines based on this scenario would be $1.6 million.

We estimate fire suppression cost savings to range from $12.5 to 20.8 million, and associated post-fire recovery cost savings of $22.5 million. The avoided carbon emissions for fuel treatment and reduced fire acreage ranges from $19 million, based on current market prices in California, to $71 million when factoring in the social cost of carbon. The social cost of carbon does not yet reflect a revenue opportunity, but because of the high importance the State of California places on climate change and associated regulations to reduce GHG emissions, we believe it is relevant to show this value. When considering cost savings for utility operations in the upper Mokelumne, the lost storage for water supply, discounted over 30 years, would be an estimated $1 million. We do not include values for other potential effects on storage or disruptions in conveyance for electricity generation; see Chapter 6 for discussion of potential risk in these areas.

All told, the benefits we accounted for in this study due to fuel treatments total between $126 and $231 million. If the fires were to occur in the tenth year after the treatment, the 3 percent discounted present value of the treatment would be $106 to $202 million ($86 to 176 million at 7 percent), accounting for the delay in avoided costs inherent with the unpredictability of when severe fires would occur.

Table 1: Total costs and benefits for Fuel Treatment Scenario

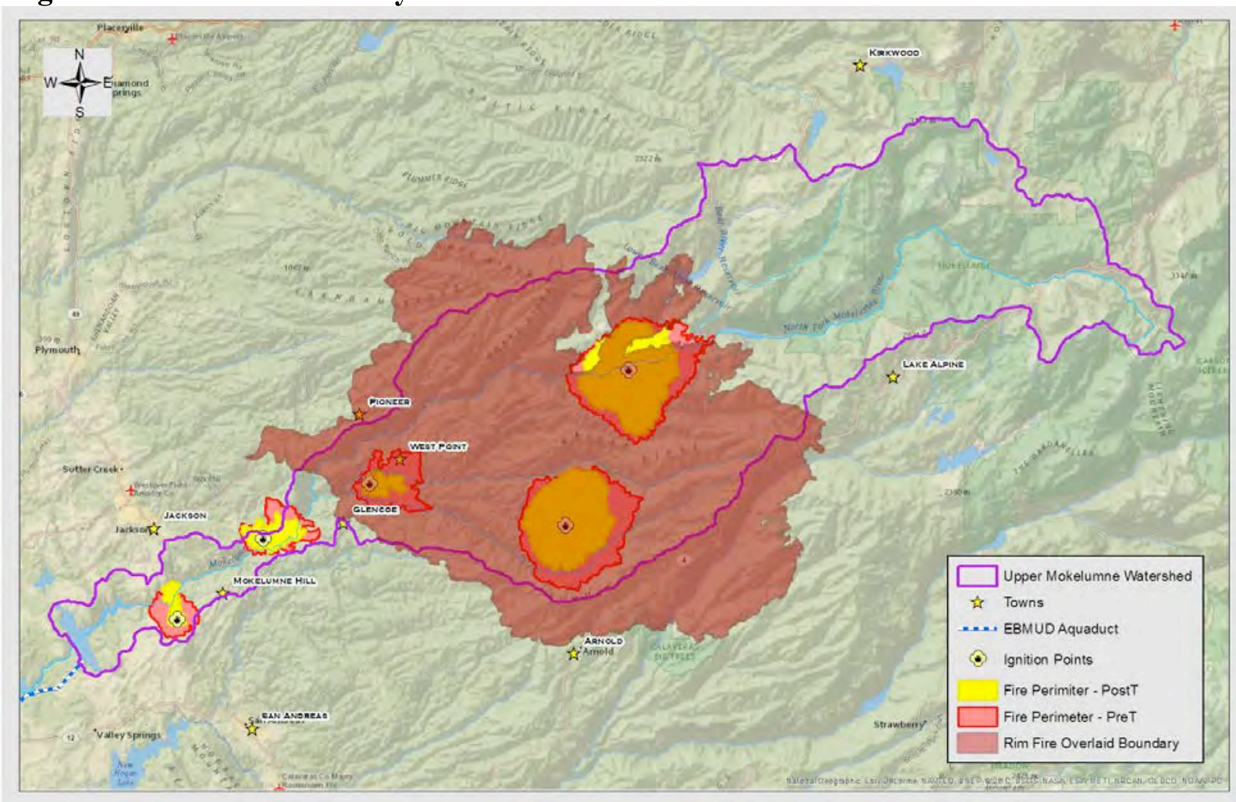
Costs		
Fuel Treatment	$16,000,000	$68,000,000
Benefits	*Low*	*High*
Structures Saved	$32,000,000	$45,600,000
Avoided Fire Cleanup	$22,500,000	$22,500,000
Carbon Sequestered	$19,000,000	$71,000,000
Merchantable Timber from Treatment	$14,000,000	$27,000,000
Avoided Suppression	$12,500,000	$20,800,000
Biomass from Treatment	$12,000,000	$21,000,000
Avoided Road Repairs and Reconstruction	$10,630,000	$10,630,000
Transmission Lines Saved	$1,600,000	$8,000,000
Timber Saved	$1,200,000	$3,130,000
Avoided Sediment for Utilities (water supply)	$1,000,000	$1,000,000
Total Benefits	*$126,430,000*	*$230,000,000*

Note: values rounded to significant figures.

Fire Modeling Implications

We based wildfire risk on the historical fire record; however, as the Rim Fire near Yosemite National Park (which occurred while this study was underway) and other recent conflagrations show, there are larger and higher intensity wildfires occurring today than in the past. As a result, the historic context of our wildfire modeling may have underestimated the scale of future wildfires in the watershed. We attempted to address this limitation with the climate change scenario and by modeling five fires, yet even these fires are considerably smaller in area than the single Rim Fire footprint (Figure 3). In short, the magnitude of the wildfire risk today may be outside of the range that we could model and predict based on the historic record and as a result our avoided costs and benefits may be similarly underestimated.

Figure 3: Rim Fire Boundary Overlaid on Mokelumne Watershed and Simulated Fires

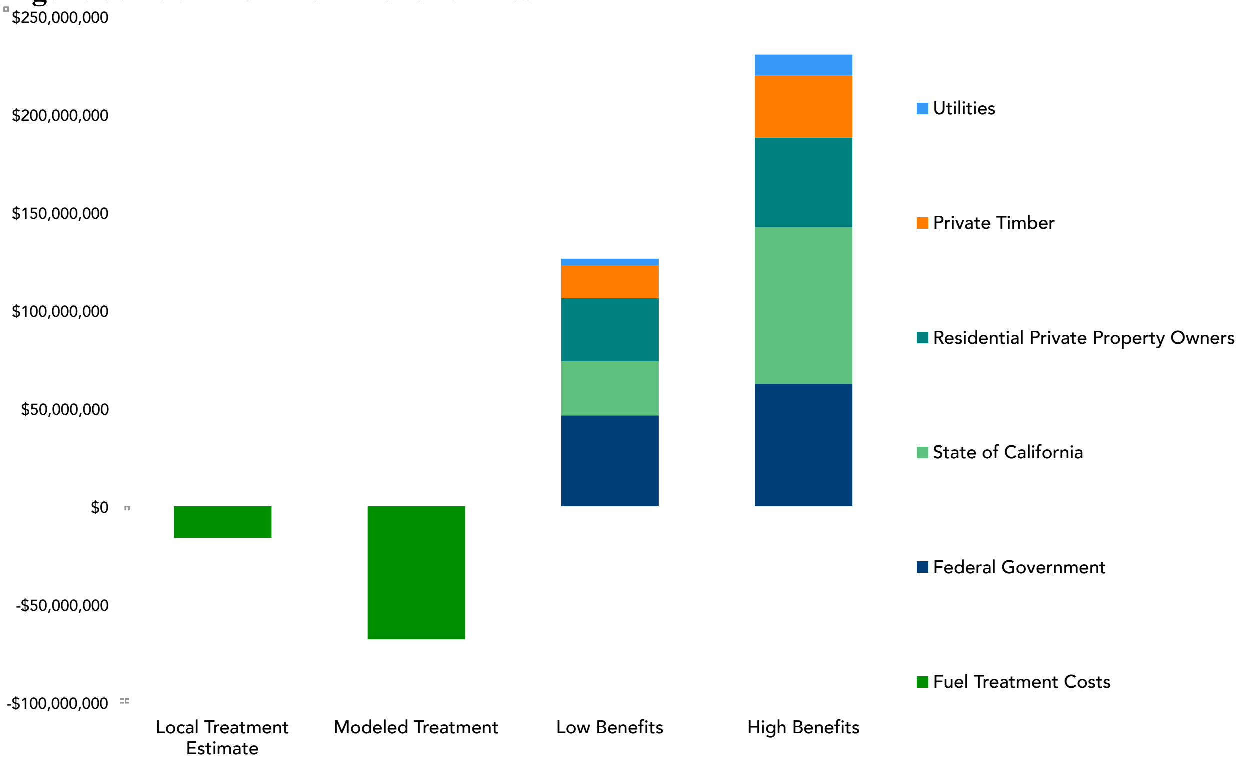


Distribution and Management Implications

This study suggests that the total quantified benefits of fuel treatment would very likely exceed the costs of treatment if fires occur over the next few decades, which is a strong possibility. These benefits accrue to a wide range of land managers and owners, public and private entities, and taxpayers and ratepayers in general. We aggregated benefits from Table 1 by beneficiary to develop Figure 3. It is not feasible to identify the precise breakdown of all benefit categories, but we did break out benefits where data allow. For example, we allocated biomass and merchantable timber benefits from fuel treatment by the breakdown of landownership within the treatment footprints with roughly 36 percent federal and 64 percent private, with 3 percent PG&E and 16 percent SPI (of the total public and private). And while the beneficiaries of carbon sequestration or carbon credit sales would be quite broad, we allocate these benefits to the State of California given the State's climate GHG emission reduction goals and regulations. We also assume the road repair costs would primarily accrue to the state, although some private, county, and federal forest roads would also require repair and reconstruction.

As we show in Figure 3, the primary beneficiaries from our modeling scenario results are the State of California, the Federal Government, and private property (owners and insurers) and timber owners. In addition to the protection of its timber assets, the Federal Government would also see substantial benefits through avoided fire suppression and recovery costs. Relative to overall benefits, the utilities' benefits from our modeling scenarios are relatively modest, but they acknowledge the value of reducing direct risk from fire to structures and transmission lines, as well as disruptions in operation.

Figure 3: Fuel Treatment Beneficiaries



Our analysis demonstrates that the federal government has the potential to benefit from a wide array of avoided costs to protect its revenue opportunities in the form of biomass and timber. Private timber assets are extensive in the fire footprint areas as well. While the overall share of benefits accruing to utilities in this particular watershed is proportionally low, the risk of disruption to water supply can have impacts that might be considered more important than their quantified market effects.[1]

Please see the full study for the numerous contributors to this research effort (full citation):

Buckley, M., N. Beck, P. Bowden, M. E. Miller, B. Hill, C. Luce, W. J. Elliot, N. Enstice, K. Podolak, E. Winford, S. L. Smith, M. Bokach, M. Reichert, D. Edelson, and J. Gaither. 2014. "Mokelumne watershed avoided cost analysis: Why Sierra fuel treatments make economic sense." A report prepared for the Sierra Nevada Conservancy, The Nature Conservancy, and U.S. Department of Agriculture, Forest Service. Sierra Nevada Conservancy. Auburn, California. Online: http://www.sierranevadaconservancy.ca.gov/mokelumne.

[1] Addressing short-term water supply disruptions can be extremely costly for utilities, requiring trucks to bring in emergency water supplies.

Changes in Masticated Fuelbed Properties over Time in the Western U.S.

Pamela G. Sikkink*
USDA Rocky Mountain Research Station, Moscow, Idaho, USA, pamelagsikkink@fs.fed.us
Robert Keane
USDA Rocky Mountain Research Station, Missoula, Montana, USA, rkeane@fs.fed.us
Theresa Jain
USDA Rocky Mountain Research Station, Moscow, Idaho, USA, tjain@fs.fed.us
Faith Ann Heinsch
USDA Rocky Mountain Research Station, Missoula, Montana, USA, faheinsch@fs.fed.us
Jim Reardon
USDA Rocky Mountain Research Station, Missoula, Montana, USA, jreardon@fs.fed.us
Bret Butler
USDA Rocky Mountain Research Station, Missoula, Montana, USA, bwbutler@fs.fed.us

Introduction

Mastication is becoming a common method for site-preparation, removing competition, and altering ladder and surface fuels in forests and shrublands of the United States where land managers are unable to use prescribed burning or treat biomass that has little to no commercial value. Mastication does not remove biomass; rather biomass remains on site and the intent of this treatment is to moderate fire intensity and severity by changing fuel bed characteristics. This is accomplished by using various mechanical methods to chip, shred, or grind the canopy or understory fuels and alter their distribution. Once on the ground, the fuels can be burned with a low-intensity prescribed fire or left to decompose.

During the past two decades, several studies have looked into the characteristics of particles and fuelbed layers created by the mastication (Kane *et al.* 2009; Stottlemeyer *et al.* 2015). Other studies have investigated how the fuel beds burn in lab settings (Ganteaume *et al.* 2011;) and under prescribed fires in the field (Kreye and Kobziar 2015). A small number of studies have examined the ecological effects of mastication left on soil surface (Faist *et al.* 2015; Perchemlides *et al.* 2008;) and when the masticated sites are burned (McIver *et al.* 2013; Southworth *et al.* 2011). One major component missing from past research, however, is insight on what happens to the masticated materials when they are left on the ground where aging and decomposition affects their flammability.

In this project, we examined several sites with different ages of masticated materials in the Rocky Mountains. We examined the physical and chemical characteristics of masticated particles to determine if these characteristics changed with age. Within the entire project, we have examined fire behavior characteristics, smoldering, and soil heating properties in experimental burns; and moisture adsorption and desorption characteristics in moisture experiments. Based on total results, we will also recommend implementation parameters that may alter the decomposition rate and fire behavior characteristics. In this paper, we will only discuss the relationship of particle characteristics and chemical composition to age.

Methods

Field measurements and material collection

Fifteen study sites were selected from northern Idaho to Arizona (Table 1). The primary characteristics used to identify a study site included its primary vegetation (mixed conifer type), mastication method, and age. Study sites located in northern Idaho were classified as "wet" climate sites based on average annual rainfall; the remainder were classified as "dry" climate sites.

Table 1: Field characteristics of study sites
(Ppine=Ponderosa pine, Doug fir = Douglas fir, NF=National Forest, EF=Experimental Forest)

Site Code	Location	State	Dominant Species	Treat date	Age of material	Mastication type
Amber	Boise EF	ID	Ppine	2004	10	Rotating head
AmberNew	Boise EF	ID	Ppine, Doug fir, snowberry	2010	4	Rotating head
BH Mix	Black Hills EF	SD	Ppine, kinnikinnick	2012	2	Mower
BH Mow	Black Hills EF	SD	Ppine, kinnikinnick	2012	2	Mower
DC1	Deception Creek EF	ID	Western hemlock, western white pine, larch, Clintonia	2004	9	Rotating head
LG	Santa Fe NF	NM	Ppine, bunchgrass	2006	8	Horizontal drum head
MEF Chip	Manitou EF	CO	Ppine, Doug fir, snowberry	2004	10	Chipped
MEF WS	Manitou EF	CO	Ppine, Doug fir, kinnikinnick	2005	9	Rotating head
PAL	Santa Fe NF	NM	Ppine, sedge	2011-2012	2	Horizontal drum head
PR3	Priest River EF	ID	Western red cedar, hemlock, white pine	2011	2	Horizontal drum head
PRCC1	Priest River EF	ID	Western white pine, western hemlock, larch	2007	6	Rotating head
Skelton	San Juan NF	CO	Ppine, Doug fir, sagebrush	2010-2011	3	Rotating head
UI	Univ.Idaho EF	ID	Ppine, ninebark	2014	0	Horizontal head
VC1	Valles Caldera Nat. Preserve	NM	Ppine, bunchgrass	2007-2008	6	Horizontal drum head
VC2	Valles Caldera	NM	Ppine, bunchgrass, Ribes	2012	2	Horizontal drum head

Each study site consisted of a 30 x 50m macroplot (Figure 2). Fuelbed depths were collected at three-meter intervals along the six vertical lines of the macroplot (small, regularly spaced vertical dots on Figure 2). Depths included thicknesses for 1) fresh litter; 2) masticated mulch; 3) mixed masticated and duff; 4) duff; and 5) mixed duff and soil.

Microplots (1x1m) were identified within the macroplot to systematically collect masticated material for lab work. Material for analysis was collected according methods developed by Hood and Wu (2006) within 0.5 x 0.5 quadrats in the lower left corner of the 1x1 m microplots. Fuel layer depths were also taken at various points within the microplot. Thicknesses of the five layers obtained from the 0.5 x 0.5 m plot (listed above) and total weights of microplot samples were used to calculate bulk density of the field layers.

Particle and layer characteristics

Fuel samples were sorted into 15 shapes classes. The shapes included cylinder, pyramid (triangle), rectangular parallelepiped, parallelepiped, ellipsoid, paraboloid, neiloid frustrum, semi-cylinder, small wood chips, wood ribbon, bark ribbon, bark piece, bark chunk, duff, and fresh litter. Each shape class was further sorted into 1h, 10h, and 100h size classes. Duff was

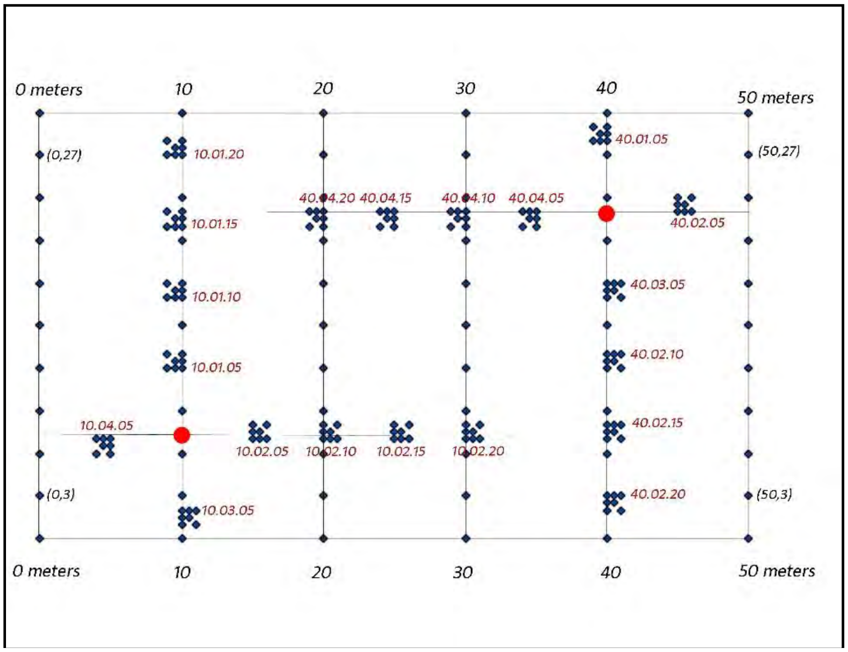


Figure 2. Sampling scales used in this project including a 30x50 macroplot for depth measurements; 1x1 m for collecting depth measures and vegetation data (large blue squares); 0.5 x 0.5 m for collecting depths and collection of masticated materials from fresh litter layer to bare soil depth (smallest blue-squares within 1x1m). Red dot = random starting point for all 1x1 m plot placements.

cleaned of masticated material and fresh litter so that it consisted of material less than 6 mm (0.25 inch) in diameter. Sorted fresh litter consisted of pine needles, cones, and other biomass deposited after mastication.

Materials for the woody shape classes were counted for total number of particles and then weighed. They were subsequently subsampled to at least 5% of the total number of particles. The subsample particles were measured with a caliper, weighed as a group, and placed in an oven at 90^{o}C. Subsample loads were dried for at least 72 hours and then weighed to get the dry weight load.

Particle density of individual pieces was measured by a displacement method using two non-mixing liquids. This method was developed by Guillermo et al (2001) to measure the bulk density of porous objects and was modified for this project to measure fuels.

Mineral content was obtained by heating samples from the duff portion of the sample in a muffle furnace for 24 hours at 550^{o}C then weighing the remaining ash.

Chemical characteristics

Four common shapes, including cylinders (round), triangles (3-sided), parallelograms (4-sided), and wood litter (small chips<3mm thick), were tested for percentage of nitrogen and carbon using a LECO Carbon Nitrogen Analyzer. The 892 samples from these shapes were ground to a fine powder, dried, and processed at the chemistry lab in the Missoula Fire Sciences Laboratory.

The heat contents of the samples were determined using an adiabatic (bomb) calorimeter. This constant-volume calorimeter is commonly used to measure the heat of content of a wide range of materials. The proportion of lignin and holocellulose (cellulose and hemicellulose) was estimated assuming the fuel heat content was a function of the ratio of these two components with heat contents of 24 MJ/kg and 17MJ/kg respectively. These measurements were conducted on the same samples used for carbon and nitrogen percentages.

Statistical analyses

Data were analyzed in three ways. Correlations between variables were tested with (1) all 15 sites combined, (2) only dry sites (11 sites), and (3) paired (old and young) plots between sites. Paired tests included comparisons between Amber:Amber New, DC1:PR3, MEFWS: Skelton, LG:Pal, and VC1:VC2. Non-parametric analysis was used because the underlying distribution of the data is unknown. Simple correlations between variables were conducted using Kendall's tau (k.t.) tests within the R statistics package (R Core Team 2015). Kendall's tau tests the relationship between two variables and provides information on the strength and direction of the relationship. Correlations were considered significant if $p<0.05$.

Results

When all 15 sites were included in each correlation test, the results were different than if just the dry sites or just paired (old and young) sites were used (Table 2). Limiting the correlation tests to dry sites eliminated the climate differences and raised the k.t. values for some tests slightly. However, paired plots showed the highest relationships between age and some variables (Table 2). Paired plots were treated using the same type of machinery and were located relatively close together, effectively eliminating differences in method or climate for the correlations, so age was the only factor tested.

Correlations with age

With data from all 15 sites combined, age had little correlation with the 25 variables tested to date (Table 2). Most of the significant correlations were negative and less than -0.20 (Table 2). Things that would normally be associated with age, such as changes in bulk density (k.t. = -0.12), carbon: nitrogen (k.t. = -0.19), and particle density (k.t. = -0.9), were not well correlated when the data from all sites were combined. When selecting data from dry sites only, climate was negated and correlations were slightly higher (average 0.20 to 0.30). Variables had both positive and negative relationships (Table 2). Correlations between chemistry variables, surface area, and volume were highest among the paired plots (Table 2). Carbon and nitrogen content, particle density, surface area, and surface area-to-volume ratio showed significant differences attributable to age when viewed as paired plots.

Heat content measurements showed significant differences across and within sites. Across all 15 sites, those particles that are structurally intact (i.e., cylinders) have a higher particle density and heat content than fractured (i.e., masticated) particles (Figure 4). This same pattern exists for percent carbon, in which intact cylinders always have more carbon than the fragmented particles do. Among paired sites, the younger mastication unit always has a higher heat content than its paired older unit (Figure 4). The pattern for carbon is more varied. Older sites generally have a higher percentage of carbon in dry climates. In moist climates, however, there is little difference in carbon between old and new sites in the calorimeter data.

Future work

Adiabatic calorimeter work to relate heat content to age and the experimental burns needs to be completed. Analysis of data on smoldering tests is in progress. Several papers on this study are in progress and scheduled for completion in spring 2017. This work will be important for managers determining criteria for mastication and burn prescriptions in mixed-conifer forests.

Table 2: Kendall's tau values for correlations of variables with age and climate. Only Kendall's tau values with significant p-values (<0.05) are shown. Paired plots include a dry and wet example.

	All Sites (15)		**Dry Sites Only (11)**		**Amber: AmberNew (Dry) Pair**	**DC1:PR3 (Wet) Pair**
	AGE	**CLIMATE**	**AGE**	**CLIMATE**	**AGE**	**AGE**
AGE	--	--	--	--	--	--
METHOD	--	--	--	--	--	--
CLIMATE	-0.28	--	-0.33	--	--	--
LITTER LOAD				0.20		
MAST LOAD						
DUFF LOAD	-0.12					
TOTAL LOAD						
1HR LOAD						
10HR LOAD						
100HR LOAD		0.13	-0.17			
LITTER BULK	-0.18	-0.12				
MAST BULK						
DUFF BULK		-0.21		-0.21		
BULK DENSITY	-0.12	-0.25		-0.26		
MINERAL CONTENT				-0.23		
NITROGEN		-0.21		-0.15	0.64	0.47
CARBON		0.17			0.49	0.34
CNRATIO	-0.19	0.24		0.20	-0.54	-0.50
LENGTH	-0.08	0.39		0.20		
WIDTH	0.03					
DRYWT						
PARTICLE DENSITY	-0.09				-0.45	
SURFACE AREA		0.19		0.33		0.51
VOLUME						0.58
SAV RATIO	-0.02	0.24	-0.15	0.30		

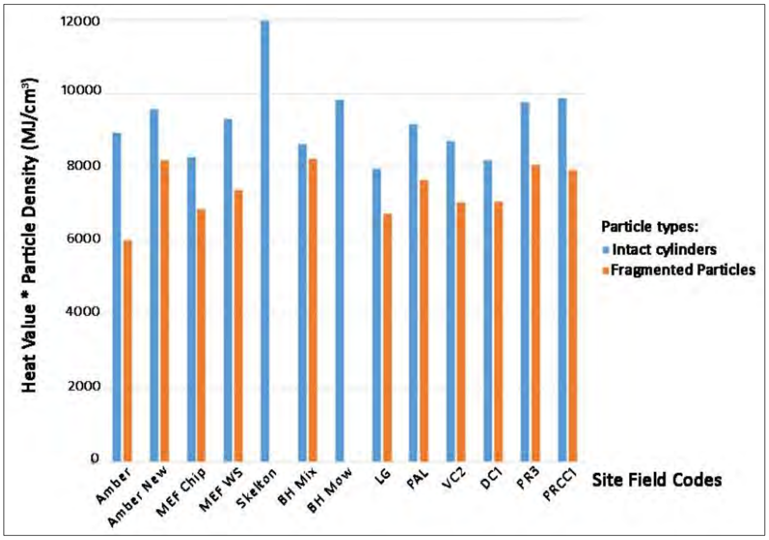


Figure 4. Heat value for intact and fragmented particles from each site. VC1, BHMow, and UI results incomplete. (See Table 1 for site descriptions.)

References

Faist AM, Stone H, and Tripp EA, 2015, Impacts of mastication: Soil seed bank responses to a forest thinning treatment in three Colorado (USA) conifer forest types. Forests 6, 30600-3074.

Ganteaume A, Marielle J, Lampin-Maillet C, Curt T, and Borgniet L, 2011, Effects of vegetation type and fire regime on flammability of undisturbed litter in southeastern France. Forest Ecology and Management 261, 2223-2231.

Guillermo O, Sarli R, Filgueira R, and D. GImenez. 2001. Measurement of soil aggregate density by volume displacement in two non-mixing liquids. Soil Sci. Soc. Am .J. 65:1400-1403.

Kane JM, Varner JM, Knapp, EE. 2009, Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. International Journal of Wildland Fire 18, 686-697.

Kreye JK, and Kobziar LN, 2015, The effect of mastication on surface fire behavior, fuels consumption and tree mortality in pine flatwoods of Florida, USA. International Journal of Wildland Fire 24, 573-579.

McIver JD and many others, 2013, Ecological effects of alternative fuel-reduction treatments: highlights of the Nationl Fire and Fire Surrogate study (FFS). International Journal of Wildland Fire 22, 63-82.

Perchemlides KA, Muir PS, Hosten PE, 2008, Responses of chaparral and oak woodland plant communities to fuel-reduction thinning in southwestern Oregon. Rangeland Ecol Manage 61. 98-109.

R Core Team, 2015, R: A language and environment for statistical computing. R Foundation for Statistical Computing Vienna, Austria. URL https://www.R-project.org

Southworth D, Donohue J, Frank JL, and Gibson J, 2011, Mechanical mastication and prescribed fire in conifer-hardwood chaparral: differing responses of ectomycorrhizae and truffles. International Journal of Wildland Fire 20, 888-896.

Stottlemeyer AD, Waldrop TA, and Wang GG, 2015, Prescribed burning and mastication effects on surface fuels in southern pine beetle-killed loblolly pine plantations. Ecological Engineering 81, 514-524.

Comparative Study of Emission Factors and Mutagenicity of Biomass Smoke from Smoldering and Flaming Combustion

Yong Ho Kim, Sarah Warren, Todd Krantz, Charly King, Richard Jaskot, Mark Higuchi, David DeMarini, M. Ian Gilmour
National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA
kim.yongho@epa.gov, warren.sarah@epa.gov, krantz.todd@epa.gov, king.charly@epa.gov, jaskot.richard@epa.gov, higuchi.mark@epa.gov, demarini.david@epa.gov, gilmour.ian@epa.gov

Michael Hays
National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA
hays.michael@epa.gov

Matthew Landis
National Exposure Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC, USA
landis.matthew@epa.gov

Abstract
Wildfire events produce massive amounts of smoke and thus play an important role in local and regional air quality as well as public health. It is not well understood however if the impacts of wildfire smoke are influenced by fuel types or combustion conditions. Here we developed a novel combustion and sample-collection system that features an automated tube furnace to control combustion conditions, and a multi-stage cryo-trap system to efficiently collection particulate and semi-volatile phases of smoke emissions. Five different types of biomass fuels (red oak, peat, pine needles, pine, and eucalyptus) were tested at two different combustion conditions (flaming and smoldering) to represent western and eastern wildland fires in the United States. The furnace sustained stable flaming and smoldering biomass burning conditions consistently for ~60 min. The multi-stage cryo-trap system (-10°C followed by -47°C, and ending in -70°C sequential impingers) collected up to 90% (by mass) of the smoke. Condensates were extracted and assessed for mutagenicity (polycyclic aromatic hydrocarbons (PAHs)- and nitroarene-type activity) in Salmonella strains TA100 and TA98+/-S9. Carbon dioxide, carbon monoxide (CO), and particulate matter (PM) concentrations monitored continuously during the combustion process were used to calculate modified combustion efficiency (MCE) and emission factors (EFs). We found that the MCE of all the biomass fuels during smoldering conditions was in a range from 63% to 83%, and during flaming conditions, was in a range from 97% to 99%. In addition, all the biomass fuel smoldering EF for CO ranged from 158 g/kg to 299 g/kg, whereas flaming EF ranged from 16 g/kg to 29 g/kg. Smoldering EF for PM ranged from 55 g/kg to 174 g/kg, whereas flaming EF ranged from 0.6 g/kg to 1.6 g/kg. A preliminary assessment of the mutagenic potential of the biomass smoke showed that flaming emissions (e.g., eucalyptus flaming emission) were more mutagenic (up to ~6 times and ~19 times in TA100 and

TA98+S9, respectively) than smoldering emissions on an equal-mass smoke exposure basis. However, on an equal-mass fuel consumption basis, smoldering emissions (e.g., red oak smoldering emission) were more mutagenic (up to ~107 times and ~90 times in TA100 and TA98+S9, respectively) than flaming emissions. Most mutagenicity emission factors in strain TA100+S9 were greater than those in strain TA98+S9, indicating that the mutagenicity was associated with PAHs. The results demonstrate that 1) type of fuel and combustion conditions have dramatic differences in emission characteristics and mutagenicity; 2) the presented system can be useful for the health risk assessment from inhalation exposure to wildfire smoke; and 3) health impacts of wildfire smoke can be assessed on an equal-mass PM exposure basis or an equal-mass fuel consumption basis. [This study was funded through the Joint Fire Science Program (JFSP) project # 14-1-04-16. This abstract does not represent official USEPA policy.]

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Conditions for Intense Vapor Formation of Heterogeneous Liquid Droplets with Their Explosive Disintegration

Maxim Piskunov
National Research Tomsk Polytechnic University, Tomsk, Tomsk Region, Russian Federation, piskunovmv@tpu.ru

Pavel Strizhak
National Research Tomsk Polytechnic University, Tomsk, Tomsk Region, Russian Federation, pavelspa@tpu.ru

Introduction

Nowadays, the state-of-art fire-fighting equipment and well-organized elimination of consequences of natural disasters are insufficient to solve forest-fire problem. Deep knowledge is required to explain regularities of origination, spreading and growth of forest fires, as well as processes of fire extinguishing associated with the intense heat exchange in the flame zone.

Investigations of large forest fire as a phenomenon, preventative measures and consequences of this natural disaster are a field of research with particular difficulties and restrictions [1, 2]. The known and persistent problems in firefighting practice are, for example, the effect of wind, interaction between wind and convective column, entrainment of firebrands of forest fuel materials with further ignition of another forest area [1]. In addition, each of these factors is difficult to take into account in case of mathematical and physical simulation of process.

However, the detail discussion on phase transition mechanisms of droplets of extinguishing liquid when interacting with high-temperature flame is of strong interest. Nevertheless, there are some restrictions as for instance the lack of experimental base about boiling and evaporation of droplets of the extinguishing agents under intense heat exchange that is typical for large forest fires.

Over recent years, the cycle of experimental and theoretical research [3–5] was performed to study the deformation of large (3–6 mm) single liquid droplets, deceleration and entrainment of droplets (0.05–0.35 mm in size) when evaporating spray flows in the counter flow of combustion products. In these experiments, the temperature conditions (about 1000 K) conform to typical large forest fires. Moreover, in the papers [6, 7] at the same temperature conditions, the significant enhancement of heat and mass transfer took place owing to the addition of solid non-metallic inclusions (from several dozens of micrometers to several millimeters).

Crucially, in the research [7], the phenomenon of intense vapor formation of liquid occurred at the internal interfaces of heterogeneous droplets. The rapid development of this mechanism contributed to the explosive breakup (disintegration) of heterogeneous liquid droplets during short time (2–6 s). As a result, small droplets (groups of droplets) detached from the liquid layer. We believe that when extinguishing forest fire using flows of the heterogeneous droplets such phenomenon will contribute to the formation of cloud consisting of the small-sized droplets and vapor. Finally, the formed cloud can cover larger area of flame and, moreover, limit the oxidizer supply in the burning area. Furthermore, the significant saving water resources can be reached by the explosive breakup. In the paper [7], the authors tried to explain the physical nature of such phenomenon, to reveal conditions for its origination and to determine system parameters that can vary during experiments. Taking into account a large amount of these parameters and difficulties to consider each of them, only several conditions of the intense vapor formation with the explosive disintegration were specified definitely. Among these are, primarily, the temperature of gas area that surrounds a heterogeneous droplet, as well as the material of inclusions and their physical parameters.

During the following research (for instance, [8–10]), other conditions to enhance heat transfer in the system under consideration are determined. Owing to these conditions, at least boiling took place.

In the paper, to combine the established regularities and conditions of the revealed novel physical phenomenon is appropriate. Afterwards the development of practical recommendations for use of the results when extinguishing large forest fires will become possible.

The purpose of the present work is to investigate, by experiment, the conditions for intense vapor formation of heterogeneous liquid droplets with their explosive breakup when heated at the temperatures that are typical for the large forest fires.

Materials and Methods

To perform the experimental research, we used the multifunctional laboratory setup equipped by high-speed camera *1*, as well as the devices to provide the optical diagnostics of combustion product flow *5*, *6* and to produce high-temperature areas *2–4*. The latter includes hot air blower *3*, muffle furnace *4* and cylindrical channel (with burner at the bottom) filled in combustion products of typical fuels *2*. Figure 1 illustrates the scheme of the setup. The red circles show the regions to insert heterogeneous liquid droplets in high-temperature area (see inset of Figure 1). The devices to heat heterogeneous droplets enable to take into account the influence of combustion product flow, the variation of the heated air velocity and the convective heating. According to the main steps, the experimental technique is similar to the one applied in research [6, 7]. However, in this paper, we will briefly present the main technical tips and explanations.

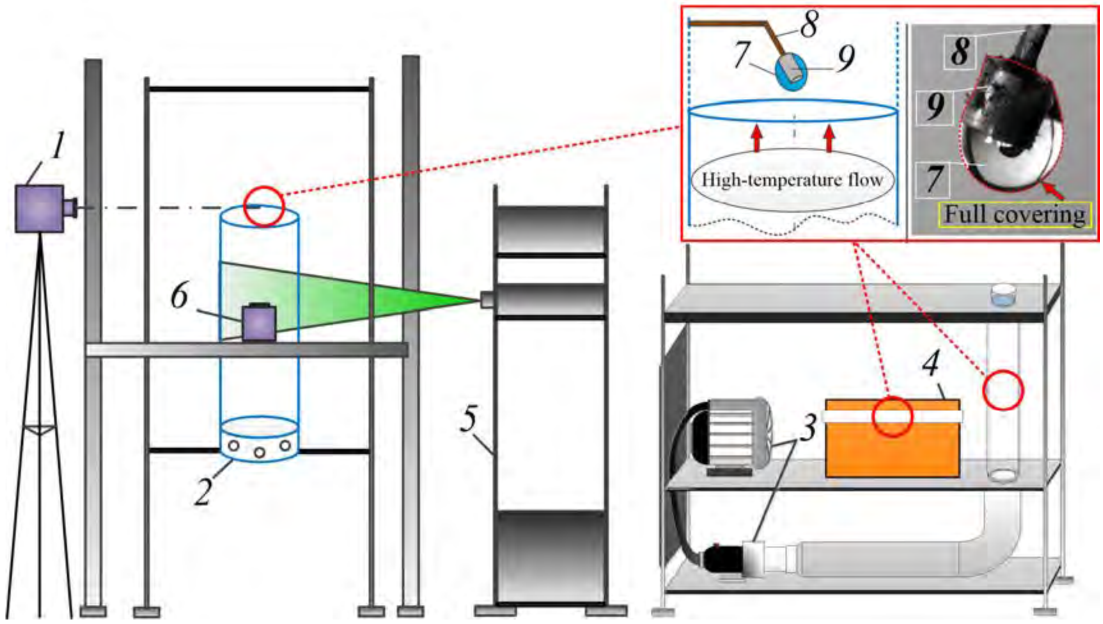

Figure 1. Scheme of experimental setup: *1* – high-speed camera; *2* – burner with cylindrical channel; *3* – hot air blower; *4* – muffle furnace; *5* – optical diagnostics of combustion products rate; *6* – cross-correlation camera; *7* – liquid droplet; *8* – ceramic rod; *9* – solid inclusion

Creation of Heterogeneous Droplets

The research performed with the heterogeneous liquid droplets fixed on ceramic rod *8* (see inset of Figure 1). The heterogeneous liquid droplet is a single solid inclusion inside the liquid droplet. The pure graphite was chosen as a material of inclusions. The size of inclusions was from 2 mm to 4 mm. The shapes of inclusions were a cylinder, cube, parallelepiped, sphere and polyhedron. Errors on measurements of solid inclusion size did not exceed 0.05 mm. The inclusions were fixed on ceramic rod *8* mechanically. The analytical balance measured the mass of inclusions. The dosing device took liquid of the required volume out of the vessel to cover the inclusion. The volume of liquid in the experiments varied in the range from 5 μl to 15 μl. The mandatory requirement for each test was a full covering of solid inclusion *9* by liquid droplet *7* (see inset of Figure 1). This condition was possible by dipping inclusion *9* in the vessel with liquid (at ~298 K) during several seconds before each experiment. Additionally, the inclusion is cooled down to the initial temperature. In the experiments, the following liquids were used: distilled water, solutions of distilled water with wetting agent, aerated water.

High-speed recording and PIV measurements

By using high-speed recording, we determined the lifetimes of heterogeneous liquid droplets in high-temperature areas and specified the regularities of their phase transitions. Errors on lifetime determination were 0.01 s.

PIV (Particle Image Velocimetry) technique was applied to monitor combustion product flow rate in the cylindrical channel. The procedure of similar measurements is presented in [6].

Temperature recording in high-temperature area

The temperature monitoring in high-temperature areas was performed by type K thermocouples fixed near the heterogeneous liquid droplets.

Method of procedure

(1) Using the moving mechanism operated by PC, a heterogeneous liquid droplet was introduced in high-temperature area.
(2) When moving droplet in the focusing point, the video recording became active.
(3) After evaporating liquid, solid inclusion was moved back from high-temperature area.
(4) Cooling and preparing next liquid droplet; determining lifetimes of droplet according to the recorded video track and temperature of area during the test.
(5) Repeating (1)–(4) points.

Under identical conditions, we performed the three series of experiments consisting of six tests for each variant of heterogeneous liquid droplet.

Results and Discussion

Figure 2 shows the typical frames of the considered physical phenomenon.

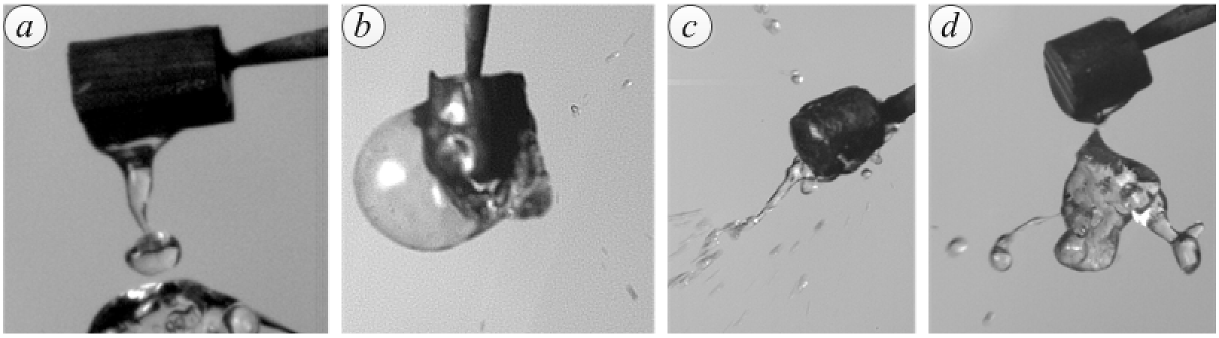

Figure 2. Examples (*a–d*) of heterogeneous droplet breakups [7]

The explosive breakup of droplet is due to the intense formation of vapor bubbles at the surface of solid inclusion. The growth of vapor bubbles at the interface of inclusion surface / liquid layer and their further evolution including the coalescence and detachment from the interface lead to filling droplet by vapor and thinning liquid film [7]. In the experiments, we observed most often from several successive explosions of large vapor bubbles to several dozens. In addition, every time the groups of small liquid droplets were detached from the liquid layer.

The conditions that contribute to intense vapor formation with explosive breakup of heterogeneous liquid droplet are as follows:

1. Heating temperature;
2. Using large (~3–5 mm) heterogeneous droplets;
3. The material of inclusion is a pure graphite; the shape of inclusion is a polyhedron (including such artificial irregularities of surface as the roughness and porosity);
4. Decreasing surface tension force of water by the addition of wetting agents with certain concentration;
5. Using aerated water as a liquid in heterogeneous droplet.

The main condition is to reach the temperature of area contributing to the formation of vapor bubbles at the interface of liquid layer / inclusion surface. In this case, the growth rate of vapor bubbles must significantly exceed evaporation rate of liquid from the surface of droplet. Furthermore, the growth rate of vapor bubbles and their further evolution mainly influence the duration of processes (explosions) that was specified in [7]. Also, using the pure graphite with high thermal conductivity is critically important. The preliminary experiments with the similar materials did not reveal any prerequisites to the nucleate boiling. The shape, as the experiments [7] showed, also play the important role to enhance heat transfer. It is obvious that the edges, irregular shape of inclusions, roughness and pores increase the heat-exchange surface area. Thus, the amount of heat supplied to the liquid layer from the inclusion grows.

In the investigations [8–10], other authors studied how to enhance heat transfer in a different way and to initiate vapor formation at the internal interfaces. As a result, using the solutions with the addition of wetting agents and the carbonation contribute to the formation of vapor bubbles at the surface of inclusions.

The solutions with the addition of surfactants and the aerated liquids are intensively used in state-of-art firefighting technologies. Therefore, the following practical recommendation can be stated to extinguish forest fires:

- The intense vapor formation with the breakup of single droplets and the further formation of vapor-droplet cloud can occur by the large (up to 4 mm) and rough (edges, pores etc.) graphite particles that are added in the flow of typical extinguishing liquid with the certain concentration. The temperature in immediate proximity to the flame zone will provide the conditions for the considered mechanism at the internal interfaces. Moreover, the mass of the formed heterogeneous flow will be higher than the one of homogeneous flow. Thus, the convective column will entrain less droplets.

The findings expand the experimental base of the research on heat transfer enhancement in the heterogeneous systems. We believe that the further study is crucial to develop the possible ways to initiate the intense vapor formation with breakup of the liquid layer of heterogeneous droplet. The performance of the experiments with the group of droplets (flow of heterogeneous droplets) in a laboratory environment and by the standardized fire sources is also recommended.

Conclusion

We stated the revealed conditions of the intense vapor formation with explosive breakup for the heterogeneous (with single large graphite inclusions) liquid droplets when heated at the temperatures that are typical for the large forest fires. In addition, to develop the future technology of the firefighting, the practical recommendation was specified.

Acknowledgements

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References

1. Wang H-H (2011) Analysis on downwind distribution of firebrands sourced from a wildland fire. *Fire Technology* **47**, 321-340.
2. Viegas DX, Simeoni A (2011) Eruptive behaviour of forest fires. *Fire Technology* **47**, 303-320.
3. Strizhak PA, Volkov RS (2016) The integral characteristics of the deceleration and entrainment of water droplets by the counter flow of high-temperature combustion products. *Experimental Thermal and Fluid Science* **75**, 54-65.
4. Volkov RS, Kuznetsov GV, Strizhak PA (2015) Water droplet deformation in gas stream: Impact of temperature difference between liquid and gas. *International Journal of Heat and Mass Transfer* **85**, 1-11.
5. Volkov RS, Kuznetsov GV, Strizhak PA (2016) Influence of droplet concentration on evaporation in a high-temperature gas. *International Journal of Heat and Mass Transfer* **96**, 20-28.
6. Volkov RS, Piskunov MV, Kuznetsov GV, Strizhak PA (2016) Water droplet with carbon particles moving through high-temperature gases. *Journal of Heat Transfer* **138**, Article ID 014502.
7. Kuznetsov GV, Piskunov MV, Strizhak PA (2016) Evaporation, boiling and explosive breakup of heterogeneous droplet in a high-temperature gas. *International Journal of Heat and Mass Transfer* **92**, 360-369.
8. Jeong YH (2008) Wettability of heated surfaces under pool boiling using surfactant solutions and nano-fluids. *International Journal of Heat and Mass Transfer*. **51**, 3025–3031.

9. Agogo H (2011) Spreading and evaporation of surfactant solution droplets. *Progress in Colloid and Polymer Science*. **139**, 1–6.
10. Power IM, Harrison AL, Dipple GM, Wilson SA, Kelemen PB, Hitch M, Southam G (2013) Carbon mineralization: From natural analogues to engineered systems. *Reviews in Mineralogy and Geochemistry*. **77**, 305-360.

Development and Application of a High-Resolution (5-m) Fuel Model Map based on LiDAR and NAIP for Marin County, California

ShihMing Huang*, Nathan Pavlovic, Tami Lavezzo
Sonoma Technology, Inc. Petaluma, CA, USA
shuang@sonomatech.com, npavlovic@sonomatech.com, tami@sonomatech.com

Stacy Drury
USDA Forest Service Pacific Southwest Research Station (formerly at Sonoma Technology), Davis, CA, USA, s.drury@fs.fed.us

Christie Neill, Tim Walsh
Marin County Fire Department, Woodacre, CA, USA
CNeill@marincounty.org, TWalsh@marincounty.org

Todd Lando
FIRESafe Marin, San Anselmo, CA, USA, toddlando@firesafemarin.org

Keywords: WUI, CWPP, LiDAR, remote sensing, fuel model, modeling

Background and Overview

In response to growing fire risk in the wildland-urban interface (WUI) and the enactment of the Healthy Forests Restoration Act in 2003, communities are increasingly using Community Wildfire Protection Plans (CWPPs) to help mitigate the risks posed by wildfire events. The distribution of fuels surrounding and across a community is a critical piece of information for CWPP development. Using up-to-date, high-resolution fuel maps, communities are able to assess fuels and model potential fire behavior should a wildfire event occur. Such modeling exercises can be used to help prioritize fuel reduction efforts; however, accurate results rely on representative information about the type of fuels available to burn, fuel moisture, and weather.

As part of the effort to update the CWPP for Marin County, California, we compiled 5-meter-resolution and 30-meter-resolution fire behavior fuel model maps to provide an updated, high-resolution data layer of current fuel conditions that is more accurate than the standard LANDFIRE fuel map (30-m). The maps were derived from available LiDAR and aerial imagery as well as datasets reflecting vegetation types and the presence of structures, roads, and water bodies. These maps are critical tools for Marin County fire hazard mitigation planning; they were used to conduct analyses of fire risk and fire hazard reduction projects described in the CWPP.

Methods

Input Datasets

LiDAR data in LAS point cloud format were obtained via the USGS EarthExplorer website. The data, which provide complete coverage of Marin County at 2-meter nominal pulse spacing or better, were collected in 2010 by the ARRA Golden Gate LiDAR Project. National Agriculture

* ShihMing Huang, 1455 N. McDowell Blvd, Suite D, Petaluma, CA, 94954; 707.665.9900; shuang@sonomatech.com

Imagery Program (NAIP) JPEG2000 orthorectified imagery collected over Marin County between June 8 and June 13, 2014, was also downloaded from the USGS Earth Explorer website.

We used three available vegetation datasets to provide information about vegetation types for portions of Marin County: (1) the 2008 Marin County Open Space District (MCOSD) vegetation dataset obtained from the California Department of Fish and Wildlife (CDFW) GIS Clearinghouse, (2) the 2009 Marin Municipal Water District (MMWD) vegetation dataset obtained from the CDFW GIS Clearinghouse, and (3) the Existing Vegetation Classification and Assessment with LANDSAT of Visible Ecological Groupings (CALVEG) dataset, mostly based on 2007 imagery, published by the USDA Forest Service Pacific Southwest Region Remote Sensing Lab. We used building footprint, water body, and road network vector data obtained from MarinMap (http://www.marinmap.org) to refine vegetation information for Marin County.

Figure 1 illustrates how the input datasets fit into the overall data processing scheme. Details of each processing step are described in the Image Processing, Fuel Model Crosswalk, and Fuel Model Adjustments sections.

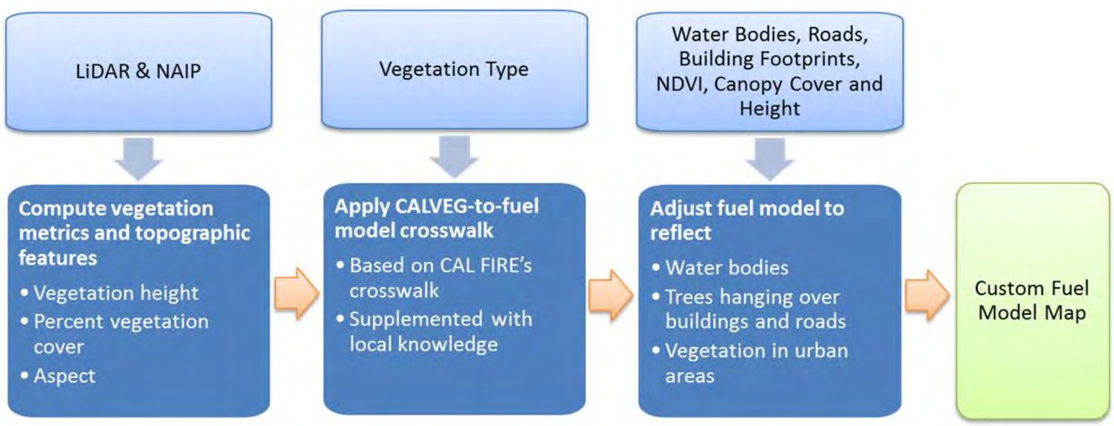

Figure 1. Process used to create the Marin County fuel model map. NDVI = Normalized Difference Vegetation Index.

Image Processing

We combined LiDAR and NAIP imagery for Marin County to obtain information about vegetation cover and topography across the county. All rasters produced for use in this project were aligned to the datasets derived from raw LiDAR point clouds, projected to UTM zone 10N using the NAD83 datum with a cell size of 5 meters.

LiDAR tiles were combined and processed using standard ArcGIS geoprocessing tools to derive bare earth elevation, slope, aspect, vegetation height, and vegetation percent cover. Vegetation height and vegetation cover on the 5-m grid were calculated using the internal point classification, which groups vegetation and building returns together. To differentiate between buildings and vegetation, Normalized Difference Vegetation Index (NDVI) values derived from NAIP imagery were used to mask locations with NDVI < 0 as non-vegetation. To exclude shrubs and other low-lying vegetation from the percent canopy cover calculation, we assigned all pixels in the percent canopy cover with a canopy height less than 3 meters to a percent canopy cover value of 0%. The vegetation and topographic information derived from these datasets were used as inputs to produce fuel model information for Marin County.

Fuel Model Crosswalk

To obtain the fuel information required for fire behavior modeling, we integrated the LiDAR- and NAIP-derived datasets with vector information reflecting vegetation type, building footprints, water bodies, and roads. The result of this analysis is a 5-meter-resolution dataset providing 40 Scott and Burgan fire behavior fuel model assignments (Scott and Burgan, 2005) for all of Marin County.

We first combined the three sources of vegetation type information, replacing the vegetation types identified by the CALVEG dataset with the more recent and localized MMWD and MCOSD classifications where valid data were available. Aspect, vegetation height, percent vegetation cover, and vegetation type datasets were used in a crosswalk to assign fuel models. We used a modified version of a crosswalk furnished by Dave Sapsis at CAL FIRE. The crosswalk assigns a fuel model to each pixel based upon that pixel's vegetation type, vegetation height, percent vegetation cover, and aspect. We modified the crosswalk to address vegetation types assigned to locations within Marin County that were not addressed by the original crosswalk, based on our knowledge of local vegetation and with feedback from Marin County Fire Captain Tim Walsh.

None of the vegetation datasets provided vegetation type information for Angel Island. We created a simple fuel model crosswalk for Angel Island based on canopy height and canopy cover values and visual examination of aerial imagery. The Angel Island fuel model information was appended to the fuel model dataset covering the rest of the county.

Fuel Model Adjustments

We modified the fuel model map described above to better account for the location of roads, structures, and water bodies based on local knowledge of the WUI communities, fuel characteristics, and fire behavior. All locations falling within a water body were modified to an unburnable fuel model. In addition, a series of filtering steps were applied to reflect the presence of flammable vegetation in urban/developed areas. To account for the flammable vegetation that was initially classified as unburnable, we used canopy cover and canopy height to reassign all urban/developed fuel model areas with an NDVI greater than 0 to a flammable vegetation class.

Next, we used road location information to assign pixels to the unburnable urban/developed fuel model or to a timber litter fuel type model based on the presence of canopy cover. Large roads (freeways and highways) were buffered to 10 m and small (local) roads were buffered to 5 m. The percent canopy cover of each pixel within the buffered roads was obtained, and roads with greater than 30% canopy cover were classified as burnable. Fuel overhanging a road may allow fire to spread over that road. Roads with less than 30% cover were classified as unburnable.

A similar approach was used to address vegetation overhanging buildings. We used the building footprints and percent canopy cover data to assign a fuel model to all building locations. Buildings with 20-40% canopy cover were classified as a timber litter fuel type model, and buildings with greater than 40% canopy cover were assigned a timber-understory fuel type model. Buildings with less than 20% canopy cover were classified as unburnable.

Landscape File Creation
A landscape file (.lcp) is required by common fire behavior models such as FlamMap to simulate fire behavior. A landscape file consists of eight layers of vegetation and geophysical information. The geophysical layers are elevation, slope, and aspect; the vegetation layers are fuel model, vegetation height, percent vegetation cover, canopy bulk density, and canopy base height.

Based on our knowledge of local vegetation, we assigned canopy base height a universal value of 0.91 m (3 ft) for all pixels assigned either a timber-understory or a timber litter fuel type model. In lieu of actual field measurements of canopy fuels in Marin County, canopy bulk density was estimated for pixels with a timber-understory or a timber litter fuel type model using plot data collected for ponderosa pine/Douglas-fir and Sierra Nevada Mixed Conifer forest types in the Interior West (Scott and Reinhardt, 2005). For each fuel model and canopy cover bin, a canopy bulk density value was assigned.

We used ArcFuels (http://www.arcfuels.org/) to composite the 5-m rasters of the eight data layers into a landscape file. In addition, we used bilinear interpolation and majority method resampling to convert these raster datasets to 30-m resolution, and created a 30-m landscape file for fire modeling in the Interagency Fuels Treatment Decision Support System (IFTDSS).

Results and Conclusion
The final 5-m fuel model map of Marin County is shown in Figure 2. We compared our high-resolution map to the standard LANDFIRE fuel map. Visual inspection of our custom fuel model map revealed not only greater detail but also more realistic distributions of fuels throughout the county, as seen in a sample area (Woodacre, CA) in Figure 3.

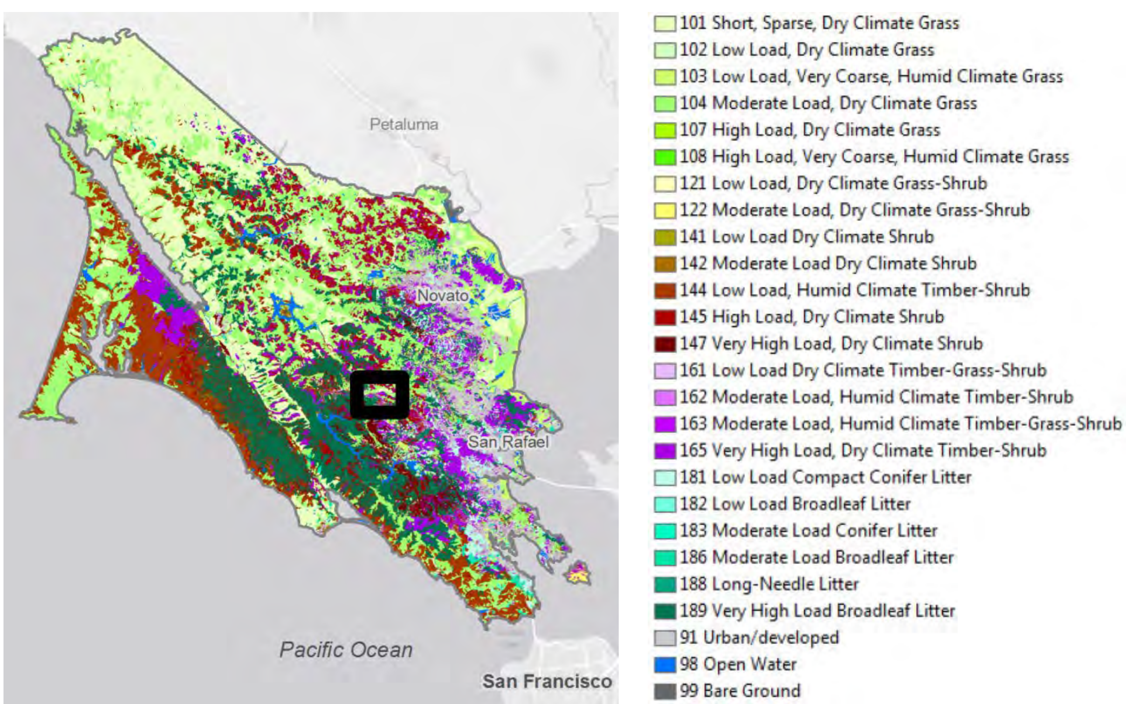

Figure 2. The 5-m custom fire behavior fuel model map of Marin County, CA. The inset boundary represents the spatial extent of zoomed-in maps in Figures 3 and 4.

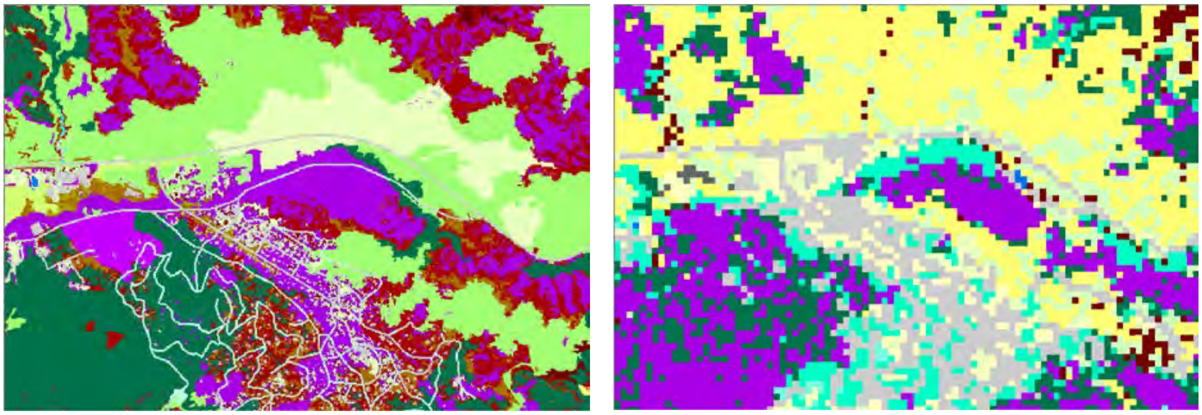

Figure 3. The 5-m custom fuel model map (left) compared to the standard 30-m LANDFIRE map (right) for Woodacre, CA. See Figure 2 for legend.

Desktop FlamMap 5 (Finney 2006) was used to model flame length based on the custom and LANDFIRE maps under identical environmental condition settings (i.e., same wind and fuel moisture inputs); the outputs for Woodacre, CA, are displayed side by side in Figure 4. Improved representation of flammability within the WUI community is evident from the pixels of medium (yellow) to very high (red) flame length distributed throughout the community, whereas LANDFIRE fuel maps tend to represent WUI areas as unburnable.

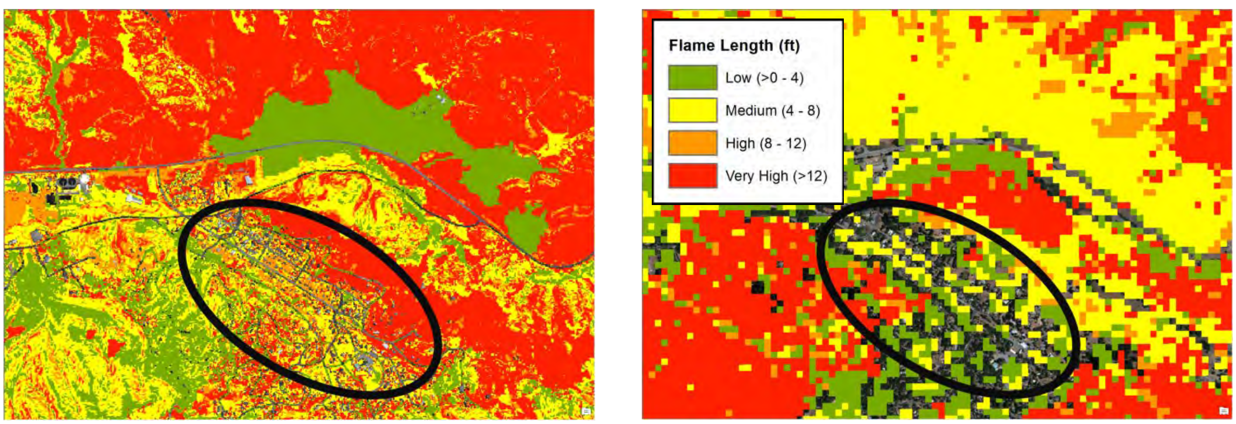

Figure 4. Flame length output from FlamMap based on the 5-m custom fuel model map (left) and the standard 30-m LANDFIRE map (right) for Woodacre, CA. Population is concentrated in the circled area within this WUI community.

A direct comparison of the distribution of fuel models was made between our resampled 30-m fuel model map and the LANDFIRE fuel map. Results are shown in Figure 5.

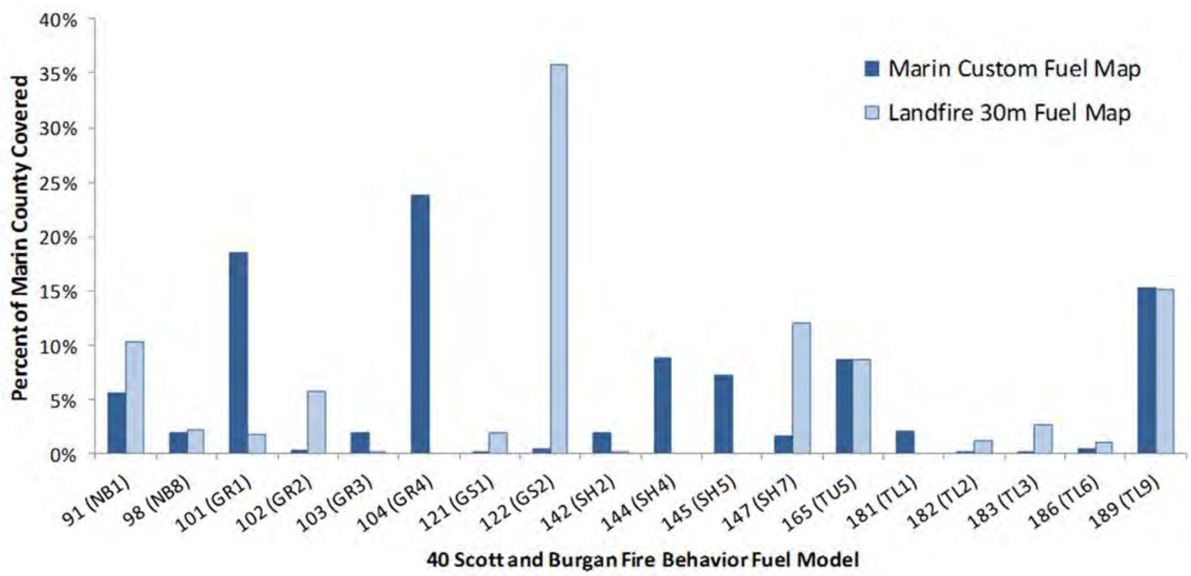

Figure 5. Proportion of Marin County assigned to each 40 Scott and Burgan fire behavior fuel model. All models representing less than 1% of Marin have been omitted for clarity. See Figure 2 for fuel model keys.

Only 14% of all locations in Marin were assigned the same fuel model in both maps. The custom fuel map reduced the urban areas represented as unburnable by 50% compared to the LANDFIRE fuel map. LANDFIRE data classified just 7.4% of Marin as grass, and a much higher proportion of the county (38%) as grass-shrub. The custom map classified 44% of Marin County as grass and less than 1% as grass-shrub, which matches information from locally validated vegetation type classifications. As a result, we conclude that the custom fuel map shows substantial improvements over the LANDFIRE fuel map. The custom fuel map was later used to support the preparation of several parts of the Marin County CWPP, including hazard and risk assessment calculations and fuels treatment planning.

Acknowledgments
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References

Finney, MA (2006) An overview of FlamMap fire modeling capabilities. In "Fuels management—how to measure success." (Eds PL Andrews and BW Butler) pp. 213–220. USDA Forest Service Proceedings RMRS-P-41, Rocky Mountain Research Station, Fort Collins, Colorado, USA. Available at http://www.fs.fed.us/rm/pubs/rmrs_p041/rmrs_p041_213_220.pdf.

Scott, Joe H. and Burgan, Robert E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

Scott, Joe H. and Reinhardt, Elizabeth D. 2005. Stereo photo guide for estimating canopy fuel characteristics in conifer stands. Gen. Tech. Rep. RMRS-GTR-145. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 49 p.

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Estimating canopy load and bulk density distribution using calibrated T-LiDAR indices

François Pimont*
INRA URFM, Avignon, France, francois.pimont@avignon.inra.fr

Maxime Soma
INRA URFM, Avignon, France, maxime.soma@avignon.inra.fr

Jean-Luc Dupuy
INRA URFM, Avignon, France, jean-luc.dupuy@avignon.inra.fr

Eric Rigolot
INRA URFM, Avignon, France, eric.rigolot@avignon.inra.fr

Frédéric Jean
INRA URFM, Avignon, France, frederic.jean@avignon.inra.fr

Introduction

Canopy fuel structure is a driver of fire behavior which affects rate of spread, intensity and crown fire potential (Van Wagner 1977, Cruz *et al.* 2005). Physically sample it is not feasible on large samples of trees. At plot scale, the inventory-based is commonly used (Baldwin *et al.* 1997, Alexander *et al.* 2004). It combines a stem inventory, allometric equations for mass and cumulative vertical distributions to estimate bulk density profiles and load. This approach can be used to reproduce the 3D structure of fuel beds though a modelling approach (Pimont *et al.* 2016). However, the allometric equations of the inventory-based approach require time-consuming measurements for calibration, their performance can be highly variable among sites (e.g. Baldwin *et al.* 1997) and there is little validation of this method.

Remote sensing techniques have long been used to estimate quantities such as leaf area index (LAI). More recently, terrestrial LiDAR (Light Detection And Ranging) scanner, referred hereinafter as TLS, emerged as a promising tool to estimate leaf area distribution (Béland *et al.* 2011, 2014). This approach is based on the relative density of returns, which is defined as the proportion of returns in a given volume relatively to the number of laser pulses crossing this volume. LiDAR technology has also shown promises for the estimation of canopy fuel structure (Skowronski *et al.* 2011, Seielstad *et al.* 2011).

Herein, we present a method based on the calibration of relative density indices to estimate canopy bulk density. The original method is described in Pimont *et al.* (2015), applied to the estimation of leaf bulk density and corrected in Pimont *et al.* (2016). Here, we present results in the context of canopy fuel structure estimation. Some of the results incorporate a second campaign of TLS acquisitions done in 2015 that are still in progress.

* INRA, UR629, Domaine de Saint Paul, Agroparc F-84914 Avignon Cedex 9, France.

Material and methods

Plot description and inventory-based method

Four 12 m diameter contrasted plots were selected in a *Quercus pubescens* forest in the South-East of France. Maximum heights varied between 8 to 12 m and basal areas between 18 and 40 $m^2 ha^{-1}$. A stem inventory was carried out and 10 trees of various diameters at breast height were felled and cut in 1-m vertical sections. Leaves and 0-6 mm twigs were collected, oven-dried and weighted. Data was used to fit allometric equations for leaf and twig biomass and vertical distribution. The combination of these equations and the stem inventory in each plot were used to estimate bulk density profiles in each plot (Pimont *et al.* 2015).

LiDAR campaigns

We conducted two different measurement campaigns on the study site. The first one was done in 2013. A FOCUS 3D 120S (FARO Technologies Inc., Lake Mary, USA) TLS instrument was used in this study with a resolution of 43.8 million points per scan. Five scans were performed on each plot from the center and the four summits of the square inscribed in the circular plot (Pimont *et al.* 2015). Similar measurements were done in 2015 with a FOCUS 3D 130X. The main difference between the two TLS is the wavelength (905 nm for the 120S and 1500 nm for the 130X), the second being more adapted to separate leaf returns from wood returns using return intensity (Béland *et al.* 2014).

Calibration of biomass indices in spherical volumes

During each campaign, ten polystyrene balls (diameter 0.1 m) were placed at different locations in the canopy of each plot, to mark out the center of virtual spherical volumes. These volumes, referred to as Calibration Volumes (CV) are bounded by a 0.7 m diameter virtual sphere, that has the same center as the polystyrene target. Once the TLS scans were performed on a plot, the leaves and twigs inside the calibration volumes were collected, oven-dried and weighted.

TLS point clouds were used to compute relative density indices in each CV, using the polystyrene targets to identify CV locations in each point cloud. Several variants of these indices were introduced to account for occlusion, leaf orientation and filtered returns (Pimont *et al.* 2015). These indices were calibrated for biomass estimation, using leaf and twig mass weighted in CVs. On going work aims at separating leaf from wood returns to improve the accuracy of estimation.

Model application

Once calibrated, relative density indices can be computed at any location in the canopy to estimate local bulk density. To estimate bulk density at plot scale, calibrated indices were computed at all nodes of a virtual grid in each plot. The 3D distributions of estimated bulk density were integrated horizontally to estimate vertical bulk density profiles that could be compared to the ones obtained with the inventory-based method.

Results

Figure 1 shows a comparison between profiles of leaf bulk density estimated with the inventory-based method (black crosses) and the TLS method using scans done in 2013 and 2015, respectively in blue and green lines. They compared well together in terms of shape, canopy height, peak bulk density, etc. At this stage it is unclear if differences observed on plot 2 are due to the TLS or the inventory-based method. In the lower part of the canopy, it is likely that the TLS-based method overestimates bulk densities, because the model interprets trunk returns as if they were foliage.

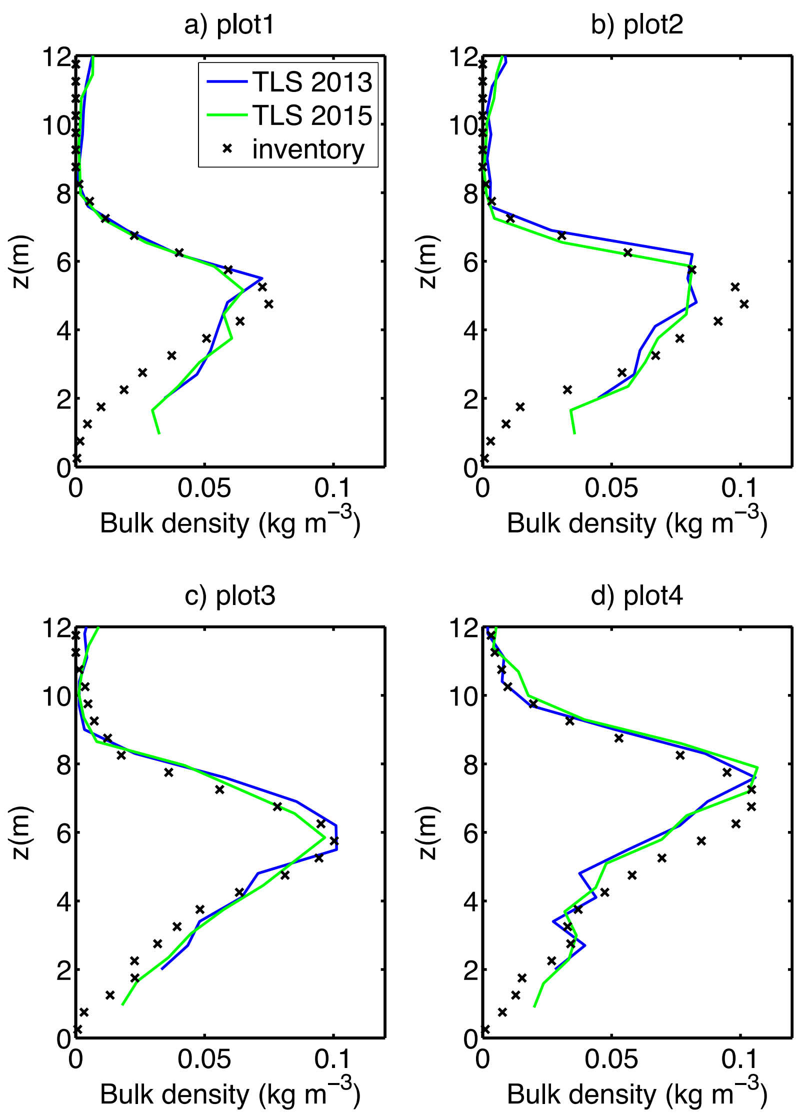

Figure 1: Leaf bulk density profiles estimated from TLS- and inventory-based methods using data from the 2013 and 2015 campaign. No separation is done between leaf and wood returns at this stage.

A similar methodology was applied to thin twigs, based on a calibration of relative density indices with twig biomass measured in calibration volumes. When compared to inventory-based-method profiles, this first attempt to estimate twig biomass with TLS showed a disappointing overestimation. This overestimation (by a factor 1.5 to 2) is explained by the fact that polystyrene balls were hanged to thin twigs, leading to an over-representation of twigs with regards to leaves in calibration volumes. We believe significant improvements should result from separation between leaf and wood returns.

Some work is still in progress to use return intensity to separate leaf and wood returns in the 2015 scans. Such separation was not possible with the 2013 scans, because leaf and wood returns showed similar intensity ranges at FOCUS 3D 120S wavelength (Pimont *et al.* 2015). We also developed a slightly different approach to remove wood returns in leaf biomass estimation, using RGB colors estimated for TLS returns by the camera incorporated in the FARO FOCUS 3D 130X. This first attempt estimated the proportion of leaf and wood returns in a spherical volume using the Excess Green index, an efficient index derived from RGB for plant segmentation (Guajardo *et al.* 2011). The method was evaluated in some spherical volumes containing wood only and performed correctly (reducing the estimation of leaf biomass in these volumes to near zero values). Figure 2 shows how leaf bulk density estimation was corrected when including leaf and wood separation, the black arrows illustrating the reduction of the estimated biomass in the lower part of the canopy, when removing trunk returns.

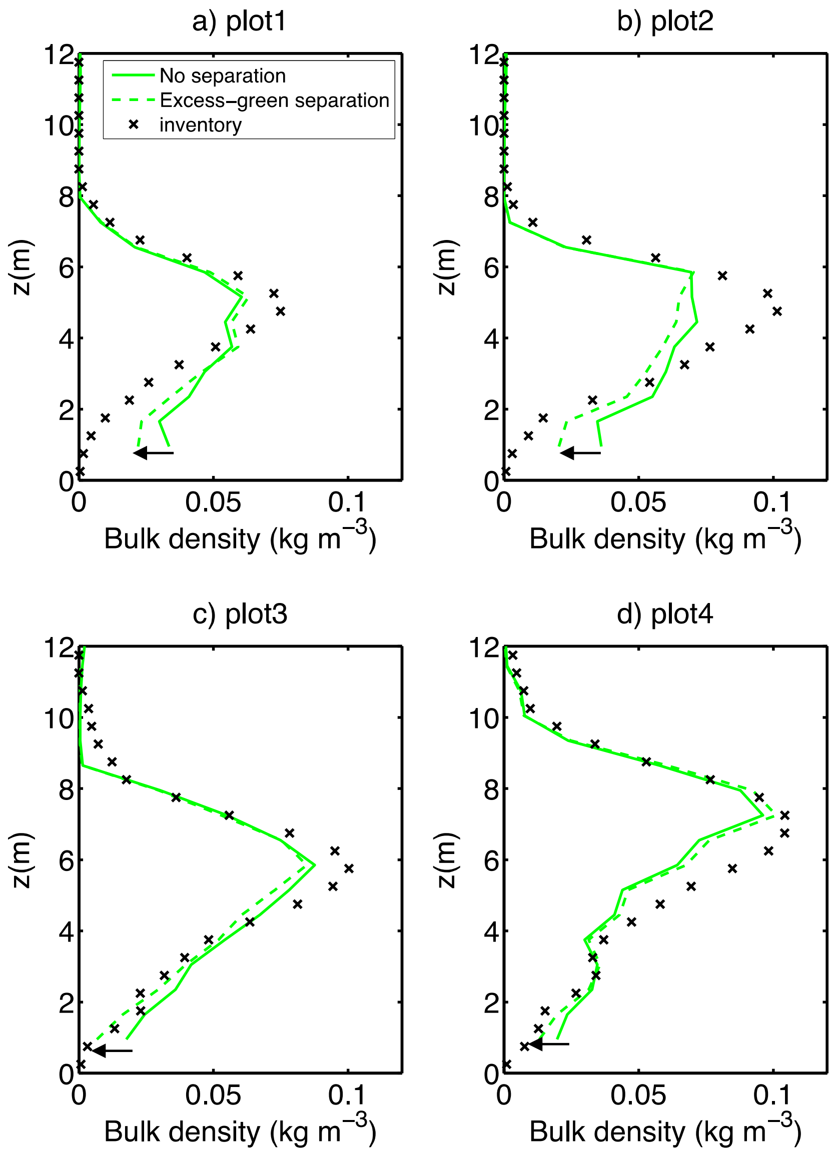

Figure 2: Leaf bulk density profiles estimated from TLS method without separation of leaf and wood returns (line green) and with Excess-green-based-leaf-and-wood separation (dashed green) using data of the 2015 campaign. The small black arrows illustrate the bulk density reduction when removing wood returns

Discussion and conclusion

Our method based on calibration of relative density indices (Pimont *et al.* 2015) yielded encouraging results. It was the first able to estimate leaf bulk density profiles in forestry plots using TLS, the previous work being limited to small trees or individual branches. The approach based on the Excess-Green index to remove wood returns is innovative and leads to promising results. Combined with an approach based on return intensity, we hope it would help to get more robust estimates of leaf biomass and distribution. Our first attempt to estimate twig biomass was not successful, but we hope that the progress in leaf and wood separation will lead to much better results.

Regarding the cost of measurement, the time required to calibrate our indices was about ten times faster that the time required to calibrate the inventory based methods. However, this time is not negligible (about 8 days to prepare the plot, to collect, oven-dry and weight the biomass, to identify the location of CV in scans, etc.). We expect that these coefficients will be relatively stable as they depend only on the distribution of foliage element at the spherical volume scale, that should not change much for a given species or group of species with similar morphologies. Variations of these coefficients are potentially predictable from foliage characteristics, such as surface to volume ratio or shoot properties (Pimont *et al.* 2009).

The method presented here is promising and has potential to become an efficient, operational methodology to estimate bulk density distribution and canopy load. It could be used in combination with airborne and space-borne remote sensing (that often requires ground measurements for calibration), for monitoring of ecosystem, or to provide data for physics-based fire models.

References

Baldwin VCJr, Peterson KD, Burkhart HE, Amatais RL, Dougherty PM (1997) Equation for estimating loblolly pine branch and foliage weight and surface area distributions. *Canadian Journal of Forest Research* **27**, 918–927.

Béland M, Widlowski JL, Fournier RA, Côté JF, Verstraete M (2011) Estimating leaf area distribution in savanna trees from terrestrial LIDAR measurements. *Agricultural and Forest Meteorology* **151**, 1252-1266.

Béland M, Baldocchi DD, Widlowski JL, Fournier RA, Verstraete MM (2014) On seeing the wood from the leaves and the role of voxel size in determining leaf area distribution of forests with terrestrial LiDAR. *Agricultural and Forest Meteorology* **184**, 82-97

Guajardo M, Pajares G, Riomoros I, Herrera PJ, Burgos-Artizzu XP, Ribeiro A (2011) Automatic segmentation of relevant textures in agricultural images. *Computers and Electronics in Agriculture* **75(1)**, 75-83.

Pimont F, Dupuy JL, Caraglio Y, Morvan D (2009) Effect of vegetation heterogeneity on radiative transfer in forest fires. *International Journal of Wildland Fire* **18**, 536–553.

Pimont F, Dupuy JL, Rigolot R, Prat V, Piboule A (2015) Estimating Leaf Bulk Density Distribution in a Tree Canopy Using Terrestrial LiDAR and a Straightforward Calibration Procedure. *Remote Sensing* **7(6)**, 7995-8018.

Pimont F, Dupuy JL, Rigolot E, Prat V, Piboule, A (2016) Correction: Pimont, F. *et al.* Estimating Leaf Bulk Density Distribution in a Tree Canopy Using Terrestrial LiDAR and a Straightforward Calibration Procedure. *Remote Sens.* 2015, 7(6), 7995-8018. *Remote Sensing* **8**, 64.

Seielstad, C, Stonesifer C, Rowell E, Queen L (2011) Deriving Fuel Mass by Size Class in Douglas-fir (Pseudotsuga menziesii) Using Terrestrial Laser Scanning. *Remote Sensing* **3**, 1691-1709.

Skowronski NS, Clark KL, Duveneck M, Hom J (2011) Three-dimensional canopy fuel predicted using upward and downward sensing LiDAR systems. *Remote Sensing of Environment* **115**, 703-714.

Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23-24.

Experimental Study on the Surface Spread of Smoldering Peat Fires

Xinyan Huang*
Department of Mechanical Engineering, University of California, Berkeley, USA,
xinyan.huang@berkeley.edu

Francesco Restuccia and Guillermo Rein
Department of Mechanical Engineering, Imperial College London, UK

Michela Gramola
Engineering Department, University of Cambridge, UK

Introduction

Smoldering wildfires in peatlands are the largest combustion phenomena on Earth, and contribute considerably to annual greenhouse gas emissions [1]. Peatlands cover 2-3% of the Earth's land surface, and are most abundant in boreal and tropical regions. They are important ecosystems for a wide range of wildlife habitats supporting biological diversity, hydrological integrity and carbon storage, storing 25% of the world's soil carbon. Annually, peat fires release huge amounts of ancient carbon roughly equivalent to 15% of the man-made emissions [2, 3], and result in the widespread destruction of ecosystems and regional haze events, *e.g.* recent megafires in Southeast Asia, North America, and Northeast Europe [1, 2]. Moreover, recent global warming dries the peatlands and increases the depth of belowground soil combustion, creating a positive feedback to the climate system [4].

Peat, as a typical organic soil, is a porous and charring natural fuel, thus prone to smoldering [1, 5]. Smoldering combustion is the slow, low-temperature, flameless burning of porous fuels, and the most persistent type of combustion phenomena [5]. Once ignited, smoldering peat fires can burn for velong periods of time (*e.g.*, months and years) despite rains, weather changes, or fire-fighting attempts [1]. Two mechanisms control the spread of smoldering combustion: oxygen supply and heat losses [5-7]. Most smoldering peat fires are initiated on the ground surface by flaming fires, lightning strikes or hot particles. Afterwards, smoldering fire spread laterally along the free surface and vertically to peat layers in-depth, dominated by forward smoldering [8], as shown in Fig. 1.

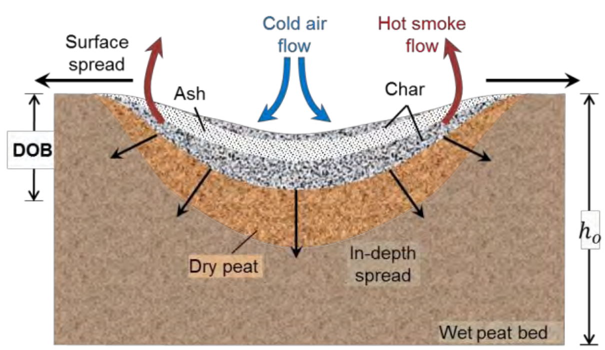

Figure 1: Schematic diagram of the smoldering fire spread along the peat surface and in-depth [8].

Compared to flaming wildfires, the fundamental chemistry and dynamics of smoldering wildfires so far are not well understood with only limited number of studies found in the literature. Ohlemiller studied the two-dimensional (2D) profiles for smoldering of dry wood-based fibres [9]. Frandsen [10] experimentally studied the ignition threshold for various bench-scale peat and other soil samples, and found a correlation between critical MC and IC, recently verified computationally in [11]. Hadden *et al.* performed a small-scale experiment with boreal moss peat, and revealed the competing pyrolysis and oxidation reactions in the char formation [12]. The depth of burn (DOB) and critical MC for extinction at the in-depth spread of peat fires have been investigated by various experiments [13] and numerical simulation [14]. The surface peat fire is found not to spread on the free surface but at a depth below ("overhang" phenomenon) [15-17], which has not been well explained or studied until now.

Experimental method

Figure 2(a) shows the schematic diagram of the experimental setup. A fire reactor with an inner dimension of 20×20×10 cm^3 and a 1.27 cm thick insulation fibre board was used to contain the peat sample. Some additional tests were also conducted with a taller (20×20×20 cm^3) fire reactor. A 20-cm coil heater was attached to one side 5 cm below the top free surface, and used to initiate a uniform smoldering front spreading in the lateral and vertical directions. The ignition protocol was fixed to be 100 W for 30 min, which is strong enough to ignite a peat sample of MC < 150%.

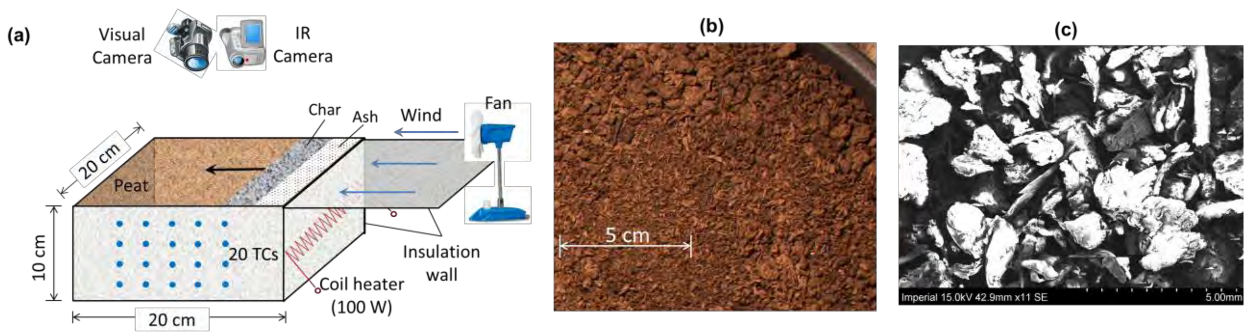

Figure 2. (a) Diagram of the experimental setup and the arrangement of thermocouples array; (b) visual image of the moss peat; and (c) scanning electron microscopy imaging of peat sample.

The peat used in the experiment is a commercial Irish moss peat (Shamrock Irish Moss Peat, Bord na Mona Horticulture Ltd.), as shown in Fig. 2(b) and (c). It is used instead of naturally sourced peat because it is readily available in large quantities, has relatively homogeneous properties and constant composition, and had been used in previous experiments in [12]. This moss peat has a dry density of 136 ± 5 kg/m^3 and a low mineral content (IC~2%). The element analysis for the organic matter shows 53.8/5.5/38.4/1.9/0.5% mass fraction for C/H/O/N/S.

Targeted MC values for peat were 5%, 50%, 100%, 130%, and 150%. Both a visual camera and an infrared (IR) camera were placed above the sample to monitor the process on the top surface. A typical smoldering fire on peat of 20×20×10 cm^3 would last between 3 and 15 h. 20 thermocouples (TCs) were arranged as an array (4 rows × 5 columns) and inserted through one sidewall into the central plane of the peat bed to measure the temperature evolution and distribution. At least three experiments were conducted at each condition for repeatability.

Experimental results

Imaging and overhangs

Figure 3(a) shows the visual and IR images for smoldering spread over peat samples with 50% MC. The IR camera was used to track the movement of the smoldering front (high irradiation region) on the top surface. Once the coil heater was on, the peat nearby was degraded into black char, and the char would be further oxidized into white ash (mainly minerals). During the 0.5 h ignition time, a uniform smoldering front was generated near a side without clear fire spread on the top surface. Afterwards, this burning smoldering front expanded out both laterally (*x* direction) and vertically (*z* direction).

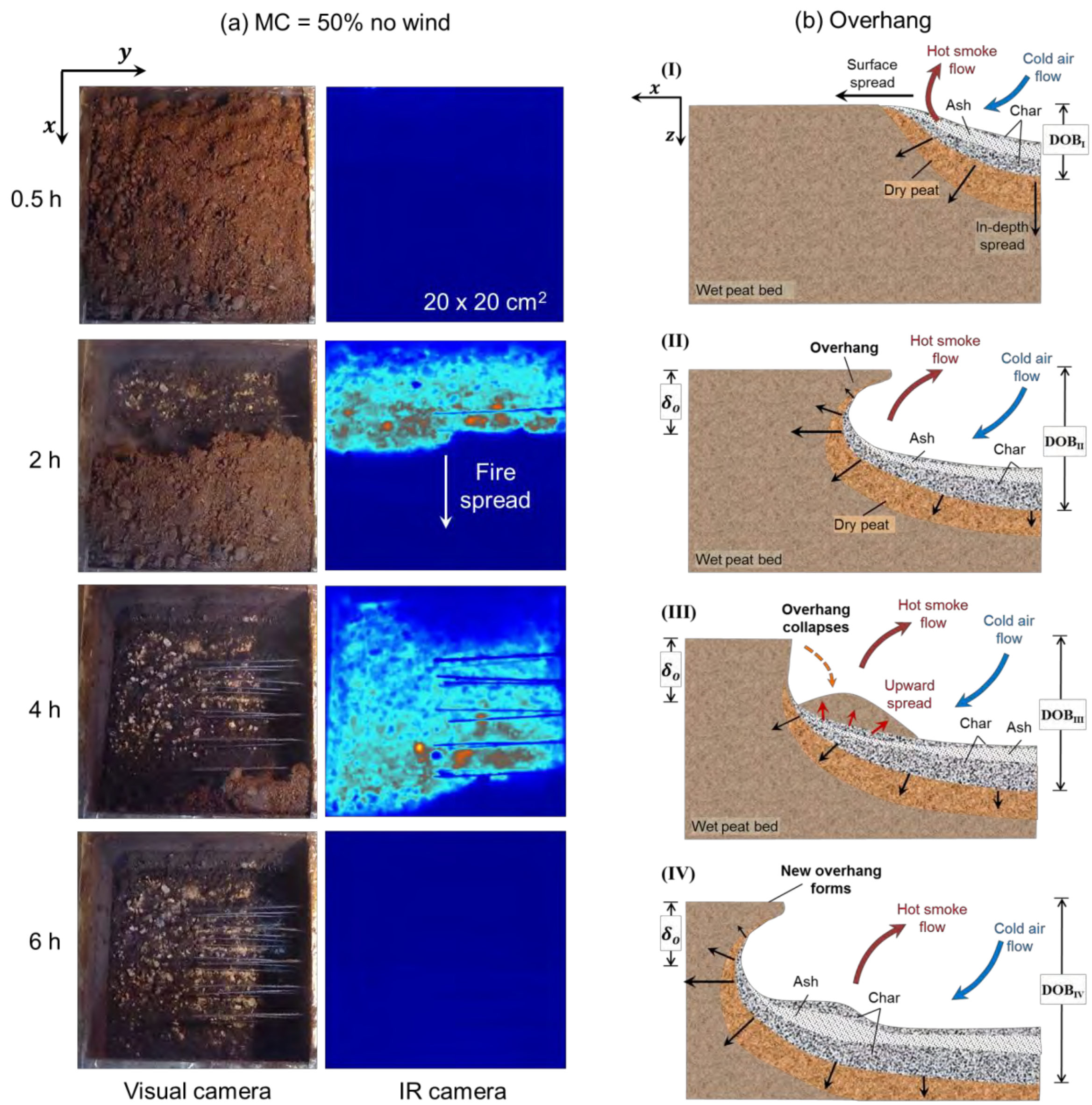

Figure 3: (a) Imaging by visual and IR camera from top for smoldering fire spread in peat sample with MC = 50% without wind, and (b) Schematic diagram for the periodic formation and collapse of overhang in smoldering spread over wet peat.

For wet peat samples (MC ≥ 50%), during the surface fire spread, a clear "overhang" could be visually observed: the smoldering fire tended to spread at a depth (i.e. overhang thickness, δ_o) below the top surface, as illustrated in Fig. 3b(II). Peat within the overhang was seen to be unburnt because it did not degrade into black char, while, for peat below the overhang, clear charring burning process was observed.

In the experiment, this overhang state was unstable because as more peat was burnt underneath, the char and ash yielded were not strong enough to support the unburnt peat above. Therefore, the overhang collapsed before it could be ignited by the burning layer below. The collapsed overhang covered the burning char back stream and evened out the leading edge, as illustrated in Fig. 3b(III). Note that the collapsed overhang was not able to extinguish the fire because it was below the critical MC [10, 11] and was even partially dried. Therefore, it would be further ignited and consumed through the upward spread. Afterwards, fire continued to spread vertically, increasing the depth of burn (DOB), and laterally, generating a new overhang shown in Fig. 3b(IV). Thus, a cycle of overhang formation and collapse was created until peat was entirely consumed.

Spread rate profile

Using visual and IR imaging at the top view (see Fig. 3a), the lateral spread rate on the free surface was measured. Note that due to the formation and collapse of overhang, peat on the free surface does not burn locally (see Fig. 3b(II)), so the visual and IR cameras actually recorded the rate of disappear (collapse) on the free surface and the spread rate of high-temperature region in a shallow layer, respectively.

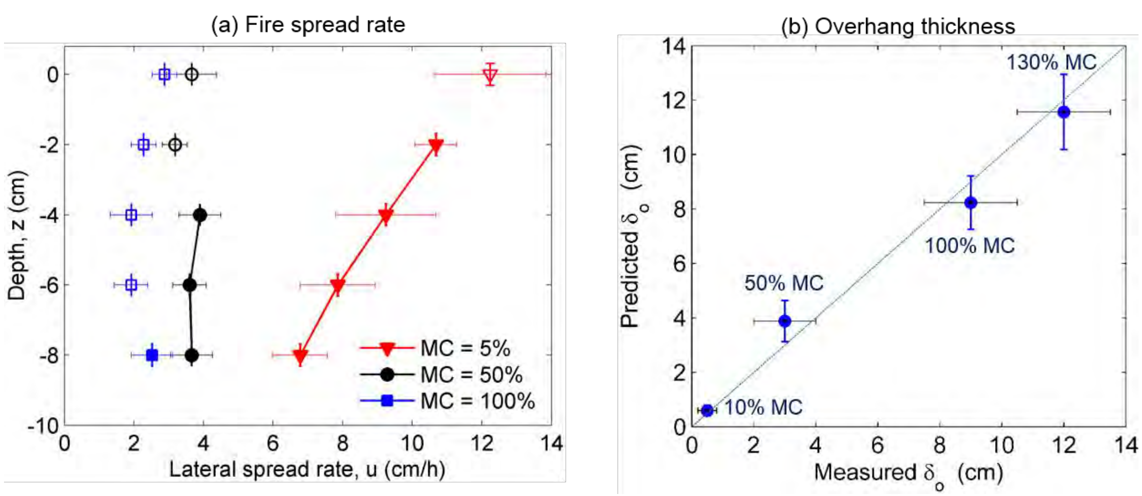

Figure 4: (a) Depth profile of the mean lateral spread rate for different moisture contents (MCs) without wind where solid symbols are found by tracking the peak temperature below overhang; hollow symbols by tracking 100°C within overhang. (b) Comparison between experimental and predicted overhang thickness (δ_o) at various moisture content (MC).

In addition, the lateral spread rate below the free surface can be estimated by tracking the thermocouple measurements [7]. Data processing showed that tracking the peak temperature and drying front (100°C) gave similar values for the spread rate. The lateral spread rate was found to be relatively constant within 10 cm over 5 thermocouples at each measured depth. Therefore, if all thermocouples in that row are below the no overhang region, their peak temperatures were tracked to estimate the mean lateral spread rate. Within the overhang layer, the drying front (100°C) was tracked. Figure 4(a) shows the depth profile of the mean lateral spread rate changing with MC without wind, where the hollow points mean that overhang occurred at that depth.

As expected, the overall spread rate profile reduces remarkably as the MC increases, indicating that moisture has a strong influence on the spread rate of peat fires. For dry peat (5% MC), the spread rate reduces significantly from 12 to 7 cm/h with increasing depth. Similar measurement was found in the experiment of smouldering dry wood-based fibres [9]. It is because as the depth increases, the ambient oxygen supply is reduced and the more ash is accumulated below the free surface. On the other hand, for wet peat samples, the lateral spread rate shows small sensitivity to the depth, implying that it is the moisture controlling the spread rate.

According to the definition of overhang thickness (δ_o): the optimal depth at which the fastest burning is achieved, the non-dimensional analysis is used to estimate the overhang thickness. The overhang thickness should relate to the spread rate difference between top and lower layers, and the thermal property of the peat bed as, $\delta_o \sim \alpha_p / \Delta u$, where the α_p is the thermal diffusivity of dry peat (~4.5×10^{-7} m^2/s [11]); Δu is the difference between the highest spread rate at the overhang thickness ($u_{\max} = u_{z=\delta_0}$) and the spread rate at the top surface ($u_{z=0} \to 0$) where burning ceases due to the large heat loss to environment. Here, $u_{\max}$ is measured as the first solid point in Fig. 4(a).

Figure 4(b) compares the predicted overhang thickness with the experimental measurement without wind in Fig. 8. In general, a good agreement is shown, supporting the critical role of spread-rate depth profile in the overhang formation.

5. Conclusions

In this work, for the first time the overhang phenomenon, peat fire spreading below the free surface, is observed with bench-scale tests using homogeneous peat samples in the laboratory. In addition, the formation and collapse of overhang is found to be periodical, and the thickness of overhang is found to increase with peat moisture. The depth profile of lateral spread rate is successfully measured by visual and infrared imaging as well as by thermocouple array. Results show that the lateral spread rate decreases with moisture content. For dry peat samples, the spread rate significantly decreases with depth because the oxygen supply is the dominant mechanism, and it decreases with depth. As the moisture content increased, the spread rate became less sensitive to the depth, suggesting moisture content became the dominant mechanism in the spread of peat fire. This experimental study provides a physical understanding of the surface spread and overhang phenomenon in peat wildfires, and explains the role of moisture and oxygen supply in peat smoldering, thus helping to understand this important natural and widespread phenomenon.

Acknowledgements

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References

1. Rein G (2013) Smouldering Fires and Natural Fuels. *Fire Phenomena and the Earth System*, ed Belcher C (John Wiley & Sons), pp 15-33.

2. Page SE*, et al.* (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420(6911):61-65.
3. Ballhorn U, Siegert F, Mason M, Limin S (2009) Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *Proceedings of the National Academy of Sciences* 106(50):21213-21218.
4. Turetsky MR*, et al.* (2015) Global vulnerability of peatlands to fire and carbon loss. *Nature Geosci* 8(1):11-14.
5. Rein G (2016) Smoldering Combustion. *SFPE Handbook of Fire Protection Engineering*, eds Hurley MJ, Gottuk DT, Hall Jr JR, Harada K, Kuligowski ED, Puchovsky M, Torero JL, Watts Jr JM, & Wieczorek CJ (Springer New York), pp 581-603.
6. Huang X, Rein G (2016) Thermochemical conversion of biomass in smouldering combustion across scales: The roles of heterogeneous kinetics, oxygen and transport phenomena. *Bioresource Technology* 207:409-421.
7. Huang X, Restuccia F, Gramola M, Rein G (2016 in press) Experimental study of the formation and collapse of an overhang in the lateral spread of smouldering peat fires. *Combustion and Flame*.
8. Huang X, Rein G (2014) Smouldering combustion of peat in wildfires: Inverse modelling of the drying and the thermal and oxidative decomposition kinetics. *Combustion and Flame* 161(6):1633-1644.
9. Ohlemiller TJ (1990) Smoldering combustion propagation through a permeable horizontal fuel layer. *Combustion and Flame* 81(3–4):341-353.
10. Frandsen WH (1987) The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Canadian Journal of Forest Research* 17(12):1540-1544.
11. Huang X, Rein G, Chen H (2015) Computational smoldering combustion: Predicting the roles of moisture and inert contents in peat wildfires. *Proceedings of the Combustion Institute* 35(3):2673-2681.
12. Hadden RM, Rein G, Belcher CM (2013) Study of the competing chemical reactions in the initiation and spread of smouldering combustion in peat. *Proceedings of the Combustion Institute* 34(2):2547-2553.
13. Benscoter BW*, et al.* (2011) Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils. *International Journal of Wildland Fire* 20(3):418-429.
14. Huang X, Rein G (2015) Computational Study of Critical Moisture and Depth of Burn in Peat Fires. *International Journal of Wildland Fire*:in press.
15. Hungerford RD, Frandsen WH, Ryan KC (1995) Ignition and burning characteristics of organic soils. *Proceedings 19th Tall Timbers Fire Ecology Conference. Fire in wetlands: a management perspective*, eds Cerulean S & Engstrom RT, p 78=91.
16. Thomas PA, McAlpine RS, Hirsch K (2010) *Fire in the Forest* (Cambridge University Press).
17. Zanon V, Viveiros F, Silva C, Hipólito A, Ferreira T (2008) Impact of lightning on organic matter-rich soils: influence of soil grain size and organic matter content on underground fires. *Nat Hazards* 45(1):19-31.

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Exploring interactions among multiple disturbance agents in forest landscapes: simulating effects of fire, beetles, and disease under climate change

Robert E. Keane
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 Highway 10 West, Missoula, Montana 59808. Phone: 406-329-4760, FAX: 406-329-4877. Email: rkeane@fs.fed.us

Rachel Loehman
US Geological Survey, Alaska Science Center, 4210 University Drive, Anchorage, AK, 99508, USA

Lisa Holsinger
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 Highway 10 West, Missoula, Montana 59808.

Introduction

In light of the potential for climate change to have adverse effects on natural, political, social, and economic systems, ecologists have been called upon to investigate the consequences of anthropogenic climate change on the world's ecosystems (Bachelet et al. 2000). However, exploration of the numerous, complex, and multi-scale interactions among ecological processes, disturbance agents, and climate drivers present intractable challenges with respect to scientific exploration as traditional field methods used to explore ecosystem responses to environmental change are inadequate to capture complex interactions that occur across large areas and long time periods (Keane et al. 2015b). Multi-scale ecological interactions often result in non-linear feedbacks that produce novel and unanticipated landscape responses to changing climates (Temperli et al. 2013). These can be explored using simulation modeling, in which computer programs are used to quantitatively simulate complex ecological processes and their interactions over decades or centuries (McKenzie et al. 2014).

Most ecological responses to climate change are best evaluated and simulated at landscape scales using landscape models (LMs). Because of their limited spatial extent, finer-scale stand models cannot fully incorporate spatial aspects of disturbance regimes (Bugmann 2001), and coarser-scale Dynamic Global Vegetation Models (DGVMs) are not designed to simulate important species- and plant-level disturbance effects such as successional trajectories and disturbance survival (Flannigan et al. 2009). Spatially explicit simulations using LMs have greatly improved our ability to explore and understand complex interactions (Scheller and Mladenoff 2007; Perry and Millington 2008). Several sources provide details on landscape change modeling (Mladenoff and Baker 1999), ecosystem dynamics (Canham et al. 2004), and spatial fire spread and effects (Gardner et al. 1999). In various reviews, LMs are described based on their design, structure, detail, resolution, and geographical area (see Keane et al. 2004; He 2008; Baker 1989; Scheller and Mladenoff 2007, respectively). To realistically predict climate change effects, LMs must be structured to simulate disturbance processes, vegetation growth and mortality, and species composition and distribution as well as their interactions across multiple scales (Bachelet et al. 2000; Purves and Pacala 2008). However, the level of mechanistic detail needed to realistically simulate important interactions among these processes and variables remains a central challenge in landscape modeling (Gustafson 2013).

In this presentation, we explore a unique subset of the many ecological interactions that occur at landscape scales—the interactions among disturbances. Disturbances influence vegetation distribution, structure, and composition, and may indirectly and directly interact with one another and with changing climate to create novel landscapes (Kitzberger et al. 2012). Warming climates have already altered interactions among disturbance regimes resulting in highly visible and rapidly occurring changes in landscape composition and structure, and the importance of these interactions have been shown in studies across the world (Green and Saladin 2005; Parker et al. 2006). To demonstrate the importance of effects of single and interacting disturbances on landscapes, we focused on a subset of disturbances that are common across many US Rocky Mountain landscapes: wildland fire (any fire that occurs in a non-developed or sparsely developed area), mountain pine beetle (*Dendroctonus ponderosae*), and white pine blister rust (*Cronartium ribicola*). We use a landscape simulation model to evaluate how single and interacting disturbances respond to changes in climate and influence landscapes. Because the magnitude, trend, and type of disturbance interactions differ across ecosystems, our simulation results cannot be wholly extrapolated to other landscapes; however, our goal in this chapter is to demonstrate the general importance of disturbance interactions in influencing future landscape composition and structure.

The Simulation Model and Application

FireBGCv2 (Fire BioGeoChemical model Version 2) is a bottom-up, mechanistic, individual tree, forest succession model containing stochastic properties implemented in a spatial domain (see Keane et al. 2011 for complete model documentation). It can be categorized as a landscape fire succession model (Keane et al. 2004), a forest landscape model (He 2008), or a landscape dynamics model (Mladenoff and Baker 1999). Versions of the model have been used to address a wide variety of research questions including climate change effects on stream temperatures (Holsinger et al. 2014), wildlife, and vegetation composition (Loehman et al. 2011); management effectiveness; grazing interactions with fire (Riggs et al. 2015); landscape structure; fuel-snag dynamics; and carbon emissions (Keane et al. 1997). FireBGCv2 simulates basic processes such as tree growth, organic matter decomposition, and litterfall using detailed physical and biogeochemical relationships (Keane et al. 2011). Long-term daily weather streams drive primary canopy processes (e.g., transpiration, photosynthesis, and respiration), vegetation phenology (e.g., curing, leaf fall), and fire dynamics (e.g., ignition, fuel moisture, spread, intensity) within the simulation landscape.

We simulated all combinations of wildland fire, mountain pine beetle, and white pine blister rust for two forested landscapes that comprise a range of climate, vegetation, and fire regime types common to the US Rocky Mountain region:

- **East Fork of the Bitterroot River (EFBR):** A 128,000 ha dry mixed-conifer ecosystem in western Montana, USA, with an historical low- to high-frequency, mixed-severity fire regime. Lower-elevation stands comprise primarily ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii)*, and higher elevation stands are dominated by lodgepole pine (*Pinus contorta* var. *latifolia)*, whitebark pine (*Pinus albicaulis*), subalpine fir *(Abies lasiocarpa),* and Engelmann spruce (*Picea engelmanii)* (Holsinger et al. 2014).

- **Yellowstone Central Plateau (YCP):** An 80,000 ha, high-elevation lodgepole pine ecosystem in Yellowstone National Park, USA, with an historical low-frequency, high-severity fire regime. Stands contain minor amounts of Douglas-fir, whitebark pine, subalpine fir, and Engelmann spruce (Clark et al. 2016[in press]).

We simulated disturbance interactions under two climate scenarios:

- **Current climate**: The recorded daily weather for the last 50+ years collected within or near each of the simulation landscapes, compiled by the National Climatic Data Center. Weather years were used in sequence, repeated for multiple cycles over a 250-year simulation period.
- **Warmer climate:** A climate change scenario in which temperatures increase by an average of 2.8 °C relative to historical weather. Climate offsets for each landscape represent an ensemble average of climate model projections for the A2 emissions scenario (IPCC 2007) downscaled to 12 km for the period 2070 to 2099 (Girvetz et al. 2009).

FireBGCv2 simulations are usually performed with multiple replicates to account for stochastic model elements (e.g., Loehman et al. 2011) but we did only one run per scenario for the purposes of illustration. For each 250-year simulation, disturbances were implemented beginning in the initial simulation year. We report two response variables sensitive to disturbance interaction effects: species composition (dominant species of each modeled stand) and tree basal area (m^2 ha^{-1}).

Results

*A*verage basal area across each landscape at all three study locations is highest under no-disturbance scenarios and is subsequently reduced by WPBR, MPB, and fire (in order of increasing influence), and then by their interactions (Figure 1). For CCE, EFBR, and YCP under current climate, fire activity alone accounted for a substantial portion of the reduction in basal area as compared with the no-disturbance scenario (8.7, 11.0, and 19.7%, respectively) while WPBR alone accounted for the least change (1.2, 1.0, and 0.3%, respectively), presumably because of the low abundance of five-needle pines. However, fire interactions with MPB and WPBR significantly changed basal area the most (Keane et al. 2015a), but fire-MPB interactions further reduced basal area (11.5, 14.7, and 13.0%) and the interactions from all three disturbances resulted in the most change (15.0, 18.6, 20.1%), even with five-needle pines a relatively minor component of our simulation landscapes. While WPBR killed less than 1.0% of basal area per year, it killed over 20% of the whitebark pine basal area. And MPB killed around 2% of basal area per year but it killed around 15% of the total basal area of the pines. Fire killed from 4-6% of the basal area per year.

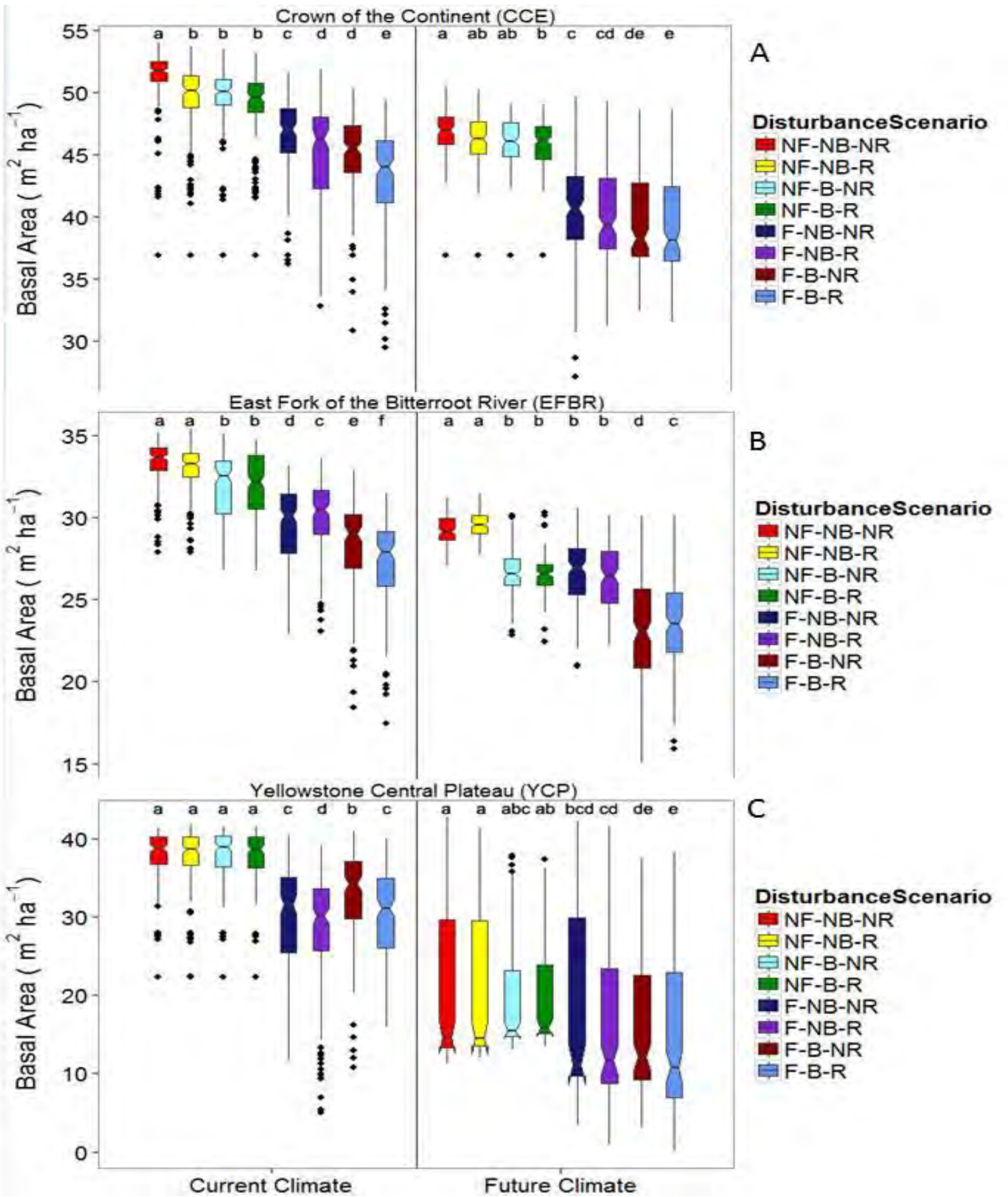

Figure 1. Boxplots showing the differences between non-disturbance scenarios with disturbance alone and disturbance combinations for both current and future climates for the three simulation landscapes: (A) Crown of the Continent (CCE), (B) East Fort of the Bitterroot River (EFBR), and (C) Yellowstone Central Plateau. Letters atop each boxplot indicate significance ($p<0.05$) across scenarios. Letters indicate the following disturbances: Fire and no fire (F, NF), MPB and no MPB (B, NB), WPBR and no WPBR (R, NR).

Disturbance interactions modeled under future climate significantly altered landscape basal area as compared with no-disturbance and current climate scenarios. All three landscapes experienced lower productivity in basal area under the no disturbance scenario with future climate (10, 13, 46% reduction in basal area for CCE, EFBR, and YCP, respectively). Again, fire was the most influential disturbance accounting for 12, 9, and 16% reductions in basal area killing about 5-7% of the basal area per year, and WPBR was the least significant disturbance (>1% basal area reductions for all landscapes). The magnitude of the basal area reductions with disturbance interactions were significantly larger under warmer climates with >15% reductions in basal area when all disturbances were simulated.

Discussion

Several important results emerged from the simulation experiment. First, disturbance interactions caused easily detectable, direct, and immediate effects on landscape basal area and species composition (Figure 1). Second, in most cases, disturbance interaction effects outweighed direct climate impacts on forests, and in all cases, disturbances and their interactions modeled under future climate significantly altered basal area and species composition (Figure 1). Third, the disturbance interactions were rarely additive across disturbances; the impact of one disturbance alone is not the same as when other disturbances are included in the simulation. Last, we found that effects of climate changes and disturbances differed across study areas because they were mediated through species-specific sensitivity and susceptibility; landscape responses may be non-linear as the result of reciprocal interactions of climate, fire, MPB, and WPBR through several disturbance cycles. We conclude that climate changes acting in tandem with these disturbances have the potential to shift landscapes to novel configurations.

Many factors determine the frequency and magnitude of landscape responses to interacting disturbances (Keane et al. 2015a). The biophysical environment – and particularly landscape composition and climate - is perhaps the most important. Species composition and configuration (i.e., vegetation pattern) controls fire behavior and fire effects, and host availability for and susceptibility to MPB attacks and WPBR infections. For example, current MPB outbreaks in North America might have been less intense and more localized if wildland fires had not been excluded over the last century because fire exclusion increased the abundance of host species of sufficient size and abundance for insect and disease epidemics (Carroll et al. 2003). Predictions of warmer temperatures and increased drought stress suggest that the total area susceptible to or affected by beetle outbreaks and large or severe fires may increase in the coming decades (Williams et al. 2013). Although climate changes directly affect forests, our results suggest that indirect effects, mediated through disturbances and interactions, have greater impact.

References

Bachelet D, James M. Lenihan, Christopher Daly, Neilson RP (2000) Interactions between fire, grazing and climate change at Wind Cave National Park, SD. Ecological Modelling 134:229-244

Baker WL (1989) A review of models of landscape change. Landscape Ecology 2: 111-133

Bugmann H (2001) A Review of Forest Gap Models. Climatic Change 51(3-4), 259-305. [In English]

Canham CD, Cole JJ, Lauenroth WK (2004). Models in Ecosystem Science. Princeton University Press, Princeton, New Jersey, USA.

Carroll AL, Taylor SW, Régnière J, Safranyik L (2003) Effects of climate change on range expansion by the mountain pine beetle in British Columbia. In: Shore T., Brooks J. E., Stone J. E. (eds) Mountain pine beetle symposium: Challenges and solutions, Victoria, British Columbia 2003. Natural Resources Canada, Canadian Forest Service, p. 223-231

Clark, Jason, Loehman, Rachel, Keane, RE. (2016[in press]) Climate changes and wildfire alter mid-century forest composition of Yellowstone National Park, but forest cover persists. Climatic Change

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. International Journal of Wildland Fire 18(5), 483-507.

Gardner RH, William H. Romme, Turner MG (1999) Predicting forest fire effects at landscape scales. In: Spatial modeling of forest landscape change: approaches and applications. In: Mladenoff DJ & Baker WL(eds) Cambridge University Press, Cambridge, United Kingdom, pp 163-185

Green DG, Sadedin S (2005) Interactions matter—complexity in landscapes and ecosystems. Ecological Complexity 2(2):117-130

Gustafson E (2013) When relationships estimated in the past cannot be used to predict the future: using mechanistic models to predict landscape ecological dynamics in a changing world. Landscape Ecology 28 (8):1429-1437. doi:10.1007/s10980-013-9927-4

He HS (2008) Forest landscape models, definition, characterization, and classification. Forest Ecology and Management 254: 484-498

Holsinger L, Keane RE, Isaak DJ, Eby L, Young MK (2014) Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a Rocky Mountain watershed. Climatic Change 124(1-2), 191-206. [In English]

disease under climate change. In: Perera A. H., Remmel T. K., Buse L. J. (eds), Simulation Modeling of Forest Landscape Disturbances. Springer, New York, USA, pp. 201-231

Keane RE, McKenzie D, Falk DA, Smithwick EAH, Miller C, Kellogg L-KB (2015b) Representing climate, disturbance, and vegetation interactions in landscape models. Ecological Modelling 309–310(0), 33-47.

Keane RE, Cary G, Davies ID et al. (2004) A classification of landscape fire succession models: spatially explicit models of fire and vegetation dynamic. Ecological Modelling 256: 3-27

Keane RE, Loehman RA, Holsinger LM (2011) The FireBGCv2 landscape fire and succession model: a research simulation platform for exploring fire and vegetation dynamics. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO USA, pp. 137

Kitzberger T, Aráoz E, Gowda J, Mermoz M, JM M (2012) Decreases in fire spread probability with forest age promotes alternative community states, reduced resilience to climate variability and large fire regime shifts. Ecosystems 15:97-112

Keane RE, Colin C. Hardy, Kevin C. Ryan, Finney MA (1997) Simulating effects of fire on gaseous emissions from future landscape of Glacier National Park, Montana, USA. World Resources Review 9(2), 177-205.

Loehman RA, Clark JA, Keane RE (2011a) Modeling Effects of Climate Change and Fire Management on Western White Pine (Pinus monticola) in the Northern Rocky Mountains, USA. Forests 2(4):832-860

Mladenoff DJ, Baker WL (1999). Spatial modeling of forest landscape change. Cambridge University Press, Cambridge, United Kingdom.

McKenzie D, Shankar U, Keane RE, Stavros EN, Heilman WE, Fox DG, Riebau AC (2014) Smoke consequences of new wildfire regimes driven by climate change. Earth's Future, n/a-n/a.

Parker TJ, Clancy KM, Mathiasen RL (2006) Interactions among fire, insects, and pathogens in coniferous forests of the interior western United States and Canada. Agricultural and Forest Entomology 8:167-189

Perry GLW, Millington JDA (2008) Spatial modelling of succession-disturbance dynamics in forest ecosystems: Concepts and examples. Perspectives in Plant Ecology, Evolution and Systematics 9: 191-210

Purves D, Pacala S (2008) Predictive Models of Forest Dynamics. Science 320(5882):1452-1453

Riggs RA, Keane RE, Cimon N et al (2015) Biomass and fire dynamics in a temperate forest-grassland mosaic: Integrating multi-species herbivory, climate, and fire with the FireBGCv2/GrazeBGC system. Ecological Modelling 296(0):57-78

Scheller RM, Mladenoff DJ (2007) An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. Landscape Ecology 22: 491-505

Temperli C, Bugmann H, Elkin C (2013) Cross-scale interactions among bark beetles, climate change, and wind disturbances: a landscape modeling approach. Ecological Monographs 83(3):383-402

Williams PA, Allen CD, Macalady AK, and six others (2013) Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Climate Change 3:292-297.

Field-Scale Testing of Detailed Physics-Based Fire Behavior Models

Eric Mueller*
University of Edinburgh, Institute for Infrastructure and Environment, Edinburgh, EH9 3JL, UK,
e.mueller@ed.ac.uk

William Mell
USDA Forest Service, Pacific Wildland Fire Sciences Laboratory, Seattle, Washington, USA,
wemell@fs.fed.us

Nicholas Skowronski
USDA Forest Service, Northern Research Station, Carbon, Fire, and Climate Sciences,
Morgantown, WV 26505, USA, nskowronski@fs.fed.us

Kenneth L. Clark, Michael Gallagher
USDA Forest Service, Silas Little Experimental Forest, New Lisbon, NJ 08064, USA,
kennethclark@fs.fed.us, michaelgallagher@fs.fed.us

Rory Hadden
University of Edinburgh, Institute for Infrastructure and Environment, Edinburgh, EH9 3JL, UK,
r.hadden@ed.ac.uk

Albert Simeoni
Exponent Inc., Natick, Massachusetts 01760, USA, asimeoni@exponent.com

Introduction

Fire behavior models have shown utility in understanding and predicting the progression and impact of wildland fires for both research and management applications. Detailed discussions of the different types of existing models can be found in the reviews by Pastor et al. (2003) and Sullivan (2009a; b). Each group of models has strengths and weaknesses that dictate the uses to which they are suited. However, of all of these groups, detailed physics-based models are the only which aim to include all of the relevant physical phenomena. These provide a number of advantages, such as allowing their use in a more flexible predictive capacity. Detailed physics-based models can also be used to develop or parameterize simplified models, such as fire spread or smoke transport models, where experimental data may not be readily available. However, a common criticism of these models, beyond computational demand, is the relatively limited extent to which they have been evaluated against experimentation, particularly at the field-scale. Such testing is a necessity given the significant number of input parameters required to run such a model, some of which may not be well characterized. Therefore, our project is designed to test model predictions against a set of experimental fire behavior measurements conducted in a forested environment.

Here, we focus on the application of one particular detailed physics-based fire behavior model, The Wildland-urban interface Fire Dynamics Simulator (WFDS), to describe a spreading fire in a forested environment representative of the Pinelands National Reserve (PNR) in New Jersey, USA, with an ultimate goal of understanding how environmental conditions and fuel characteristics can modify potential fire behavior. Such information can be of use to managers and firefighters.

Wind is a key driving variable in wildland fire behavior, and therefore the drag coefficient, which appears in the momentum equation as a sink term due to vegetation drag, is an important parameter. However, the approach for defining this parameter has not been rigorously tested for physics-based fire behavior models. There are two different formulations commonly used to model this momentum drag within the raised fuel layer (shrubs and canopy), and these are described in more detail below. We tested both approaches with the objective of simulating fire behavior in a pine-dominated stand, and find that this choice varies the predicted quasi-steady spread rate by a factor of 1.6. This difference is linked to heat transfer ahead of the fire front, which in turn is related to the flame height.

Methods

Experimental methods

In order to provide the requisite data for model testing, measurements were made of experimental fires carried in the Pinelands National Reserve (PNR) in New Jersey. The overstory of the experimental blocks was predominantly pitch pine (Pinus rigida Mill.), and the shrub layer in the understory was composed of huckleberry (Gaylussacia spp.), blueberry (Vaccinium spp.), and scrub oaks (Quercus spp.). Measurement techniques included both remote sensing, yielding quantities such as spread rate from aerial IR and pre- and post-fire canopy bulk density (CBD) from aerial LiDAR, and point-based measurements, yielding quantities such as wind speed (both at and below canopy height), temperatures, and radiative heat fluxes. A full treatment of all experimental measurements is beyond the scope of this presentation, though an example of some early analysis can be found in Mueller et al (2014). The present simulations focus on one of the experimental fires, conducted in March 2014.

Numerical methods

WFDS is a Computational Fluid Dynamics (CFD) model that uses Large Eddy Simulation (LES) to directly resolve turbulent eddies that are larger than grid scale, and includes submodels for combustion, radiative transport, subgrid-scale turbulence. It is built upon the Fire Dynamics Simulator (FDS) (McGrattan *et al.* 2010), and employs a multiphase formulation for the description of subgrid-scale vegetation elements, originally developed by Grishin (1997) and Larnini et al. (1998). Details specific to the WFDS formulation can be found in Mell et al. (2007, 2009), and only aspects relevant to the problem formulation are discussed here.

The simulations presented focus on a sub-section of interest from the full experimental burn block, as shown in Figure 1. This choice was made in order to reduce run times and thus facilitate the study of a number of parameters that are not well defined experimentally, before moving on to larger scale simulations. The area encompassed by the numerical domain was 240 m x 225 m x 76.5 m. The horizontal grid resolution was 0.5 m x 0.5 m, while the vertical resolution was 0.5 m at ground level and, starting at a height of 2*h* (where *h* is canopy height), was stretched progressively to 1.5 m. A north wind was specified by a fixed velocity profile at the maximum y-boundary. The magnitude at canopy height was 3.9 ms^{-1} (following measured values), and a logarithmic profile was used above canopy and an exponential profile below. Key input parameters related to the vegetation are based on experimental measurements, and are given in Table 1. A vertical profile of CBD for live needles, considered to be the main

Table 1: Key vegetation input values for surface-to-volume ratio (σ), bulk density (ρ_b), element density (ρ_e), and moisture content (M). Subscripts refer to live canopy needles (ln), dead litter layer needles (dn), and fine woody shrub fuels (s1-3). Shrub fuels are subdivided into diameter categories of 0-2 mm (s1), 2-4 mm (s2), and 4-6 mm (s3).

Parameter	Value	Parameter	Value	Parameter	Value
σ_{ln}, σ_{dn}	4661 m^{-1}	$\rho_{e,dn}$	615 $kg \cdot m^{-3}$	$\rho_{b,s1-3}$	0.181 $kg \cdot m^{-3}$
$\rho_{b,ln}$	see Figure 2	M_{dn}	20 %	$\rho_{e,s1-3}$	512 $kg \cdot m^{-3}$
$\rho_{e,ln}$	787 $kg \cdot m^{-3}$	σ_{s1}	4000 m^{-1}	M_{s1-3}	61 %
M_{ln}	114 %	σ_{s2}	1333 m^{-1}		
$\rho_{b,dn}$	20.6 $kg \cdot m^{-3}$	σ_{s3}	800 m^{-1}		

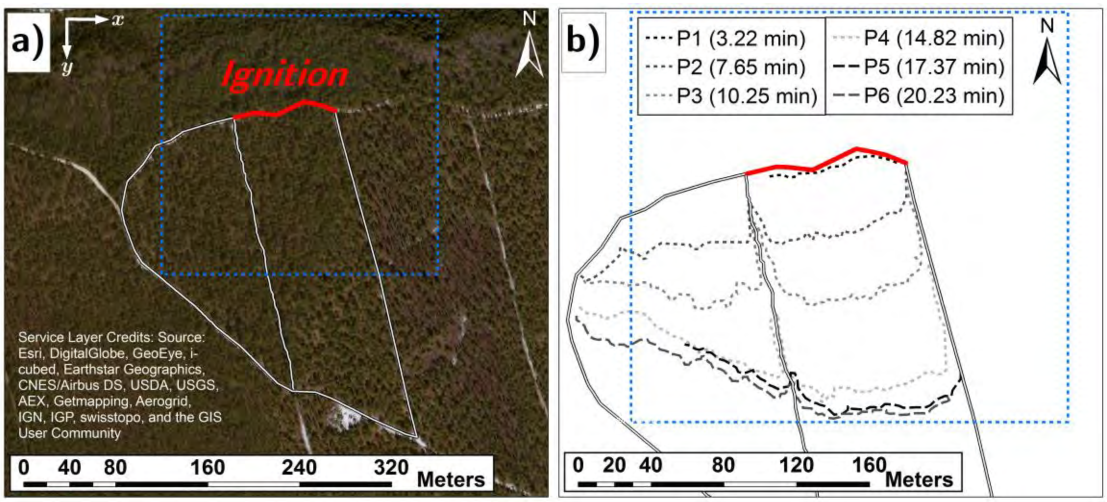

Figure 1: (a) Satellite imagery and (b) close up of fire progression contours (obtained from aerial IR imagery) of the experimental burn block. The numerical simulation domain is overlaid (dotted blue line), and the simulated ignition line is shown in red.

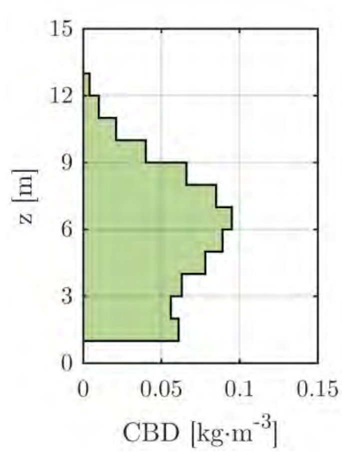

Figure 2: Block average of live needle CBD used for the simulations, as determined from calibrated LiDAR data. Note that as shrub fuels dominate below 1 m, the bulk density within this volume is specified from field sampling values (see Table 1) and are not included here.

contributors of fire intensity and momentum drag, in the forest canopy (Figure 2) was obtained from an average over the whole region of 10 m x 10 m raster data generated from the LiDAR measurements (Skowronski *et al.* 2011). The vertical resolution is 1 m. CBD in the shrub layer (lowest 1 m) and the litter layer of dead needles was obtained from destructive sampling pre-fire (Table 1).

In many LES-CFD studies of flow through forest canopies, a drag force is represented in the form of Equation 1, which is dependent on the one sided leaf area density (a_f) and the drag coefficient (c_d) set as a fixed value, depending on the vegetation characteristics.

$$\langle F_{d,i} \rangle_{V_b} = -\rho c_d a_f u_i |\mathbf{u}| \qquad (1)$$

This approach has been used to test WFDS for canopy flow previously (Mueller *et al.* 2014), and has also been applied to FIRETEC, another physics-based fire behavior model (Pimont *et al.* 2009). However, a number of studies employing the multiphase formulation for wildland fire modeling consider the bulk influence of the many subgrid particles by summing the contribution of each (e.g. Morvan and Dupuy 2004; Mell *et al.* 2009), resulting in a form following Equation 2. Here, c_d is a Reynolds number-dependent quantity based on the assumed particle geometry (cylinders, in our case), c_s is a shape factor ($1/(2\pi)$ for cylinders), and the other quantities are defined based on the vegetation (see Table 1).

$$\langle F_{d,i} \rangle_{V_b} = -\rho c_d c_S \sigma_e (\rho_b/\rho_e) u_i |\mathbf{u}| \qquad (2)$$

These two formulations are tested for modeling drag forces in both the canopy and shrub layer in the numerical simulation described above, with $c_d = 0.25$ for Equation 1. With this choice, for a given vegetation type, Equation 2 will result in greater drag, particularly at low velocities. For example, for live pine needles at a CBD of 0.05 $kg \cdot m^{-3}$ and a velocity of 0.1 ms^{-1}, the drag from Equation 2 will be 10 times greater. With increasing velocity, the ratio of the relationships reaches an asymptote at a value of 2.5.

Results and Discussion

A logical starting place for analyzing the simulation results is with broad fire behavior descriptors such as progression, or spread rate. Figure 3 shows that static drag coefficient progresses more rapidly during the initial stages (during which a surface fire was observed), but has a good match to the experimental spread rate from P2-P4 (during which a period of crown fire occurred). The dynamic formulation matches quite well initially (P1-P2), but under-predicts the more rapid spread following P2. In general, the time for the fire to reach 100 m increases by nearly 1.6 for the dynamic drag coefficient. In neither case is the simulation able to predict the sudden drop in fire spread following P4. However, this steady spread is expected as the modeled fuel loading is spatially homogenous and the wind speed is temporally homogenous, giving no reason for a sudden change in fire behavior.

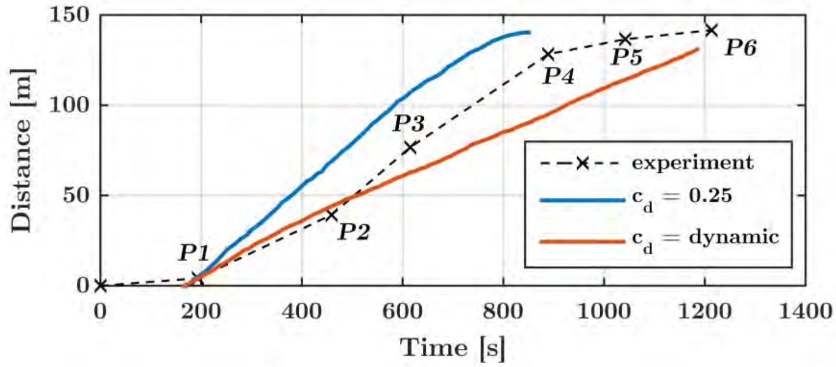

Figure 3: Simulated fire front progression (solid lines) compared with experimental progression (symbols). In both cases, the progression is determined by evaluating the distance traveled from the ignition line along a transect halfway between the center and rightmost road in Figure 1. Due to uncertainties associated with modeling the ignition process, the simulation times have been shifted so that the time of the fire at P1 is consistent for all cases and only the progression following this point is considered.

In order to better understand the reasons for these different predictions, an investigation of some more detailed aspects of the fire behavior was carried out. Figure 4 shows an example assessment of flame structure (T > 300 °C) and the characteristic radiative heat flux to the needle litter bed. It is clear that the higher air flow from the lower drag values result in taller flames (though the flame angles appear similar) with a greater depth, and thus higher heat fluxes (with a peak value roughly 1.7 times that for the dynamic drag coefficient). This increased thermal transfer to the fuel results in the more rapid fire spread observed in Figure 3. An investigation of the simulated fuel bulk density and consumption will help reveal which fire behavior (and thus drag formulation) is more in line with expectations, given that average values are used compared to the range of bulk densities observed in the experiments.

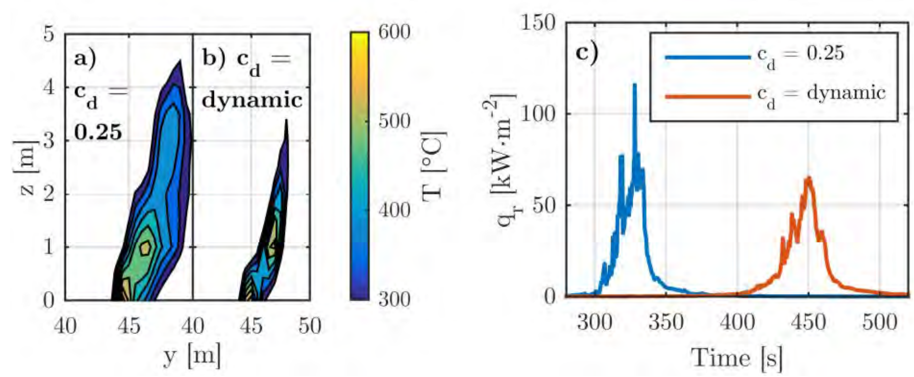

Figure 4: Examples of simulation difference in terms of (a) 5-s average of flame front temperatures along a transect on the y-axis (bisecting the flame front), and (b) incident radiative flux onto the needle litter fuel bed. Both figures represent the fire after traveling 45 m, or close to P2.

Conclusions

In this work, it is shown that WFDS is capable of giving a reasonable prediction of fire progression when compared to the experimental data. However, for this scenario, the results are sensitive to the formulation of the drag coefficient. The differences in broad fire behavior are linked to more fundamental characteristics of the flames, with a static drag coefficient tending towards larger flames and faster spread. Ongoing experimental analysis of these types of characteristics (such as temperatures and heat fluxes) will shed more light on the quality of the two different approaches, but ultimately a more robust characterization of drag within these types of fuel beds is recommended. Finally, implementation of heterogeneous descriptions of wind and vegetation will help assess the ability of the model to capture the dynamic fire behavior observed in the experiments.

References

Grishin AM (1997) 'Mathematical modeling of forest fires and new methods of fighting them.' (Publishing house of the Tomsk state university)

Larini M, Giroud F, Porterie B, Loraud J-C (1998) A multiphase formulation for fire propagation in heterogeneous combustible media. *International Journal of Heat and Mass Transfer* **41**, 881–897.

McGrattan K, Hostikka S, Floyd JE (2010) Fire dynamics simulator (version 5), user's guide. *NIST special publication* **1019**, 1–186.

Mell W, Jenkins MA, Gould J, Cheney P (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* **16**, 1–22. doi:10.1071/WF06002.

Mell W, Maranghides A, McDermott R, Manzello SL (2009) Numerical simulation and experiments of burning douglas fir trees. *Combustion and Flame* **156**, 2023–2041. doi:10.1016/j.combustflame.2009.06.015.

Morvan D, Dupuy JL (2004) Modeling the propagation of a wildfire through a Mediterranean shrub using a multiphase formulation. *Combustion and Flame* **138**, 199–210. doi:10.1016/j.combustflame.2004.05.001.

Mueller E, Mell W, Simeoni A (2014) Large eddy simulation of forest canopy flow for wildland fire modeling. *Canadian Journal of Forest Research* **44**, 1534–1544. doi:10.1139/cjfr-2014-0184.

Mueller E, Skowronski NS, Clark KL, Kremens R, Gallagher MR, Thomas JC, El Houssami M, Filkov AI, Butler BW, Hom J, Mell WE, Simeoni A (2014) An experimental approach to the evaluation of prescribed fire behavior. In 'Proc. 7th Int. Conf. For. Fire Res.', Coimbra, Portugal.(Coimbra, Portugal)

Pastor E, Zarate L, Planas E, Arnaldos J (2003) Mathematical models and calculation systems for the study of wildland fire behaviour. *Progress in Energy and Combustion Science* **29**, 139–153.

Pimont F, Dupuy JL, Linn RR, Dupont S (2009) Validation of FIRETEC wind-flows over a canopy and a fuel-break. *International Journal of Wildland Fire* **18**, 775–790. doi:10.1071/WF07130.

Skowronski NS, Clark KL, Duveneck M, Hom J (2011) Three-dimensional canopy fuel loading predicted using upward and downward sensing LiDAR systems. *Remote Sensing of Environment* **115**, 703–714. doi:10.1016/j.rse.2010.10.012.

Sullivan AL (2009a) Wildland surface fire spread modelling, 1990–2007. 1: Physical and quasi-physical models. *International Journal of Wildland Fire* **18**, 349–368.

Sullivan AL (2009b) Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. *International Journal of Wildland Fire* **18**, 369–386. doi:10.1071/WF06144.

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Fire Weather Drives the Population Collapse of Obligate-seeder Forests: The Case of *Eucalyptus delegatensis* in the Australian Alps

David MJS Bowman*
School of Biological Sciences, University of Tasmania, Hobart, Tasmania, Australia,
david.bowman@utas.edu.au

Lynda D Prior
School of Biological Sciences, University of Tasmania, Hobart, Tasmania, Australia,
lynda.prior@utas.edu.au

Grant J Williamson
School of Biological Sciences, University of Tasmania, Hobart, Tasmania, Australia,
grant.williamson@utas.edu.au

Brett R Murphy
Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT, Australia, brett.p.murphy@cdu.edu.au

Abstract

Forests that regenerate exclusively from seed following high-severity fire are particularly vulnerable to local extinction if fire frequency leaves insufficient time for regenerating plants to reach sexual maturity. We illustrate this using obligate seeding alpine ash (*Eucalyptus delegatensis*) forests in the montane regions of Victoria, Australia, that were burnt by megafires in 2003, 2007 and 2013, including some areas that were burnt three times.

Eucalyptus delegatensis is a tall, long-lived tree that regenerates following fire disturbance, which stimulates the release of seed from an aerial seedbank. If regenerating stands are burnt before they reach sexual maturity (after about 20 years) the species suffers local extinction and can only re-establish via gradual colonisation (Bowman *et al*. 2013). Aerial and field surveys in an area that was burnt by three fires (2003, 2007 and 2013) in the Alpine National Park, Victoria, demonstrated the complete population collapse of this species (Bassett *et al*. 2014).

We evaluated the relative importance of extrinsic (such as fire weather and climate cycles) and intrinsic (such as fire hazard) factors in driving the demographic collapse of these obligate seeder forests. Geospatial analyses showed only a small effect of stand age on remote sensing estimates of crown defoliation, but a substantial effect of forest fire weather, as measured by forest fire danger index (FFDI). Analysis of meteorological data over the last century showed that peaks in 5-year running average FFDI cycles precede major fires in the *E. delegatensis* forests.

Such strong extrinsic climate/weather drivers of high severity fires matches similar conclusions concerning the effect of climate change on western USA forests and Mediterranean basin shrublands dominated by obligate seeders (e.g. Moritz *et al.* 2004; Westerling *et al*. 2011) and is

*Corresponding author: School of Biological Sciences, Private Bag 55, University of Tasmania, Hobart, Tasmania, Australia 7000. david.bowman@utas.edu.au; http://www.utas.edu.au/plant-science/people/academic/David-Bowman

consistent with the ‘interval squeeze model’ model (Enright *et al*. 2015), which postulates the vulnerability of obligate seeder forests to demographic collapse in response to reduced tree growth rates and worsening fire weather under climate change.

References

Bassett OD, Prior LD, Slijkerman CM, Jamieson D, Bowman DMJS (2015) Aerial sowing stopped the loss of alpine ash (*Eucalyptus delegatensis*) forests burnt by three short-interval fires in the Alpine National Park, Victoria, Australia. *Forest Ecology and Management* **342**, 39-48.

Bowman DMJS, Murphy BP, Neyland DLJ, Williamson GJ, Prior LD (2014) Abrupt fire regime change may cause landscape-wide loss of mature obligate seeder forests. *Global Change Biology* **20**, 1008-1015.

Enright, NJ, Fontaine, JB, Bowman, DMJS, Bradstock, RA, Williams, RJ (2015) Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. *Frontiers in Ecology and the Environment* **13**, 265-272.

Moritz M., Keeley JE, Johnson EA, Schaffner AA (2004) Testing a basic assumption of shrubland fire management: how important is fuel age? *Frontiers in Ecology and the Environment* **2**, 67-72.

Westerling AL, Turner MG, Smithwick EAH, Romme WH, Ryan MG (2011) Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences* **108**, 13165-13170.

*Corresponding author: School of Biological Sciences, Private Bag 55, University of Tasmania, Hobart, Tasmania, Australia 7000. david.bowman@utas.edu.au; http://www.utas.edu.au/plant-science/people/academic/David-Bowman

Geomonitoring of Forest Fire Danger Using GIS and Remote Sensing: Case Study for Typical Area of Tomsk Region

Nikolay Baranovskiy*
National Research Tomsk Polytechnic University, Tomsk, Russian Federation,
firedanger@narod.ru

Elena Yankovich
National Research Tomsk Polytechnic University, Tomsk, Russian Federation,
yankovich@tpu.ru

Marina Engel
Institute of Atmospheric Optics SB RAS, Tomsk, Russian Federation, angel@iao.ru

Vladimir Belov
Institute of Atmospheric Optics SB RAS, Tomsk, Russian Federation, belov@iao.ru

Introduction

To present time the method of prognostic modeling of forest fire danger based on probabilistic criteria and deterministic models of ignition is developed [1]. Factor of storm activity can be marked out among various ignition sources of forest fuel. Cloud-to-ground lightning discharge leads to forest fire occurrence [2]. The further development of prognostic modeling is possible using physically proved mathematical models of forest fuel ignition by a current of cloud-to-ground lightning discharge. Creation of information-computational and geoinformation systems [3] should become the further development of technologies for forest fire forecasting in this direction. Using of geoinformation technologies provides the spatial data analysis and results visualization.

Such systems can be developed for various scale of territories. For example, ISDM-Rosleshoz system [4] functions in Russia and there is a creation of ForestGIS system in Ukraine [5] for an estimation, monitoring and forecasting of forest fire danger in territories of state scale. During too time, industry geoinformation systems are maintained in each timber enterprise [6]. However, such systems do not consider forest fire danger.

The purpose of present article is development of geoinformation system prototype for an estimation of the forest fire danger caused by storm activity using specialized program tools and remote sensing data.

Probabilistic Forest Fire Danger Assessment

The probabilistic approach to estimation of the forest fire danger is used.

A formula for definition of forest fire occurrence probability is presented below [7]:

$$P_j = \left[P(A)P(A_j/A)P(FF/A,A_j) + P(L)P(L_j/L)P(FF/L,L_j)\right]P_j(D),$$

Here P_j is the probability of forest fire occurrence for a j interval at a controlled forest area; P(A) is the probability of anthropogenic load; $P(A_j/A)$ is the probability of fire source existence on the j day; $P_j(FF/A, A_j)$ is the probability of fire occurrence as a result of the anthropogenic load in the stratum; P(L) is the probability of dry storm occurrence on the stratum territory; $P(L_j/L)$ is the probability of ground storm discharge; P_j $(FF/L,L_j)$ is the probability of lightning-induced forest fire occurrence under the condition that dry storm may occur on the stratum territory; $P_j(D)$ is the probability of fire occurrence in weather conditions of forest fire maturation (the probability of the forest fuels layer to be dry); j index corresponds the day of fire danger season. The following behavior scenario of a human in the forest is chosen: when the storm occurs, the human is trying to leave the forested area or to find shelter, i.e. there is no anthropogenic load when there is a storm (incompatible events).

GIS Structure

The described geoinformation system at first carries out preliminary processing of the entrance information. Data on hot points from products MODIS Terra/Aqua [8] are used. Then attributive tables are forming next stage. Data import on storm activity of network WWLLN [9] is used. Then the prepared information arrives in the output agent of geospatial data where there is a definitive formation of initial data for subsystems of GIS-system and mathematical models of trees ignition by the cloud-to-ground lightning discharge [10]. The analysis of thermal anomalies on controlled forested territories using remote sensing data is carrying out at this stage. Forest fire danger estimation is carrying out at a following stage. Results are visualizing on an electronic map of controlled forested territories. Topological base described in Fig. 1.

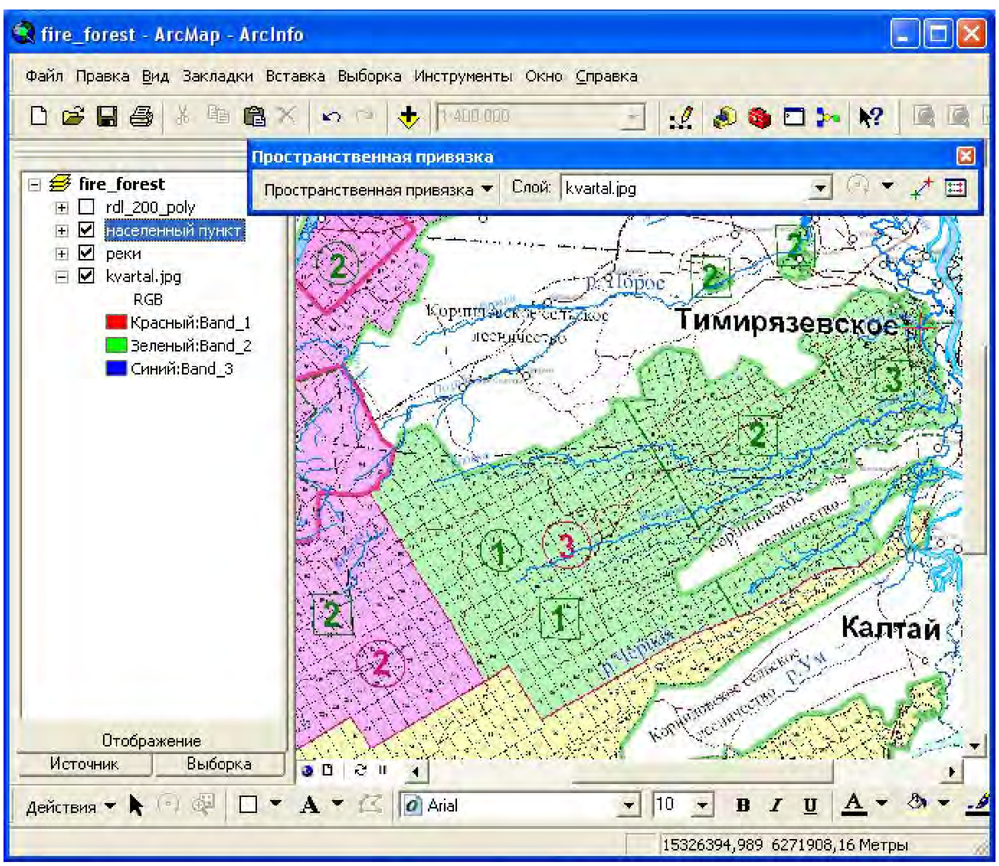

Figure 1: GIS topological base (Timiryazevskiy forestry) for assessment of lightning-caused forest fire danger

Results and Discussion

Forest fire danger of Tomsk region is determined by presence of a considerable share of the coniferous woods, developed flammable surface cover and the hot dry summer. The climate of Tomsk region is sharp-continental of boreal type. There are conditions especially favorable for occurrence of forest fires in territories with continental climate. Three peaks of seasonal fire activity are expressed in forests of Tomsk region depending on weather conditions: spring fires, summer steady fires and autumn. Feature of Tomsk region forests is combustible material presence in all plantings. Mainly surface fires (98,5 %) develop in region, on a share of crown fires correspond 1,1 % of incidents and 12,5 % of the burnt area. There are underground fires even less often. The share of fires for the anthropogenous reasons on years is stable enough, and fires from a lightning discharge have cyclic character. The periods with mass thunder-storms are replaced by quieter.

The created GIS-system should carry out the basic function: to classify forests on level of fire danger in the conditions of influence of storm activity. Realization of technique for estimation of forest fire danger caused by storm activity allows to develop following recommendations:

1) It is necessary to have actual forest taxation descriptions of controlled forests (age of a forest stand, change of shares of trees of deciduous and coniferous breeds);
2) Ground fuels descriptions should be included in standard forest taxation description;
3) Forest site is a minimal area to carry out a precision estimation of forest fire danger;
4) Quarter and local forestry are the basic for estimation of forest fire danger;
5) It is necessary to assign forest wardens for monitoring over fire-dangerous forest plots near to settlements;
6) It is expedient to mount and establish the observant towers equipped with systems of video registration and remote access, for example, on channels of cellular communication GSM in places of high concentration of fire-dangerous sites. Observation point can be equipped with GPS or GLONASS navigator and the cellular modem for this purpose.
7) It is necessary to organize optimum routes of flights of planes for the purpose of monitoring of the most fire-dangerous areas in distant territories.
8) It is necessary to process remote sensing images for fire-dangerous territories at availability of the satellite information.

The selective estimation of forest fire danger for the territory of the Timiryazevskiy local forestry of the Timiryazevskiy forestry of Tomsk region spent. It is established as a result of such estimation, that only coniferous and the part of the mixed forests represents fire danger caused by storm activity.

Conclusion

The prototype of geoinformation system for estimation of the forest fire danger caused by storm activity is presented in this paper. The system includes databanks of forest taxation descriptions, map-raster with geobinding and layer with data of remote sounding. The complex estimation of the forest fire danger caused by storm activity is possible based on ground data evaluation, computing models of ignition and remote sensing monitoring of hot spots in forests.

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Forest Department of Tomsk region provided forest taxation descriptions.

References

1. Baranovskiy NV (2012) Thermophysical aspects of prognostic modeling of forest fire danger. Dissertation (TPU, Tomsk) (In Russian)
2. Amatulli G, Perez-Cabello F, Dula Riva J (2007) Mapping lightning/human-caused wildfires occurrence under ignition point location uncertainty. *Ecological Modelling* **200**, 321-333.
3. Vakalis D, Sarimveis H, Kiranoudis C et al. (2004) A GIS based operational system for wildland fire crisis I. Mathematical modelling and simulation. *Applied Mathematical Modelling* **28**, 389-410.
4. Podolskaya AS, Ershov DV, Shulyak PP (2011) Application of a method for estimation of forest fire occurrence probability in ISDM-Rosleshoz. *Modern problems of remote sounding of the Earth from space* **8**, 118-126. (In Russian)
5. Zharikova MV, Baranovskiy NV, Lyashenko EN (2012) Conceptual project of the web-oriented geographical information system for the forecast of forest fire danger. *Fire and Explosion Safety* **21**, 62-68. (In Russian)
6. Kuznetsov VI, Kozlov NI, Homyakov PM ПМ (2005) Mathematical modeling of forest evolution for management of a forestry (LENAND, Moscow) (In Russian)
7. Baranovskiy N, Zharikova M (2014) A Web-Oriented Geoinformation System Application for Forest Fire Danger Prediction in Typical Forests of the Ukraine. in Lecture Notes in Geoinformation and Cartography. Thematic Cartography for the Society (Eds. Bandrova T, Konecny M, Zlatanova S). pp. 13-22. (Springer, Heilderberg)
8. Kir'yanova EY., Savin IY (2013) Crop canopy heterogeneity detected based on MODIS satellite data as an indicator of contrast in soil patterns. *Russian Agricultural Science* **39**, 342-345. (In Russian)
9. Lay EH, Holzworth RH, Rodger CJ, Thomas JN, Pinto O Jr., Dowden RL (2004) WWLL global lightning detection system: Regional validation study in Brazil. *Geophysical Research Letters* **31**, 1-5.
10. Kuznetsov GV, Baranovskiy NV (2014) Mathematical simulation of heat transfer at coniferous tree ignition by cloud-to-ground lightning discharge. *EPJ Web of Conferences* **76**, Paper 01028, 1-6.

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High Fidelity Reduced Order Models for Wildland Fires

Alan M. Lattimer*
Virginia Tech, Blacksburg, VA, USA, alattime@vt.edu

Brian Y. Lattimer
JENSEN HUGHES, Blacksburg, VA, USA, blattimer@jensenhughes.com

Serkan Gugercin
Virginia Tech, Blacksburg, VA, USA, gugercin@vt.edu

Jeffrey T. Borggaard
Virginia Tech, Blacksburg, VA, USA, jborggaard@vt.edu

Kray D. Luxbacher
Virginia Tech, Blacksburg, VA, USA, kraylux@vt.edu

Introduction

The modeling and simulation of fires is a complex, multi-scale problem. The need to create accurate models extends from prevention to prediction to damage control management. Since these problems are so complex, even models of moderately-sized fires in relatively small domains require significant computational resources and time to solve. Further, the actual physics are often difficult to model exactly, e.g. the exact fuel loading and distribution in a burning room or wildland fire. To this end, much of the focus in the fire community has been on simplifying the physics of the problem to obtain reasonable models. Current techniques for reducing fire models, such as proper orthogonal decomposition (POD) (see Kunisch and Volkwein [2002], Hinze and Volkwein [2005], Sharma et al. [2013], Volkwein [2013]), often have limited effectiveness due in large part to the inherent nonlinearities that exist in fire models. Regardless of the size of the reduced-order model (ROM), the nonlinearities must still be evaluated at the full-order of the model. This issue, referred to as the *lifting bottleneck*, must be addressed in order to fully realize the computational gains for a given reduced-order model. In this paper, we examine reduced-order modeling for two different fire models. For the wildland fire-spread model given by Mandel et al. [2008], we employ DEIM (see Chaturantabut and Sorensen [2010]) to address the computational bottleneck associated with the nonlinearity in the model. We then examine fire-plume models in relation to the underlying structure of the fire. Additionally, we evaluate the quality of the ROM with regards to capturing the essential features of the fire.

Wildland Fire-Spread Model

Large-scale models for real-time simulations, as required for predicting wildland fires, are avoided due to limited computational resources. On the other hand, lower spatial resolution limits the physics that can be captured by the models. Reduced-order modeling is an approach that retains the physics of the problem while simultaneously reducing the computational costs. The accuracy and improved computational efficiency are demonstrated by building a ROM for a wildland fire spread model.

*ICAM, 765 West Campus Dr., Blacksburg, VA, USA, alattime@vt.edu

Basic Description

We explored a reduced-order model (ROM) for the phenomenological model suggested in Mandel et al. [2008] to predict flame front propagation in wildland fires given by

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} - v \frac{\partial T}{\partial x} + \alpha \left(S e^{-\widetilde{\beta}/(T-T_0)} - \gamma (T - T_0) \right), \tag{1}$$

$$\frac{\partial S}{\partial t} = -\gamma_S S e^{-\widetilde{\beta}/(T-T_0)}, \tag{2}$$

where T is the temperature, and S is the mass fraction of fuel in a propagating fire. Using constant parameters and wind velocity, the nonlinearity of this model occurs via a reaction term.

Proper orthogonal decomposition (POD) is the most commonly used technique to produce ROMs for complex nonlinear dynamics Hinze and Volkwein [2005]. POD has been used to reduce wildland fire-spread models (e.g. Mandel et al. [2008]) in Sharma et al. [2013], Guelpa et al. [2014] to achieve modest gains in computational performance. Though ROMs using POD are effective, they can be significantly improved for nonlinear systems by addressing the so-called *lifting bottleneck* using the Discrete Empirical Interpolation Method (DEIM) described below. This lifting bottleneck occurs when computing the reduced nonlinear term, since standard POD first lifts the reduced variables up to the full-order dimension, evaluates the nonlinear term, then projects the result back down to reduced dimension. Therefore, the computational gains compared to the original model are limited since the nonlinear terms are computed at the full-order dimension.

Discrete Empirical Interpolation Method (DEIM)

Suppose we have a nonlinear system given by $\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{f}(\mathbf{x}(t))$ where $\mathbf{A} \in \mathbb{R}^{n\times n}$, $\mathbf{x} : \mathbb{R} \to \mathbb{R}^n$, and $\mathbf{f} : \mathbb{R}^n \to \mathbb{R}^n$. Suppose that $\mathbf{V} \in \mathbb{R}^{n\times r}$ is the projection matrix that we determine using POD. Then using a Galerkin projection we see that the ROM would be

$$\dot{\mathbf{x}}_r(t) = \underbrace{\mathbf{V}^T\mathbf{A}\mathbf{V}}_{\mathbf{A}_r : r\times r}\mathbf{x}_r(t) + \underbrace{\mathbf{V}^T}_{r\times n}\underbrace{\mathbf{f}(\mathbf{V}\mathbf{x}_r(t))}_{n\times 1}, \tag{3}$$

where $\mathbf{x}_r : \mathbb{R} \to \mathbb{R}^r$. For the nonlinear term, $\mathbf{x}_r(t)$ must be lifted back to the original size of the state space, i.e. $\mathbf{V}\mathbf{x}_r(t) \in \mathbb{R}^n$, before evaluating $\mathbf{f}$. This implies that the computational complexity of calculating the nonlinear term is order n.

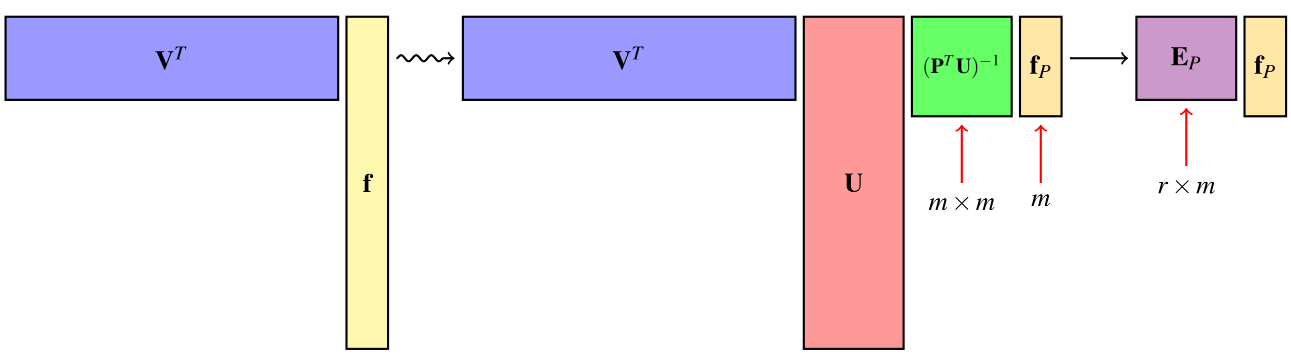

Figure 1: Visual depiction of the DEIM approximation $\mathbf{V}^T\mathbf{f}(t) \approx \mathbf{E}_P\mathbf{f}_P(t)$.

We can reduce this complexity be employing DEIM Chaturantabut and Sorensen [2010], a discrete variant of the Empirical Interpolation Method introduced in Barrault et al. [2004]. Given the nonlinear dynamics in (3) from the nonlinearity $\mathbf{f}: \mathbb{R}^n \to \mathbb{R}^n$, during a simulation, in addition to the snapshots of the state-vector $\mathbf{x}$, we collect snapshots of the nonlinearity $\mathbf{f}$. Then, we compute the DEIM-projection matrix $\mathbf{U}$ as the leading left-singular vectors of the nonlinear snapshots, i.e., we compute a POD basis for the nonlinearity. Let $\mathbf{U} \in \mathbb{R}^{n\times m}$, where $m \ll n$. Then, the DEIM approximation of $\mathbf{f}$ is given by

$$\widehat{\mathbf{f}}(t) = \mathbf{U}(\mathbf{P}^T\mathbf{U})^{-1}\mathbf{P}^T\mathbf{f}(t), \tag{4}$$

where $\mathbf{P}$ is the $n \times m$ DEIM-selection operator, obtained by selecting certain columns of the $n \times n$ identity matrix $\mathbf{I}$. The reduced nonlinear term, then, becomes

$$\mathbf{f}_r(\mathbf{x}_r(t)) \approx \mathbf{V}^T\mathbf{U}(\mathbf{P}^T\mathbf{U})^{-1}\mathbf{P}^T\mathbf{f}(\mathbf{V}\mathbf{x}_r(t)). \tag{5}$$

We emphasize that, in contrast to the analytical formula given by (5), for a numerical implementation, one computes $\mathbf{f}_r(\mathbf{x}_r(t))$ without lifting $\mathbf{x}_r(t)$. Instead, one evaluates $\mathbf{f}_r(\mathbf{x}_r(t))$ at selected rows of $\mathbf{V}\mathbf{x}_r(t)$. The selection operator $\mathbf{P}$ enforces interpolation at the selected indices of $\mathbf{f}$, called the DEIM indices, and those indices are computed via a greedy search process. When we have a component-wise nonlinearity, as we do here, we can move $\mathbf{P}$ into the nonlinear function. We can then define $\mathbf{E}_P := \mathbf{V}^T\mathbf{U}(\mathbf{P}^T\mathbf{U})^{-1}$ and $\mathbf{f}_P(t) := \mathbf{f}((\mathbf{P}^T\mathbf{V})\mathbf{x}_r(t))$, where $\mathbf{E}_P \in \mathbb{R}^{r\times m}$ and $(\mathbf{P}^T\mathbf{V}) \in \mathbb{R}^{m\times r}$ only have to be computed once. For details, we refer the reader to the original source Chaturantabut and Sorensen [2010]. In our implementation, we employ a new variant of DEIM recently developed by Drmac and Gugercin [2015] where the greedy search is performed via a pivoted QR decomposition.

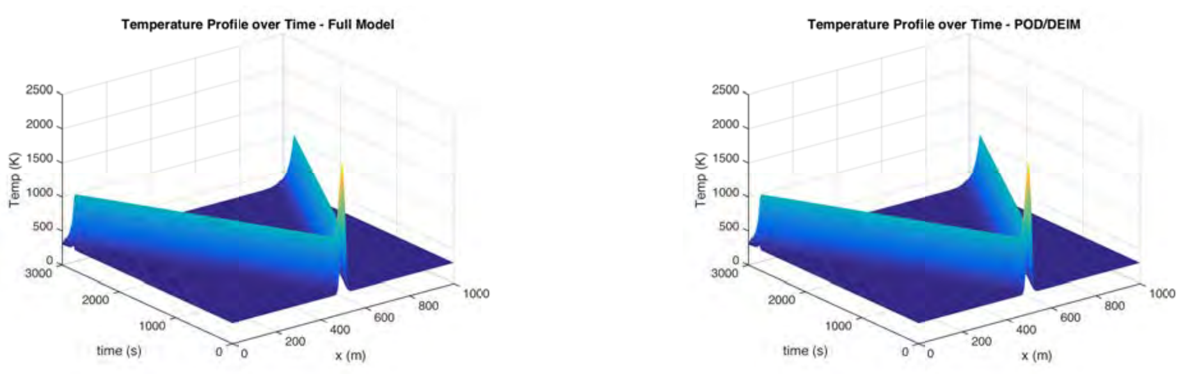

Figure 2: FOM versus the POD/DEIM ROM where $r_T = 250, r_S = 150$, and $r_{DEIM} = 250$.

Methods and Numerical Results

For the wildland fire-spread model (1)-(2), we can discretize the system using finite differences to create the following discretized model

$$\begin{bmatrix}\dot{\mathbf{T}}(t)\\ \dot{\mathbf{S}}(t)\end{bmatrix} = \begin{bmatrix}\mathbf{A}_T & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\mathbf{T}(t)\\ \mathbf{S}(t)\end{bmatrix} + \begin{bmatrix}\alpha\mathbf{f}[\mathbf{T}(t),\mathbf{S}(t)]\\ -\gamma_S\mathbf{f}[\mathbf{T}(t),\mathbf{S}(t)]\end{bmatrix}, \tag{6}$$

where $\mathbf{f}[\mathbf{T}(t),\mathbf{S}(t)] = \mathbf{S}(t)e^{-\beta/(\mathbf{T}(t)-T_0)}$ is the nonlinear function that is approximated using DEIM. Additionally, separate POD bases were built for the temperature and fuel mass fractions. This also saved computational costs since the fuel mass fraction did not require as many basis vectors to accurately represent the results. For our testing we used the parameter values specified in Mandel et al. [2008], and the system was discretized from 0 to 1000 m in 0.2 m increments and solved over 3000 s. The initial condition has a fire at the 500 m location. The fire then propagates across the domain towards both boundaries based on equations (1-2) as seen in Figure 2.

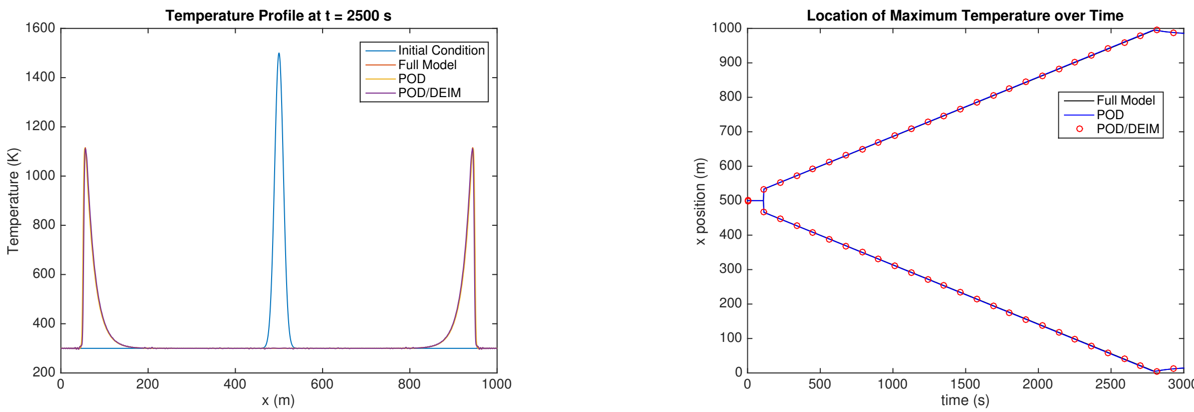

Figure 3: Fire spread for FOM, POD, and POD/DEIM.

Using the data snapshots created, r_T and r_S number of POD bases for T and S, respectively, were created. Further, POD was enhanced by projecting the nonlinearity using 250 DEIM vectors. Figures 2 and 3 show that the POD/DEIM ROM provides an excellent approximation of the full-order model (FOM) matching both the flame front location and temperature profile quite well.

Table 1: Results for the ROM. Solution time for the FOM was 99.1 s

# POD Vectors	POD			POD/DEIM		
$r_T/r_S/r_{DEIM}$	Time (s)	Speed up	Rel Error	Time (s)	Speed up	Rel Error
70/35/250	1.33	74.6	1.7471e-02	0.13	760.1	1.7594e-02
200/150/250	15.4	6.38	4.3329e-03	0.72	137.6	5.2877e-04
200/200/250	18.5	5.31	1.8478e-02	0.84	118.2	1.3873e-02

As shown in Table 1, the solution times increase when more POD/DEIM vectors are used, but even the largest ROM using POD only was five times faster than the FOM. Further the relative error between the full-order and reduced-order model solutions was less 2% in all cases with a minimum of 0.43% when using 200 POD vectors for T and 150 POD vectors for S. When using POD with DEIM, the solution times were significantly better than POD alone while maintaining essentially the same error. The results demonstrate that using POD with DEIM can reduce the computational time by 2-3 orders of magnitude while retaining the physics and prediction accuracy.

Fire Plumes

Fire-plume simulations involve fine scale discretizations of coupled nonlinear PDEs. The complexity of the simulations are such that one cannot expect reduced-order models to accurately capture every feature of the simulations. In fact, a fundamental premise of reduced-order modeling in these cases is an underlying low-dimensional manifold for the full-order simulation.

However, many of the applications of fire modeling do not require knowledge of the states at every point in time and space, but rather they need to capture certain characteristics of the fire that would be useful for either making safety design decisions or to evaluate real-time fire suppression strategies. When considering how well a ROM of a fire matches the full-order fire model, we consider the following: 1) Dynamics, 2) Magnitude, and 3) Oscillation frequency and amplitude. We see that these criteria do not seek to strictly minimize an error between the FOM and ROM at some particular time step, but they do measure the efficacy of the ROM in representing the fire.

Description and Methods

Using the Fire Dynamics Simulator (FDS) software we generated a 2D full-order model of a 40 kW methane plume fire. Data was captured for 500 time steps evenly spaced over 20 seconds. To produce a ROM for this data, we used the PDE in (7)-(9) for our model.

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u}\cdot\nabla\mathbf{u} - \nabla p + \nu\nabla^2\mathbf{u} - \beta\mathbf{g}(T - T_\infty), \tag{7}$$

$$0 = \nabla\cdot\mathbf{u}, \tag{8}$$

$$\frac{\partial T}{\partial t} = -\mathbf{u}\cdot\nabla T + \alpha\nabla^2 T. \tag{9}$$

In particular, we wanted to investigate how close we could get to the actual fire model without

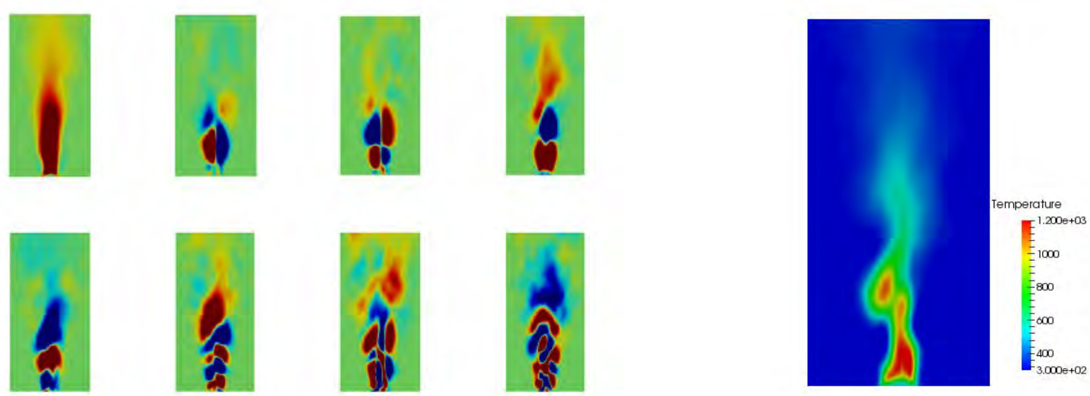

Figure 4: The left image shows the temperature POD modes for the small plume fire. Here we show POD modes 1, 2, 3, 4, 5, 10, 15, and 20 from left to right, top to bottom. On the right we show a typical reconstructed image created from the POD modes.

incorporating the combustion. From the snapshots, we created r POD basis modes for the u velocity, v velocity, and temperature T and used them to project the full-order PDE. Looking at the POD modes in Figure 4, we see that even though a fire seems to have random behavior, there are some underlying structures that exist. Further, the initial POD modes capture the overall shape and distribution of the fire, whereas the higher modes capture the finer details. The ROM seems to do a good job of capturing the dynamics of the system. While not exact, we do see the types of the oscillations of the mean and maximum temperatures and velocities indicative of a fire. The model was not quite as good at approximating the mean or maximum of the temperature or velocity. This is most likely due to the contribution of combustion in the FOM. Finally, the frequency of the temperature and velocity oscillations matches the FOM very well. However, the amplitudes of the oscillations were not as large as the FOM. Overall, the ROM does a good job of capturing the fire dynamics, but to truly match the magnitude of the fire, the combustion aspect will need to be incorporated.

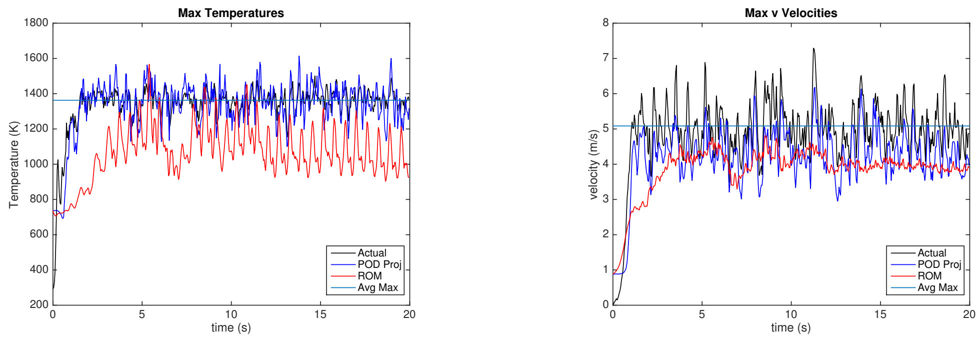

Figure 5: Maximum temperature and vertical velocity comparison between ROM and FOM with $r = 20$.

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References

Maxime Barrault, Yvon Maday, Ngoc Cuong Nguyen, and Anthony T. Patera. An ‘empirical interpolation’method: application to efficient reduced-basis discretization of partial differential equations. *Comptes Rendus Mathematique*, 339(9):667–672, 2004.

Saifon Chaturantabut and Danny C. Sorensen. Nonlinear model reduction via discrete empirical interpolation. *SIAM Journal on Scientific Computing*, 32(5):2737–2764, 2010.

Zlatko Drmac and Serkan Gugercin. A New Selection Operator for the Discrete Empirical Interpolation Method–improved a priori error bound and extensions. *arXiv preprint arXiv:1505.00370*, 2015.

Elisa Guelpa, Adriano Sciacovelli, Vittorio Verda, and Davide Ascoli. Model reduction approach for wildfire multi-scenario analysis. *Parte: http://hdl. handle. net/10316.2/34013*, 2014.

Michael Hinze and Stefan Volkwein. Proper orthogonal decomposition surrogate models for nonlinear dynamical systems: Error estimates and suboptimal control. In *Dimension Reduction of Large-Scale Systems*, pages 261–306. Springer, 2005.

K. Kunisch and Stefan Volkwein. Galerkin proper orthogonal decomposition methods for a general equation in fluid dynamics. *SIAM Journal on Numerical analysis*, 40(2):492–515, 2002.

Jan Mandel, Lynn S. Bennethum, Jonathan D. Beezley, Janice L. Coen, Craig C. Douglas, Minjeong Kim, and Anthony Vodacek. A wildland fire model with data assimilation. *Mathematics and Computers in Simulation*, 79(3):584–606, 2008.

Balaji R. Sharma, Manish Kumar, and Kelly Cohen. Spatio-Temporal Estimation of Wildfire Growth. In *ASME 2013 Dynamic Systems and Control Conference*, pages V002T25A005–V002T25A005. American Society of Mechanical Engineers, 2013.

Stefan Volkwein. Proper orthogonal decomposition: Theory and reduced-order modelling. *Lecture Notes, University of Konstanz*, 2013.

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Ignition from fire perimeter and assimilation into a coupled fire-atmosphere model

Adam K. Kochanski
Research Assistant Professor, Atmospheric Sciences Department, University of Utah, Salt Lake City, UT, adam.kochanski@utah.edu

Mary Ann Jenkins
Research Professor, Atmospheric Sciences Department, University of Utah, Salt Lake City, UT

Volodymyr Y. Kondratenko, Research Software Engineer, Pacific Metrics, Golden, CO

Jan Mandel, Professor, University of Colorado Denver, Denver, CO

Sher Schranz, Associate Director, Cooperative Institute for research in the Atmosphere, Colorado State University, Boulder, CO

Martin Vejmelka, Scientist, Institute of Computer Science, Academy of Sciences of the Czech Republic, Prague, Czech Republic

Craig B. Clements, Associate Professor, Department of Meteorology, San Jose State University, San Jose, CA

Braniff Davis, graduate student, Department of Meteorology, San Jose State University in San Jose, CA

Introduction

Assimilation of fire perimeter data into a numerical coupled atmosphere wildfire-fire prediction model is key to simulating wildfires that at the moment of detection have already evolved to a noticeable perimeter, especially when the exact ignition location is unknown. In the case of long-lived (multi-day) fires, cyclical assimilation of newly available perimeter observations may be used to correct the model state and potentially improve the fire spread prediction. In existing operational wildfire spread models without two-way coupling with the atmosphere, the state of the fire does not affect the state of the atmosphere, the existing fire perimeter may be simply specified by the burnt area and ignited at once. After the whole fuel inside the perimeter burns the fire will naturally propagate outward from the burnt area. In a coupled numerical fire-atmosphere prediction framework however, the ignition procedure itself affects the atmospheric state (especially local updrafts near the fire line and the near fire winds). Therefore, more attention is needed during the ignition process to assure that the atmospheric component of the model does not become numerically unstable due to the excessive heat flux released during the ignition, and that realistic fire-induced atmospheric circulation is established at ignition time. In this work we use WRF-SFIRE to test four different approaches to the perimeter ignition process. For each, we compare in-plume updraft velocities to values observed during the FireFlux2 experiment and to values from a WRF-SFIRE benchmark simulation based on the actual FireFlux2 ignition procedure.

Modeling setup

The numerical experiments are performed using the coupled fire-atmosphere model WRF-SFIRE (Mandel et al. 2011). WRF-SFIRE couples WRF (Weather Research Forecasting System: (Skamarock et al. 2008) with SFIRE, a fire spread model based on a semi-empirical approach to fire propagation (Rothermel 1972) and the level-set method for fire tracking (Osher and Fedkiw 2003). WRF provides realistic meteorological forcing that is used to drive the parameterized fire progression (Fig. 1), while heat and moisture fluxes at the fireline are fed back into WRF so that the atmospheric state responds to the presence of the fire. The fire-affected winds are used to compute the fire's rate-of-spread, resulting in a two-way atmosphere-fire coupling. WRF-SFIRE aims to capture the important fire-atmosphere feedbacks and explicitly simulate pyroconvection without external parameterizations. Recent enhancements to WRF-SFIRE include a predictive fuel moisture model with meteorological components that provides detailed temporal evolution of fuel moisture (Mandel et al. 2014).

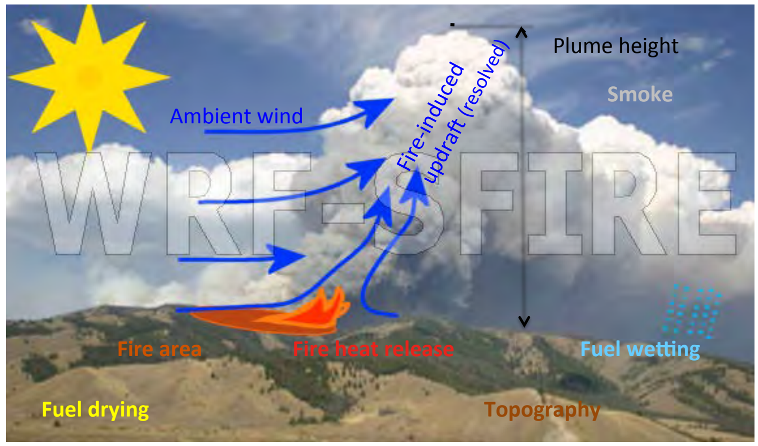

Figure 1. Schematic representation of WRF-SFIRE.

Figure 2. Model domain with the location of ignition lines (yellow and orange), the measurement tower (red point), and the perimeters at 300s and 312s from the simulation start derived from IR observations.

In the following sections we present numerical simulations of a grass land fire on flat ground, mimicking the FireFlux2 prescribed burn (Clements et al. 2014). The model domain covered an area of 1000mx1600m at 10m atmospheric resolution, with a surface fire mesh of 1m resolution (1:10 fire:atmosphere grid refinement ratio). The model top was set to 1200m and 80 vertically stretched levels were used with depths varying from 2m at the surface to 37.75m at the domain top. Open boundary conditions were used so that the fire-induced turbulence does not contaminate the inflow. The simulation was started at 15:00:00 (hh:mm:ss) on 31st Jan 2013. The model was run for 15 minutes with a time step of 0.25s and output saved at 5s intervals. Fire ignition was started 252s into the simulation in the form of two ignition lines progressing from the ignition center to the sides of the plot, as shown in Fig. 2. Tall grass (fuel category 3) with a fuel moisture of 18%, depth of 1.25m, and load of 1.08kg/m^2 was used to characterize the fuel. The atmospheric model was initialized with vertical profiles of wind, temperature, and moisture derived from the main tower (Fig. 2) and radiosonde observations prior to the burn.

Results from the benchmark simulation

In order to have a reference point for the different ignition strategies tested in this study, we performed one benchmark simulation. It was started from two ignition lines corresponding to the actual FireFlux2 ignition procedure (see Fig. 2), and run continuously for 15 minutes. The time series of the updraft velocities near the fire front head are presented in Fig. 3. The figure shows pyroconvection visible first at 20m above the ground level (AGL) and subsequently at 10m and 6m AGL as the tilted plume hit the sensors at lower elevations. The maximum simulated updraft velocities were 5.1m/s, 4.4m/s and 3.4m/s at 20m, 10m and 6m AGL respectively, compared to observed 7.5m/s 5.9m/s and 4.4m/s. The main reason for the discrepancy is that the simulated fire head slightly missed the tower location. The maximum simulated updrafts at the fire head were significantly higher and closer to observations (7.0m/s, 6.2m/s and 4.9m/s at 20m, 10m and 6m AGL, respectively).

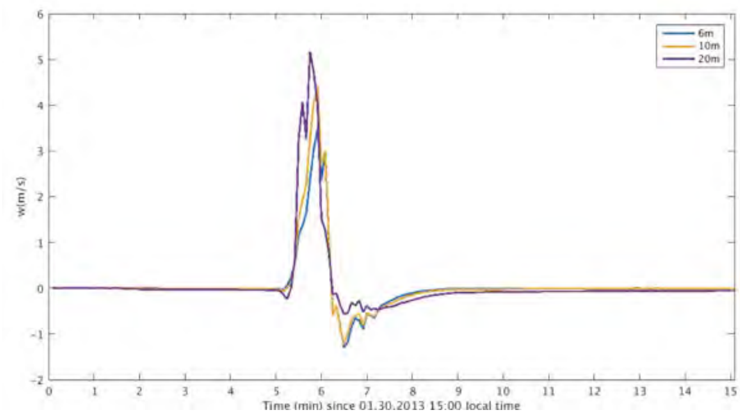

Figure 3. Simulated updraft velocities at the location of the main tower at 6m, 10m and 20m above the ground level for the benchmark run.

Instantaneous ignition of entire area contained by fire perimeter

As a first test, the fire was instantaneously ignited from the fire area encompassed by the perimeter presented as purple line in Fig. 2. This simulation led to unrealistically high fire heat flux that induced very strong updraft/downdraft couplets. The fire did not reach the tower before updraft velocities at 10m reached 52 m/s, violating the CFL (Courant–Friedrichs–Lewy) numerical stability condition and terminating the run.

Fire perimeter ignition with inside fuel

In the second test, the same fire is instantaneously ignited, but only along the fire perimeter. This scenario corresponds to a situation when a fire perimeter is known (for instance from airborne IR observation), but there is no information about the amount of fuel available within the fire perimeter. This strategy effectively reduces the instantaneous fire heat flux and improves the model stability so that simulation completes without violating the CFL condition. Unfortunately, the updraft velocities simulated in this case (see Fig 4) do not match the benchmark simulations and observations. The maximum updraft occurs at 10m as opposed to 20m, which indicates that the convective column is not fully evolved by the time the fire front hits the tower location. Vertical velocities are underestimated (less than 4 m/s maximum updraft), with peaks at all levels occurring at the same time indicating a close to vertical plume. Downdrafts are also active for about 5 minutes after the fire maximum updraft occurred, that are not visible in the benchmark run. At 11 minutes into the simulation, secondary updrafts appear at 6m and 10m AGL, most likely artifacts of the ignition technique. Although the perimeter ignition procedure applied in this case solves the stability problem, the presence of unburned fuel within the fire perimeter results in propagation of the fire both inward (inside the ignited perimeter) and outward (outside of it). It seems that the additional buoyancy associated with the secondary fire front consuming the fire inside the perimeter negatively impacts the circulation near the fire head making it less realistic.

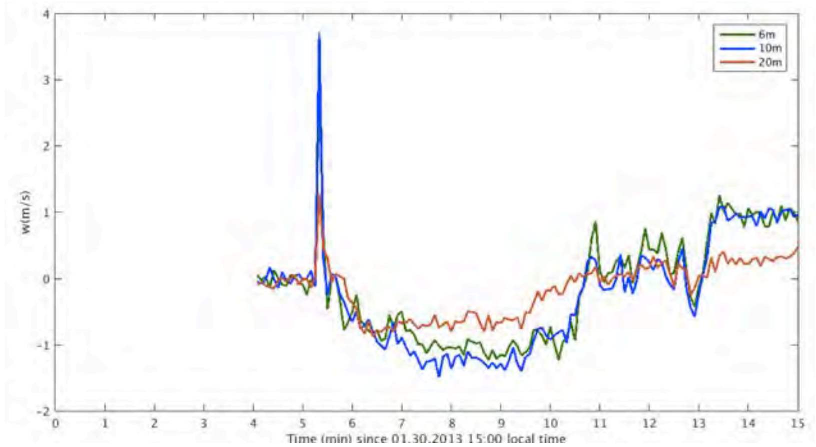

Figure 4. As in Fig.3 but for the instantaneous ignition from the perimeter.

Fire perimeter ignition without inside fuel

This technique is similar to the previous one with the fuel ignited along the fire perimeter, but in this case the fuel inside of the fire perimeter was set to zero so that the fire could propagate only outside the perimeter. By removing the fuel available for burning from inside the perimeter, the formation of the secondary fire front behind the fire head is avoided. Compared to the previous case, the updraft structure from this run is much closer to the benchmark simulation. The vertical velocities increase with height as expected, but their values at 6m and 10m AGL are significantly smaller than in the benchmark run (2.8m/s and 3.5m/s *vs.* 3.4m/s and 4.4m/s), while the updraft at 20m is much stronger than in the benchmark run (9.7ms vs. 5.5m/s). These discrepancies suggest that when the simulated fire passed the tower location the fire-atmosphere equilibrium was not yet fully established. This strategy, even though providing better results than the previous ones, may be difficult to apply in a case of a real fire. The fire perimeter observation itself does not carry explicit information about the fuel state within it. In reality there are often regions behind the fire front that did not burn or are still burning after the fire front passage. The assumption that all the fuel inside the fire perimeter has burned is convenient from the modeling standpoint but may be unrealistic in a case of an actual wildland fire that does leave patches of unburned and still burning fuel behind the fire front.

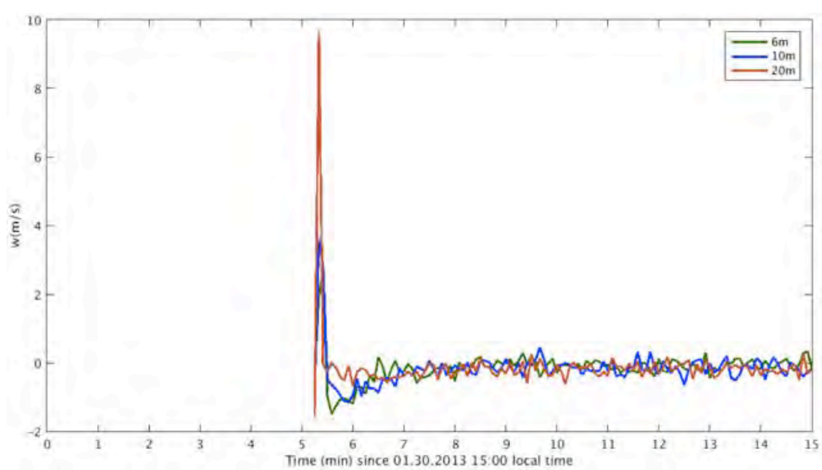

Figure 5. As in Fig.3 but for the instantaneous ignition from the perimeter with the fuel removed from inside of the fire perimeter

Gradual ignition from the fire replay

To assure that fuel is depleted within the fire perimeter and that the atmospheric circulation is in sync with the fire, the following procedure is deployed. First a synthetic history of the fire's progression is generated. The historical fire progression up to the restart time is encoded in the fire arrival matrix so that isochrones represent fire position at any given time. At any simulation time, the burned area corresponds to the points with the fire arrival time earlier than the simulation time (fire was already there), while the area outside of the fire perimeter corresponds to the points with the fire arrival time later than the simulation time (fire is not yet there). The fire arrival time matrix used in this case is generated by a bi-harmonic spline interpolation of the 2D time arrival data corresponding to the ignition point and the two observed fire perimeters shown in Fig. 2. The fire arrival time matrix (Fig. 6) is used prior to the observed perimeter time in place of the fire propagation model. Heat and moisture from the fire is released into the atmosphere gradually so that atmospheric circulation consistent with fire's growth is continuously established. The coupled model simulation then continues from the perimeter time. The method used in this study is a simplification the method originally developed by Kondratenko et. al (2011) and Mandel et. al (2012, 2016), where the time reversal is not computed using a marching method driven by the rate of spread computed from a wind field, but by an interpolation of the observed fire arrival time data. The time series of the vertical velocities simulated using the gradual fire ignition, shown in Fig. 7, suggest that at restart time the fire plume was fully evolved. The maximum updraft velocities of 7m/s, 4.9 m/s and 4.6m/s at 20m, 10m and 6m, respectively, match the observations and benchmark simulation better than model results using ignition strategies presented earlier. Fig. 7 shows updraft velocities increasing in height and a time shift of about 5s between peaks indicating the

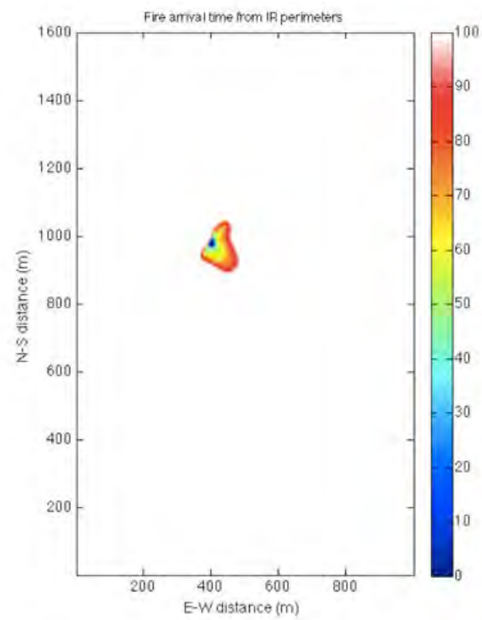

Figure 7. Fire arrival time (s) derived from IR perimeters, representing the history of the fire propagation (first 100s since the ignition start).

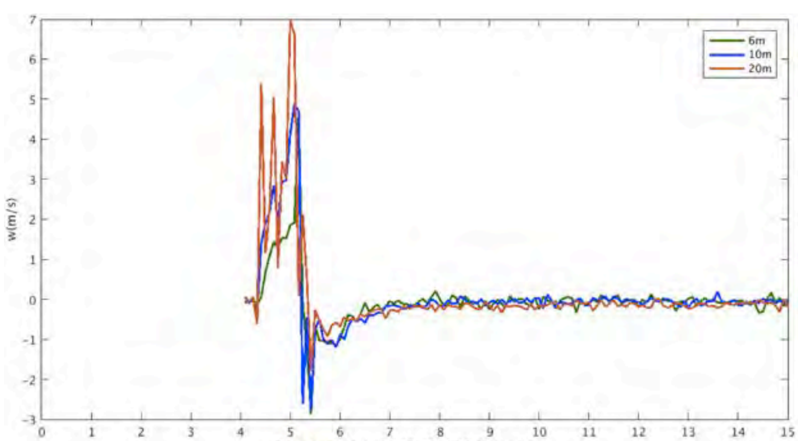

Figure 6. As in Fig.3 but for the gradual ignition from the synthetic fire history.

observed downwind plume tilt. There were no stability issues in this run, as the fire is not ignited instantaneously. The replay from the fire history assures that fuel is depleted within the fire perimeter, avoiding the formation of an artificial secondary fire front. By igniting the fire gradually from the fire history, the atmosphere equilibrates with the fire during the fire replay procedure, which results in significantly improved fire plume representation at the WRF-Sfire restart time as compared to other methods tested in this study.

As a next step, but not shown here, this method will be tested on a wildland fire, where actual airborne fire perimeters will be utilized cyclically to reduce the fire spread prediction error, maintaining realistic representation of the fire plume.

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References

Clements, C.B., B. Davis, D. Seto, J. Contezac, A. Kochanski, J.-B. Fillipi, N. Lareau, B. Barboni, B. Butler, S. Krueger, R. Ottmar, R. Vihnanek, W.E. Heilman, J. Flynn, M.A. Jenkins, J. Mandel, C. Teske, D. Jimenez, J. O'Brien, B. Lefer, 2014: Overview of the 2013 FireFlux II grass fire field experiment. In: Viegas, D.X., ed. Advances in Forest Fire Research. Coimbra, Portugal: Coimbra University Press: 392-400.

Kondratenko, V.Y., J.D. Beezley, A.K. Kochanski, and J.Mandel, "Ignition from a fire perimeter in a WRF wildland fire model," Paper 9.6, 12th WRF Users' Workshop, National Center for Atmospheric Research(2011)

Mandel, J., J. D. Beezley, and A. K. Kochanski, 2011: Coupled atmosphere-wildland fire modeling with WRF 3.3 and SFIRE 2011. Geoscientific Model Development, 4, 591-610.

Mandel, J., J.D. Beezley, and A.K. Kochanski, V. Kondratenko, and M. Kim, 2012: Assimilation of Perimeter Data and Coupling with Fuel Moisture in a Wildland Fire - Atmosphere DDDAS (2012) Procedia Computer Science 03/2012, 9. DOI: 10.1016/j.procs.2012.04.119.

Mandel, J., S. Amram, J.D. Beezley, G. Kelman, A.K. Kochanski, V. Y. Kondratenko, B.H. Lynn, B. Regev, and M. Vejmelka, 2014: Recent advances and applications of WRF–SFIRE. Nat. Hazards Earth Syst. Sci., 14, 2829–2845,doi:10.5194/nhess-14-2829-2014.

Mandel, J., A. Fournier, MA Jenkins, A.K. Kochanski, S. Schranz, M. Vejmelka (2016) Assimilation of Satellite Active Fires Detection Into a Coupled Weather-Fire Model, (2016). In Proceedings for the 5th International Fire Behavior and Fuels Conference April 11-15, 2016, Portland, Oregon, USA.

Osher, S., and R. Fedkiw, 2003: Level Set Methods and Dynamic Implicit Surfaces. Springer.

Ottmar, R. D. and S.P. Baker, 2007: Forest floor consumption and smoke characterization in boreal forested fuelbed types of Alaska. JFSP 03-1-3-08 Final Report.

Rothermel, R C., 1972: A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-115. (Ogden, UT).

Skamarock, WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG (2008) A description of the Advanced Research WRF version 3. NCAR Technical Note 475, http://www.mmm.ucar. edu/wrf/users/docs/arw_v3.pdf, retrieved December 2011.

Impacts of wildfire smoke plumes on regional air quality

Alexandra Larsen, Brian J. Reich,
North Carolina State University, Raleigh, NC, USA, aelarsen@ncsu.edu, brian_reich@ncsu.edu

Mark Ruminski
National Oceanic and Atmospheric Administration, Camp Springs, MD, USA,
mark.ruminski@noaa.gov

Ana G. Rappold*
US Environmental Protection Agency, Research Triangle Park, NC, USA,
Rappold.Ana@epa.gov

INTRODUCTION

Wildfire smoke contains hazardous levels of air pollution, posing a serious threat to respiratory and cardiovascular health (Dennekamp et al. 2011; Rappold et al. 2011; Johnston et al. 2012; Morgan et al.; Dennekamp et al. 2015 Haikerwal et al. 2015; Haikerwal et al. 2015). Recent trends in U.S. fire activity point to an increase in numbers and severity of large wildfires. Smoke plumes from these fires are transported long distances, necessitating an improved understanding of smoke plume impacts on regional-scale air quality and their impacts on public health. Since the 1970's, the frequency of large fires (1000+ acres) has doubled and the frequency of very large fires (10,000+ acres) has increased fivefold (Climate Central, 2012). These trends are expected to continue due to effects of prolonged periods of drought, increasing spring and summer temperatures, earlier snowmelt, population growth and land-use practices (Littell et al. 2009). Such projections are cause for concern to both local and regional air quality.

In this manuscript, we explore the extent to which wildfires affect regional air quality by estimating the change in air pollutant concentrations at the regional air quality monitoring stations and in Air Quality Index (AQI) values on smoke-impacted days relative to clear days. We determine geographical regions impacted by smoke plumes with the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS) and we characterize regional air pollution with daily concentrations of ozone, fine particulate matter ($PM_{2.5}$) and species of $PM_{2.5}$ measured at monitoring sites across the continental U.S. for an eight-year period, 2006 to 2013. We estimate relative change in air pollution with a two-stage approach that ensures a statistically rigorous characterization of smoke impacts by taking into account both the spatial nature of the data and the spatial correlations induced by large plumes covering multiple sites. The results of this analysis include site-by-site and overall estimates of relative change in concentrations of ozone, $PM_{2.5}$ and $PM_{2.5}$ constituents, as well as a characterization of the smoke impacts on the number of unhealthy air quality days at each monitoring site in the study.

DATA

We obtained shape files of smoke plumes that define the geographic extent of smoke from the NOAA Hazard Mapping System (HMS). Shape files of daily smoke plumes were downloaded from ftp://satepsanone.nesdis.noaa.gov/volcano/FIRE/HMS_smoke/ (Figure 1). We obtain ozone, total $PM_{2.5}$ and $PM_{2.5}$ constituent measurements for 2006 to 2013 from the U.S. Environmental Protection Agency's (EPA) Air Quality System database. We use daily average 8-hour ozone measurements, daily average concentrations of $PM_{2.5}$ measured by Federal Reference Method (FRM) and daily average of $PM_{2.5}$ species from the Interagency Monitoring of PROtected Visual Environments (IMPROVE) network. The species of $PM_{2.5}$ included sulfate, nitrate, potassium, mercury, elemental carbon (EC) and organic carbon (OC). Ozone concentrations were measured daily, while total $PM_{2.5}$ and speciated $PM_{2.5}$ readings are typically collected every third or sixth day. We used daily temperature recorded at the nearest NOAA station within 50 km of the ozone and FRM monitoring sites. For IMPROVE sites, we used mean daily temperature recorded at the monitoring sites. We denote 'plume days' as days on which visible smoke plumes are detected in the vertical column above a monitoring site.

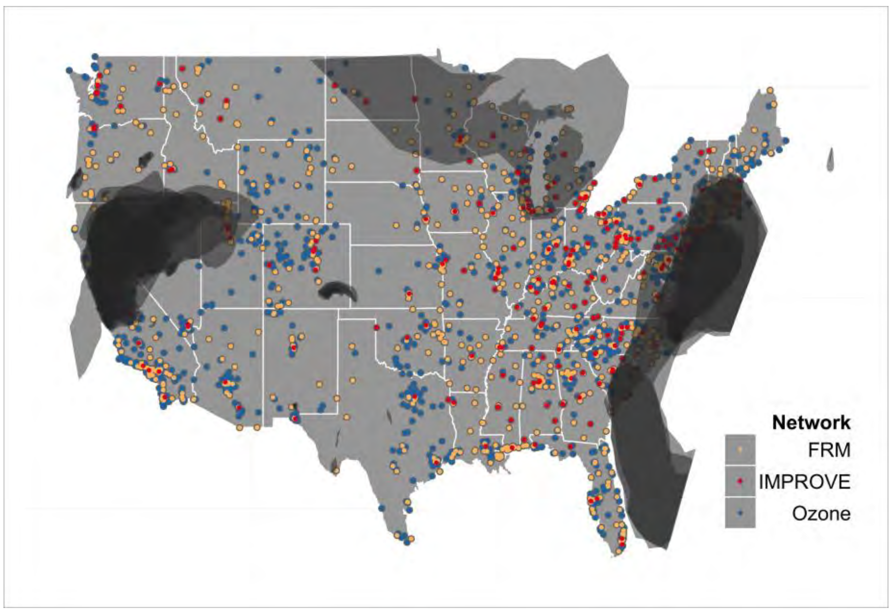

Figure 1: Geographic distribution of environmental monitoring sites for ozone, PM2.5 and species of PM2.5 and HMS smoke plumes on a single day in June 2008.

We quantify the impact of smoke plume days on unhealthy air quality using Air Quality Index (AQI) for ozone and $PM_{2.5}$ daily values. AQI is a public health tool published daily by the EPA to inform the public of the health effects associated with air pollution in a given area. For each pollutant, AQI classifies air quality into one of six health risk categories ("Good", "Moderate", "Unhealthy for Sensitive Groups", "Unhealthy", "Very Unhealthy" and "Hazardous ") coded by six distinct colors (Green, Yellow, Orange, Red, Purple and Maroon). For ozone, AQI values consistent with the 2008 ozone standard were downloaded with the data. AQI values for daily $PM_{2.5}$ were calculated from the data (http://www.epa.gov/airnow/aqi-technical-assistance-document-dec2013.pdf). We did not identify any Hazardous "Maroon" days. We summarize the number of days in each of the AQI categories attributable to plume days by calculating the percent of days in plume for each AQI category and the odds of each color code observed on a plume day versus a non-plume day.

METHODS

We examine the impact of smoke on air pollution with a two-stage analysis for each pollutant separately. In the first stage, we estimate the plume effect on pollutant concentrations at each monitoring site separately; in the second stage we pool these results to estimate an overall plume effect (Dominici et al. 2006). The first-stage model for the (log-transformed) air pollutant concentrations at a monitoring site *s* on day *t*, $Y_{s,t}$, is:

$$\log\left(Y_{s,t}\right) = \alpha_s + h_s(t) + g_s(T_t) + \beta_s plume_{s,t} + \epsilon_{s,t}. \qquad (1)$$

Confounding effects of daily temperature (T_t) are accounted for with the smooth function, g, using natural splines with two degrees of freedom. We compared several choices and found that two degrees of freedom minimized BIC (Swartz 1978). Seasonal trends are modeled with the smooth function, h, using natural splines with four degrees of freedom per year, or 32 degrees of freedom total. Controlling for seasonality ensures that the effect of plume is not confounded with the effect of warm summer days typically associated with high ozone values. The variable $plume_{s,t}$ is an indicator of HMS-detected smoke plume presence in the vertical column of monitor *s* on day *t*. The plume coefficient or plume effect, β_s, describes log-percent change in pollutant concentration on days with plumes relative to days without plumes, adjusted for seasonality and meteorological conditions. A positive estimate of β_s is evidence for increased pollutant concentrations during plume episodes as compared to clear days. A negative estimate indicates the converse. We assume the errors, $\epsilon_{s,t}$, are normally distributed with zero mean and constant variance. The first stage analysis is conducted separately by site using the lm function in R, giving us site-specific plume effect estimates $\widehat{\beta_s}$ and standard errors υ_s.

In stage two, we combine the first-stage estimates of the plume effect to estimate the overall effect μ. The second stage model is $\widehat{\beta_s} = \beta_s + \nu_s e_s$, where β_s is the true plume effect at site *s* and e_s is univariate Gaussian error. The true plume effect at location *s* is decomposed as $\beta_s = \mu + \varepsilon_s$, where μ is the overall mean plume effect and ε_s captures the variation in the true effect. We consider two models (spatial and non-spatial) for each of the two error terms leading to four formulations of this model in total. In the non-spatial models, e_s and ε_s are independent over locations indexed by *s*, whereas in the spatial models, correlation between errors at two locations, for example e_s and e_r, decays exponentially with the distance between sites *s* and *r*. Parameters of the decay function are estimated from the data. We estimate stage-two plume effects and the overall plume effect using the model that produces the lowest BIC value among all four formulations. Because we use log-response, the 'plume effect' and 'overall plume effect' estimates are calculated, respectively, as follows: ($(exp(\beta_s) - 1) \times 100\%$) is the measure of relative change in pollutant concentration over the estimated daily concentration value without plume at a site s; ($(exp(\mu) - 1) \times 100\%$) is the overall measure of relative change.

RESULTS

The plume effects on ozone and $PM_{2.5}$ exhibited a strong spatial pattern. Among the four stage-two models, we found the one with a full spatial structure best fit both ozone and $PM_{2.5}$ pollutants, indicating spatial correlation among site-specific error terms as well as spatial variation in the true unobserved plume effect. In Figure 2, we present estimates from the model of best fit for ozone and $PM_{2.5}$. The plume effect on ozone was the largest in the Southeast, and in few scattered locations in the Northeast and around St Louis, MO (12.3-24.7% increase, Figure 2, left panel). The lowest plume effects on ozone were found in the Rocky Mountain area and Southern California. For $PM_{2.5}$ concentrations at FRM monitoring locations, smoke plumes had the highest impact in the Southeast, Midwest and Pacific Northwest regions (34.7-78.4% increase, Figure 2, right panel). The lowest plume effects on $PM_{2.5}$ were found in the Great Lakes Region and Southern California. Nationally, the average impact of wildfire plumes on ozone and $PM_{2.5}$ was estimated at 8.4% (SE 0.2%) and 29.3% (SE 0.4%), respectively. We also examined the frequencies of each AQI code on both clear and plume days (Table 1). Overall, plume days accounted for a larger percentage of unhealthy days than healthy days.

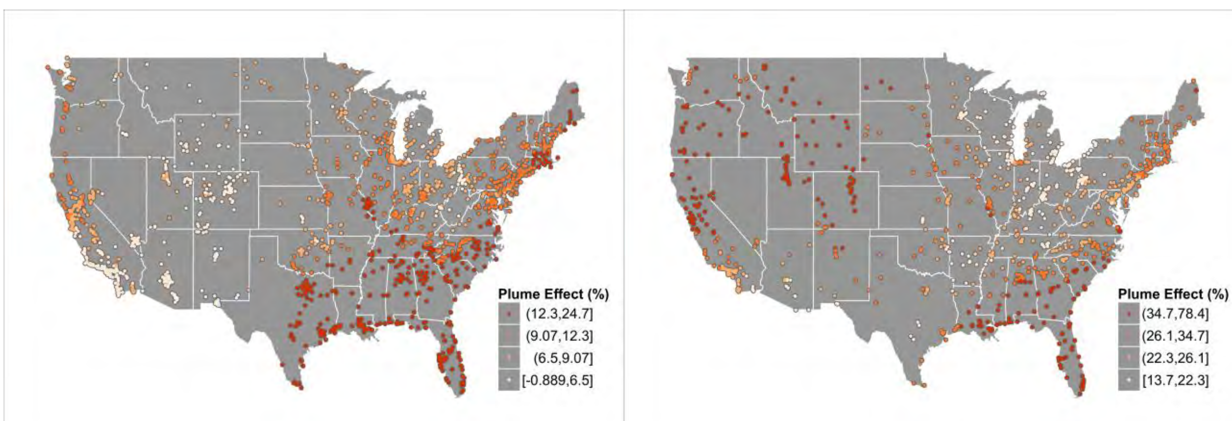

Figure 2: Geographic distribution of the estimated change in pollutant concentration on plume days relative to clear days for ozone (left) and $PM_{2.5}$ (right) by quartiles.

Concentrations of $PM_{2.5}$ components measured at IMPROVE sites also increased during plume events. Total $PM_{2.5}$, Potassium, Sulfate and Nitrates were best fit by the model with spatial $\widehat{\beta}_s$ and a non-spatial distribution of the true plume effect, indicating a stronger influence of 'plume properties' than the geography of the site. EC was best fit by the model of spatial heterogeneity, possibly indicating the effect of regional variation in type of vegetation. OC favored both spatial $\widehat{\beta}_s$ and spatial plume effect indicating that the associated regional and measurement errors are both spatially correlated. Mercury was best fit by the non-spatial model that assumed independence between all sites. Overall, spatially averaged concentrations of $PM_{2.5}$ species were significantly elevated in plume events. The estimated percent change (SD) of the national average plume effect for each pollutant are: EC, 21.3 (1.0); OC, 30.6 (3.8); Nitrate, 10.5 (1.6); Sulfate, 13.8 (1.6); Potassium, 29.8 (1.3); and Mercury, 17.4 (7.4).

	AQI Color Code	Green	Yellow	Orange	Red	Purple
Ozone	Code distribution - clear days	89.5%	9.15%	1.26%	0.082%	0.0057%
	Code distribution - plume days	70.3%	24.0%	5.27%	0.425%	0.0277%
	% Plume Days by code	6.1%	18.0%	25.8%	30.1%	28.8%
	Odds Ratio	0.278	3.13	4.34	5.20	4.82
$PM_{2.5}$	Code distribution - clear days	70.6%	28.8%	0.58%	0.083%	0.0004%
	Code distribution - plume days	46.4%	51.7%	1.65%	0.25%	0.0061%
	% Plume Days by AQI code	4.2%	10.6%	15.8%	16.5%	50.0%
	Odds Ratio	0.360	2.65	2.88	3.02	15.0

Table 1: Percent of AQI days on clear and on plume-affected days and the percent of days in each of the AQI categories attributable to plume days by calculating the percent of days in plume for each category and the odds of each code observed on a plume versus a non-plume day.

DISCUSSION

We demonstrated measurable changes in pollution levels at the environmental monitoring sites on the days with visible plumes for years 2006 through 2013. We implemented a two-stage statistical model to combine plume effects across stations and to account for spatial heterogeneity of plume effects at monitoring sites. Ozone concentrations on days with visible plumes were on average 8.4% higher than on the clear days, while $PM_{2.5}$ concentrations were on average higher by 29.3%. All species of $PM_{2.5}$ analyzed here were elevated as well (highest: OC, 30.6%; lowest: nitrate, 10.5%). We note important geographical patterns in both frequency of plumes above monitors and magnitude of plume effect and discuss at length the limitations of the data and methods.

During the examined period, frequency and impacts of smoke plumes on air quality were not limited to the regions where most large fires take place. Within the continental U.S., the highest frequency of plume coverage was observed in the Northwest coastal and mountainous regions (Washington, Oregon, Idaho, Montana) but also in the central parts of the country where large fires are less common, accounting for regional transport as well as smoke from local, smaller fires. Additionally, some of the highest relative increases in pollution were observed in the regions where large fires are less frequent and these impacts were not the same for the two pollutants. For example, in the Southeast we observed the largest changes in $PM_{2.5}$ and ozone levels, while in the mountainous west, we observed large changes only for $PM_{2.5}$ and in the northeast and the Midwest, we observed large changes for ozone only.

The evidence of smoke plume impacts on air quality was reflected on the number of unhealthy air quality days as well. More specifically, while only 6.3% of $PM_{2.5}$ monitor-days and 7.7% ozone monitor-days experienced plume coverage, plume days accounted for 16% of days categorized as unhealthy (code Orange, Red and Purple combined) for $PM_{2.5}$ and 27% of unhealthy days for ozone. In other words, the odds of unhealthy days for ozone and $PM_{2.5}$ were 3.3 and 2.5 times higher on plume days than on non-plume days, respectively.

In summary, our research has shown that smoke plumes bring consistent and non-marginal increases in ozone, $PM_{2.5}$ and components of $PM_{2.5}$, and account for a disproportionate number of unhealthy air quality days. We observed that $PM_{2.5}$ and ozone impacts are not uniform across all geographic locations, and that the additional ozone production by plume is visible over densely populated regions. As the frequency of large fires increase and emissions from all other sources decrease, large fires are expected to take a larger role in regional air quality and pose an increasing concern to public health.

BIBLIOGRAPHY

Climate Central (2012). The Age of Western Fires. Available: http://www.climatecentral.org/news/archive/2012 [accessed 1 February 2016].

Dennekamp M, Straney LD, Erbas B, Abramson MJ, Keywood M, Smith K, et al. (2015). Forest Fire Smoke Exposures and Out-of-Hospital Cardiac Arrests in Melbourne, Australia: A Case-Crossover Study. *Environmental Health Perspectives,* **123**, 959-964.

Dennekamp M, Abramson MJ (2011). The Effects of Bushfire Smoke on Respiratory Health. *Respirology* **16**, 198–209.

Dominici F, Peng RD, Bell ML, Pham L, Mcdermott A, Zeger SL, et al. (2006). Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *JAMA,* **295**, 1127.

Haikerwal, Anjali, Muhammad Akram, Malcolm R. Sim, Mick Meyer, Michael J. Abramson, and Martine Dennekamp (2015). Fine Particulate Matter (PM 2.5) Exposure during a Prolonged Wildfire Period and Emergency Department Visits for Asthma. *Respirology,* **21**, 88-94.

Haikerwal, Anjali, Muhammad Akram, Anthony Del Monaco, Karen Smith, Malcolm R. Sim, Mick Meyer, Andrew M. Tonkin, Michael J. Abramson, and Martine Dennekamp (2015). Impact of Fine Particulate Matter (PM 2.5) Exposure During Wildfires on Cardiovascular Health Outcomes. *Journal of the American Heart Association,* **4**, 7.

Johnston FH, Henderson SB, Chen Y, Randerson JT, Marlier M, Defries RS, et al. (2012). Estimated Global Mortality Attributable to Smoke from Landscape Fires. *Environmental Health Perspectives*, **120**, 695–701.

Rappold AG, Stone SL, Cascio WE, Neas LM, Kilaru VJ, Carraway MS, et al. (2011). Peat Bog Wildfire Smoke Exposure in Rural North Carolina Is Associated with Cardiopulmonary Emergency Department Visits Assessed through Syndromic Surveillance. *Environmental Health Perspectives* **119**, 1415–1420.

Landscaping with Ornamental Trees and Exterior Structure Features Using EcoSmart Fire Model

Mark A. Dietenberger, Ph.D.,
USDA, FS, Forest Products Laboratory, Madison, Wisconsin, USA, mdietenberger@fs.fed.us

Charles R. Boardman
USDA, FS, Forest Products Laboratory, Madison, Wisconsin, USA, cboardman@fs.fed.us

Introduction

EcoSmartFire is a Windows program that models heat damage and piloted ignition of structures from radiant exposure to discrete tree fires. It calculates the radiant heat transfer from cylindrical shaped fires to the walls and roof of the structure while accounting for radiation shadowing, attenuation, and ground reflections. This approach is in contrast to the mainly anecdotal knowledge in various publications regarding fire protection in the Wildland Urban Interface (WUI), including the NFPA 1144, ICC WUI code, and the well regarded ANR Publication 8228: Home Landscaping for Fire (Nader, et. al., 2007). For example, Nader recommends a home defense zone, a clearance of flammable vegetation (with some exceptions) up to 30 feet from the house. In contrast, a physics-based fire risk model can allow variation on this 30 feet clearance making the landscaping adaptable to any home lot configuration. Further, Nader describes a fuel-thinning zone 30 feet (10m) to 100 feet (33m) from a house in which fuel modification limits any development of surface spread or ladder fires. However, there are alternatives to the fuel thinning such as noncombustible fencing, extending the home defense zone, removing only the forest floor litter, or using resistive structure cladding, such as a stucco wall. Within the home defense zone, the ornamental vegetation was described as being fire resistant and maintaining a spacing of 10 (3m) feet between combustible objects. This cautious approach would seem to be overly conservative if the goal of fire risk modeling is to prevent structure ignition in a worst-case scenario of simultaneously igniting the ornamental vegetation with a strong ember shower.

EcoSmartFire is still a work in progress but the physics-based model has been calibrated by comparison with selected fire tests in a previous work (Dietenberger and Boardman, 2016). Further validation and additional material properties should be added in future work. Here, the PC version is exercised to determine fire and damage risk predictions exploring the sensitivity to relevant parameters and geometric configurations. Some of these parameters were limited due to the user interface of the on-line web version (part of EcoSmart Landscapes) which shares the core fire calculation engine. The PC version runs from text files and allows full exploration of the fire program features. The parameters varied in this work are tree positioning and trimming, fire resistant exterior claddings, radiation blocking with fences and outbuildings, ground covering reflection coefficient, and flame attenuation by blocking burning trees. These program features are demonstrated using a single structural wall.

On-line ecoSmart Landscape with Fire Model for Worst Case example

The on-line fire model considers the following worst-case wildfire scenario. A large concentration of small embers serve as a pilot for tree crown fires, but not for significant direct heating of structure material. These embers cause simultaneous ignition of the stressed ornamental vegetation within the home defense and fuel thinning zones, which then radiate to the structure. Since weather conditions are not within control of the homeowner, the worst weather is assumed: dry conditions for the vegetation (moisture content at 20%), wind speed of 5.7 m/s, and ambient temperature at 25 degrees Celsius. An average ground condition of grass in the yard and dry litter surrounding the trees results in the surface reflection around 0.3. The model for calculating the tree heat release rate is primarily for pine trees, due to the available data. Extension to other tree types will need verification in laboratory tests of the species burn. For the on-line application the home is limited to 4 walls (with selection of wood or vinyl siding) and 1 flat-roof (with selection of cedar shakes or Class A asphalt shingle) for exposure of up to 9 trees burning, located anywhere and of any size on the lot.

As our test location, we choose a home in Hidden Valley Lake California. The Hidden Valley Structure Protection report describes improved fire protection using a hand crew during a wildland urban interface fire in this location http://www.wildfirelessons.net/orphans/viewincident?DocumentKey=215deac1-199c-4031-9d1e-11d9ce96939e, and provides a google map image in their Figure 7. The ecoSmart Landscape software can obtain the same map image, but we focus on a single home lot shown in Figure 1.

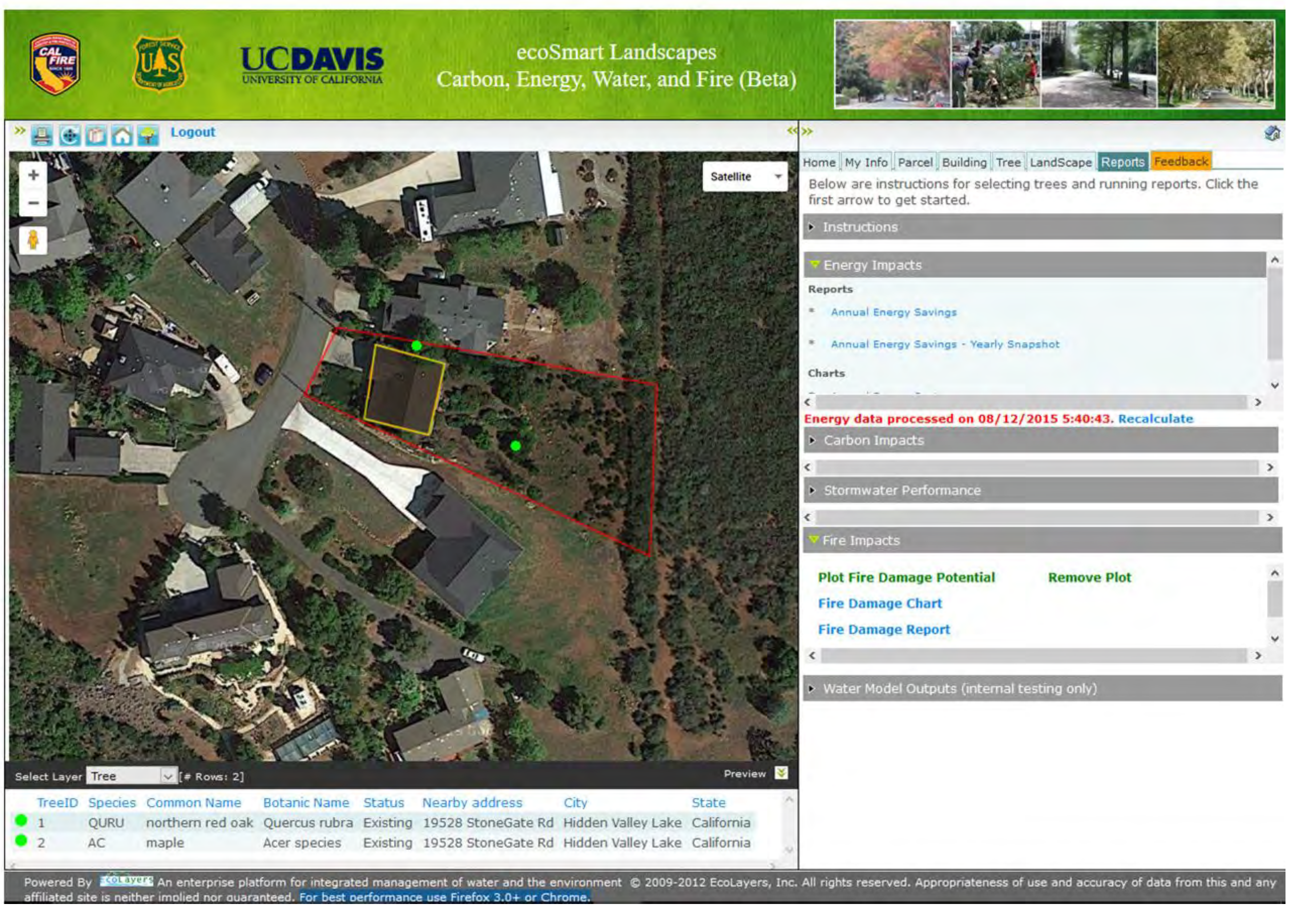

Figure 1. Output from ecoSmart Landscape for fire modeling of a Hidden Valley site.

The homeowners in the aftermath of this WUI fire may be wondering how to protect their homes better, particularly if access to active fire protection becomes limited the next time around. If they rely on anecdotal knowledge, which is available on various websites, the inclination would be the lowest cost approach, which is to first harden the homes against the embers, and secondly, to do vegetation clearance to 30 feet (10 m) and thinning in the zone beyond. This in effect would be a barren landscape if all homeowners execute this vegetation management approach. In our particular example of Figure 1, with two modeled trees placed on the lot, results indicate that the house adjacent to the burning trees would experience minimal damage to a supposed redwood siding, although not to the level of piloted ignition. Note that the criteria for both damage and ignition uses the more accurate critical temperatures rather than on the overly conservative critical heat fluxes (Dietenberger and Boardman, 2016). From this limited analysis, one might extrapolate that the ornamental vegetation can pretty much be kept intact for this and other lots, as long as the home has been upgraded where necessary to protect only against ember showers.

Physical Modeling Features of PC-based ecoSmart Fire Model

However, to consider the thinning beyond the 30 feet will require the use of the PC-based fire model that can calculate for the many trees in the zone, and provide alternate fuel loading or protection strategies that are lower cost than the continuous thinning otherwise required. In addition, the PC-based fire model has more options for structure protection (i.e. stucco siding) and ability to consider fencing or outbuilding or ground cover management, as the alternative to the thinning in the zone beyond 30 feet (10 m). The PC-based fire model allows other weather related cases, to allow other worst-case scenarios, although certain limitations still exist, such as not being able to model tilted fires in the strong winds or to model the tree-to-tree fire spread progression. These modeling enhancements would be a subject for future development of the fire model. Within the constraint of this presentation, only a single wall structure needs analyzing, in order for the reader to realize that this is a physics-based fire model, which is designed to evaluate design options enhancing passive WUI fire protection.

Trees Positioning and Trimmings

To be able to choose any number, position, and size of trees the fire model was developed to divide the exposed wall into numerous surface elements and then to combine the many radiant heat sources for predicting the surface temperature rise of each surface element. To achieve model efficiency and good accuracy, vector analysis algorithms were developed wherever possible. For this presentation, we choose an example where a homeowner values privacy of closely spaced trees, to the point that the 10 feet spacing between combustible items are eliminated. Further, the line of trees is 20 feet from the combustible wall and tree heights are assumed controlled via species selection or trimming. Note that no requirements at all are made to select fire resistant species (as the model already selects conservatively the more flammable species based on available data).

Fire Resistant Cladding on Structures

Alternatively, suppose the homeowner in the previous example again values privacy, but needs the vegetation to be within 5 or 10 feet of the wall. In that case, it may be likely that a stucco wall is appropriate for 5 feet, whereas any combustible siding might be used at the spacing of 10 feet, providing the height of trees or bushes are more controlled, probably by continuous trimming.

Radiation Blocking with Fences and Outbuildings

Further, the homeowner may have no control of combustibles beyond the lot, or that beyond the home defense zone, and greatly desires the undisturbed woodland scenery. However, fencing to block thermal radiation from an intense wildfire (assuming the structure is protected against the ember showers) should be viable. To maintain a view with a possible tall fencing, the homeowner might invest in ceramic panes for a see-through barrier to fire. The height of the fence is precisely calculated due to the high resolution of surface elements on the structure wall and of the burning multiple trees. The efficiency of radiation blocking calculations is achieved through intricate vector analysis algorithms. The example of fence radiation blocking at different heights will be presented.

Ground Covering Reflection Coefficients

If the homeowner prefers not to have fences and yet highly values the undisturbed woodland scenery, then ground cover modification and minimal trimming (i.e. just the lower branches) could be sufficient, particularly in relation to a fire resistant home. Any forest floor litter will need to be removed as the leaves have a reflection coefficient of 0.45 in comparison to a typical soil reflection of 0.2. Removal of the lowest branches should not impend the scenery, but could reduce thermal radiation from a crown fire, by both controlling spatial and temporal extent of potential crown fires. The ecoSmart fire model does calculate the crown fire size and duration, for the more accurate surface temperature rise on the structure surface. The example of varying ground cover will be presented.

Flame Attenuation by Burning Trees

Finally, one can imagine a row of trees specifically selected for their ability to attenuate the flame radiation from the next row of burning trees further back. To complete the attenuation might only require a few rows of trees. The consequences of this situation might be reduction of the fuel thinning zone from the conservative 100 feet to perhaps 50 feet, which would be much more controllable by homeowner, and also be lower cost for thinning. A physics-based fire model provides the opportunity for a fire performance-based analysis, and avoids relying on anecdotal conservative estimation of the fire risk. The example of varying tree packing on the flame attenuation of burning trees will be presented.

Summary

A physics-based fire model is recommended to supplement the generic fire protection recommendations for homeowners in the Wildland Urban Interface. Some of the features of EcoSmartFire have been demonstrated, showing the potential new flexibility afforded homeowners able to calculate the effects of tree placement and wall construction on fire risk. Further enhancements and validation to the model would be helpful to make it more useful for the general public.

References

Nader,G., Nakamura, G., Lasaux, MD, Quarles, S., Valachovic, Y. (2007) Home Landscaping for Fire, ANR Publication 8228.

Dietenberger, MA, Boardman, CR (2016) EcoSmart Fire as Structure Ignition Model in Wildland Urban Interface: Predictions and Validations, *Fire Technology Journal,* in Press

Lessons Learned from an Unexpected Spread Event on a Large Fire in a Remote Mountain Park

David Finn*
Wildfire Management Branch, Alberta Agriculture & Forestry, Rocky Mountain House, Alberta, Canada, Dave.Finn@gov.ab.ca

Kelsy Gibos*
Wildfire Management Branch, Alberta Agriculture & Forestry, Edson, Alberta, Canada
Kelsy.gibos@gov.ab.ca

Introduction

History of Large Mountain Fires in Alberta

Alberta has two primary fire regime zones, the Boreal - Foothills and the Rocky Mountain Montane Cordilleran area. During the period from 1961 to 2002, 92% of fires occurred in the combined Boreal – Foothills natural region of Alberta while only 6% of fires occurred in the Montane – Cordillera natural region. The remaining 2% of fires occured in Alberta's Prairie - Parkland and Canadian Shield natural regions (Tymstra *et al*. 2005). The Montane-Cordillera natural region featured in this discussion displays considerable variation in fire regime components, due primarily to topographical influences. Mountain ranges both break up fuel continuity and define moisture and wind regimes by virtue of their orientation, while elevation retards the onset of fire season. Further to this, subalpine areas in Alberta are regarded as lightning shadow areas with significantly fewer strikes (Rogeau 2009 2010). These fire regime inputs combine to create both a significantly different fire environment than the boreal forest landscape of Alberta, especially in the Subalpine natural sub region common here. As discussed by Baker and others, the subalpine natural sub region does demonstrate a long return interval – high intensity fire regime (Baker 2009). The subject fire of this paper occurred in such a sub-alpine environment. Other sub-alpine

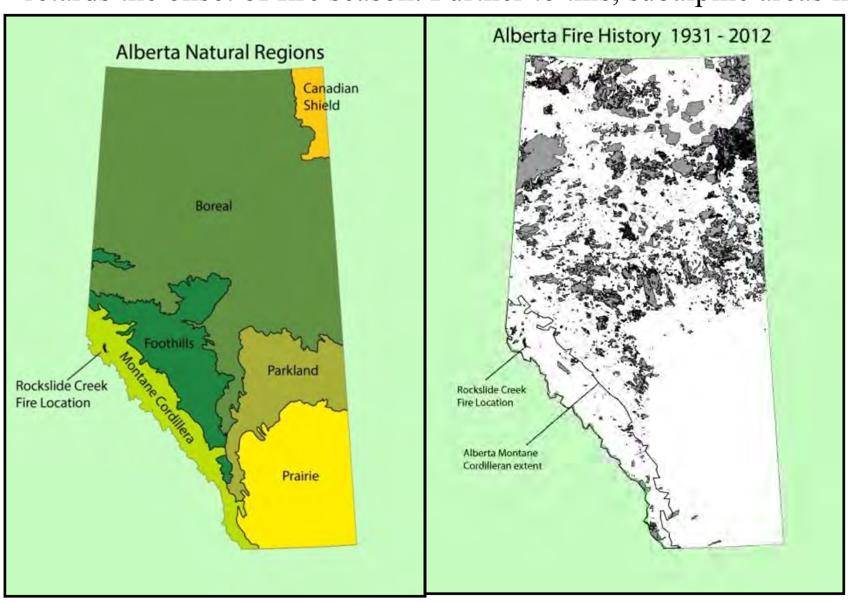

Figure 1 Alberta Canada Natural Regions and 1931-2012 aggregate fire perimeter map

fires in recent years generally follow this trend as well, although the Rockslide Creek fire ignited and burned relatively early in the year. A histogram plot of fires by year seems to show a noticeable trend emerging in the Montane-Cordilleran natural region of Alberta. While the focus of this paper is not on fire occurrence trends, one cannot help but notice a surge in fire numbers in the Montane Cordilleran area of Alberta in the last 10-15 years. Certainly there have been dry years in past with corresponding spikes in fire numbers, but the number and spacing of fire occurrence years seens to be noticeably increasing. Several fires from the Author's experience are brought forward to show the seasonality change from the Rockslide Creek fire. In the author's experience, Montane-Cordilleran fires are usually summer to late fall events, often the result of wind events like Foehn winds (locally known as Chinooks). That late season occurrence window even extends into winter in some noteworthy Alberta fires, occurring as late as December and January, following very dry autumns with very little snowfall and, invariably, driven by, again, the Foehn wind events common to the area. The Rockslide Creek fire, occurring in early June, was anomalous in both its start date, the rapid growth it exhibited, and the large size that it attained.

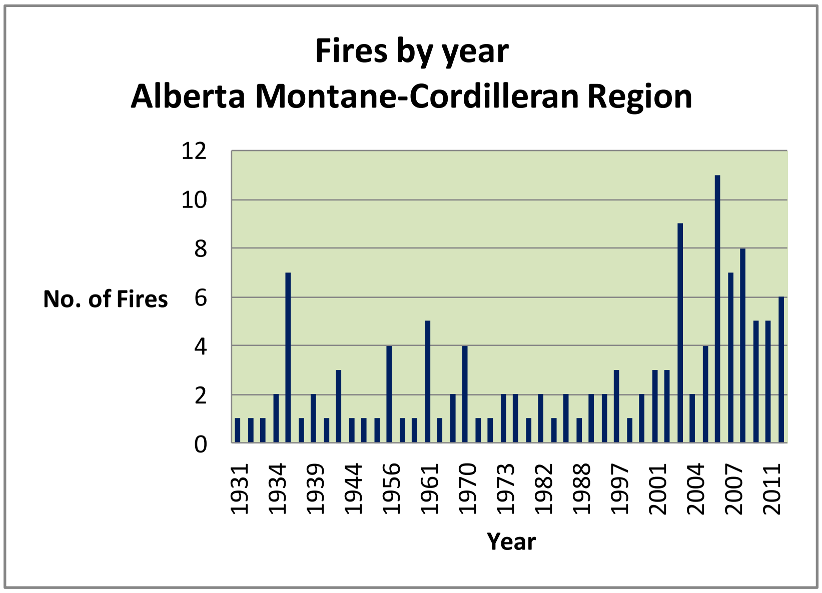

Figure 2. Fire numbers by year in the Alberta Montane-Cordilleran region

Background:

While multiple large fires burned elsewhere in dry 2015 spring conditions in the boreal forest across the province of Alberta, a rare lightning strike ignited a fire in the Wilmore Wilderness, a remote mountain park in west-central Alberta. Given the infrequency of large fires in this region and the mild, only recently thawed conditions, fire managers did not expect the fire to erupt and take a 7.5 mile (12 kilometer) run in under four hours. In three days, the fire burned over 30,000 acres (12,000 hectares) of decadent, upper foothills and subalpine forest and challenged traditional suppression tactics with intense fire behaviour and steep, inaccessible terrain. Even though Alberta's fire suppression agency followed traditional detection and response rules, fire managers of all experience levels and different jurisdictions were surprised at the spread and intensity of this fire at high elevation outside of the 'traditional' fire danger season for this area. This paper explores some of the decision traps and human dimensions of managing fire in an infrequent fire regime while providing some solutions to alleviate the potential for a future 'surprises'.

Chronology of Events on the Rockslide Creek Fire

Fire danger ratings were into the Very High and Extreme categories for much of the province of Alberta following a month of above average temperatures and below average rainfalls related to El Niño. Fire lookout personnel detected the Rockslide Creek Fire in Alberta's Wilmore Wilderness Park on 8th June 2015 a few days following the passage of convective thunderstorms.

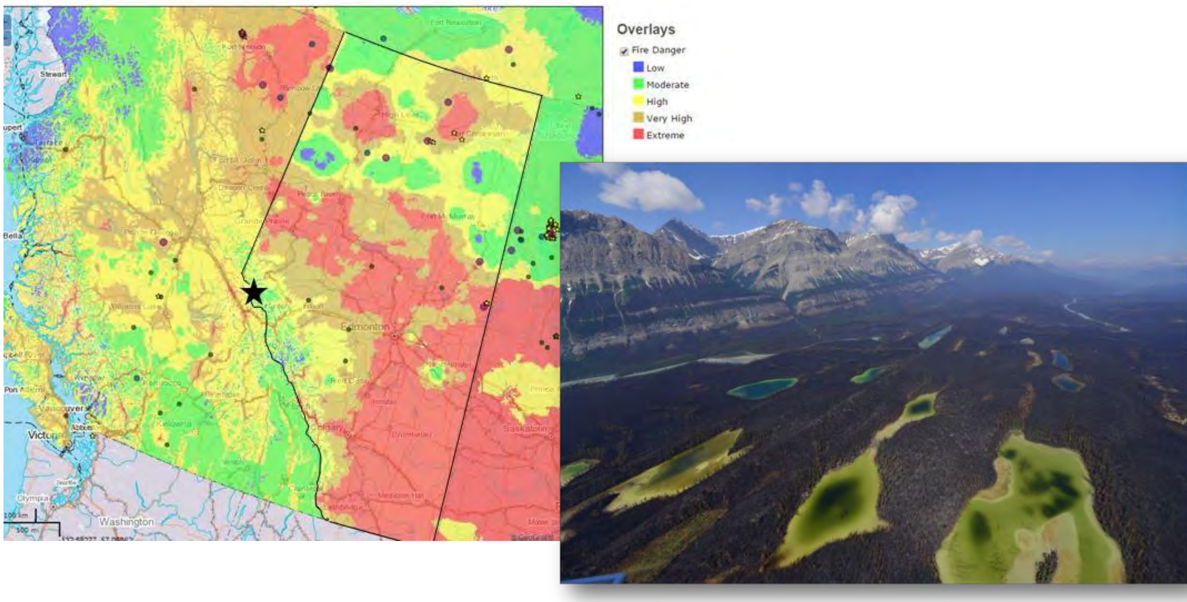

Figure 3. LEFT: Map showing location of the Rockslide Creek fire in relation to the rest of Alberta (indicated by the star). Colors indicate fire danger categories. Circles show locations of other large fires (> 2,000 acres or 1,000 hectares). RIGHT: Image of the Rockslide Creek Fire in the Smoky River drainage of Willmore Wilderness Park (Photo credit: K. Luhtasaari).

The fire started in decadent black spruce (*Picea mariana)* and lodgepole pine (*Pinus contorta* subsp. *latifolia*) forest that had only recently become snow-free. Some of the tree buds showed indication of flush, suggesting the onset of the 'spring-dip' (Jolly *et al* 2015) and sub-surface fuels were still frozen. The fire was at high elevation (5,000 feet or 1600 meters), mid slope in a wide north-south aligned river valley with remote and difficult access both by air and by foot. The fire area had been under a suspected 'dry slot' (Schoeffler 2013) synoptic pattern that brought dry subsiding air and gusty winds. Ignitions in Wilmore Wilderness Park are rare with an average of seven lightning strikes per year across its entire area. The fire return interval is long for most of the park area (>250 years) with the last large fire in the area likely to have been around 1936 (Rogeau 2015).

A helitack crew was dispatched to the fire at 1626 hrs and assessed it at 1700 hrs as a crown fire moving at 45 Chains/hr (15 meters/minute) driven by a westerly wind at 12 mph or (20 km/h) in mild conditions 64°F (18°C), and a relative humidity of 33%. The fire was approximately 24 acres (10 hectares) in size at time of assessment. Nearby values at risk included a few remote park cabins and preferred habitat of the endangered mountain caribou (*Rangifer tarandus)*. The nearest community was Grande Cache located nearly 30 miles (50 kilometers) to the north.

Given the mild weather, time of year and only recently snow-free conditions, the fire was expected to run to the top of the ridgeline before it would diminish with the diurnal drop in winds and temperature. Instead, the fire organized itself into a run spanning the breadth of the Smoky River valley (about three miles/ five kilometers) wide and filled in another 2050 acres (830 hectares) before the night was through.

The following day the fire sat with minimal spread and only a few small uphill runs. Conditions continued to be dry and warm and aerial ignition operations burnt out fuel between a nearby creek and the active fire perimeter to curb any additional spread to the south. On 10 June, crossover conditions and moderate southerly winds drove the fire another four miles (six kilometers) further north. So far, the observed fire behavior matched fire manager's expectations and experience given the fire danger and weather conditions.

On June 11^{th}, wind speed increased to over 40 mph (60 km/h) in the Smoky Valley- an event that falls in the 100^{th} percentile of over 20 years of weather data collected in the area. This pushed the fire another six miles to the north (10 kilometers) and added on another 14,000 acres (5500 hectares) all within three hours. Field reports of observed wind speeds surprised local fire managers and fire behaviour analysts who then tried to adjust tactics and spread projections to fit the anticipated change in fire behaviour.

Discussion

A rare, early season mountain fire in the Albertan Rocky Mountain provides an opportunity to explore a number of lessons learned. Analyses of fire behavior and After Action Reviews are common approaches to fire review but they often fail to tease out the human dimensions of decision-making.

Lessons Learned

Decision traps

When experienced fire managers flew over the Rockslide Creek Fire they were a bit amazed at the fire's intensity and rapid spread because 'it just does not happen up there at this time of year.' Our personal experience drives the way we react to events- we experience a feeling of security based on our comfort with our actions during similar past event, often while unaware of some potential danger. Predetermined ideas like: 'it's spring time', 'the snow has only just recently melted', 'we usually get rain in June', 'it's too cold in the mountains for fire' or 'we don't get fire in Wilmore (wilderness area) in June' can distract us from noticing key fire weather triggers or fuel conditions that are outside of normal. This overconfidence in our judgment leads to failure to collect key factual information because we are so sure of our assumptions and opinions. Most decision makers commit some kind of error along the way and authors (Russo and Schoemaker 1989) describe these as 'decision-traps'.

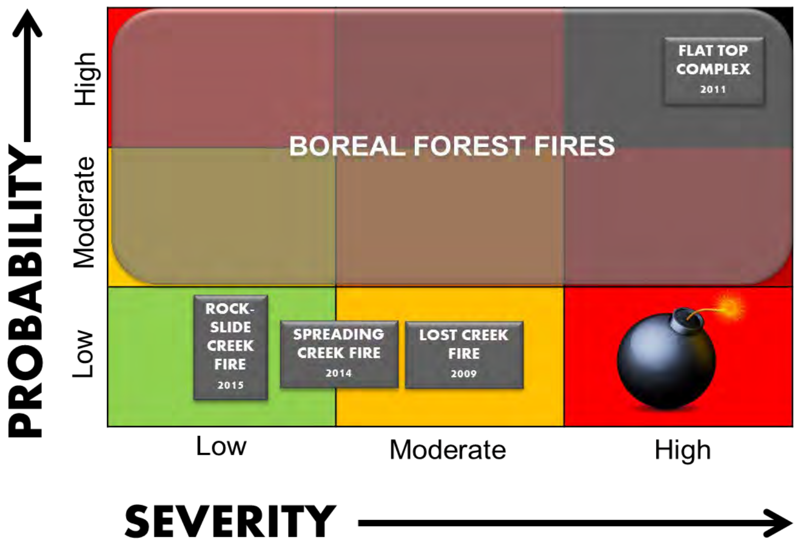

Figure 4. Probability/Severity matrix

In order to make good decisions, we must revisit these errors to identify the pitfalls in our personal decision-making process. We depend on rules of thumb in a place like Wilmore because we do not have our own boots on the ground out there- we are fully dependent on experience and remote weather monitoring stations. These 'anchors' implicitly drive our expectations, so we must become explicitly aware of them. What factors are influencing your decisions? To avoid the decision trap, we should be asking for feedback to calibrate our embedded thoughts (How much overwinter precipitation was there? How are conditions now? How does the current weather compare to the historic weather? We must also always strive know what we do not know and seek to find ways to compensate for the uncertainty. We have to be aware of the "Tyranny of the Urgent[1]" situations that divert our focus. Situational awareness is another discipline that is designed to overcome this tunnel vision.

Conclusions

The 2015 Rockslide Creek fire occurred in a quiet, out of the way corner of Alberta, during a period when mountain fires were normally at a minimum, and the standing boreal forest fire load was very high. Due to those circumstances, the fire was largely un-anticipated, and while the Alberta fire response/suppression framework was robust enough to deal with the fire in a prompt fashion, the fire did surprise people whose jobs it was not to be surprised. For high-reliability organizations, these outlier events do not offer any rebate in their consequences. The agency has to forego the luxury-of-trends to highlight where attention is required, and deliberately focus on all corners of the landscape in a deliberate, systematic fashion, similar to the commercial pilot keeping an eye on dozens, if not hundreds of gauges and indicators monitoring the overall health of his or her aircraft. Likewise, the fire management agency needs to establish systems that over-ride human shortcomings and monitor conditions and elicit a response when (infrequent) conditions are met. The cumulative set of smoke detectors in all homes in a town that together provide fire warning to the fire department is a suitable analogy.

1 Hummel, Charles E., Pamphlet on time management, 1994, InterVarsity Press

References

Baker, William L (2009) Fire Ecology in Rocky Mountain Landscapes, Island Press

Jolly WM, Hintz J, Kropp RC, Conrad ET (2014) Physiological drivers of live foliar moisture content 'spring dip' in *Pinus resinosa* and *Pinus banskiana* and their relationship to foliar flammability. In 'VII International Conference on Forest Fire Research Conference Proceedings'. (Ed DX Viegas). 17-21 November, Coimbra, Portugal. 9 pp.

Rogeau M-P (2009) Fire Regime Study, R11 FMU, Alberta, Alberta Dept. of Sustainable Resource Development

Rogeau M-P (2010) Fire regimes of Alberta's southern Canadian Rockies and important fire years, Proceedings, 3rd Fire Behavior and Fuel Conference, Spokane, WA, IAWF.

Rogeau, MP (2015) *Unpublished data.* Fire history study: Meadowland, Deveber, Sheep and Smoky valley in Willmore Wilderness Park and Grande Cache Area, Alberta, Canada. Internal Report. Wildfire Management Branch, Alberta Agriculture and Forestry. 85 pp.

Russo JE and Schoemaker PJH (1989) Decision traps: the ten barriers to brilliant decision-making and how to overcome them. 304 pp. (Fireside Publishing)

Schoeffler FJ (2013) Large wildfire growth influenced by tropospheric and stratospheric dry slots in the United States. In '17th Conference on the Middle Atmosphere Conference Proceedings'. 17-21 June, Newport, Rhode Island. 25 pp.

Tymstra C, Wang D, Rogeau M-P (2005) Alberta Wildfire Regime Analysis, Alberta Government PFFC Report 2005-1

Mapping Severe Fire Potential across the Contiguous United States

Brett H. Davis*
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory.
bhdavis@fs.fed.us

Matthew H. Panunto
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory.
mpanunto@fs.fed.us

Gregory K. Dillon
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory.
gdillon@fs.fed.us

Introduction

The Fire Severity Mapping System (FIRESEV) project is an effort to provide critical information and tools to fire managers that enhance their ability to assess potential ecological effects of wildland fire. A major component of FIRESEV is the development of a Severe Fire Potential Map (SFPM), a geographic dataset covering the contiguous United States (CONUS) that quantifies the potential for wildland fires to burn with higher severity should they occur (Dillon et al 2011a). We developed this map using empirical observations and statistical models to relate biophysical conditions at the time and location of a fire to the resulting severity. For our purposes, burn severity refers to the degree to which aboveground biomass has been altered as expressed in the change between pre- and post-fire satellite imagery (Lentile et al 2006). Our aim in creating the SFPM is to explore the relationships between site characteristics and burn severity (Dillon et al 2011b) and to provide land managers with a tool that can forecast the potential severity of future fires.

*Corresponding author. 5775 Highway 10 West, Missoula, MT, 59808. Phone: 406-329-7379. Fax: 406-329-4877.

Methodology

Building on the work of Holden et al 2009, we developed a set of statistical models, each relating a suite of independent geospatial variables to 30 years of burn severity data developed by the Monitoring Trends in Burn Severity (MTBS) project. MTBS is an ongoing project to map the severity of all large fires that have occurred since 1984 (Eidenshink et al 2007). We partitioned continuous measures of burn severity into a binary dataset of ‘higher severity’ vs. ‘lower severity’. We produced models to determine the relationship between the two severity classes and site characteristics such as pre-fire vegetation, temporally-specific 1000-hour fuel moistures and a suite of topographic variables. We developed these models separately for forest and woodland vs. non-forest settings in each of 25 distinct ecological regions. The resultant statistical models are used to estimate, based on current measures of our predictor variables, the probability that fire at a particular point on the landscape will result in higher burn severity, should that location burn. These results were used to create a digital map depicting severe fire potential for every 30-meter pixel across CONUS.

Study Area(s)

Our study area consisted of the entirety of CONUS but we completed the project in two phases, the west in 2012 and the east in 2016. Because fire behaves differently under disparate biophysical and climatic conditions it was necessary to divide our study area up into smaller subsets based on modified US EPA ecoregions (Omernik 1987) with some consolidation (Fig. 1). In addition, burn severity measurement and interpretation are different in forest and woodland vs. non-forest settings. Therefore, we further divided each mapping region into these two broad vegetation cover types. We used the mapping regions and cover types to stratify statistical modeling. This resulted in 50 predictive models (25 regions x 2 cover types).

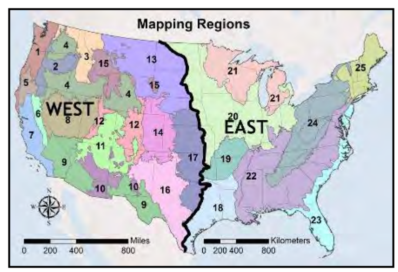

Figure 1: Mapping regions

Data acquisition

We obtained burn severity data for over 12,000 fires that occurred between 1984 and 2013 from MTBS (http://www.mtbs.gov/index.html). We divided the continuous measures of burn severity from MTBS into ‘severe’ vs. ‘not severe’ categories. Due to differences in the quantity and distribution of burn severity data, modeling methodologies differed slightly between the east and the west. One of these differences is the definition of a ‘severe’ fire. For the west, where high-severity fire is more commonplace, we divided the burned pixels into ‘high’ vs. ‘low to moderate’ severity categories. In the east, we divided burned pixels into ‘moderate to high’ vs. ‘low’ severity. Our methodologies for creating categorical definitions of low, moderate and high severity are comparable, but not identical, to those used by MTBS.

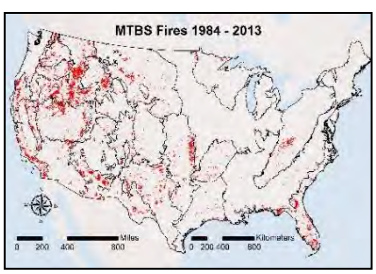

Figure 2: MTBS fires

For our site characteristic data, we acquired 30-meter Digital Elevation Models (DEMs) from the National Elevation Dataset (NED; http://ned.usgs.gov/) and used them to create a suite of topographic indices. We also used the DEMs to model solar radiation, which reflects the influence of topography on vegetation. To represent pre-fire vegetation conditions in the west, we used the Normalized Difference Vegetation Index (NDVI), which we derived from pre-fire Landsat imagery acquired from MTBS. In the east, we obtained moderate-resolution imaging spectroradiometer (MODIS) NDVI data from the United States Geological Service (USGS; https://lpdaac.usgs.gov/). As a measure of seasonal drought, we used 1000-hour fuel moistures at the time of each fire in our dataset. Fuel moisture data were derived using 4km resolution downscaled North American Regional Reanalysis (NARR) data (Abatzoglou 2013). A total of 17 variables were developed as predictive inputs.

Modeling

Once we had acquired and processed the input data, we generated a spatially-balanced, random sample representing 1% of all burned pixels. We used the ~ two million sample point locations to extract values for all of our predictor variables.

We used the Random Forest machine-learning algorithm (Breiman 2001) to develop our statistical models. Random Forest is an extension of classification and regression tree modeling techniques. It divides inputs into training and testing datasets and uses the training data to create models and the testing data to validate the accuracy of its models. Random Forest also has the ability to rank how important each input variable is in terms of its predictive power. We used Random Forest modeling with 1500 classification trees and selected the optimal model with the lowest classification error. This resulted in 50 separate Random Forest models, one each for forest and woodland and non-forest cover types in each of our 25 mapping regions.

Results

Our Random Forest modeling results showed a strong relationship between site characteristics and the resultant burn severity. In forest and woodland cover types cross-validated classification

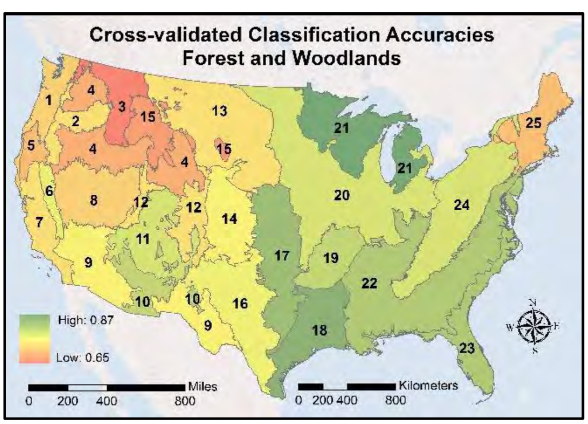

Figure 3: Classification accuracies – Forest & Woodlands

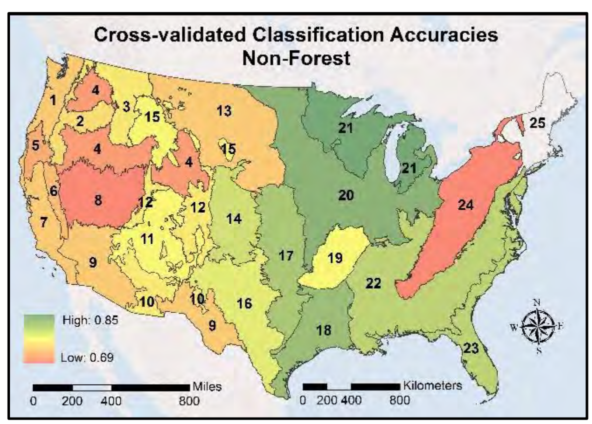

Figure 4: Classification accuracies - Non-Forest

accuracies ranged from 65 to 87% with a median of 73% (Fig. 3). In the non-forested areas, classification accuracies ranged from 69 to 85% with a median of 76% (Fig. 4). The number of predictor variables selected in the optimal Random Forest models ranged from four to ten in the forest and woodlands models and four to nine in the non-forest models with medians of six and seven respectively. In terms of variable importance rankings, elevation, 1000-hr fuel moisture and NDVI were generally in the top four predictor variables, often with some combination of solar radiation, slope and broad-scale topographic position.

Mapping

Using the Random Forest models created in the modeling process, we predicted potential burn severity using contemporary landscapes with spatially-comprehensive and temporally-representative predictor variables. Topographic variables are static but vegetation and 1000-hour fuel moistures are not. We used recent NDVI vegetation data and constant 1000-hour fuel moisture values at a variety of common fire weather thresholds (80th, 90th and 97th percentiles). Constant fuel moisture values are necessary because it is not possible to know them in advance. Each of the 1500 classification trees in the Random Forest models classify every 30-meter pixel on the landscape into either the severe or not severe categories resulting in 1500 predictions of binary severity. The product of this analysis is a map showing the percentage of classification trees that predicted severe fire. Figures 5 and 6 show the results of these predictions at the 90th percentile 1000-hour fuel moisture level for the west and the east respectively. In the west, we are forecasting the potential for high severity fire and in the east the potential for moderate to high severity fire.

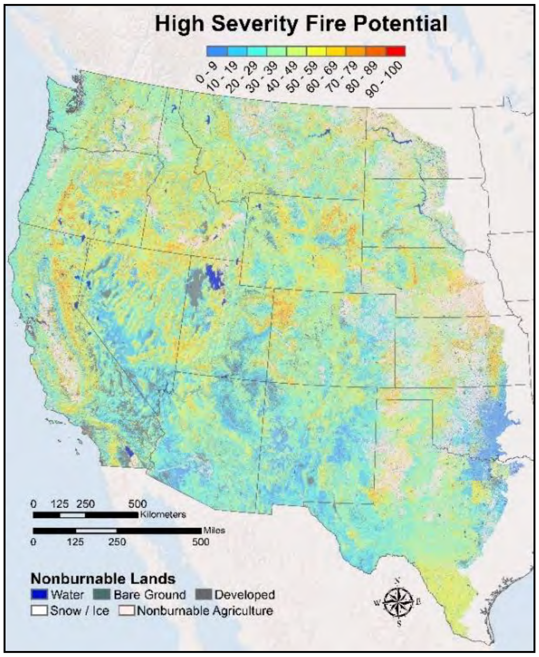

Figure 5: Western burn severity potential

Discussion

When coupled with information regarding current landscape conditions, the Severe Fire Potential Map can assist managers in identifying areas where fire may help restore fire-adapted ecosystems and where it might have less favorable impacts. Its potential uses include:

- Planning for future wildfires - pre-existing product can inform managers as to whether an ignition may lead to desirable or undesirable ecological impacts.

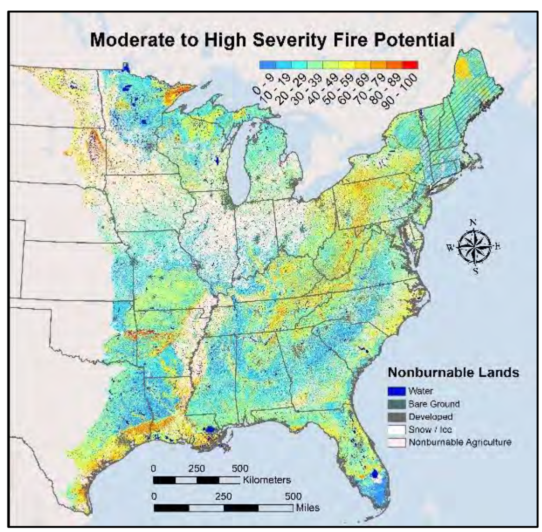

Figure 6: Eastern burn severity potential

- Planning prescribed burns – informs potential ecological consequences of prescribed fire.
- Fuel treatment planning – helps managers focus on areas where fire may burn with an undesirable severity.
- Immediate post-fire rehabilitation – identifying those areas most likely to need mitigation treatments (e.g. soil stabilization) before traditional post-fire burn severity products (e.g. BAER and RAVG) are available.

The completed SFPM is currently available online at http://www.frames.gov/firesev for the western US and at http://www.frames.gov/firesev/east for the eastern US. This map product will be incorporated into existing decision support frameworks such as the Wildland Fire Decision Support System (WFDSS) in the near future. A General Technical Report (GTR) describing the methods, map products and validation metrics is also forthcoming. The development of the Severe Fire Potential Map has provided an opportunity to enhance our understanding of the environmental influences on burn severity and has provided a new resource to support fire management decisions.

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References

Abatzoglou, J. T. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology*, *33*(1), 121-131.

Breiman, L. (2001). Random forests. *Machine learning*. *45*(1), 5–32.

Dillon, G., P. Morgan, and Z. A. Holden. (2011a). Mapping the potential for high severity wildfire in the western United States. *Fire Management Today 71*(2), 25-28.

Dillon, G. K., Holden, Z. A., Morgan, P., Crimmins, M. A., Heyerdahl, E. K., & Luce, C. H. (2011b). Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. *Ecosphere*, *2*(12), art130.

Eidenshink, J. C., Schwind, B., Brewer, K., Zhu, Z. L., Quayle, B., & Howard, S. M. (2007). A project for monitoring trends in burn severity. *Fire Ecology*, *3*(1), 3-21.

Holden, Z. A., Morgan, P., & Evans, J. S. (2009). A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. *Forest Ecology and Management*, *258*(11), 2399-2406.

Lentile, L. B., Holden, Z. A., Smith, A. M., Falkowski, M. J., Hudak, A. T., Morgan, P., Benson, N. C. (2006). Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire*, *15*(3), 319-345.

Omernik, J. M. (1987). Ecoregions of the conterminous United States.*Annals of the Association of American geographers*, *77*(1), 118-125.

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Modeling Fuels and Fire Effects in 3D with FuelManager and STANDFIRE

François Pimont*
INRA URFM, Avignon, France, francois.pimont@avignon.inra.fr

Russell Parsons
USFS RMRS, Missoula, Montana, USA, rparsons@fs.fed.us

Eric Rigolot
INRA URFM, Avignon, France, eric.rigolot@avignon.inra.fr

Jean-Luc Dupuy
INRA URFM, Avignon, France, jean-luc.dupuy@avignon.inra.fr

François de Coligny
INRA AMAP, Montpellier, France, coligny@cirad.fr

Rodman Linn
LANL EES, Los Alamos, New Mexico, USA, rrl@lanl.gov

Introduction

Scientists and managers need robust ways to assess how fuel treatments alter fire behavior, yet few tools currently exist for this purpose. In recent years, the physics-based fire models FIRETEC (Linn and Cunningham 2005, Pimont *et al.* 2009, Dupuy *et al.* 2011) and WFDS (Mell *et al.* 2007) have shown promise in this context since they explicitly account for 3D fuel structure (Pimont *et al.* 2011). However, there remains a need for tools which facilitate getting fuel data into these models as well as for assessments of how fuel changes affect fire behavior, both immediately and over time. Here, we introduce two spatially-explicit-fuel-modeling systems designed to interact with these models, called FuelManager (Pimont *et al.* 2016, Rigolot *et al.* 2010) and STANDFIRE. Both systems are modules in, and build upon, the common architecture of the CAPSIS (Computed Aided Projection of Strategies in Silviculture) platform[1] (Dufour-Kowalski *et al.* 2012), an integrated modeling framework for forestry research, and enable fuel data from various sources to be used as inputs to physics-based fire models. Both modules rely on the *Fire* library, that also enables simulation of fuel treatments and fire effects.

Model Description

The Fire library – for more information see http://capsis.cirad.fr/capsis/help_en/firelib

The *Fire* library is a computer code library which represents wildland fuels as spatially-explicit 3D objects in a CAPSIS scene (Fig. 1). Different kinds of vegetation are represented in either as *Plants* (with specific coordinates and dimensions) or as collections of plants called

* INRA, UR629, Domaine de Saint Paul, Agroparc F-84914 Avignon Cedex 9, France.
[1] http://www.inra.fr/capsis

LayerSets. Both approaches include descriptions of multiple fuel *Particle* types (leaves, needles and twigs of various sizes, either live or dead), characterized by their mass to volume ratio, surface area to volume ratio and moisture content. Each *Plant* has a position, a diameter at breast height, crown dimensions and geometry. Each particle type associated with a given *Plant* has a mass and a vertical distribution within the crown, typically computed using DBH and H allometries. A *LayerSet* is a flexible approach for representing groups of plants when it is impractical to describe them as individual plants. Within a *LayerSet*, various fuel components can be mixed together and assigned different characteristics. A *LayerSet* occupies a volume of space within a *Scene* and is represented as a right prism with a polygonal base face parallel to the ground.

The *Fire* library enables the computation of fuel properties, such as loads and cover fractions in a given strata, or to visualize the scene in 3D. The *Fire* library also provides a number of ways to apply fuel treatments, such as thinning, either to the whole scene or to specific areas within a scene. The primary purpose of this library, however, is to enable the export of a fuel scene as inputs to FIRETEC or WFDS to simulate fire behavior. Because these fire models capture key interactions between the fuels, fire and atmosphere, they provide unique capabilities for assessing how fuel changes affect fire behavior. Additionally, fire model outputs such as local fire intensities and residence times provide useful data to estimate fire effects to trees, using empirical models of damage and mortality, such as Van Wagner (1973) and Peterson and Ryan (1986).

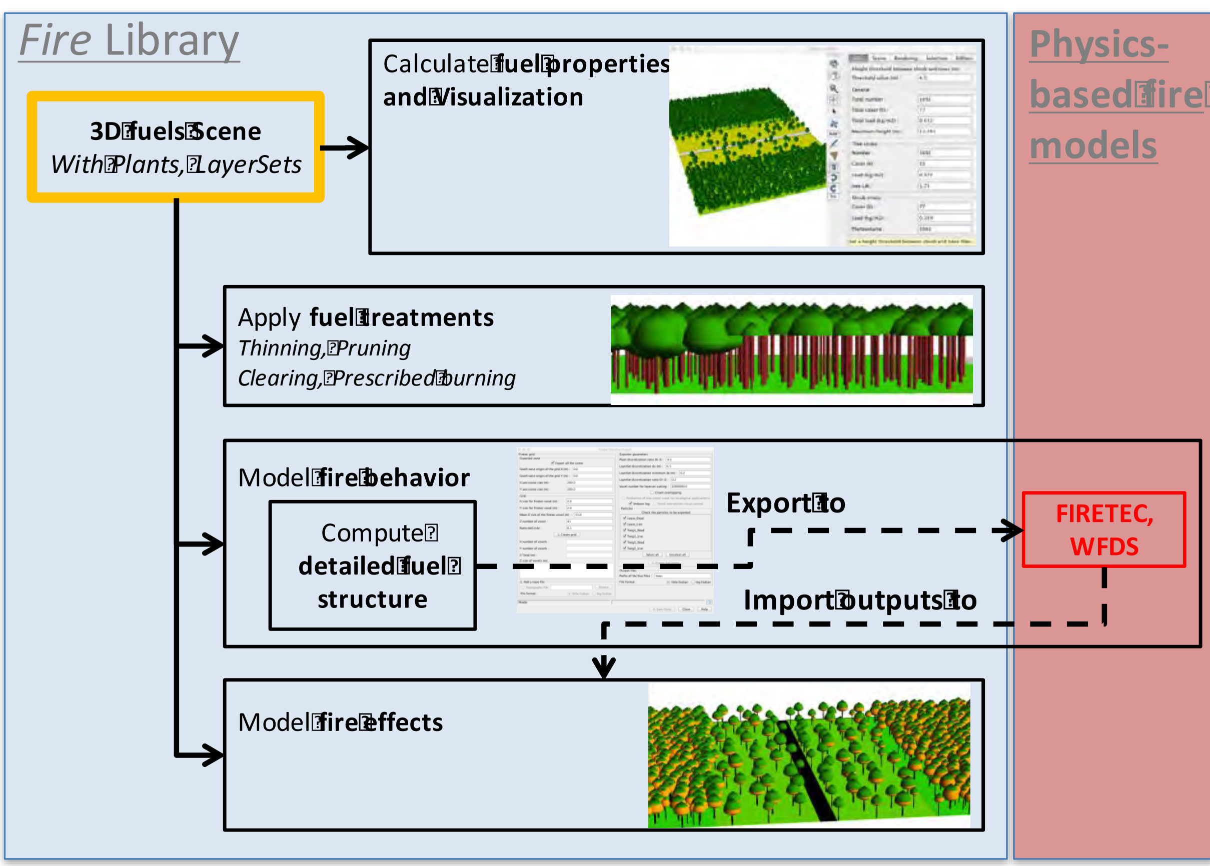

Figure 1: Features available in the *Fire* library (used by FuelManager and STANDFIRE).

STANDFIRE – for more information see: http://capsis.cirad.fr/capsis/help_en/standfire

In the US, FFE-FVS (Crookston and Nixon 2005) is the primary tool used to assess how fuel treatments affect fire at stand scales. STANDFIRE extends FFE-FVS' capabilities by connecting it to physics-based fire models, while continuing to use FVS to model growth over time. The core of the module relies on the *Fire* library described above, but STANDFIRE also includes additional components to import data from FFE-FVS and to read additional files required to build the scene, which describe fuel particle characteristics and tree crown geometry (Fig. 2). STANDFIRE also includes post processors for the WFDS model. In most cases, when users do not have spatially explicit data, STANDFIRE uses the Stand Visualization System (SVS) file, which has tree coordinates, to model trees in 3D. This one-acre square can be extended with STANDFIRE to cover larger extents by sampling from the tree data in the SVS file. Default values are available for fuel properties when those values or equations are unknown. To date, this is the first system to link FVS-FFE and physics-based models.

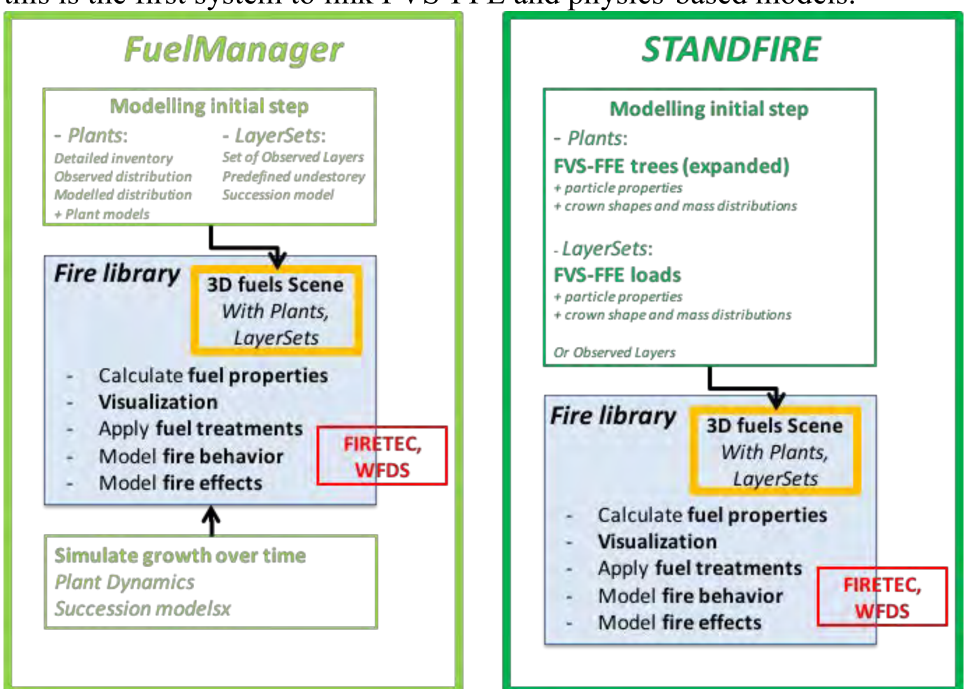

Figure 2: Architecture of FuelManager and STANDFIRE modules

FuelManager (for more information see: http://capsis.cirad.fr/capsis/help/fireparadox)

FuelManager was developed as a stand-alone module to build input data for physics-based models (Pimont *et al.* 2016). The core of the module is again the *Fire* library, but FuelManager includes its own models for *Plant* distributions, based on either detailed inventories (stem map), observed distributions of stem (by DBH classes) or modeled distributions. FuelManager includes some growth models for *Plants* and a succession model for *LayerSets* to simulate growth over time.

Example applications

Building FIRETEC input data for the International Crown Fire Modeling Experiment (ICFME). The ICFME crown fire experiment is a key dataset for physics-based model evaluation. Field data (Alexander et al. 2004) were used to parameterize individual *Plant models* in FuelManager. Three dimensional fuel scenes were then generated for use as input for FIRETEC for the full extent of the experiments by sampling from observed tree stem distributions. Data for four plots were used to compare predictions of fire behavior and radiant fluxes with experimental values (Pimont *et al.* 2014) (Fig. 3).

a) b)

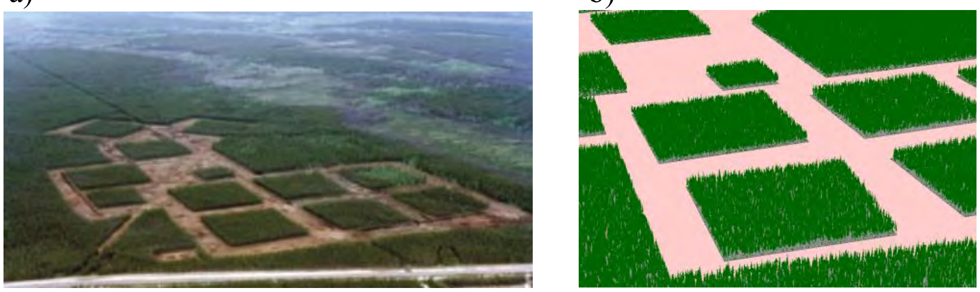

Figure 3: Comparison between (a) Photograph of ICFME experiment and (b) modeled aerial view using FuelManager

Investigating fuel management scenarios (Pimont et al. 2016)

FuelManager and STANDFIRE both benefit from the CAPSIS architecture for modeling vegetation changes over time and with fuel treatments. This allows comparison of alternative states resulting from various sequences of events.

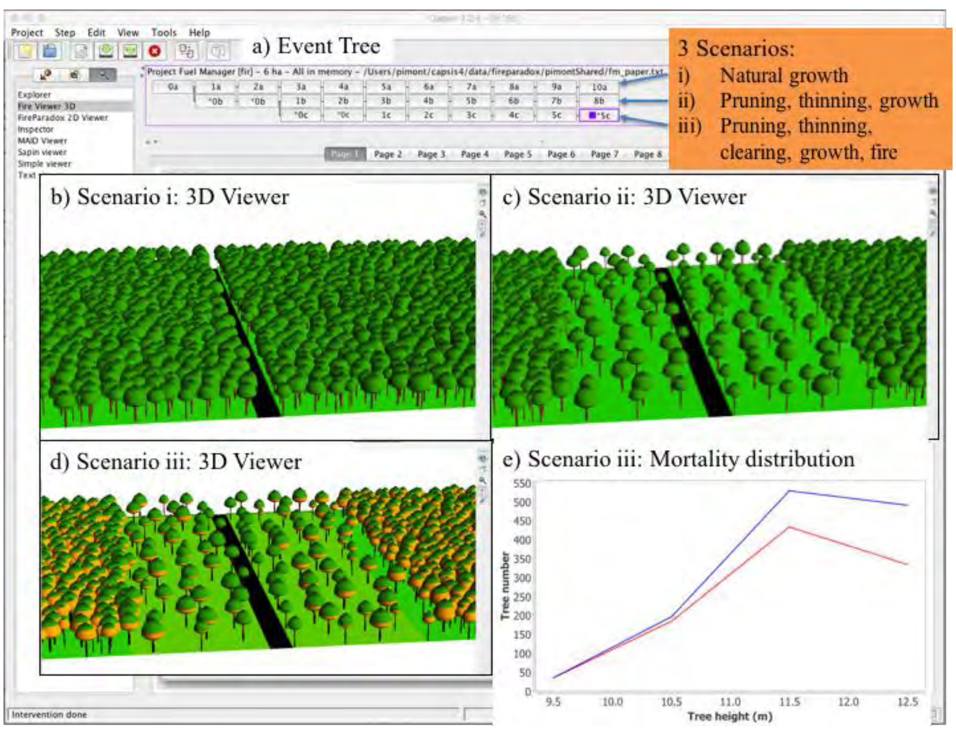

Figure 4: Views of FuelManager GUI illustrating Aleppo pine stands following three sequences of events: a) Event tree b) Initial stand with road passing through forest c) Crown spacing-based thinning to specified distance

from road d) Visualization of modeled crown scorch from prescribed fire, and e) Comparison of the distribution of modeled killed trees (in red) to the pre-fire distribution (in blue).

Comparison of crown space thinning fuel treatments with STANDFIRE

Using fuels data measured at the Tenderfoot Experimental Forest in central Montana, we used STANDFIRE and WFDS to examine the potential changes in fire behavior that might arise with different thinning treatments. Figures 5a and b shows 3D fuels and fire behavior at the same point in time for four different simulations with different crown space thinning, and three associated change metrics for each of those simulations.

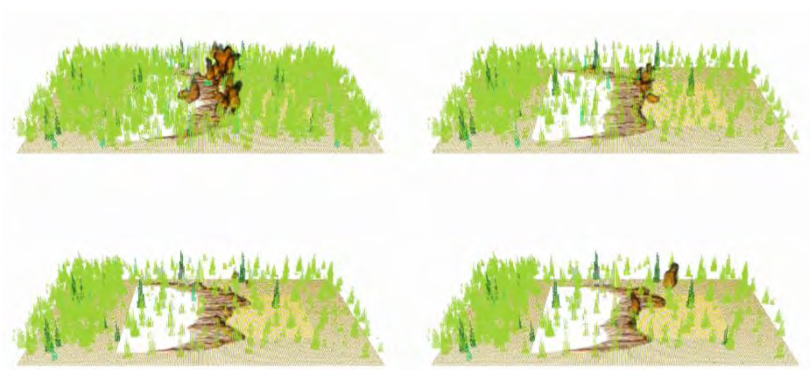

Figure 5a. 3D fuels and fire behavior at the same point in time for four different simulations with different crown space thinning: (upper left: no thinning; upper right, 5' crown spacing; lower left, 10' crown spacing; and lower right, 15' crown spacing.

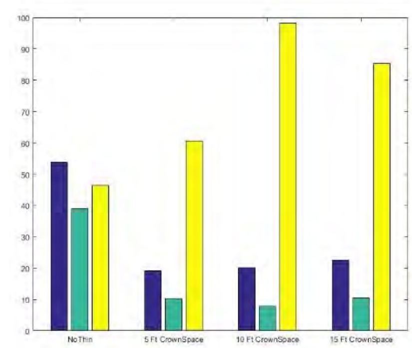

Figure 5b. 3 metrics of change for each simulation shown at left: 1) canopy fuel mass loss (%, blue bars), predicted mortality (%, green bars) and surface fire rate of spread (m min^{-1}, yellow bars).

Discussion and conclusion

FuelManager and STANDFIRE provide detailed fuel inputs for physics-based fire models, FIRETEC and WFDS, and can be used to explore how fuel management efforts may affect fire behavior. They integrate a wide range of fuel modeling capabilities, numerous recent fire-effect research results and recent technologies for visualization and *Scene* manipulation to provide a suite of capabilities relevant to examinations of fuel management scenarios.

FuelManager has shown to be a powerful and flexible tool in the context of fuel modeling, offering various applications (Pimont *et al.* 2016). STANDFIRE is in active development but more documentation is forthcoming. Both modules increase our capabilities to examine relationships between fuels, fire behavior and fire effects. They also increase the robustness of fire modeling studies using FIRETEC and/or WFDS, since input data are built in a transparent and reproducible manner.

At present, only thirteen species (mostly European fire prone species) are represented in FuelManager, but users can easily incorporate simple *Plant* models for other species without additional coding, since pre-defined equations and parameters can be defined in a separate text file (*speciesFile*[2]). Equations for crown dimension and biomass are often available in literature. Vertical distributions are less often available, but the user can rely on those already available in

[2] http://capsis.cirad.fr/capsis/help_en/firelib/speciesfile

the *speciesFile*. STANDFIRE will ultimately apply to a much larger set of species and ecosystems, since it builds connections to the US system FFE-FVS, which is widely used to facilitate fuel modeling throughout the United States.

References

Alexander ME, Stefner CN, Mason JA, Stocks BJ, Hartley GR, Maffey ME, Wotton BM, Taylor SW, Lavoie N, Dalrymple GN (2004) 'Characterizing the Jack Pine – Black Spruce Fuel Complex of the International Crown Fire Modelling Experiment (ICFME).' Information Report NO>R-X-393. Canadian Forest Service Northern Forestry Centre, 49 pp.

Crookston NL, Dixon GE (2005) The forest vegetation simulator: a review of its structure, content, and applications. *Computers and Electronics in Agriculture* **49(1)**, 60-80.

Dupuy J-L, Linn RR, Konovalov V, Pimont F, Vega JA, Jimenez E (2011) Exploring coupled fire/atmosphere interactions downwind of wind-driven surface fires and their influence on backfiring using the HIGRAD-FIRETEC model. *International Journal of Wildland Fire* **20**, 734-750.

Dufour-Kowalski S, Courbaud B, Dreyfus P, Meredieu C, de Coligny F (2012) Capsis: an open software framework and community for forest growth modeling. *Annals of Forest Science* **69 (2)**, 221-233.

Linn RR, Cunningham P (2005) Numerical simulations of grassfires using coupled Atmosphere fire model: basic fire behavior and dependence of wind speed. *Journal of Geophysical Research* **110**, D131007.

Mell W, Jenkins MA, Gould J, Cheney (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* **16**, 1-22.

Peterson DL, Ryan KC (1986) Modeling post-fire conifer mortality for long-range planning. *Environmental Management* **10**, 797-808.

Pimont F, Dupuy JL, Linn R, Dupont S (2009) Validation of FIRETEC wind-flows over a canopy and a fuel-break. *International Journal of Wildland Fire* **18**, 775–790.

Pimont F, Dupuy JL, Linn R, Dupont S (2011) Impact of tree canopy structure on wind-flows and fire propagation simulated with FIRETEC. *Annals of Forest Science* **68(3)**, 523-530.

Pimont F, Dupuy JL, Linn RR (2014) Fire effects on the physical environment of a building in the WUI using FIRETEC. In *Advances in Forest Fire Research* (Ed DX Viegas), Chapter 3 - Fire Management, 749-757.

Pimont F, Parsons R, Rigolot E, Coligny F, Dupuy, J-L, Dreyfus P, Linn R (2016) Modeling fuels and fire effects in 3D : model description and applications. *Environmental Modelling and Software* 80, 225-244.

Rigolot E, de Coligny F, Dreyfus L, Leconte I, Pezzatti B, Vigy O, Pimont, F (2010) FUEL MANAGER: a vegetation assessment and manipulation software for wildfire modeling. *Proceedings of the VI International Conference on Forest Fire Research*. Viegas DX (Ed).

Van Wagner CE (1973) Height of crown scorch in forest fires. *Canadian Journal Forest Research* **3(3)**, 373-378.

Modeling of Thunderstorm Induced Wind Shifts

Gary L. Achtemeier
USDA Forest Service Southern Research Station, Athens GA, Retired

Scott L. Goodrick
USDA Forest Service Southern Research Station, Athens GA, sgoodrick@fs.fed.us

Introduction

Shifting winds present hazardous conditions to fire crews as slow-spreading lower intensity flanking fires can quickly transform into raging high-intensity head fires. Thunderstorms are one driver of potential wind shifts. During the life cycle of a thunderstorm surface winds shift from inflows feeding the updraft of developing thunderstorms to outflows as downdrafts develop in the later stages of the storm's evolution. Thunderstorm outflows are capable of traveling long distances across the landscape, resulting in strong wind shifts in areas with minimal signs of changing weather.

Thunderstorm induced wind shifts have had a role in a number of firefighter fatalities. Haines (1988) described the role of a thunderstorm on the 1981 Ransom Road Fire in Florida that resulted in a ninety-degree wind shift and an increase in wind speeds from an average of 7 to 25 miles per hour (11 to 41 kilometers per hour) with gusts reaching 52 mph (84 kph). Goens and Andrews (1998) suggest that a thunderstorm downdraft played a role in the 1990 Dude Fire fatalities in Arizona. Channeling of the outflow winds through the rugged terrain led to the rapid down- and cross-slope fire spread that entrapped the firefighters.

In this paper, we describe results from a thunderstorm-induced wind model capable of describing the evolution of outflow winds. The model is designed to allow fire personnel to assess the risk of changes in wind speed and direction, and take action to move fire crews to safety up to 30-60 minutes before wind shifts arrive at a fire site. The model links real-time operational radar precipitation data with ambient temperature and relative humidity to map locations and fields of outflow wind velocities as they evolve relative to local terrain during the course of the day. The 2013 Yarnell Hill Fire is used as a case study.

Model Description

The outflow model combines a simple density current model developed for simulating nocturnal smoke movement (Achtemeier, 2005) with a simplified description of the thunderstorm life cycle. Thunderstorms are envisioned as "black boxes" whose intensity is determined by the intensity of radar precipitation measurements. The strength of the downdraft is determined from the combination of precipitation intensity, ambient temperature and potential for evaporation as precipitation falls through dry sub-cloud air. The downdraft strength relates to the outflow temperature thus producing the cold air mass that pushes beyond the parent storm, displacing nearby warmer air masses. The boundary of the cold air mass (gust front) is a near-discontinuity in temperature, wind direction, and wind speed.

Results

On June 30,2013 nineteen members of the Granite Mountain Interagency Hotshot Crew died on the Yarnell Hill Fire in central Arizona. While much is unknown concerning this tragic event, changes in fire behavior induced by changing weather conditions had a role as winds shifted throughout the afternoon. At 1630 local standard time, thunderstorm outflows reached the southern perimeter of the fire. Winds increased substantially; the fire turned south and overran the Granite Mountain IHC at about 1642 LST (Yarnell Hill Serious Accident Investigation Report, 2013). The following is our attempt to recreate the wind shifts of this event with a tool that can eventually be used on fire incidents to better convey the threat of potential wind shifts.

Figure 1 shows the relationship between Yarnell, the radar site in Flagstaff AZ and various topographic features. Yarnell is approximately 92 miles (142 km) west-southwest of the radar site. Important topographic features include the Mogollon Rim near Flagstaff with elevation approximately 7600 ft (2320 m) and two mountain ranges between the Mogollon Rim and Yarnell. Prevailing thunderstorm movement was from the northeast at about 10 mph which caused most thunderstorm outflows to be concentrated along the southwest-facing slopes of the Mogollon Rim.

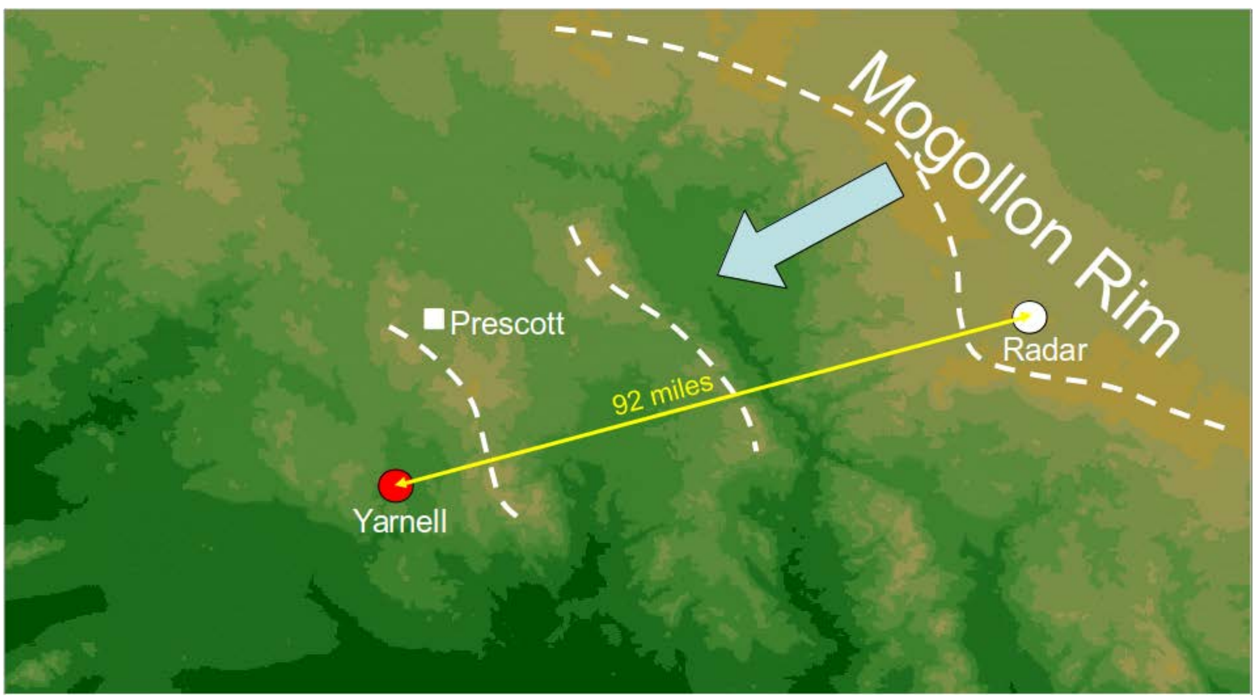

Figure 1:Topographic features in study area. Darker greens are lower elevations while tans show higher elevations. Dashed lines indicate edge of Mogollon Rim and select mountain ranges.

Convection began late morning along the Mogollon Rim and by 1200 LST the outflow boundaries from several strong storms had begun to merge along a northwest to southeast axis along the Rim (Figure 2a). By 1335 LST, outflows from storms pushing off the Mogollon Rim had merged into a single boundary advancing toward the southwest (arrows in Figure 2b). Meanwhile, outflows from the storms over high ground northwest of Yarnell were pushing toward lower elevations toward the southeast. By 1430 LST, outflows had merged into a single boundary and new storms were forming over the first mountain range southwest of the Mogollon Rim (Figure 2c). At 1500 LST, The southwest-moving outflow boundary had stalled along the mountain range just east of Yarnell (Figure 2d).

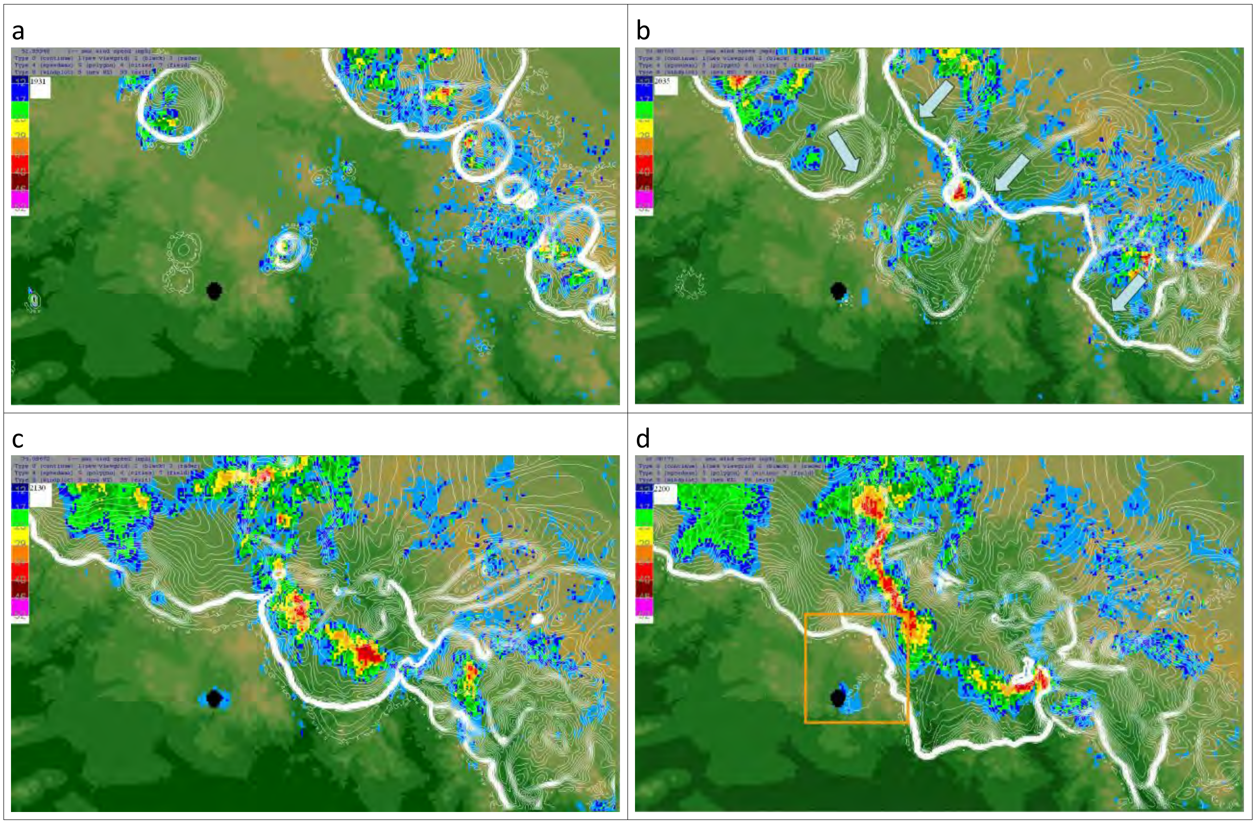

Figure 2: Radar precipitation echoes overlain on the elevation map and thunderstorm outflows identified by white contours for a) 1231 LST, b) 1335 LST c) 1430 LST and d) 1500 LST. The blackened area identifies the location of the Yarnell fire smoke plume as observed by radar at an elevation of 8,000 feet. The orange box in (d) represents the area of focus in Figure 3.

By 1500 LST the outflow boundary reached the closer of the two ridges northeast of Yarnell (Figure 3). New storms began to form as air was forced upward by the ridge. The ridge presented a barrier to the southwestward advance of the outflow boundary until the newly developing storms contributed additional cool dense air to fuel the gravity currents. By 1515 LST the outflows surged through a gap in the ridge and began southwestward at 40-46 mph (64-74 kph). At 1615 LST the outflow boundary reached the northern boundary of the radar-observed Yarnell smoke plume. Meanwhile, a second outflow surge has breached a second gap in the ridge to the east-northeast and is racing toward Yarnell from the east. By 1645 LST the outflows have merged and shifted the winds to blow from the northeast over the Yarnell fire.

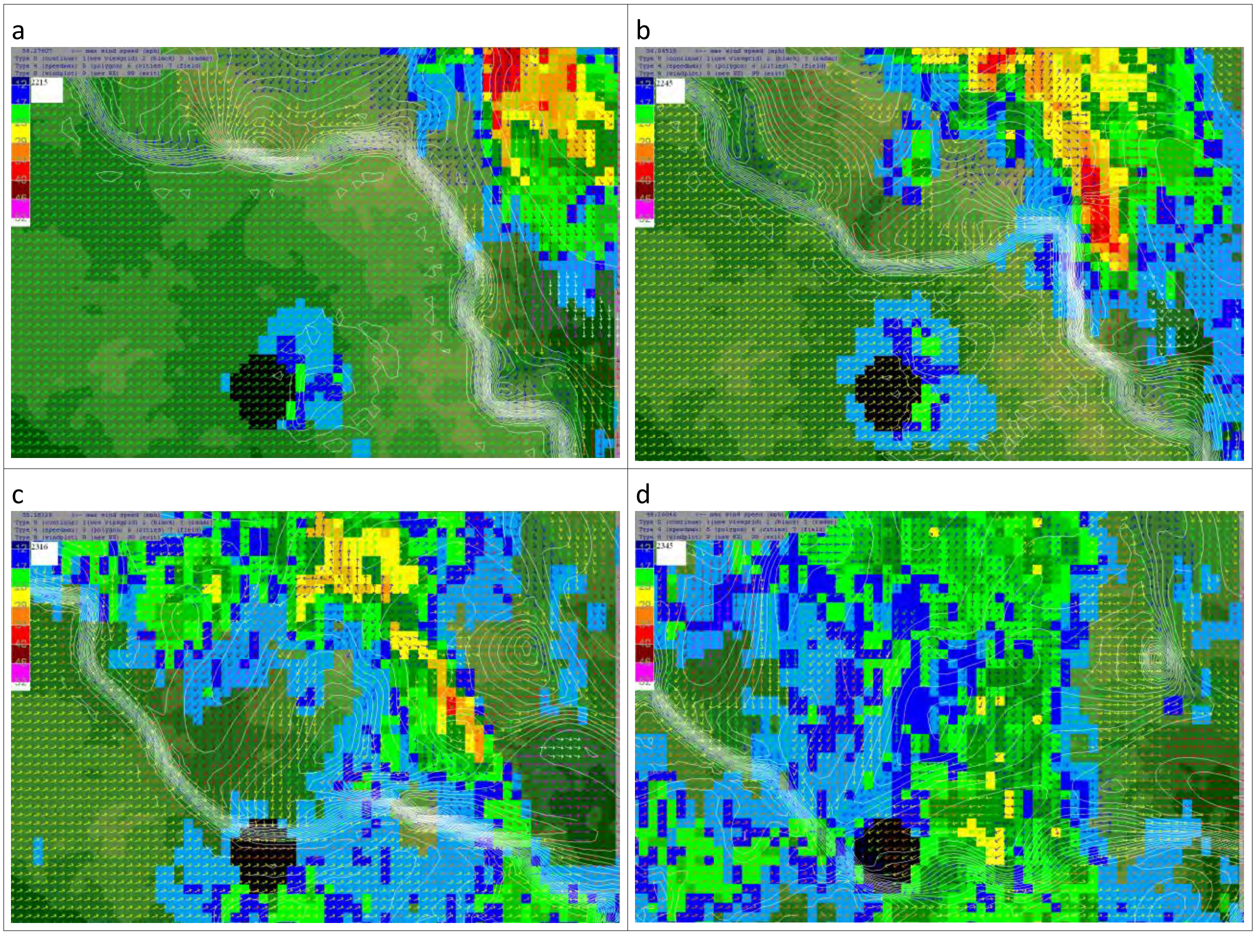

Figure 3: Closeup of radar echoes overlaid on terrain with modeled evolution of the outflow boundary (white line) as it progresses toward the Yarnell Hill Fire at a) 1515 LST, b) 1545 LST, c) 1615 LST and d) 1645 LST.

Summary

Overall the model did a reasonable job of capturing the complexities of the outflows as they evolved over the course of an afternoon and traveled roughly 90 miles from the initial area of convection. Topographic channeling of the outflows was effectively captured by the model which contributed to the model doing a good job of conveying the complexity of the evolving wind field far beyond what is currently conveyed in weather forecasts.

The model captured the major wind shifts associated with the thunderstorm outflows. However, there were other weaker wind shifts that occurred mid-afternoon that were not captured in this simulation. As the model is solely focused on simulating the evolution of the outflows there are other aspects of the flow that are neglected. Slope flows induced by solar heating of the terrain would influence the evolution of the outflows to some degree but are currently neglected. The simple, single layer formulation of a density current is an additional limiting factor as three dimensional effects may also play a role. Despite these limitations the model did supply a useful description of the evolution of surface wind field for this event as the model captured the most dominant features of the flow and the simplifying assumptions allows the model computations to be performed fast enough for this tool to be useful in an operational environment.

References

Achtemeier GL (2005) Planned Burn-Piedmont. A local operational numerical meteorological model for tracking smoke on the ground at night: Model development and sensitivity tests. *International Journal of Wildland Fire* 14, 85-98.

Goens DW and Andrews PL (1998) Weather and fire behavior factors related to the 1990 Dude Fire near Payson, Arizona. In *Proceedings, 2nd Symposium on fire and forest meteorology.* Boston MA, American Meteorological Society, 153-158.

Haines DA (1988) Downbursts and wildland fires: a dangerous combination. *Fire Management Today* **49**(3) 8-10.

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Multiphase CFD Model of Wildland Fire Initiation and Spread

Vladimir Agranat*
Applied Computational Fluid Dynamics Analysis, Thornhill, Ontario, Canada, vlad@acfda.org

Valeriy Perminov
Tomsk Polytechnic University, Tomsk, Russia, perminov@tpu.ru

Introduction

Wildland fires are extremely complex and destructive phenomena and their behavior depends on the state of vegetation, meteorological conditions and ground terrain. Experimental studies of wildfire behavior are expensive and challenging tasks. This makes the development of robust and accurate models of wildfire behavior an extremely important activity. There are various types of wildland fire models: statistical, empirical, semi-empirical and physics-based. This paper is devoted to the development and validation of a physics-based multiphase Computational Fluid Dynamics (CFD) model of wildland fire initiation and spread and smoke dispersion.

Over the past 30 years, a significant progress in the development of physics-based wildfire models has been achieved. In particular, fully physical multiphase wildfire models have been developed by Grishin *et al.* (1986), Grishin 1997, Porterie *et al.* 1998, 2000, Morvan and Dupuy 2001, Mell *et al.* 2007. According to a review by Morvan 2011, one of the most advanced models of this type is the three-dimensional (3D) model, WFDS (Wildland-urban interface Fire Dynamics Simulator), developed by the National Institute of Standards and Technology (NIST) and the U.S. Forest Service. The validation of WFDS is ongoing: its recent validation was conducted by Menage *et al.* 2012 with using the experimental data of Mendes-Lopes *et al.* 2003 on surface fire propagation in a bed of *Pinus pinaster* needles. The same set of data was also used by Porterie *et al.* 2000 in validating their multiphase model.

In the present study, a fully physical multiphase 3D model of wildland fire behavior was developed and incorporated into the commercial general-purpose CFD software, PHOENICS, employed as a framework and a solver. The model contains the main features proposed by previous researchers, i.e. Grishin 1997 and Porterie *et al.* 1998, 2000, and it accounts for all the important physical and physicochemical processes: drying, pyrolysis, char combustion, turbulent combustion of gaseous products of pyrolysis, exchange of mass, momentum and energy between gas and solid phase, turbulent gas flow and convective, conductive and radiative heat transfer. It has been validated using the experimental data of Mendes-Lopes JMS *et al.* 2003. The predicted rate of spread (ROS) of wildfire compares quantitatively well with its experimental values obtained at various wind speeds (from 1 to 3 m/s). The use of PHOENICS software as a framework for modeling allows model applications by potential users (students, researchers, fire management teams, etc.) without any special CFD background due to availability of user-friendly software interface, documentation and technical support. Moreover, an open and general structure of software enables users to modify the model, test various built-in models of turbulence and radiation, try various numerical schemes and import geometries from CAD packages in order to model complex shapes of objects in wildland-urban interface (WUI).

Physical and Mathematical Formulation

Following a multiphase modeling approach proposed by Grishin 1997 and Porterie *et al.* 2000 the forest is considered in this paper as a chemically reactive multiphase medium containing gas phase with a volume fraction of ϕ_g and condensed phase with a volume fraction of ϕ_s (liquid water, dry organic matter, solid pyrolysis products and mineral part of fuel). The interaction between phases is modeled by two sets of phase governing equations linked with proper source terms expressing the gas flow resistance, multiphase heat transfer and chemical reactions. The model accounts for drying, pyrolysis, char combustion, turbulent combustion of gaseous products of pyrolysis, turbulent gas flow and heat transfer. In this study, the radiative heat transfer is approached with a simple radiation model similar to widely used P1 – approximation and soot formation is ignored. The Arrhenius-type kinetics is used for heterogeneous reactions (drying, pyrolysis and char combustion) and the eddy dissipation concept (EDC) of Magnussen and Hjertager 1976 is applied for modeling the gaseous combustion. Turbulence is modeled by using the renormalization group (RNG) *k*-*ε* model. Figure 1 shows the 3D domain containing the gas flow region, a fuel bed representing the forest and an ignition line. The specific sizes of domain and fuel bed vary in various case studies.

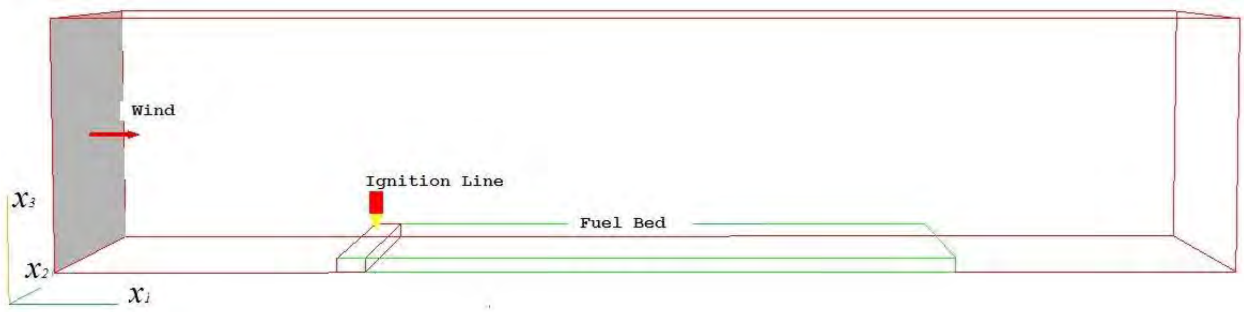

Figure 1: Computational domain: wind, ignition line and fuel bed

The gas phase governing equations are written in a generic form as follows:

$$\frac{\partial}{\partial t}(\rho\Phi)+\frac{\partial}{\partial x_i}\left(\rho u_i\Phi-\Gamma_\Phi\frac{\partial\Phi}{\partial x_i}\right)=S_\Phi \qquad (1)$$

Here, *t* is the time; x_i is the spacial coordinate (i=1, 2, 3); ρ is the gas mixture density; u_i is the velocity component in x_i direction and the specific expressions for dependent varibale, *Φ*, diffusive exchange coefficient, Γ_Φ, and source term, S_Φ, are given in Table 1 below. The gas phase volume fraction, ϕ_g, is taken equal to unity in equation (1) as ϕ_g = 1-ϕ_s, where the volume fraction of condensed phase, ϕ_s, is very small in the present study (ϕ_s<0.016). The gas density is calculated from the ideal gas law equation of state for mixture of gases: $p=\rho RT\sum_{\alpha=1}^{3}\frac{c_\alpha}{M_\alpha}$, where *p* is the gas pressure; *T* is the absolute gas temperature; *R* is the universal gas constant; c_α is the mass fraction of α - species of gas mixture; index α = 1,2,3, where 1 corresponds to oxygen, 2 - to carbon monoxide, 3 - to all other components of gas mixture ($\sum_{\alpha=1}^{3}c_\alpha=1$); M_α is the molecular weight of α-component of gas phase.

Table 1. Dependent variables, effective exchange coefficients and source terms in equation (1)

Conservation of	Φ	Γ_Φ	S_Φ
Mass	1	0	$\dot{m}$
x_i – momentum	u_i	$\mu + \mu_t$	$-\frac{\partial p}{\partial x_i} + \rho g_i - \frac{1}{8} A_s C_d \rho u_i \mid \bar{u} \mid$
Enthalpy	h	$\frac{\mu}{\Pr} + \frac{\mu_t}{\Pr_t}$	$m_5 q_5 - A_s h_s (T - T_s) + 4\varepsilon_1 \sigma (T_3^4 - T^4)$
Mass of α – species	c_α	$\frac{\mu}{Sc} + \frac{\mu_t}{Sc_t}$	$m_{5\alpha}$
Turbulent kinetic energy	k	$\mu + \frac{\mu_t}{\sigma_k}$	$\rho(P_k + W_k - \varepsilon)$
Dissipation rate of turbulent kinetic energy	ε	$\mu + \frac{\mu_t}{\sigma_\varepsilon}$	$\rho \frac{\varepsilon}{k}(C_{\varepsilon 1} P_k - C_{\varepsilon 2} \varepsilon + C_{\varepsilon 3} W_k - R_{RNG})$

Here, h is the gas enthalpy; k is the turbulent kinetic energy; ε is the dissipation rate of turbulent kinetic energy; μ and μ_t are the dynamic molecular and turbulent viscosities calculated from equations: $\mu = \frac{1.479 \times 10^{-6} T^{1.5}}{(T + 116.275)}$, $\mu_t = C_\mu \rho k^2 / \varepsilon$; Pr, Sc, Pr_t and Sc_t are the molecular and turbulent Prandtl and Schmidt numbers; σ_k, σ_ε,, C_μ,, $C\varepsilon_1$, $C\varepsilon_2$, $C\varepsilon_3$ are the empirical constants of turbulent model; g_i is the gravity acceleration component ($\vec{g} = (0,0,-g)$); $\bar{u}$ is the gas velocity vector having three velocity components u_1, u_2, u_3; A_s is the specific wetted area of fuel bed ($A_s = \phi_s\ \sigma_s$); σ_s is the surface-area-to-volume ratio of solid particle; C_d is a particle drag coefficient ($C_d = 24(1+0.15\ Re_{es}^{0.687})/\ Re_{es}$, Re_{es}<800) depending on the effective particle Reynolds number, $Re_{es} = \rho \mid \bar{u} \mid d_{es}/\mu$,which is calculated using the equivalent spherical particle diameter, $d_{es}=6/\sigma_s$; h_s is the particle heat transfer coefficient ($h_s = \lambda Nu_s / d_s$) depending on the heat conductivity of gas, λ, particle Nusselt number, Nu_s , and equivalent diameter of cylindrical particle, $d_s=4/\sigma_s$; Nu_s is a function of particle Reynolds number, $Re_s = \rho \mid \bar{u} \mid d_s/\mu$: $Nu_s = 0.683 \mathrm{Re}_s^{0.466}$; q_5 is the heat release rate of gas phase combustion of carbon monoxide (q_5=1.E+7 J/kg); σ is the Stephan-Boltzman constant; T_S is the absolute temperature of solid phase; T_3 is the 'radiosity temperature' defined as $(R_I/(4\sigma))^{1/4}$,where R_I is the incident radiation (Wm^{-2}); ε_1 is the absorption coefficient of gas phase; P_k, W_k are the turbulent production terms; R_{RNG} is an additional term proposed in the RNG k-ε model ($R_{RNG} = 0$ in k-ε model). The mass rates $\dot{m}$, m_5 , m_{51} and m_{52} are defined as (see Grishin 1997 and Porterie *et al.* 2000)

$$\dot{m} = (1-\alpha_c)R_1 + R_2 + \frac{M_C}{M_1}R_3,\ m_5 = \frac{4\rho\varepsilon}{k}\min(c_2, \frac{c_1}{0.5}),\ m_{51} = -\frac{1}{2}\frac{M_1}{M}m_5 - R_3 \quad (2)$$

$$m_{52} = \nu_g(1-\alpha_c)R_1 - m_5,\quad R_1 = k_1\rho_1\varphi_1 \exp(-E_1/RT_S),\ R_2 = k_2\rho_2\varphi_2 T_S^{-0.5}\exp(-E_2/RT_S)$$

$$R_3 = \frac{3}{8}k_3\rho\varphi_3\sigma_s c_1 \exp(-E_3/RT_S)$$

Here M, M_1 and M_C are the molecular weights of gas mixture, oxygen and carbon; α_c and ν_g are the coke number and the fraction of combustible gaseous products of pyrolysis defined by Grishin *et al.* 1986 and Grishin 1997 (α_c = 0.06, ν_g = 0.7); R_1 , R_2 and R_3 are the mass rates of chemical reactions (pyrolysis, evaporation and char combustion) approximated by Arrhenius laws whose parameters, i.e. pre-exponential constants k_i and activation energies E_i, are available from Grishin *et al.* (1986) and Porterie *et al*. 2000: k_1 = 3.63E+4 s^{-1}, k_2 = 6.E+5 $K^{1/2}$ s^{-1}, k_3 = 430 ms^{-1}, E_1/R = 7250 K, E_2/R = 5800 K, E_3/R = 9000 K.
The rates of degradation of condensed phase are computed from the equations (Grishin 1997):

$$\rho_1\frac{\partial\varphi_1}{\partial t}=-R_1,\rho_2\frac{\partial\varphi_2}{\partial t}=-R_2,\rho_3\frac{\partial\varphi_3}{\partial t}=\alpha_C R_1-\frac{M_C}{M_1}R_3,\rho_4\frac{\partial\varphi_4}{\partial t}=0,\sum_{i=1}^{5}\varphi_i=1,\varphi_S=\sum_{i=1}^{4}\varphi_i. \quad (3)$$

As suggested by Grishin 1997 and Porterie *et al*. 2000, the solid particles are considered thermally thin and their temperature is computed from the following conservation equation:

$$\sum_{i=1}^{4}\rho_i C_{pi}\varphi_i\frac{\partial T_S}{\partial t}=-q_1R_1-q_2R_2+q_3R_3+4\varepsilon_2\sigma(T_3^4-T_S^4)+A_s h_s(T-T_S) \quad (4)$$

Here and above ρ_i, φ_i and C_{pi} are the density, volume fraction and specific heat of a phase component (1 – dry organic substance, 2 – liquid water, 3 – condensed products of pyrolysis, 4 – mineral component of fuel, 5 – gas phase); q_i are the heat release rates of chemical reactions. In this study, for i = 1, 2, 3 and 4, ρ_i = 680, 1000, 200 and 200 kgm^{-3}; C_{pi} = 2.0, 4.18, 0.9 and 1.0 $kJkg^{-1}K^{-1}$; q_1 = 418 Jkg^{-1} and q_3 = 1.2E+7 Jkg^{-1} as in Porterie *et al*. 2000 and q_2 = 3.E+6 Jkg^{-1} as in Grishin *et al.* (1986)). The initial volume fractions of condensed phase are calculated from equations (Grishin *et al.* (1986)):

$$\varphi_{1e}=\frac{\rho_0(1-\nu_{ash})}{\rho_1},\varphi_{2e}=\frac{W\rho_0(1-\nu_{ash})}{100\rho_2},\varphi_{3e}=0,\varphi_{4e}=\frac{\rho_0\nu_{ash}}{\rho_4} \quad (5)$$

Here, ρ_0 is the bulk density of fuel; ν_{ash} is the ashes content (ν_{ash} = 0.04); W is the fuel moisture content (%). In the first validation study (see next section), ρ_0 = 10 kgm^{-3}, W = 10%, and equations (5) result in the following initial values of φ_i: φ_{1e} = 0.014, φ_{2e} = 9.1E-4, φ_4 = 8.E-4.
The radiative transfer equation (RTE) is written with use of a PHOENICS variable, T_3:

$$\frac{\partial}{\partial x_i}\left(\lambda_3\frac{\partial T_3}{\partial x_i}\right)=4\varepsilon_1\sigma(T_3^4-T^4)+4\varepsilon_2\sigma(T_3^4-T_S^4);\ \lambda_3=4\sigma T_3^3/(0.75(\varepsilon_1+\varepsilon_2)+1/W_{gap}) \quad (6)$$

Here, ε_1 and ε_2 are the absorption coefficients of gas and solid phases; ε_1, which depends on gas temperature and mass fractions of products of gaseous combustion, was taken equal to a constant value of 0.1 for simplicity in this study; $\varepsilon_2 = \phi_s\sigma_s/4=\phi_s/d_s$ according to Porterie *et al.* 1998.
Equation (6) is a formulation similar to RTE in P1-approximation used by Porterie *et al.* 1998

with the only difference that an additional term, $1/W_{gap}$, is included as proposed in PHOENICS documentation on IMMERSOL radiation model (W_{gap} is the gap between the solid walls).

Results and Discussion

The model described in the previous section was validated in a case, which was studied experimentally by Mendes-Lopes JMS *et al.* 2003 and numerically by Porterie *et al.* 1998, 2000 and Menage *et al.* 2012. In this case, the fuel bed has the following input parameters (according to Porterie *et al.* 1998, 2000): a height of 5 cm, a fuel load value of 0.5 kg/m^2 , a needles density of 680 kg/m^3 , a bulk fuel density of 10 kg/m^3, an initial moisture content of 10% and a surface-area-to-volume ratio of needles of about 5511 m^{-1}. A 2.2 m x 1 m x 0.05 m fuel bed was considered within a 4.2 m x 1 m x 0.9 m domain (see Figure 1). For the sake of simplicity, a 2D formulation was applied by ignoring the gas flow and transport of mass and energy in x_2 direction. A computational grid of 190x40 cells was used based on grid sensitivity study. The ignition source was located at the beginning of fuel bed (at 1 m distance from the origin) and the ignition was simulated by introducing a volumetric heat source of 0.1 m length over the whole fuel bed width and height (its temperature was linearly increased from 700°K to 1000°K during the first 8 seconds of simulation). The three wind speeds of 1, 2 and 3 m/s were considered. The focus of our study was on the model capabilities to predict the fire rate of spread (ROS) measured by Mendes-Lopes JMS *et al.* 2003 and to reproduce the main flow patterns predicted numerically by Porterie *et al.* 1998, 2000. The ROS was calculated (in accordance with Porterie *et al.* 1998, 2000) as a speed of propagation of the isotherm T_s = 600°K (or 500°K) at the ground level. Figure 2 shows the transient propagation of pyrolysis front defined with use of isotherm T_s = 600°K for three wind speeds of 1, 2 and 3 m/s. The quasi-steady values of ROS defined as rates of change of front positions with time are 1.2, 2.5 and 4.3 cm/s respectively. These values are well compared with the experimental ROS values of Mendes-Lopes JMS *et al.* 2003 (measured at zero slope of bed): 1.04, 2.08 and 4.92 cm/s respectively.

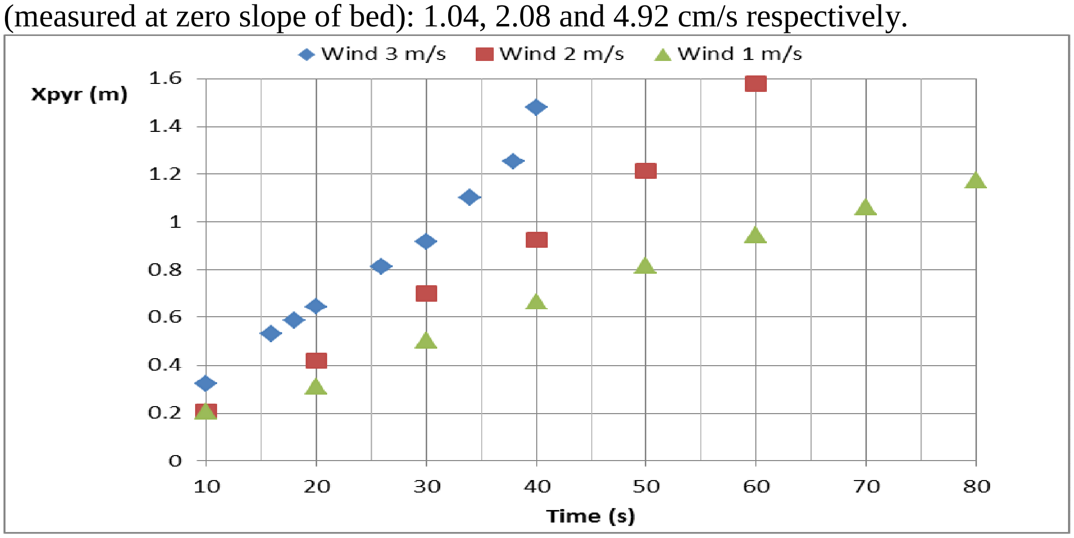

Figure 2. Pyrolysis front propagation for three wind speeds of 1, 2 and 3 m/s

Figure 3 shows the distributions of solid phase temperature, T_s, and mass fractions of oxygen (C1) and carbon monoxide (C2) (a gaseous product of pyrolysis) predicted for a wind speed of 1 m/s at x_3 = 0 m and t = 20 s. The fuel bed heating from propagating fire causes water evaporation, pyrolysis (between 400°K and 500°K) and char combustion (at about 700°K). The carbon monoxide, which is released during pyrolysis, participates in gaseous combustion and its mass fraction drops to zero. The oxygen mass fraction reduces in pyrolysis zone due to creation of CO in that zone and then it drops to zero within the combustion zone due to oxygen consumption.

Figure 4 shows the distributions of gas temperature and velocity predicted at t = 40 s for wind speeds of 1 and 2 m/s (top and bottom respectively). At a wind speed of 1 m/s, a large clockwise eddy is formed ahead of strong buoyant plume and the plume is oscillating with time. As wind speed increases from 1 to 2 m/s, a transition from buoyancy-dominated regime to wind-driven regime is observed and the plume becomes more stable. These flow patterns were also reported by Porterie *et al*. 2000.

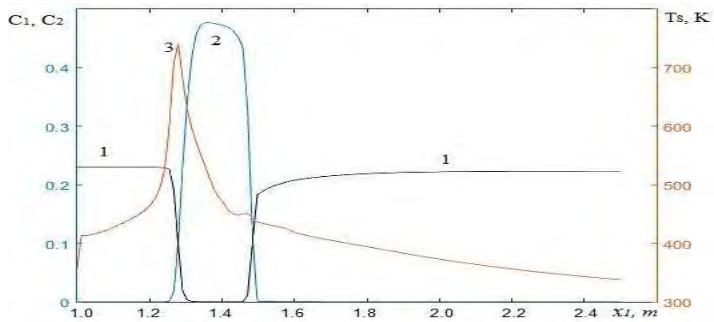

Figure 3. Solid phase temperature (3) and mass fractions of oxygen (1) and carbon monoxide (2) for wind speed of 1 m/s at t = 20 s

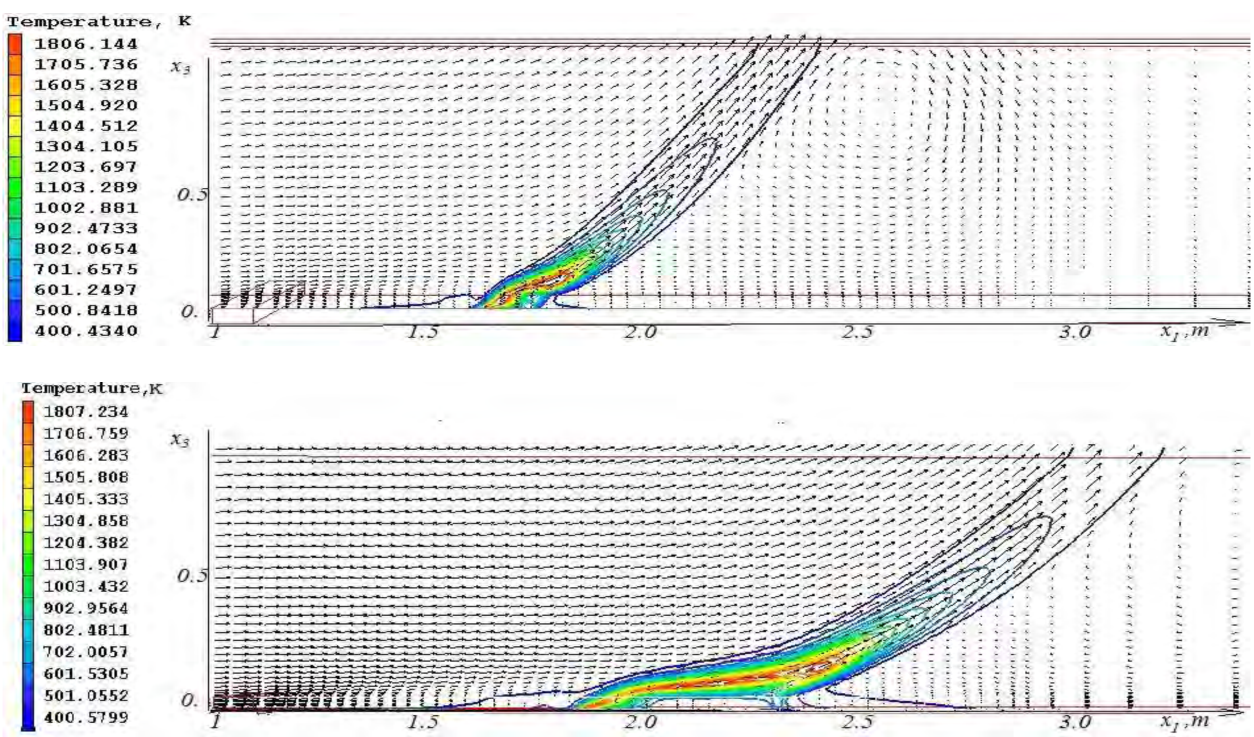

Figure 4. Gas temperature and velocity vectors at wind speeds of 1 m/s (top) and 2 m/s (bottom) at t = 40 sec

Conclusions

A multiphase CFD model of wildfire initiation and spread has been developed and incorporated into the multi-purpose CFD software, PHOENICS. The model accounts for all the important physical and physicochemical processes: drying, pyrolysis, char combustion, turbulent combustion of gaseous products of pyrolysis, exchange of mass, momentum and energy between gas and solid phase, turbulent gas flow and convective, conductive and radiative heat transfer. Turbulence is modeled by using the RNG k-ε model and the radiative heat transfer is approached with a model similar to P1-approximation. The Arrhenius-type kinetics is used for heterogeneous reactions (drying, pyrolysis and char combustion) and the eddy dissipation concept is applied for modeling the gaseous combustion. The model was validated using the experimental data of Mendes-Lopes *et al.* 2003 on surface fire propagation in a bed of *Pinus pinaster* needles studied in a wind tunnel. The predicted rate of spread (ROS) is well agreed with experimental values obtained at various wind speeds (from 1 to 3 m/s). The model is being further developed by modifying the radiative heat transfer model and it will be validated using the data on large forest fires including crown fires.

References

- Grishin AM (1997) 'Mathematical modeling of forest fires and new methods of fighting them.' (Ed. FA Albini) (Tomsk State University Publishing: Tomsk, Russia)
- Grishin AM, Zverev VG, Shevelev SV (1986) Steady-state propagation of top crown forest fires. *Combustion, Explosion and Shock Waves* **22**, 101-108.
- Magnussen BF, Hjertager BH (1976) On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion. *Proceedings of the Combustion Institute*, **17**, 719-729.
- Mell W, Jenkins MA, Gould J, Cheney Ph (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire* **16**, 1–22
- Menage D, Chetehauna K, Mell W (2012) Numerical simulations of fire spread in a *Pinus pinaster* needles fuel bed. *6th European Thermal Sciences Conference (Eurotherm 2012).*
- Mendes-Lopes JMC, Ventura JMP, Amaral JMP (2003) Flame cheracterisics, temperature-time curves, and rate of spread in fires propagating in a bed of *Pinus pinaster* needles. *International Journal of Wildland Fire* **12**, 67-84.
- Morvan D (2011) Physical phenomena and length scales governing the behaviour of wildfires: a case for physical modelling. *Fire Technology* **47** 437-460.
- Morvan D, Dupuy JL (2001) Modeling of fire spread through a forest fuel bed using a multiphase formulation. *Combustion and Flame* **127**, 1981-1994.
- PHOENICS On-Line Information System: www.cham.co.uk/ChmSupport/polis.php .
- Porterie B., Morvan D, Larini M, Loraud JC (1998) Wilfire propagation: a two-dimensional multiphase approach. *Combustion*, *Explosion and Shock Waves* **34**, 26-38.
- Porterie B., Morvan D, Larini M, Loraud JC (2000) Firespread through fuel beds: modeling .of wind-aided fires and induced hydrodynamics. *Physics of Fluids* **12**, 1762-1782.

New frontiers in fuel sampling:
Techniques for measuring surface fuel loadings for fire management in the US

Robert E. Keane
USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory,
5775 Highway 10 West, Missoula, Montana 59808. Phone: 406-329-4760, FAX: 406-329-4877.
Email: rkeane@fs.fed.us

Introduction

Measuring fuel properties in the field is the most accurate and consistent method for fire managers and researchers to collect the inputs needed for fuel description, and fire behavior and effects simulation (Keane 2015). Quantification of fuel properties is accomplished by field sampling; measuring fuel characteristics *in situ* to estimate fuel properties. And since there is a great diversity of fuel components, coupled with a large number of fuel characteristics, there are numerous sampling approaches and designs to estimate fuel properties at the particle, component, and fuelbed scale. Here, field sampling is a general term used to describe the wide range of approaches for measuring only one specific fuel property – loading or mass per unit area.

Operational sampling facilitates the planning, design, and eventual implementation of a fire management application. Often, management oriented sampling designs do not require the same degree of accuracy as research sampling, so they are often less intensive, not as costly, and easier to implement (Lutes et al. 2006). Management sampling efforts are designed to be applied across large areas by technicians with little to high levels of training in fuel sampling. This presentation is a summary of the latest surface fuel sampling technologies for management applications by both indirect and direct methods for all fuel components including litter, duff, fine woody debris (FWD; woody particles < 25 cm diameter) and coarse woody debris (CWD; woody particles greater than 25 cm diameter).

Indirect Fuel Sampling

These methods involve quantifying fuel loadings using techniques that don't directly involve measuring the fuel property, but rather, use other sources to quantify loadings. This usually involves subjectively assigning loadings by comparing with existing data (association), inspecting fuel conditions and visually comparing to reference conditions (visual), or correlating with remotely sensed imagery.

Associative Techniques

The most common associative technique involves **using existing data or information**, often collected by someone else from somewhere else, to estimate loading values for the area of concern or project area. Fuel loading data collected for another area, for example, may be associated to the area in question if the two areas are deemed similar, perhaps based on vegetation composition, disturbance histories, and biophysical site conditions. Catchpole and Wheeler (1992) call this approach the comparative yield method and mention it could be improved by using statistics, photos, and expertise to aid in the data assignment. The problem with this technique is that each site and project area is ecologically unique and the extrapolation of loadings from one site to another might ignore those important but subtle factors that influenced component loadings, such as differences in basal area, tree density, disturbance history, topographic setting, and stand structure. Another commonly used associative technique is to **assign fuel loadings to a sample area based on the sampled area's vegetation characteristics**. Many fuel classifications were built by summarizing plot-based fuel component loadings across categories in vegetation and related classifications such as structural stage, cover type, and potential vegetation type (Keane 2015).

Another associative method is **using mapped loading values** from readily available digital geospatial products as fuel loading estimates. The LANDFIRE National Project, for example, mapped four fuel classifications across the United States (Reeves et al. 2009) and many have used the loading values from these classifications to quantify loadings for a specific project area. This method, while inexpensive, quick, and easy, is not recommended until existing fuel maps are much improved. Locally created fuel maps may have sufficient quality, but regional and national maps should only be used for fuel analyses at broad scales, not at the project level. Depending on the resolution, fuel maps could still be useful for stratifying the sample area (or target population) into subunits to make sampling efforts more efficient.

Visual Techniques

Visual techniques involve assessing the loading of fuel components from ocular estimates. This level of resolution and accuracy may be acceptable for some fuel applications, such as describing fuels to other professionals. However, it is rare that anyone can accurately estimate loadings of all fuel components by eye, especially for FWD, duff, and litter.

Perhaps the most popular comparative visual technique is the **photo series**. Surface fuel loadings are ocularly estimated using a set of photos that present stand conditions for various vegetation types and site conditions. Photos were taken of representative fuel types in a particular geographical region, and then fuel component loadings were measured for the photo footprint and the summary of those loadings is reported next to the photo in the photo series publication. These photo series publications are taken to the field and the observed conditions in the field are visually matched to the best photo and the loading computed for the photographed stand are used for the loadings of the matched stand. Despite its huge popularity, the photo series has yet to be comprehensively evaluated across many vegetation types or environmental conditions. Sikkink and Keane (2008) found loading estimated using photo series approaches were often inaccurate and difficult to repeat across observers, albeit there were some limitations in the training of the crews. While photo series may give loading estimates to the resolution needed for management decisions, future uses of loading estimates, such as predicting smoke emissions and carbon inventories, may demand a more accurate and repeatable method of loading estimate.

The **new photoload method** uses calibrated, downward-looking photographs of known fuel loads for woody, shrub, and herbaceous fuels to compare with conditions in the field (Keane and Dickinson 2007a, b). These ocular estimates can then be adjusted for diameter, rot level, and fuelbed height. There are different photoload methods for logs, FWD, shrubs, and herbaceous material, but there are no photoload methods for measuring duff and litter loading. The photoload technique differs from photo series in that assessments are made by comparing field fuel conditions to smaller scale downward-pointing photographs of graduated fuel loadings. Photoload methods are much faster and easier than fixed-area and planar intercept techniques with comparable accuracies (Sikkink and Keane 2008), and they can be used in multi-stage sampling strategies where a fraction of the total plots are also destructively sampled and correlated to photoload samples to develop a means for correcting all photoload estimates (Keane et al. 2012b). However, Keane and Gray (2013) found the photoload technique requires extensive training to be used effectively; inexperienced users often could not consistently and accurately estimate high fuel loads.

Fuel classifications can also be used as a sampling method. In this technique, a fuel classification class is visually identified in the field, and the loadings assigned for that class are used as the sampled loadings. Fuel classifications that use vegetation to classify fuelbeds are probably the most uncertain, while classifications that contain dichotomous keys for identifying classes based on fuelbed properties, such as the FLM classification (Lutes et al. 2009b), are best for fuel assessment because they can be used by inexperienced crews to estimate fuel loadings with moderate accuracies (Keane et al. 2013).

Another visual method uses **fuel hazard assessments** across different fuel strata to obtain loading estimates for various components in the fuelbed. Originally developed by Gould et al. (2008) for Australia, this method involves making hazard assessments for the overstory and intermediate canopy layers, and then elevated, high, and low surface fuel layers. Each layer is given a score based on fuelbed attributes including percent canopy cover, presence of stringy bark, and suspended dead material. These scores are summarized and correlated to actual fuel loadings using statistical models (Gould et al. 2011).

One last visual technique involves using **cover-volume** methods to calculate loadings from visually estimated canopy cover and height. In this technique, canopy cover is estimated by eye for those components with small and variable fuel particles that are grouped together into one component, such as shrubs, herbs, and trees, and an estimate of measured or estimated height is also made in a fixed area sample unit for those components. Some fuel sampling packages, such as FIREMON (Lutes et al. 2006), describe how to estimate canopy cover and how to visually estimate height. Volumes of the assessed components (volume includes air pockets) are then calculated by multiplying the proportion cover (% cover divided by 100) by height (m) and sampling area (m^2). Loadings are then estimated by multiplying volume (m^{-3}) by bulk density estimates (kg m^{-3}) for the sample unit. Bulk densities for litter, duff, shrub, and herb components can be found in the literature (Brown 1981; Keane et al. 2012b) or estimated from a small proportion of the plots using destructive sampling.

Imagery Techniques

Imagery techniques involve using advanced statistical analysis to correlate fuel loadings to the digital signatures in the digital imagery. A potentially useful imagery technique is the quantification of fuel loads using image processing techniques or software. Years ago, Fahnestock (1971) calculated loading for several fuel components using a dot grid projected on color photographs of a cross-section of bayberry shrub fuel layer. Today there are sophisticated image processing approaches that use computer software. The stereoscopic vision technique (SVT), for example, involves taking stereoscopic photos of the fuelbed in the field then inputting the digital photos into computer-image recognition software to identify woody fuels and then compute loading volume (Arcos et al. 1998; Sandberg et al. 2001).

Another emerging technology is the use of ground based lidar to estimate fuel loads for some fuelbeds (Loudermilk et al. 2009). Here, a terrestrial scanning lidar (TSL) unit is mounted on a truck or some other vehicle to obtain scan distances for ground fuels at sub-cm scales. The lidar signal can then be related to loading by constructing statistical models where destructively sampled loadings for various components are correlated to the lidar imagery scan distances. It is sometimes difficult to differentiate between fuel components using TSL in heterogeneous fuelbeds but still possible. This technique may only be possible for research purposes in the near future because the TSL instrument is rather expensive (>$40,000), demands a high level of expertise to use and analyze, and it is also difficult to transport and use in complex terrain.

Direct Methods

These methods involve directly sampling or measuring characteristics of fuel particles to calculate loading. This usually involves direct contact with the fuel, such as measuring dimensions of particles using calipers, estimating depths of duff and litter using rulers, or collecting particles for drying and weighing in the lab.

Planar Intercept

Planar intercept (PI) techniques are the most commonly used sampling methods for sampling downed woody fuels for both management and research (Catchpole and Wheeler 1992; Dibble and Rees 2005) and both inventory and monitoring projects (Waddell 2001; Busing et al. 2000). PI sampling involves counting woody fuel particles by diameter size classes, or by directly measuring individual particle diameters, as they intercept a vertical sampling plane that is of a fixed length and height (Brown 1970, Brown 1974). These intercepts are then converted to loadings using standard formulae (Brown 1974). Advantages of the PI method are that it is easy to use and easy to teach (Lutes et al. 2009a; Lutes et al. 2006). Novice field technicians can be taught this method in a short time (1 hr) to achieve moderately repeatable measurements. The method can also be easily modified to adjust for local conditions, available expertise, and sampling conflicts, such as long plot times, scattered woody fuels, or slash. The sampling plane can be any size, shape, or orientation in space and samples can be taken anywhere within the limits set for the plane (Brown 1971). It also requires few specialized equipment; often a plastic ruler and cloth tape are the only gear needed.

However, there are some problems to the PI method. First, it only can be used for estimating downed dead woody loading; loadings for other fuel components, such as canopy fuels, litter, and duff, must be estimated with entirely different methods. This is problematic because the sampling unit for PI (transect) does not always scale to the fixed area plot methods used for other components or other forest and range inventories (Keane and Gray 2013). CWD transects, for example, are usually too long to fit within the area of standard plot sizes. PI sampling designs are also difficult to merge with other sampling designs because the PI was designed to sample entire stands, not fixed-area plots. PI methods also require a large number of transects under highly variable fuel conditions, which may be time- and cost-prohibitive for operational sampling efforts. Keane and Gray (2013) found that over 200 m of transect were needed on a 0.05 ha plot to sample FWD within 20% of the mean. Moreover, some feel that it is difficult to repeat particle intercept counts with any degree of reliability (Sikkink and Keane 2008).

Fixed area plots

In contrast to unequal probability strategies, such as, PI, fixed area plots (FAP) are based on equal probability sampling methods and have been adapted from vegetation composition and structure studies to sample fuels (Mueller-Dombois and Ellenberg 1974). In FAP sampling, a plot of any geometric shape, often round or square, is used as a sampling unit and all fuels within the plot boundary are measured using any number of fuel measurement methods including destructive collection, volumetric measurements, vertical depths of duff and litter layers, and particle counts by size class) (Keane et al. 2012b) . FAPs can be any size, and often the best sampling efforts scale the size of the FAP to the fuel being measured (e.g., small plots for FWD, large plots for CWD). Because FAP approaches require significant investments of time and money, they are more commonly used to answer research questions rather than to monitor or inventory fuels for management planning. However, new methods have been designed to use FAP in operational sampling projects (Keane and Gray 2013)

The FAP method may be a more ecologically appropriate method for obtaining accurate fuel loading estimates for many surface fuel components. FAP techniques tend to give a better representation of the actual variation observed in the field for surface fuel components (Keane and Gray 2013). FAP sizes and number can be adjusted to reduce sampling times but may result in reduced precision of fuel loading estimates. FAP size can also be adjusted to account for the spatial scaling of loading by fuel size. Larger fuels (CWD), for example, can be sampled with larger plots to fully account for spatial distributions in sample estimates. Moreover, FAP sampling is easily adapted or merged with other protocols commonly used to sample other fuel components or other ecosystem attributes. And last, it may be more practical to sample fuels using FAP methods because many fuel components can be linked together in the same sampling unit. The main limitation of the FAP sampling method is that there has yet to be a set of standardized operational FAP protocols for surface fuel sampling. Many fuels professional are unfamiliar with the FAP technique and don't have the knowledge and expertise to create their own FAP methods.

Distance sampling

Another new method is perpendicular distance sampling (PDS) which samples logs using probability proportional to volume concepts (Gove et al. 2012; Ducey et al. 2013; Williams and Gove 2003). With PDS, the total volume of the logs on a landscape can be estimated from counts of logs at various sample points. Loading can then be estimated by multiplying volume by particle density (kg m-3) estimates. PDS is named because a log is selected to the sample if a line from a sample point intersects the central axis of the log at a right angle and the length of this line is less than some limiting distance that changes along log length in a manner that is based on the sampling design. There are many variants of PDS including the distance-limited protocol for PDS, which uses a fixed distance from the perpendicular line to estimate volume then loading (Ducey et al. 2013). Transect relascope, point relascope, and prism sweep sampling use angle gauge theory to expand on the PDS and line-transect method for sampling coarse woody debris (Stahl 1998; Gove et al. 2005; Bebber and Thomas 2003). This method is most effective for measuring CWD (Gove et al. 2012), but Ducey et al. (2008) demonstrated PDS can be used to estimate other ecological attributes, perhaps finding a future use in FWD loading estimation.

Cover and volume sampling

An alternative to the above direct methods is applying the abundant methods that directly measure canopy cover in vegetation sampling efforts to fuel sampling, as opposed to visually estimating canopy cover as presented above. Canopy cover is directly measured using a suite of methods, techniques, and protocols for ecological inventories and research efforts (Krebs 1999; Mueller-Dombois and Ellenberg 1974), and some of these may potentially be applied to measuring fuel loading. Point sampling, for example, involves using a vertically placed rod of a small diameter to determine the particle that it contacts, and the number of contacts per particle type (i.e. fuel component) is then used to estimate cover. If applied to fuel sampling, the number of contacts can be correlated with the destructive sampling estimates of biomass. Measures of the height of each contact can be augmented with number of contacts to associate both cover and average height with loading (Catchpole and Wheeler 1992). The problem with cover methods for estimating loadings is that canopy cover, regardless of how it's measured, may be poorly correlated with fuel loadings (Catchpole and Wheeler 1992). Many of these cover methods provide repeatable estimates with low bias compared to visual techniques, but the use of cover methods to assess all fuel component loadings would not be recommended.

The volume method involves sampling the dimensions of a fuel particle or component to compute volume then multiplying volume by particle density or bulk density to get loading. An advantage of the volume method is that it can be used at particle, component, and fuelbed scale. Fuel component volume can indirectly calculated using the proportion measured cover (% cover divided by 100) and multiplying it by height (m), sampling area (m^2), and bulk density (kg m^{-3}). Hood and Wu (2006) used the cover-volume approach to calculate loadings of masticated fuelbeds. Fuel component or particle dimensions can also be measure to directly estimate volume. Litter loading, for example, can be estimated by (1) measuring litter depths within a 1 m^2 microplot, (2) computing an average depth (m), (3) multiplying by sample unit FAP area (1 m^2) to calculate volume, and (4) calculating loading by multiplying volume (m^3) by bulk density (kg m^{-3}) and dividing by area of microplot (m^2). Volume can also be used to estimate mass of a fuel particle by (1) measuring particle dimensions (length, width, and depth), (2) estimating a volume by multiplying length, width, and depth, and then (3) multiplying particle volume by particle density to get dry weight. Loading is then calculated by summing all particle dry weights over sample unit (FAP) area.

Destructive sampling

Destructive sampling involves removing fuel by clipping, collecting, drying, and weighing the material. An alternative is to (1) collect and weigh the wet fuel in the field; (2) subsample that fuel to dry and weigh to estimate a moisture content, and then (3) use the subsampled moisture content to adjust the wet field weight to dry weight. Destructive sampling can be scaled for any sampling design or objective. Fuel particles can be collected individually, as a group (shrub or tree), or on fixed area plots. Destructive sampling almost always involves subsampling a fuel component or fuelbed so statistical methods are often required to summarize subsampled estimates to describe the sampling area. Often, destructive sampling is used to create predictive biomass equations for a fuel component, such as a tree or shrub. This predictive equation can then be applied to inventory data to compute loading. Most destructive sampling is for research rather than operational management inventory and monitoring.

Integrated surface fuel sampling

Sampling projects are rarely designed using only one sampling approach or technique. The diversity of surface fuel components coupled with the constraints of limited resources always result in a project-level sampling designs that compromise statistical rigor to ensure success by integrating the above techniques and approaches. Conventional standardized surface fuel sampling protocols nearly always recommend using planar intercept techniques for woody fuel loading and volume approaches for litter, duff, shrub and herb (Lutes et al. 2006). The photoload approach has been augmented with planar intercept, fixed area log sampling, and volume estimates for duff and litter (Keane et al. 2012b). Catchpole and Wheeler (1992) mention a sampling technique called "double sampling" where destructive techniques are used on a subsample of fixed area plots to calibrate loading estimates from visual techniques. Keane et al. (2012b) used double sampling for another reason -- to adjust visual estimates using statistical regression. This melding of approaches, techniques, and intensities may aid in successful sampling designs, but the resultant loading estimates have different error distributions, variability, and usefulness for each fuel component.

References

Arcos A, Alvarado E, Sandberg DV Volume estimation of large woody debris with a stereoscopic vision technique. In: Proceedings: 13th Conference on Fire and Forest Meteorology, Lorne, Australia, 1998. International Association of Wildland Fire., pp 439-447

Bebber DP, Thomas SC (2003) Prism sweeps for coarse woody debris. Canadian Journal of Forest Research 33:1737-1743

Brown JK (1971) A planar intersect method for sampling fuel volume and surface area. Forest Science 17 (1):96-102

Brown JK (1974) Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report GTR-INT-16 Ogden, UT, USA 34 pp.

Brown JK (1978) Weight and density of crowns of Rocky Mountain conifers. United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station, Research Paper INT-197 Ogden, UT USA 56 pp.

Brown JK (1981) Bulk densities of nonuniform surface fuels and their application to fire modeling. Forest Science 27:667-683

Brown JK, Bevins CD (1986) Surface fuel loadings and predicted fire behavior for vegetation types in the northern Rocky Mountains. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-358 Ogden, UT USA 9 pp.

Brown JK, Oberheu RD, Johnston CM (1982) Handbook for inventoring surface fuels and biomass in the Interior West. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-129 Ogden, UT, USA 48 pp.

Busing R, Rimar K, Stolte KW, Stohlgren TJ, Waddell K (2000) Forest health monitoring. Vegetation pilot field methods guide.Vegetation diversity and structure down woody debris fuel loading. USDA Forest Service, National Forest Health Monitoring Program, Washington, D.C., USA 54 pp.

Catchpole WR, Wheeler CJ (1992) Estimating plant biomass: A review of techniques. Australian Journal of Ecology 17 (2):121-131.

Dibble AC, Rees CA (2005) Does the Lack of Reference Ecosystems Limit Our Science? A Case Study in Nonnnative Invasive Plants as Forest Fuels. Journal of Forestry 103 (7):329-338

Ducey MJ, Williams MS, Gove JH, Roberge S, Kenning RS (2013) Distance-limited perpendicular distance sampling for coarse woody debris: theory and field results. Forestry 86 (1):119-128.

Ducey MJ, Williams MS, Gove JH, Valentine HT (2008) Simultaneous unbiased estimates of multiple downed wood attributes in perpendicular distance sampling. Canadian Journal of Forest Research 38 (7):2044-2051

Fahnestock GR (1971) Weight of brushy forest fire fuels from photographs.Forest Science 17 (1):119-124

Fischer WC (1981) Photo guide for appraising downed woody fuels in Montana forests: Interior ponderosa pine, ponderosa pine-larch-Douglas-fir, larch-Douglas-fir, and Interior Douglas-fir cover types. USDA Forest Service, Intermountain Research Station, General Technical Report INT-197 Ogden, UT USA 133 pp.

Gould JS, Lachlan McCaw W, Phillip Cheney N (2011) Quantifying fine fuel dynamics and structure in dry eucalypt forest (Eucalyptus marginata) in Western Australia for fire management. Forest Ecology and Management 262 (3):531-546.

Gould JS, McCaw W, Cheney N, Ellis P, Matthews S (2008) Field Guide: Fire in Dry Eucalypt Forest: Fuel Assessment and Fire Behaviour Prediction in Dry Eucalypt Forest. CSIRO PUBLISHING, Canberra, ACT Australia 33 pp. ISBN: 0643102760

Gove JH, Ducey MJ, Valentine HT, Williams MS (2012) A distance limited method for sampling downed coarse woody debris. Forest Ecology and Management 282 (0):53-62.

Gove JH, Ducey MJ, Valentine HT, Williams MS (2013) A comprehensive comparison of perpendicular distance sampling methods for sampling downed coarse woody debris. Forestry 86 (1):129-143.

Gove JH, Williams MS, Stahl G, Ducey MJ (2005) Critical point relascope sampling for unbiased volume estimation of downed coarse woody debris. Forestry 78 (4):417-431

Hood S, Wu R (2006) Estimating fuel bed loadings in masticated areas. In: Andrews PL, Butler BW (eds) Fuels Management—How to Measure Success, Portland, Oregon USA, 2006. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41 pp 333-345

Keane RE (2015) 'Wildland fuel fundamentals and applications.' (Springer: New York)

Keane RE, Dickinson LJ (2007a) Development and evaluation of the photoload sampling technique. USDA Forest Service Rocky Mountain Research Station, Research Paper RMRS-RP-61CD Fort Collins, CO USA 44 pp.

Keane RE, Dickinson LJ (2007b) The Photoload sampling technique: estimating surface fuel loadings using downward looking photographs. USDA Forest Service Rocky Mountain Research Station, General Technical Report RMRS-GTR-190 Fort Collins, CO USA 44 pp.

Keane RE, Gray K (2013) Comparing three sampling techniques for estimating fine woody down dead biomass. International Journal of Wildland Fire 22 (8):1093-1107.

Keane RE, Gray K, Bacciu V (2012b) Spatial variability of wildland fuel characteristics in northern Rocky Mountain ecosystems. USDA Forest Service Rocky Mountain Research Station, Research Paper RMRS-RP-98 Fort Collins, Colorado USA. 58 pp.

Keane RE, Herynk JM, Toney C, Urbanski SP, Lutes DC, Ottmar RD (2013) Evaluating the performance and mapping of three fuel classification systems using Forest Inventory and Analysis surface fuel measurements. Forest Ecology and Management 305:248-263.

Krebs CJ (1999) Ecological Methodology. Second edn. Benjamin Cummings, New York, NY, USA

Loudermilk EL, Hiers JK, O'Brien JJ, Mitchell RJ, Singhania A, Fernandez JC, Cropper WP, Slatton KC (2009) Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. International Journal of Wildland Fire 18 (6):676-685. doi:http://dx.doi.org/10.1071/WF07138

Lutes DC, Benson NC, Keifer M, Caratti JF, Streetman SA (2009a) FFI: a software tool for ecological monitoring*. International Journal of Wildland Fire 18 (3):310-314.

Lutes DC, Keane RE, Caratti JF (2009b) A surface fuels classification for estimating fire effects. International Journal of Wildland Fire 18:802-814

Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC, Sutherland S, Gangi LJ (2006) FIREMON: Fire effects monitoring and inventory system. USDA Forest Service Rocky Mountain Research Station, General Technical Report RMRS-GTR-164-CD Fort Collins, CO USA 222 pp.

Mueller-Dombois D, Ellenberg H (1974) Aims and methods of vegetation ecology. John Wiley and Sons, New York, New York., USA 234 pp.
Reeves MC, Ryan KC, Rollins MC, Thompson TG (2009) Spatial fuel data products of the LANDFIRE project. International Journal of Wildland Fire 18:250-267
Reinhardt E, Scott J, Gray K, Keane R (2006b) Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. Canadian Journal of Forest Research 36 (11):2803-2814.
Sandberg DV, Ottmar RD, Cushon GH (2001) Characterizing fuels in the 21st century. International Journal of Wildland Fire 10:381-387
Sikkink PG, Keane RE (2008) A comparison of five sampling techniques to estimate surface fuel loading in montane forests. International Journal of Wildland Fire 17 (3):363-379.
Stahl G (1998) Transect relascope sampling - A method for the quantification of coarse woody debris. Forest Science 44:58-63
Waddell KL (2001) Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecological Indicators 1:139-153
Williams MS, Gove JH (2003) Perpendicular distance sampling: an alternative method for sampling downed coarse woody debris. Canadian Journal of Forestry Research 33:1564-1579

PREDICTIVE MODELING AND MAPPING OF WILDLAND FIRE IN LANSDOWNE CORRIDOR OF LESSER HIMALAYAS: A FUTURE PERSPECTIVE FOR TIGER CONSERVATION

Amit Kumar Verma,
Forest Research Institute (Deemed) University, Dehradun, Uttarakhand-248006, India
Email: amitvermafri@gmail.com

ABSTRACT

The present study deals with maximum entropy model (MaxEnt) of fire in Lansdowne corridor, which connects Rajaji Tiger reserve with Corbett Tiger reserve and facilitates movement of big cats and elephants in between these two protected areas of lesser Himalayas. Forest fires cause huge economic and ecological losses and release considerable quantities of carbon and is an important factor inflating the global burden of carbon emissions. Forest fire is impacting the behavioral as well as ecological traits of tigers (*Panthera tigris*) and making the habitat inhabitable. Moreover the post fire impacts are much more hazardous since the micro and macro habitat characteristics directly affect the tiger habitat. The most predominant impact is depletion in prey species which directly impacts the tiger by motivating them to move towards human habitations resulting in man-animal conflict in the form of livestock depredation and human attacks. The lack of early forest fire prediction system in the landscape is making man-animal conflict mitigation more challenging. Hence the present study was attempted to model the coverage of forest fire to make informed decision with respect to forest fire management.

Objectives and Methodology

We used Maximum Entropy (MaxEnt) ecological niche modeling framework to predict the potential areas under fire across the Lansdowne corridor and to identify key environmental variables associated with fire occurrence. We have used n=200 spatiotemporally independent fire incidence locations after auto-correlation testing in DivaGIS (Hijmans *et. al.*, 2002; Phillips *et. al.*, 2006; Pearson *et. al.*, 2007). The model was developed using fire occurrence points in the Lansdowne corridor, and 31 parameters including bioclimatic environmental, anthropogenic (distance to village, distance to road, distance to drainage, distance to Forest watch tower), topographic (slope, aspect, elevation), Forest type and Forest canopy density variables were used. All variable layers were resampled at 30m spatial resolution using the nearest neighbor re-sampling technique in ERDAS imagine 2013 and spatial multicollinearity

was tested using ENM Tools where the variables with $r > 0.7$ were dropped from the analysis (Warren *et. al*., 2010). The accuracy of the model was assessed using the area under the curve (AUC) of a receiver operating characteristic (ROC) plot and to assess the variables importance we adopted a jackknife procedure (Yang *et. al*., 2013). Hence, 100 model predictions were averaged to produce a probability map. Additionally, for demonstration of high and marginal fire area, all values above 0.6 were categorized as high fire and those between 0.2 and 0.6 as marginal fire areas.

Results

Out of total 22 independent variables selected only 12 variables contributed 96.9% towards predicting the occurrence of fire. The model performed well, with a low omission rate at 10% threshold ($p<0.0002$). Based on a 10% training presence logistic threshold, values below 0.2 were selected as no fire area. The model predicted that about 9.70 % (127.04 km^2) area falling under high fire followed by marginal fire 38.29 % (501.11 km^2) and about 52.00% (680.5 km^2) under no fire category. The results demonstrated that the dry deciduous forest having moderate canopy density and near to village were more impacted than other forest. Forest canopy density, Forest type, distance to village and elevation were highest contributors with 59.3%, 19.2%, 5.2%, and 1.9% respectively. The area under the curve (AUC) score was (0.844) for the training data from our model, which indicates a moderate to excellent predictive ability of the model.

Conclusions

The map resulted in the present modeling will be of great help in conservation plans and serve as a bench mark for collection of presence and absence data on forest fire. Forest canopy density and Forest type plays an important role in predicting the occurrence of fire, Our model output and previous field surveys revealed that the occurrence of fire in dry deciduous forest having moderate canopy density ranged up to 2000 m elevation. The high fire areas predicted in the study should be used prioritized for carrying out adaptive forest management to mitigate forest fire and conserve Tiger habitat in Lansdowne corridor. This study exemplifies the usefulness of prediction model of forest fire and offers a more effective way for management of forest fire. Overall this study depicts the model for conservation of tiger’s natural habitat and forest conservation by all means which is beneficial for both the wildlife and human beings for future prospective.

References

Hijmans, R. J., Guarino, L., and Rojas, E. (2002). DIVA-GIS, version 2. A geographic information system for the analysis of biodiversity data. *Manual*. International Potato Center, Lima, Peru.

Pearson, R.G., Raxworthy, C.J., Nakamura, M., and Peterson, A.T. (2007). Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeography*, **34**: 102–117.

Phillips, S.J.. Anderson, R.P., and Schapire, R.E. (2006). Maximum entropy modelling of species geographic distributions. *Ecological Modelling*, **190** (3-4): 231-259.

Semwal R.L. (2005). The Terai Arc Landscape in India, Securing Protected Areas in the Face of Global Change, Forests & Biodiversity Conservation Programme World Wide Fund for Nature-India, New Delhi

Warren, D.L., Glor, R.E, and Turelli, M. (2010). ENM Tools: a toolbox for comparative studies of environmental niche models. *Ecography*, **33**:607-611

Yang, X.Q., Kushwaha, S.P.S., Saran, S., Xu, J. and Roy, P. S. (2013). Maxent modeling for predicting the potential distribution of medicinal plant *Justicia adhatoda* L. in lesser Himalayan foothills. *Ecological Engineering*, **51**: 83–87.

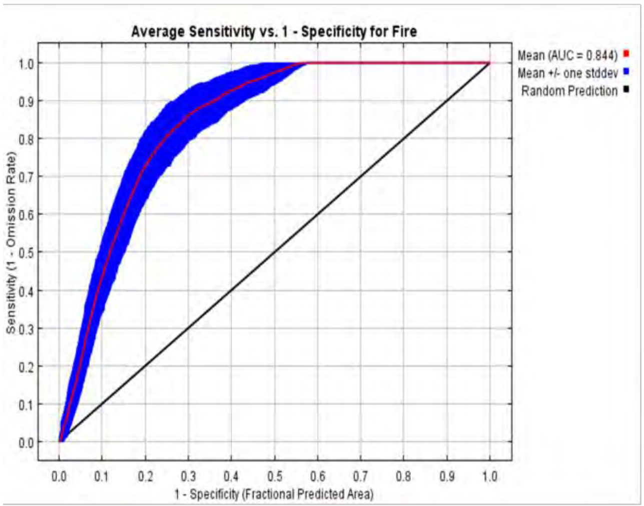

Figure 2 Sensitivity vs. 1-specificity for fire

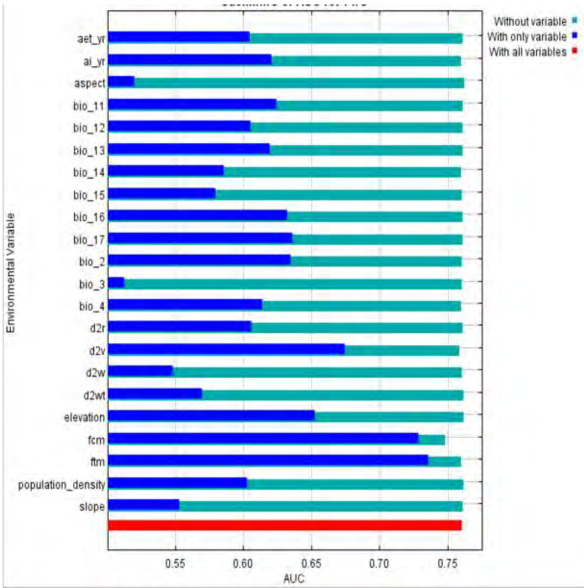

Figure 3 Jackknife of training set for fire

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Real-Time Smoke Monitoring Using Rapid Deploy Equipment to Aid in Fire Management and Ensure Public Safety

Mike Slate, P.E.
Field Operations Manager/ Principal 970-484-7941
Air Resource Specialists, Inc., Fort Collins, CO, USA, mslate@air-resource.com

Ricardo Cisneros, Ph. D. MPH
Air Resource Specialist 559-297-0706 ext. 4904
U. S. Forest Service, Clovis, CA USA, rcisneros@fs.fed.us

Introduction

The USDA-Forest Service Fire Management and Air Programs in Region 5 established the two-year Southern Sierra Pilot Project (SSPP) to evaluate available beta attenuation monitoring (BAM) instrumentation, monitoring methods, and practical quick-response management tools to communicate potential air pollution impacts from prescribed and wildland fire. The Forest Service contracted Air Resource Specialists, Inc. (ARS) to procure, integrate, test, and provide technical support of this equipment.

PM_{10} and $PM_{2.5}$ are the predominant pollutants in smoke emitted from wildland fires and can have severe health effects for firefighters and at-risk populations, especially those with chronic pulmonary and cardiac diseases (Sandberg et al., 18). Stationary Met One BAM-1020s and portable E-BAM particle instruments were used to monitor PM_{10} and $PM_{2.5}$ emissions for the SSPP. Met One's BAM-1020 beta attenuation mass monitor is a federal reference method that meets the EPA requirements for monitoring PM_{10} compliance, but can be limited in use by land management agencies due to a lack of portability and reliance on AC power. The E-BAM was developed as a smaller portable device that does not require environmental housing (heating or air conditioning), and can be supported with AC or solar power.

This study demonstrated that wildfire smoke concentrations can be effectively monitored with BAM particulate monitors in real-time with live data posted to a website. Access to real-time data has proven to be an advantageous tool for both fire managers and land managers by enabling them to effectively predict the spread and intensity of a fire and evaluate smoke exposure for firefighters and neighboring populations.

Materials and methods

Instrumentation and Site Specifications

The SSPP has been developed to test the utility, accuracy, reliability, monitoring, and data management requirements of BAM particulate monitors in a comprehensive network. The test network for this study included 3 BAM-1020 units deployed in particulate-sensitive communities to characterize baseline and event conditions, and approximately 10 portable E-BAM units deployed in rural locations to characterize the impacts of smoke events from prescribed burning and wildland fire. The SSPP site-network included 13 individual monitoring sites which can be seen on the map shown in Figure 1.

Each particle monitor site also included several meteorological parameters. Both the Kernville and Pinehurst BAM-1020 units were collocated with RAWS (Remote Automated Weather Station) instrumentation. All other sites (BAM-1020 and E-BAM) incorporated Met One meteorological instruments.

All units were equipped with ORBCOMM or Iridium satellite modems to deliver data in "near real-time" to the Interagency Smoke Monitoring Web site (http://app.airsis.com/USFS/). Each modem was equipped with a unique USFS identification tracking number. Individual site overviews by instrument type follow.

Figure 1: Southern Sierra Pilot Project Monitoring Locations

Figure 2: Pinehurst Monitoring Station

Figure 3: Camp Nelson Monitoring Station

The Kernville site contained one BAM-1020 and a collocated RAWS Meteorological Station. The site was located in the Sequoia National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #49.

The Pinehurst site contained one BAM-1020 and a collocated RAWS Meteorological Station. The site was located in the Sequoia National Forest. Figure 2 above shows the site configuration. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #50.

The Springville site contained one BAM-1020 with several Met One meteorological sensors, a 2B Technologies ozone analyzer, and an AUTOMET datalogger. The site was located in the Sequoia National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #51.

The Camp Nelson site contained one E-BAM with several meteorological sensors. The site was located in the Sequoia National Forest. Figure 3 above shows the site configuration. Data were configured to collect and post on the Smoke Monitoring Website under the ORBCOMM modem identification #45.

The Cedar Grove site contained one E-BAM with several meteorological sensors. The site was located in the Sequoia National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #55.

The Kennedy Meadows site contained one E-BAM with several meteorological sensors. The site was located in the Sequoia National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #47. The event-based unit was used to monitor $PM_{2.5}$ emissions from the Crag Wildland Fire Use, a prescribed burn in the surrounding area.

The Lakeside site contained one E-BAM with several meteorological sensors. The site was located in the Sierra National Forest at the Lakeside work center next to Hume Lake. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #55, to monitor a prescribed burn in the Hume Lake region.

The Porterville site contained two E-BAMs with several meteorological sensors. The site was located in the Sequoia National Forest headquarters parking lot in Porterville, California. The site configuration can be seen in Figure 4 below. Data were collected and posted on the Smoke Monitoring Web site under the ORBCOMM modem identification #46 and #47.

Figure 4: Porterville Monitoring Station

Figure 5: Trimmer Monitoring Station

The Sequoia Kings Canyon (or Hume Lake) site contained one E-BAM with several meteorological sensors. The site was located in the Sequoia National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #46 to monitor the Comb Fire Wildland Fire Use burn in the surrounding area

The Sequoia Lake site contained one E-BAM with several meteorological sensors. The site was located at Sequoia Lake in the Sequoia National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #55 to monitor the Grant E and Grant G prescribed fires in the surrounding area.

The Three Rivers site contained one E-BAM with several meteorological sensors. The site was located in the Sierra National Forest. Data were collected and posted on the Smoke Monitoring Web site under the ORBCOMM modem identification #55 to monitor the High Bridge prescribed burn in the surrounding area.

The Trimmer site contained one E-BAM with several meteorological sensors. The site was located in the Sierra National Forest. Data were collected and posted on the Smoke Monitoring Website under the ORBCOMM modem identification #52. The site configuration can be seen above in Figure 5.

The Tuolumne City site contained one E-BAM with several meteorological sensors. The site was located in the Stanislaus National Forest. Data were collected and posted on the Smoke Monitoring Web site under the ORBCOMM modem identification #48.

Routine Operations

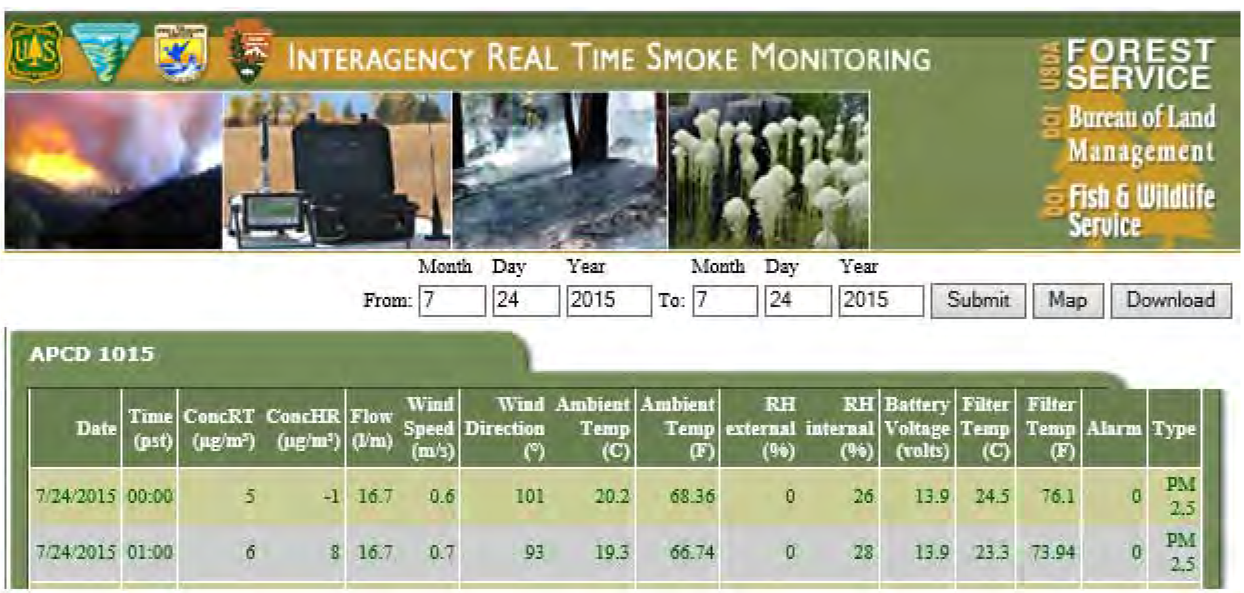
Each site operator received a BAM-1020 and/or E-BAM User's Guide which outlined instrument-specific, bi-weekly and monthly maintenance checks. Site operators were responsible for maintaining the instrument and reporting noted problems to ARS instrument specialist Mike Slate. Completed bi-weekly and monthly maintenance checklist sheets were sent to ARS after each site maintenance visit was completed. Semiannual (six-month) maintenance and calibration checks were performed by ARS field specialists.

Data Management, Validation and Reporting

Real-time data was collected via ORBCOMM satellite using an instrument-specific modem identification number. All particulate and meteorological data were transmitted hourly to the Interagency Smoke Monitoring Web server (located at Oceaneering headquarters in San Diego) and to Air Resource Specialist's Air Quality Data Base (AQDB).

Each business day, ARS' specialized team of data analysts verified that all data were received and identified operational problems or data inconsistencies. Preliminary data validation was performed monthly by data analysts. During both the preliminary and final validation processes, all data were screened for quality, consistency, and instrument-related malfunctions.

Weekly updates consisting of raw stack plots and brief operational timelines for all operational sites within the SSPP were routinely provided to the Region 5 Air Program Managers. Graphic and tabular data summaries of validated data for all operational sites were provided to Region 5 Air Program Managers on a monthly basis. Real-time data could be viewed at the Interagency Smoke Monitoring Website. An example of the detailed site data that can be obtained from the website is shown below in Figure 6. The website is maintained by Oceaneering of San Diego, CA. Questions about the website can be directed to Cole Morton at cmorton2@oceaneering.com



Date	Time (pst)	ConcRT (µg/m³)	ConcHR (µg/m³)	Flow (l/m)	Wind Speed (m/s)	Wind Direction (°)	Ambient Temp (C)	Ambient Temp (F)	RH external (%)	RH internal (%)	Battery Voltage (volts)	Filter Temp (C)	Filter Temp (F)	Alarm	Type
7/24/2015	00:00	5	-1	16.7	0.6	101	20.2	68.36	0	26	13.9	24.5	76.1	0	PM 2.5
7/24/2015	01:00	6	8	16.7	0.7	93	19.3	66.74	0	28	13.9	23.3	73.94	0	PM 2.5

Figure 6: Real-time data from the Interagency Real Time Smoke Monitoring website (http://app.airsis.com/USFS/)

Results

The use of BAM particulate monitors in conjunction with the Interagency Real Time Smoke Monitoring website was successful in providing up-to-date conditions of smoke concentrations and local meteorological conditions, such as wind speed and wind direction, during wildland fire events. This has helped to assist fire managers' ability to predict fire movement and intensity, allowing them to more efficiently make decisions regarding when and where to focus fire mitigation resources.

Smoke concentration data can be used to estimate long- and short-term smoke exposure to firefighters and support personnel; real-time access to this data can help determine shift changes or identify instances when personnel should be removed from a fire in order to prevent respiratory health issues. In addition, smoke concentration data has aided in estimating smoke exposure to residents in the vicinity of a wildfire or prescribed burn. In the case of a wildfire, it may provide the evidence needed to initiate the evacuation of communities in danger. In the case of prescribed burns, it can be used as evidence to prove that there is no smoke inhalation danger despite unfounded complaints of nearby residents. This evidence can allow burning to continue without the risk of lawsuits.

These systems can be deployed and operational by one person in 30 minutes or less. This allows the monitoring system to be moved quickly as conditions change so that monitoring can be conducted down-wind of the fire without danger of being consumed by the fire. Because they have low power requirements, systems are easily operated with solar panels and batteries, which optimizes their mobility and ease of setup. Monitoring is not restricted to places with line power.

The iridium satellite network allows data transmissions from anywhere on Earth in two minutes or less with no dish or antenna alignment necessary. This system ensures reliable communications in any location, regardless of access to cellular service, and can be set up by personnel without any communications experience.

Discussion

Since the study was conducted, other agencies and land managers have contracted ARS to design and construct similar systems. The National Park Service, the Bureau of Land Management, the U.S. Fish and Wildlife Service, Environment Canada, and multiple state governments and industrial clients have all purchased and successfully utilized similar systems.

The technology used to measure particulates continues to improve. Most recently, ARS has developed a portable system that utilizes a DustTrak DRX which allows simultaneous measurement of PM_{total}, PM_{10}, $PM_{respiratory}$, $PM_{2.5}$ and PM_{1}. Furthermore, the satellite communications supporting these systems continue to advance and decrease in cost.

Website design continues to improve and can be customized to meet the needs of the user. Website accessibility is versatile and can be made available to the public, password protected for internal use only, or can be accessed via smart phone.

References

Sandberg DV, Ottmar RD, Peterson JL, Core J (2002) 'Wildland fire in ecosystems: effects of fire on air.' USDA Forest Service, Rocky Mountain Research Station Research Paper RMRS-GTR-42. (Ogden, UT)

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Relationships between Firing Pattern, Fuel Consumption, and Turbulence and Energy Exchange during Prescribed Fires

Kenneth L. Clark*, Michael Gallagher
USDA Forest Service, Northern Research Station, Silas Little Experimental Forest,
New Lisbon, NJ 08064, USA, kennethclark@fs.fed.us, michaelgallagher@fs.fed.us

Warren E. Heilman
USDA Forest Service, Northern Research Station, Eastern Area Modeling Consortium,
Lansing, MI 48910, USA, wheilman@fs.fed.us

Nicholas Skowronski
USDA Forest Service, Northern Research Station, Carbon, Fire, and Climate Sciences,
Morgantown, WV 26505, USA, nskowronski@fs.fed.us

Eric Mueller
University of Edinburgh, Institute for Infrastructure and Environment, BRE Centre for Fire
Safety Engineering, Edinburgh, UK, e.mueller@ed.ac.uk

Albert Simeoni
Exponent, Inc., Natick, MA 01760, USA, asimeoni@exponent.com

Introduction

Fuel loading and consumption during prescribed fires are well-characterized for many pine-dominated forests, but relationships between firing practices, consumption of specific fuel components, and above-canopy turbulence and energy exchange have received less attention (Ottmar et al. 2016, Clements et al. 2016). However, quantitative information on how firing patterns and the resultant fire behavior control the consumption of surface, understory and canopy fuels is important for "fine tuning" the effectiveness of fuel reduction treatments while simultaneously minimizing the adverse impacts of ember transport and smoke dispersion on local air quality. To better understand these relationships, we estimated fuel consumption using pre- and post-burn destructive sampling to quantify surface and understory fuels and LiDAR data to quantify canopy fuels, and measured turbulence and energy exchange from a network of above-canopy towers using sonic anemometers and meteorological sensors during eight prescribed fires ranging in intensity from low-intensity backing fires to high-intensity head fires in the New Jersey Pinelands. In two stands with relatively low surface and understory fuel loading, a backing and an attempted head fire were ignited, respectively. In the remaining six stands with relatively high surface and understory fuel loading, three backing and three head fires were ignited. We then explored the relationships between firing practice and the resultant fire behavior, consumption of surface, understory and canopy fuels, and above-canopy heating and turbulence.

Materials and methods

Fuel loading and consumption in each stand were estimated from pre- and post-burn sampling in 1 m^2 plots (n = 10 to 32 per stand). Forest floor samples (L horizon only) were dried at 70 ºC, separated into 1-hr fine, 1-hr wood and 10-hr wood, and weighed. Shrubs, seedlings and saplings < 2 m tall were separated into foliage, 1-hr stems and 10-hr stems, and dried and weighed. Canopy fuel loading and consumption were estimated from pre- and post-burn LiDAR acquisitions, calibrated for pitch pine canopies (Skowronski et al. 2011, Clark et al. 2013). One to three above-canopy flux towers were located in each stand to be burned, and one to three control towers were located in the adjacent burn block and/or in similar forests in the Pinelands. All towers were instrumented with one to three sonic anemometers (RM Young model 81000V, Traverse City, MI, USA) and fine wire thermocouples (Omega Engineering, Inc., Stamford, CT, USA). Turbulent kinetic energy was calculated for 1-minute intervals, and values were not corrected for the effects of the fire (i.e., we did not use a pre-fire or control values as 1-minute means to calculate horizontal and vertical wind velocity deviations). Delta values between maximum sonic temperatures and TKE values were calculated for control towers versus the towers in burn blocks. In addition to sonic anemometers and thermocouples, control towers were instrumented with standard meteorological sensors (air temperature, relative humidity, wind speed and direction) 4 meters above canopy and at 2 meters within the canopy, and 10-hr fuel moisture and temperature, soil temperature and soil heat flux sensors (Clark et al. 2012, Heilman et al. 2015). All prescribed burns were conducted within a fairly narrow range of conditions, with ambient air temperature between 0.9 ± 0.9 and 16.7 ± 1.7 °C, relative humidity between 20.2 ± 1.1 and 38.6 ± 3.6 %, and wind speeds between 1.5 ± 0.3 and 4.3 ± 0.6 m s^{-1} (mean ± 1 SD; Table 1).

Table 1. Forest type, surface and understory fuel loading, and consumption estimated from pre- and post-burn sampling, meteorological conditions during the burn, and predominant fire behavior for eight prescribed burns in the New Jersey Pinelands.

Forest type	Fuels[a] (tons ha^{-1}) Pre-burn	Consumed	Meteorological conditions Air (ºC)	RH (%)	Wind (m sec^{-1})	Fire behavior
Low fuel loading						
1. Pine oak	11.0 ± 2.5	5.1	5.8 ± 1.4	21.6 ± 2.2	2.2 ± 0.3	Backing fire
2. Pine scrub oak	9.7 ± 2.4	4.7	3.7 ± 0.9	20.2 ± 1.1	2.7 ± 0.4	Attempted head fire
Low intensity burns						
3. Pine oak	16.1 ± 5.2	8.0	0.9 ± 0.9	31.1 ± 3.0	3.0 ± 3.0	Backing fire
4. Pine scrub oak	21.4 ± 3.5	10.2	9.0 ± 1.3	34.9 ± 7.1	2.2 ± 0.4	Backing fire
5. Pine scrub oak	15.7 ± 5.8	9.9	7.2 ± 1.2	34.3 ± 2.0	4.3 ± 0.6	Backing fire
High intensity burns						
6. Pine oak	14.8 ± 3.9	6.9	8.6 ± 1.9	37.1 ± 8.4	2.1 ± 0.6	Flanking fire, torching
7. Pine scrub oak	15.5 ± 3.8	10.4	7.6 ± 1.0	38.6 ± 3.6	1.5 ± 0.3	Head fire, torching
8. Pine scrub oak	17.0 ± 3.1	11.6	16.7 ± 1.1	33.1 ± 4.5	2.9 ± 0.4	Head fire, torching

[a]Sum of forest floor and understory fuels loading and consumption estimated from 1 m^2 plots.

Results and Discussion

Surface and understory fuel loading and consumption followed the order fine fuels on the forest floor > understory vegetation > 1 + 10-hr wood on the forest floor in all stands. Consumption of fine, 1 + 10-hr wood, and understory fuels were all strong functions of initial loading, with a trend towards greater proportional consumption of understory vegetation with increasing fire intensity (Fig. 1). Torching and significant canopy fuel consumption occurred only during the three head fires. The strong relationship between loading of specific fuels and consumption is similar to results obtained from a landscape-scale census of 35 prescribed burns across upland forest types in the Pinelands which represented a wider range of initial fuel loading and consumption estimates (Clark et al. 2015).

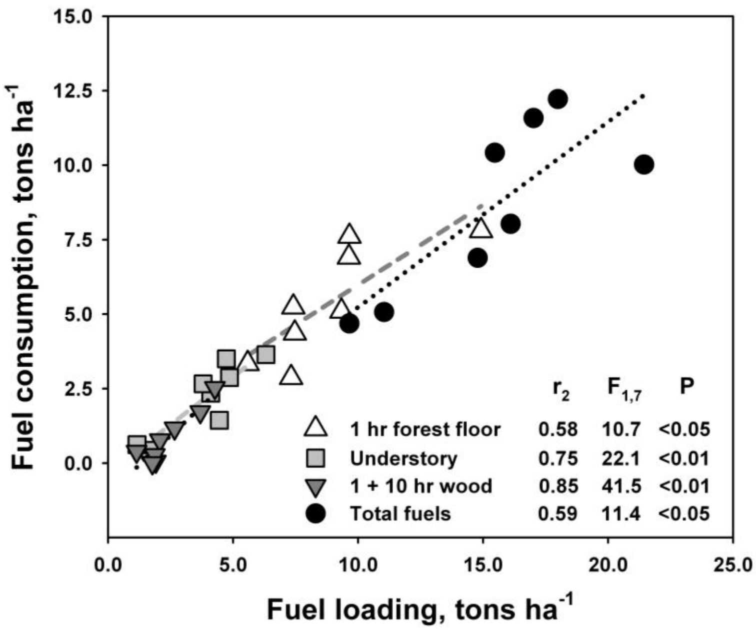

Figure 1. Surface and understory fuel loading and consumption estimated from 1.0 m^2 plots (n=10 to 32 in each burn) during eight prescribed burns in the New Jersey Pinelands.

10 Hz vertical wind speed, 10 Hz air temperature, and turbulent kinetic energy (TKE; m^{-2} s^{-2}) measured above-canopy from towers during low-intensity backing fires were enhanced up to 1.1, 4.8 and 1.1 times over values at control towers. During high-intensity fires, values were enhanced up to 4.3, 13.8, and 5.6 times over those at control towers, respectively (Fig. 2, Table 2). Maximum values for above-canopy 10 Hz vertical wind speed, 10 Hz air temperature, and TKE in head fires were 9.4 m s^{-1}, > 142 °C, and 9.7 m^2 s^{-2}. There was a significant relationship between peak Δ air temperature and peak Δ TKE during fires (Figure 3; $r^2 = 0.56$, $F_{1,7} = 10.0$, $P < 0.05$). Surprisingly, other relationships were much weaker; total fuel (surface + understory + canopy) consumption was only weakly related to maximum Δ temperature above the canopy during fires ($r^2 = 0.25$, $F_{1,7} = 3.4$, P = NS), and the relationship between total fuel consumption and Δ TKE during fires was especially weak ($r^2 = 0.10$, $F_{1,7} = 1.8$, P = NS).

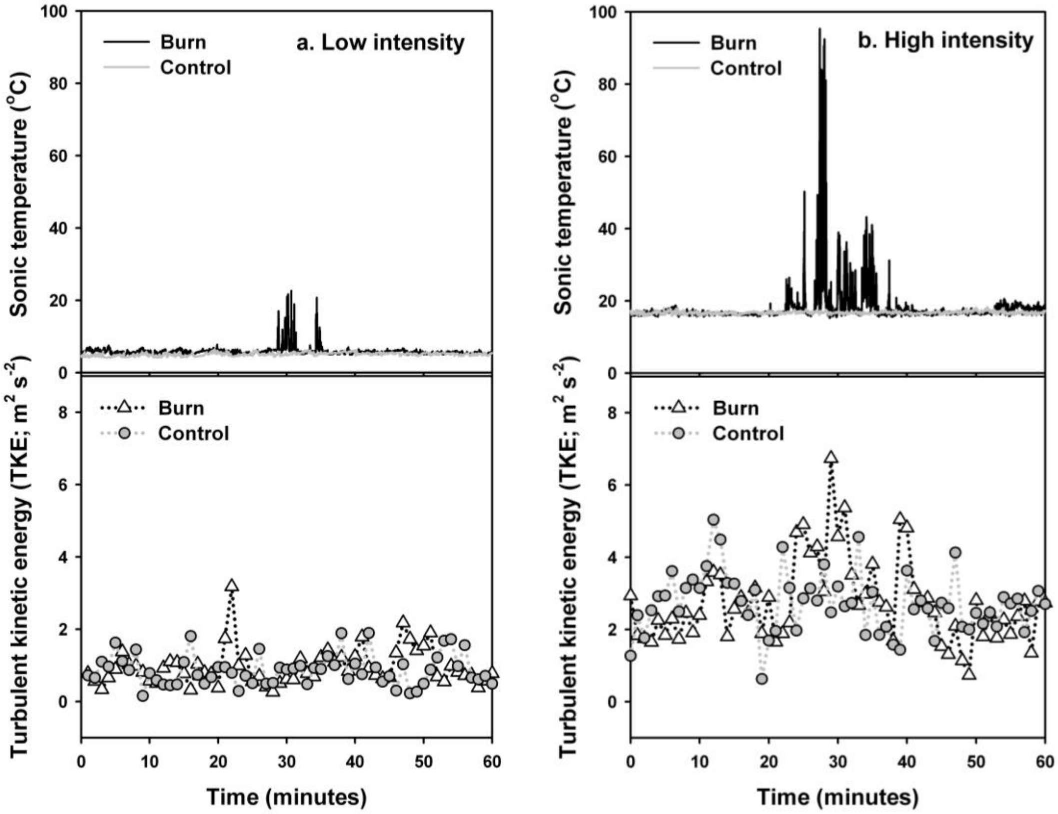

Figure 2. Above-canopy air temperature (°C) and turbulent kinetic energy (TKE; $m^2\ s^{-2}$) measured using sonic anemometers in burned and control stands during prescribed burns in (a) a pine – oak stand with low fuel loading burned in 2012 (stand #1 in Tables 1 and 2), and (b) a pitch pine-scrub oak stand burned in a head fire in 2014 (stand #8 in Tables 1 and 2). Sonic temperature and 3-D wind speed data were measured at 10 Hz. Sonic temperature data were then integrated to 1-second averages, and TKE values are 1-minute averages.

Table 2. Forest type, maximum 1-second vertical wind speed (w; $m\ s^{-1}$), maximum above-canopy 1-second sonic air temperature (ºC), and turbulent kinetic energy above the canopy in burned and control stands for eight prescribed burns in the New Jersey Pinelands. Values are means ± 1 SD. Maximum 10 Hz values are shown in parentheses.

Forest type	Vertical wind speed ($m\ s^{-1}$)		Air temperature (ºC)		TKE ($m^2\ s^{-2}$)	
	Control	Burn	Control	Burn	Control	Burn
Low fuel loading						
1. Pine oak	1.9 ± 0.3	2.2 ± 0.3 (3.3)	6.5 ± 0.1	24.6 ± 7.4 (31.8)	3.27	3.17
2. Pine scrub oak	2.6 ± 0.9	3.6 ± 0.7 (5.9)	8.0 ± 0.1	57.3 ± 4.9 (67.6)	3.64	3.69
Low intensity burns						
3. Pine oak	2.7 ± 0.3	3.1 ± 0.3 (3.7)	2 .6 ± 0.1	31.2 ± 1.3 (32.3)	3.64	4.63
4. Pine scrub oak	2.9 ± 0.3	2.7 ± 0.6 (3.8)	10.8 ± 0.3	41.7 ± 2.5 (44.2)	3.06	2.77
5. Pine scrub oak	3.2 ± 0.5	4.1 ± 1.4 (5.8)	10.8 ± 0.2	31.7 ± 4.6 (51.5)	8.80	8.70
High intensity burns						
6. Pine oak	3.3 ± 0.3	5.3 ± 1.5 (8.3)	11.0 ± 0.1	99.7 ± 9.8 (121.0)	3.28	7.70
7. Pine scrub oak	1.5 ± 0.1	6.5 ± 2.3 (9.4)	9.9 ± 0.2	109.6 ± 54.7 (142.1)	1.74	9.72
8. Pine scrub oak	3.2 ± 0.5	5.4 ± 3.2 (9.0)	20.7 ± 0.1	122.3 ± 5.3 (127.3)	5.03	6.95

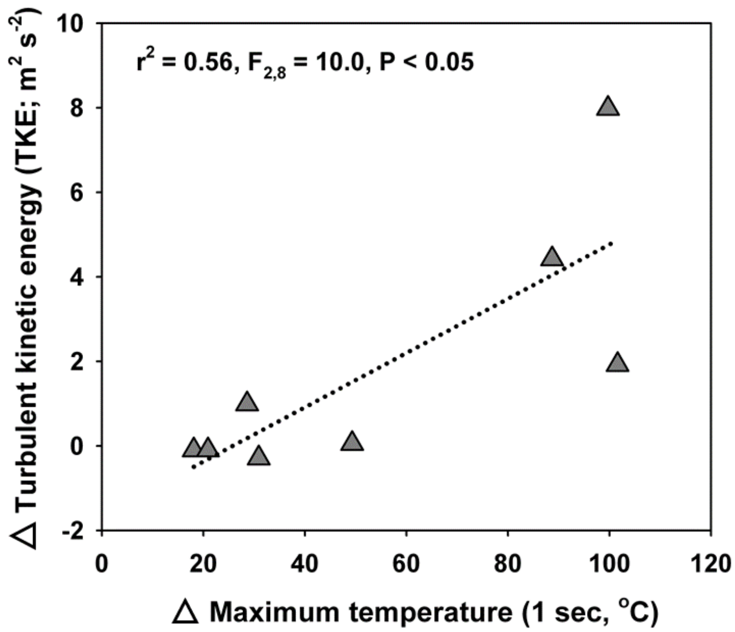

Figure 3. The relationship between maximum above-canopy Δ temperature and maximum Δ turbulent kinetic energy for the eight prescribed burns.

Our results indicate that low-intensity fires in the Pinelands can be highly effective at reducing fine and woody fuels on the forest floor, but are less effective at reducing understory vegetation and ladder fuels in the lower canopy. Residence time of low-intensity flame fronts on the forest floor was a key factor in their effectiveness in consuming surface fuels. Head fires resulted in much greater consumption of canopy fuels, but not necessarily greater consumption of surface fuels, and enhanced turbulent transfer of smoke and embers above the canopy. In some cases, high intensity fires are preferable for their ecological benefits, but are usually not feasible in WUI areas where ember management and fire-line control during hazardous fuel reduction treatments are also major objectives. These results can assist wildland fire managers assess tradeoffs between reducing hazardous fuels and mitigating emissions when planning and conducting prescribed fires. Our research also provides valuable information for the development and evaluation of next-generation fire behavior and smoke emission models.

Conclusions

Consumption of forest floor and understory fuels was strongly correlated with initial loading, and was less affected by firing practice (backing vs. head fires). Longer residence times of flame fronts during low-intensity backing fires contributed to their effectiveness in reducing surface and understory story fuels. Consumption of ladder and canopy fuels only occurred during high intensity fires, but these are also associated with higher turbulence and greater potential for smoke dispersion and ember production. Our results can assist wildland fire managers optimize hazardous fuel reduction goals while minimizing adverse local air-quality impacts and ember production when planning and conducting prescribed fires.

References

Clark KL, Skowronski N, Gallagher M (2015) Fire management and carbon sequestration in Pine Barren forests. Journal of Sustainable Forestry **34**, 125-146,

Clark KL, Skowronski N, Gallagher M, Carlo N, Farrell M, Maghirang M (2013) Assessment of Canopy Fuel Loading Across a Heterogeneous Landscape Using LIDAR. Joint Fire Sciences Program, Project 10-1-02-14, Final Report, 47pp.

Clark KL, Skowronski N, Gallagher M, Renninger H, Schäfer K (2012) Effects of invasive insects and fire on forest energy exchange and evapotranspiration in the New Jersey pinelands. Agricultural and Forest Meteorology **166**, 50-61.

Clements CB, Lareau NP, Seto D, Contezac J, Davis B, Teske C, Zajkowski TJ, Hudak AT, Bright BC, Dickinson MB, Butler BW (2016) Fire weather conditions and fire–atmosphere interactions observed during low-intensity prescribed fires–RxCADRE 2012. International Journal of Wildland Fire **25**, 90-101.

Heilman WE, Clements CB, Seto D, Bian X, Clark KL, Skowronski NS, Hom JL (2015) Observations of fire-induced turbulence regimes during low-intensity wildland fires in forested environments: implications for smoke dispersion. Atmospheric Science Letters **16**, 453-60.

Ottmar RD, Hudak AT, Prichard SJ, Wright CS, Restaino JC, Kennedy MC, Vihnanek RE (2016) Pre-fire and post-fire surface fuel and cover measurements collected in the south-eastern United States for model evaluation and development–RxCADRE 2008, 2011 and 2012. International Journal of Wildland Fire **25**, **1**0-24.

Skowronski NS, Clark KL, Duveneck M, Hom J (2011) Three-dimensional canopy fuel loading predicted using upward and downward sensing LiDAR systems. Remote Sensing of Environment **115**, 703-714.

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Spatial Analysis of the Influence of Fire Severity on Forest Structure on the North Rim of Grand Canyon National Park

Valentijn Hoff*
National Center for Landscape Fire Analysis, Missoula, Montana, USA,
valentijn.hoff@firecenter.umt.edu

Eric Rowell
National Center for Landscape Fire Analysis, Missoula, Montana, USA,
eric.rowell@firecenter.umt.edu

Tim Wallace
National Center for Landscape Fire Analysis, Missoula, Montana, USA,
tim.wallace@firecenter.umt.edu

LLoyd Queen
National Center for Landscape Fire Analysis, Missoula, Montana, USA,
lloyd.queen@firecenter.umt.edu

Casey Teske
National Park Service, Grand Canyon National Park, Flagstaff, Arizona, USA,
casey_teske@nps.gov

Eric Gdula
National Park Service, Grand Canyon National Park, Flagstaff, Arizona, USA,
eric_gdula@nps.gov

Christopher Marks
National Park Service, Grand Canyon National Park, Flagstaff, Arizona, USA,
christopher_marks@nps.gov

Introduction

Fire is an important process in the forests on the North Rim of Grand Canyon National Park. Frequent lightning and an active fire management program have led to recent fire history that is restoring fire as a process and creating a resilient landscape. The North Rim is located on the Kaibab Plateau, where an elevation gradient and associated moisture gradient from the canyon rim to the top of the plateau (Halvorson 1972) result in a range of vegetation types. Ponderosa pine (Pinus Ponderosa) dominates the majority of the forest close to the canyon rim, with mixed conifer and spruce-fir forests occurring at higher elevations (Rasmussen 1941). Fire managers are working hard to restore a high frequency, low severity fire regime in the Ponderosa pine forests, by using both natural ignitions and prescribed fire. The mixed severity fires that occur at higher elevations typically have a lower fire return interval and a mosaic of various fire severities.

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

It is easy to imagine a strong relationship between fire severity and forest structure. We characterize forest structure as how biomass is distributed in a forest, both horizontally and vertically. Fire consumes biomass, the amount dependent the availability. A high severity fire will consume more biomass than a low severity fire and leave biomass in a different configuration than a low severity fire. Of course, forest structure is not the only factor influencing fire severity. Other factors that influence fire severity are topography, the condition of the fuels, weather events, and management techniques. A dry period leads to fuels that are more available, a high wind event causes different fire behavior and a burnout might temper fire behavior. These changes in fire behavior can lead to an increase or decrease in fire severity.

For this project, we investigated the influence of fire severity, time-since-fire, topography, and vegetation type on a resulting forest structure. We used fires that burned between 2000 and 2012. We used forest structure data derived from a 2012 lidar acquisition. Lidar has the capability to provide data to calculate several forest structure metrics, over a large area, using a consistent, objective methodology.

Fire managers would like fire to leave a mosaic of structure types that is resilient. This means it can vary over time and space, but the changes fall with a natural range of variability. The increase in size and number of patches that burned with a high severity is of particular concern to fire managers. High severity patches have increased in size and number (Hoff et al 2014), but only comprise less than 10% of the landscape. Comparing multiple entry high severity patches based on forest structure will help increase the understanding of how patches increase in size.

The goal of this project is to learn more about the role fire severity plays in the mosaic of forest structure found on the North Rim of Grand Canyon National Park.

Methods

Fire and GIS staff from Grand Canyon National Park provided the fire severity data with perimeters and differenced normalized burn ratio (dNBR) values for fires that burned since 2000. They also provided vegetation data including lifeforms, alliances, and associations, based on 2012 data. The aerial lidar data for the Kaibab Plateau was collected between August 25 and September 5, 2012. The lidar data has a nominal pulse density of 10 pulses/m^2, a greater than 50 percent side lap, and a scan angle within 14° of nadir.

We started with a data driven approach, where we only investigated the role of fire severity on lidar derived forest structure data. We then added vegetation data and time-since-fire data.
We processed the lidar point cloud using LAStools (Isenburg, 2011) to derive multiple canopy metric rasters at 20m cell size. Cliff areas around the rim of the canyon with drastic topography changes resulted in height artifacts, which we masked out of the final rasters. Further geoprocessing utilized ArcGIS 10.3 (ESRI, 2016). The lidar-derived metrics used in this study were elevation, slope, aspect, mean height of canopy, maximum height of canopy, canopy cover, canopy base height, standard deviation of canopy height, and surface roughness.

We classified points initially as either bare earth points or canopy points, with the canopy points' heights normalized to height above ground. Elevation data were rasterized into a digital

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

elevation model (DEM) from points classified as bare earth in the ground/canopy separation algorithm in LASTools. Elevations of the North Rim, minus the cliff edges ranged from 2178-2797m MSL. We calculated slope and aspect using the DEM, with slope as percent (range of 0-333%) and aspect denoted as a compass direction (0-360°), with the Spatial Analyst extension in ArcGIS. Mean height of canopy included all canopy points from above ground to the highest canopy point for each 20m pixel. Maximum height represents the highest point value for each 20m cell. We calculated canopy cover in LASTools as the number of canopy first returns divided by the number of all first returns. Canopy base height is defined here as the mean height minus one standard deviation of canopy points. Standard deviation of canopy height is calculated both from the ground and using only points above the fuel bed (>1.5m). Surface roughness is the standard deviation of canopy points within the surface fuel bed (<1.5m) and gives insight into the presence or lack of objects underneath the canopy. Surface roughness for the acquisition area ranged from 0-1.35m.

Secondary processing of canopy cover and standard deviation of height provided the structure classes. We developed structure classes for the North Rim of the Grand Canyon using methods after Rowell et al. 2006. Classes were defined using thresholds for canopy cover (<35%, 35-65%, and >65%) and breaks between standard deviation of the lidar canopy height model (STD <4.5 and >4.5). This method yielded six structure classes representative of the overstory canopy. Canopy cover characterizes the distribution of the canopy horizontally; standard deviation depicts distribution of the canopy vertically. The resulting six classes depict the landscape as either 1) Open/Even-age, 2) Open/Multi-strata, 3) Semi-closed/Even-age, 4) Semi-closed/Multi-strata, 5) Closed/Even-age, 6) Closed/Multi-strata.

Fire as a process is dependent on the availability of surface and ladder fuels that drive the flaming front across a landscape. Therefore, additional segmentation of the landscape was required to incorporate the influence of surface fuels. Using the surface roughness technique (Seielstad and Queen 2003), we define three surface roughness classes (<0.25, 0.25-0.5, and >0.5) which are representative of low grassy fuels, moderate height fuels with intermixed shrub and conifer regeneration, and tall shrubs and conifer regeneration. The combination of these metrics produced eighteen structure classes that are representative of the gradient of expected structure ranging from Ponderosa pine to mixed conifer landscapes.

Using the structure classification as a zonal mask, we conducted zonal statistics for dNBR and mean height on eight fires that occurred on the North Rim of GRCA over a period of nine years using spatial analyst in ArcGIS. Two fires, Outlet (2000) and Poplar (2004), which have a high proportion of high severity, burned through mixed conifer stands and the other seven fires are amalgamations of wildland, wildland fire use, and prescribed fire concentrated on the ponderosa pine dominated peninsulas that dominate lower elevations of the North Rim.

We used Random Forests (Breiman, 2001) to see how fire severity influenced the different structure variables. We used a Gini index to rank the influence of severity on each variable. We then plotted partial dependence plots for each variable to see the influence of severity independent from other variables.

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

Results

After analyzing each fire individually, we found that the area of forest covered by each individual fire has different metrics that are most influenced with a change in fire severity. As expected, spatial variables, such coordinates and elevation, are more important when splitting the results per fire. When we looked at the aggregate of all fire occurrences on the North Rim, the structure class, mean height and lifeform are the top three variables that explain differences in previous fire severity. The structure classes (Figure 1) that incorporate canopy cover, standard deviation and surface roughness performed better than any other variable. Yet each of these three variables did not perform very well when assessed individually. Partial dependence plots show influence of fire severity on a particular variable. The plot for the 18 structure classes shows classes with a larger shrub and regeneration component are more likely to occur after higher fire severity. Fire severity also influences the occurrence of vegetation lifeforms, with the deciduous shrub class increasing in area following high fire severity. A higher surface roughness follows higher fire severity. The lowest mean height and the lowest crown base height follow higher fire severity. The standard deviation of the height in the structure classes decreases following higher fire severity. The amount of high fire severity also increases with increase in elevation, which coincides with a change in vegetation types. Some spatial autocorrelation was expected and spatial variables can help explain the relationship between fire severity and the structure that follows. Because both forest structure and fire severity occur in spatial groups or patches, the coordinates and elevation values are usually more alike within fires than between fires.

The structure classification suggests that 67% of the landscape of the North Rim is in some state of dense even-aged or multi-stage forest. The predominance of multi-stage and high regeneration conditions appears to reside in higher elevation mixed-conifer stands. Dense multi-stage with little regeneration occurs on the peninsulas and lower plateau regions where fire occurs frequently. Dense and moderate even-aged stands with moderate and high regeneration are generally products of high severity fire, though they also potentially contain large areas of deciduous unburned forests, e.g. Aspen, as elevation increases.

On a per fire basis, fires along the peninsulas of the North Rim of the GRCA have mean dNBR values for each structure class that are consistent between fires. The highest variability dNBR is associated with structure classes that typically have had some portion of overstory removal from high severity fire. In cases where the overstory has been retained, there are generally lower dNBR values that are best exemplified by structure classes where there is moderate to high canopy closure and low stature surface fuels. For large high severity fires that sometimes result in a type conversion from mix conifer to shrubby fuels there is a clear trajectory of high dNBR values for the structure classes representing low shrubby and moderate regeneration structure. For both the Poplar and Outlet fires, these conditions represent a departure from expected normal behavior, in the lower elevation areas. Regression analysis between mean height and dNBR as a function of structure class demonstrates a moderate relationship ($r^2 = 0.50$) that in large high severity burns there is a wholesale reduction of canopy height for the Poplar and Outlet fires. For all other fires there is no correlation between canopy height and dNBR as these fires are generally involving surface fuels with marginal group torching and some small patches of high severity that represent small fractions of structure classes.

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

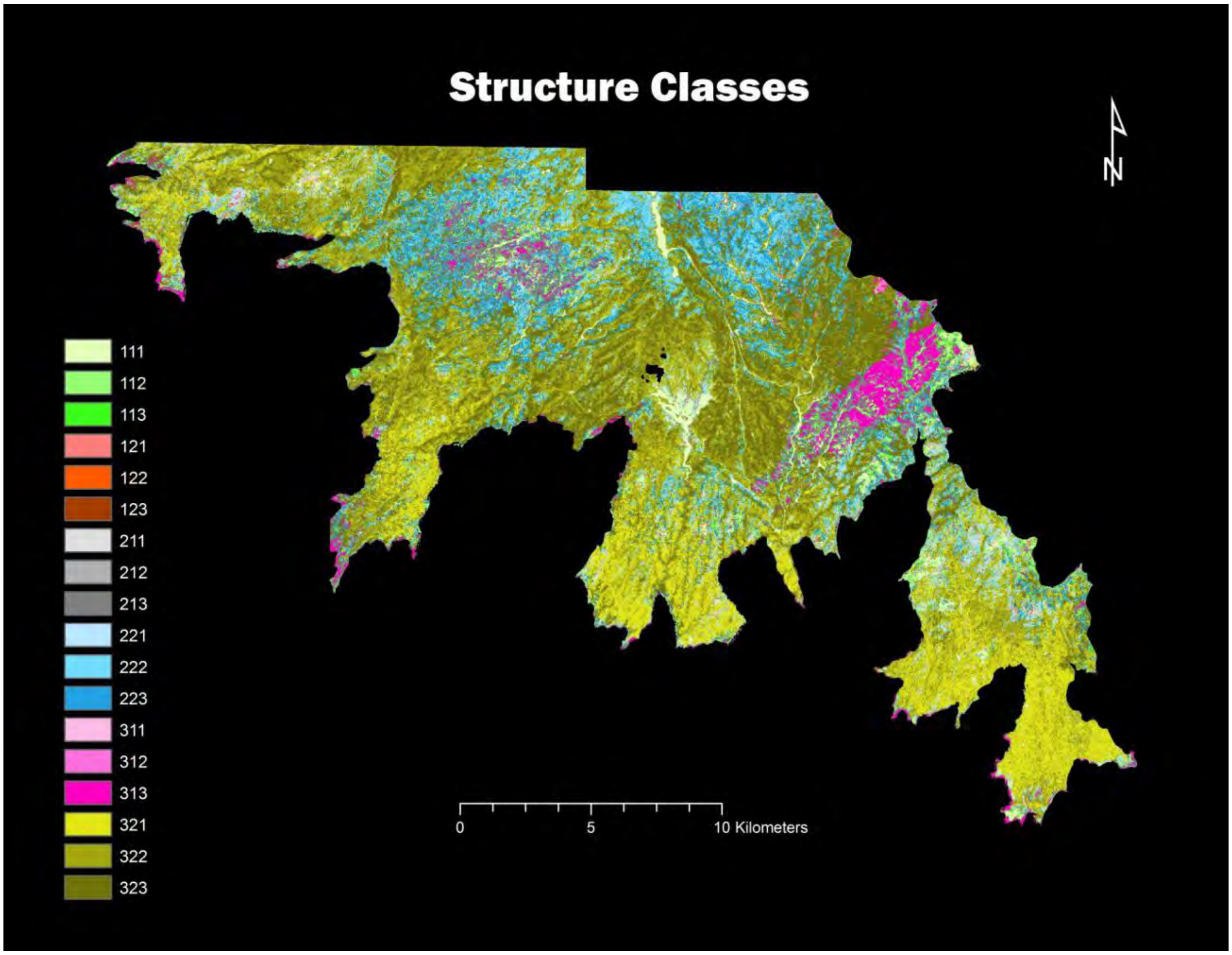

Figure 1: The spatial distribution of the structure classes as defined using canopy cover, standard deviation of the height and surface roughness. Note the structure classes in the 310 range (shades of pink) following high severity fire.

Discussion

Fire severity does have an effect on forest structure. A higher severity has a larger effect, but occurs only in a relatively small area on the North Rim. The structure classes that have higher vertical variability are more likely to follow a higher fire severity than other structure classes. This occurs more frequently in the mixed conifer forest and is less likely to happen in the more open Pondarosa pine forest on the lower elevation peninsulas. The repeated low intensity fires have created a structure that does not change much after each fire. Areas with a mean height of the canopy of less than 7m are likely to have experienced a high severity fire, where brush has become the dominant vegetation. A highly developed and parameterized variable, the 18-bin structure class, performed better than the next best variable; mean height. This shows that fire severity and forest structure have a complex relationship, with several structure variables changing based on fire severity. However, fire severity has a strong influence on this one simple metric, mean height. The low mean height following high severity fire, and the lack of change in mean height following low severity fire can aid in a quick assessment of forest structure without

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

looking into vertical and horizontal heterogeneity. This does reduce the effect of fire severity on forest structure to a binary effect; high severity often leaves a low canopy height and low severity does not affect canopy height. Low severity does affect surface roughness and canopy base height.

Our research has shown the influence of fire severity on forest structure, per the metrics that we defined. Future research will include a longer fire history to explore the influence of time-since-fire and the influence of multiple severities in-depth. Only a relatively small area of the North Rim has burned since the lidar acquisition. Fire severity influences forest structure and vice-versa, a future lidar acquisition will provide the opportunity to test predictions for the influence of forest structure on fire severity.

References

Breiman, L., 2001. Random forests. *Machine learning*, *45*(1), pp.5-32.

Environmental Systems Research Institute Incorporated (ESRI), (2015). ArcGIS Desktop 10.3

Halvorson, W.L. 1972. Environmental influence on the pattern of plant communities along the North Rim of Grand Canyon. American Midland Naturalist 87: 222-235.

Isenburg, M. LAStools - efficient tools for Lidar processing. © 2011 version 150701, http://lastools.org.

Hoff, V., Teske, C.C., Riddering, J.P., Queen, L.P., Gdula, E.G. and Bunn, W.A., 2014. Changes in severity distribution after subsequent fires on the North Rim of Grand Canyon National Park, Arizona, USA. *Fire Ecology*,*10*(2), pp.48-63.

Rasmussen, D.I., 1941. Biotic communities of Kaibab plateau, Arizona. *Ecological Monographs*, *11*(3), pp.230-275.

Rowell, E., Seielstad, C., Vierling, L., Queen, L. and Shepperd, W., 2006. Using laser altimetry-based segmentation to refine automated tree identification in managed forests of the Black Hills, South Dakota. *Photogrammetric Engineering & Remote Sensing*, *72*(12), pp.1379-1388.

Seielstad, C.A. and Queen, L.P., 2003. Using airborne laser altimetry to determine fuel models for estimating fire behavior. *Journal of Forestry*,*101*(4), pp.10-15.

*32 Campus Dr. 437 CHCB
Missoula, MT 59812
Valentijn.hoff@firecenter.umt.edu

Spatially weighted hedonic property models for homes vulnerable to wildfire

David Rossi*
Department of Forest and Rangeland Stewardship, Colorado State University
Fort Collins, Colorado, USA
djrossi@rams.colostate.edu

Anne Byrne
Department of Agricultural and Resource Economics, Colorado State University
Fort Collins, Colorado, USA
anne.byrne@colostate.edu

Introduction

Scenic amenities near forested landscape represent an environmental amenity accruing to nearby landowners which competes with the dis-amenity of possibly damaging wildfire. This research seeks to determine how the implied value of aesthetic amenities compare to the dis-amenity of wildfire risk factors in Boulder County, Colorado. This can be accomplished by careful examination of the implicit relationship between nearby forest attributes and observed willingness-to-pay for residential land in a wildland-urban interface/intermix (WUI). A spatially weighted hedonic property model is used to glean insight into the preferences homebuyers have for (a) wildland-urban areas with moderate to high levels of vegetation density in their neighborhood and (b) a property's exposure to recent wildfire activity.

Hedonic modeling in the WUI

Several studies have previously analyzed the risk preferences of residential landowners in fire-prone communities using hedonic property models. In a case study analysis in Los Alomos, New Mexico, Loomis (2004) found that residential landowners rationally update their perception of a property's risk following wildfire events. Kim and Wells (2005) are the first to specifically estimate the implied value of medium forest canopy closure in a hedonic property study of residential transactions in Flagstaff, Arizona. Their results suggest that medium levels of vegetation in a community jointly benefit landowners through aesthetic values and reductions in wildfire risk compared to levels of high vegetation density. Donovan et al. (2007) use spatially weighted hedonic property models to determine if residential landowners capitalize wildfire risk information into land prices across a WUI region in Colorado Springs, Colorado. Their models find that the availability of risk maps have a significant impact on residential land prices in the community. Specifically, residential landowners in the WUI update their perceptions of risk in light of this new information by subsequently placing a lower premium on homes with hazardous building material and a higher premium on homes with more fire-resistant characteristics.

Comparing the aesthetic amenity from the dis-amenity of wildfire risk factors in a hedonic model

The research presented here builds on the work of Huggett et al. (2008) who use a least squares model for Chelan County, Washington to obtain separate estimators for both the marginal value of aesthetic amenities in the WUI and the negative impact of wildfire risk factors. They note the importance of not using a single neighborhood variable to estimate the negative amenity of wildfires because the proximity to elevated fire activity and risk factors is correlated with desirable scenic amenities in the WUI. Failure to include a separate estimator for aesthetic amenities may skew conclusions regarding homeowner perception of wildfire risk factors.

This research extends the analysis to a case study in Boulder County, Colorado and presents a spatially weighted model to compare the marginal impacts of scenic vegetation in the WUI and less nearby fire activity on percentage changes in sales prices. A spatially weighted hedonic model is used here to correct for biased and inefficient estimators that typically accompany a spatial dataset under four alternative definitions of nearest neighbors. The applied hedonic model that follows uses a cross-sectional term to capture the added aesthetic value of homes in communities with varying levels of neighborhood vegetation and housing density. Specifically, this study compares the relative changes in values for residential land in interface and intermix development regions. The model also attempts to separately capture the negative change in value from exposure to wildfire risk factors by including the impact of recent wildfire activity in the proximity around each residential land transaction.

Materials

Geo-coded data on residential housing transactions are available from the Boulder County assessor's office. These data contain structural attributes of each property sold between 2008 and 2014. Sales prices are deflated using the mean home price index for Boulder County in the year 2010. Point data on wildfire activity are available through the U.S. Geological Survey (wildfire.cr.usgs.gov/firehistory/about.html). Centroids from all wildfire activity occurring within 1.75 miles in the five years prior to each transaction are counted and joined to the housing transaction data.

The spatial classification of the WUI and vegetation characteristics are collected by the SILVIS Lab at the University of Wisconsin (silvis.forest.wisc.edu/maps/wui). All parcels in Boulder County are divided into areas of non-WUI development, 'interface' development, or 'intermix' development (Radeloff et al., 2005). These vegetation characteristics and housing density information from the U.S. census are used in the model to capture preferences for open space and scenic amenities in the hedonic model.

All environmental characteristics are joined and merged with the geo-coded transaction data in ArcMap 10.3.1. Spatially weighted regression models are fit using the 'spdep' package in the R statistical programming language (Bivand et al., 2013; Bivand and Piras, 2015). A sample of the population data frame is needed to estimate spatial models with the available computing power. Summary statistics for the sample of 5000 transactions in Boulder County from 2008-2014 are given in Table 1.

Table 1 – Summary Statistics on sample of housing transactions (2008-2014)

	Mean	Median	St. Dev.	N
Inflation adjusted Sales Price	$199,280	$159,141	158384.7	5000
Age of the structure	30.24 years	27.00 years	21.7475	5000
Total Finished Square Footage of the property	1663 sq. ft.	1453 sq. ft.	805.9997	5000
Number of Bedrooms	3.173	3.0000	1.1054	5000
Number of Bathrooms	2.642	3.000	1.0839	5000
Housing Density of neighborhood	1253.297 houses per sq. km	937.634 houses per sq. km	1204.176	5000
Count of Recent Wildfire Activity Within 1.75 miles	0.1212 wildfires	0.0000 wildfires	0.8337	5000
Number of non-WUI Transactions: 2936 Number of Interface Transactions: 1753 Number of Intermix Transactions: 311				

Methods

Failure to account for a spatial lag structure of the dependent variable could yield inefficient estimates of marginal impacts in a least squares regression (LeSage and Pace, 2009). Biased parameters may also arise from the omission of important neighborhood variables, but could also arise from the exclusion of positive externalities like the positive impacts of desirable characteristics of neighboring properties on any given property (LeSage and Pace, 2009). These two issues drive the motivation for a spatial Durbin model.

An application of a semi-log spatial Durbin model is used to estimate the hedonic price function:

$$\ln P_{it} = \rho \mathbf{W} \ln P_{it} + \mathbf{X}\beta + \mathbf{WX}\gamma + \varepsilon_{it}$$

The dependent variable ($\ln P_{it}$) represents the natural log of sales price at each location i in year t. $\mathbf{W}$ represents an NxN row-standardized weights matrix. Specifications are tested using 5, 10, 15, and 20 nearest neighbors to check for differing results under alternative definitions of neighbors to each observation. Use of the spatial Durbin specification allows for a spatial autoregressive term (ρ) to capture the spatial dependency of the dependent variable. This allows the model to capture the impact of nearby sales prices on the impact of any one sales price. The model also addresses any concern over biased estimators as a lag term on the independent variables

(γ) corrects any spatial dependence of model errors. A spatial lag of independent variables allows the structural and environmental characteristics of neighboring observations to influence the sales price for observation i. β represents a Kx1 vector of population parameters describing the direct impacts of a property's characteristics for which the applied model will obtain estimates. The NxK design matrix, $\mathbf{X}$, contains the structural and neighborhood characteristics that are suspected to have an influence on sales prices. In this case, the independent variables are: age of the home, total finished square footage, number of bedrooms, number of bathrooms, housing density of the neighborhood, a cross-sectional term describing the vegetation density of the neighborhood, a trend variable (year), and the number of centroids from wildfire footprints that fall within 1.75 miles of a property 5 years prior to its transaction date.

Results

A common factor hypothesis test is conducted to determine if the estimated Spatial Durbin model with the lagged dependent and independent variables represents a significant improvement over a model which only captures the spatial error structure. Results of the Liklihood ratio tests and Wald tests indicate a Durbin specification better describes the data over a spatial error model and yields different estimates of impacts on land prices. Using alternative definitions of neighbors in the weights matrix ($\mathbf{W}$) only slightly changes the parameter estimates. Estimates of impact on changes in sales price differ from those obtained using a least squares regression, but not drastically different from those obtained from spatial error models which do not capture the spatial dependency of the dependent variable. The spatial autoregressive parameter on the dependent variable (ρ) and several of the average lagged impacts of the independent variables are statistically significant in the Durbin model. This implies that the spatially lagged parameters on the dependent and independent variables significantly improve the model fit. The Durbin model removes spatial dependencies which create inefficient estimates of marginal effects. Indirect impacts of the model are the average of impacts of the characteristics of nearest neighbors. Total impacts and fit statistics of the Durbin models under alternative definitions of neighboring observations are summarized in Table 2. Total impact estimates yield that a residential property experiencing a wildfire within 1.75 miles of a residential property in the five years prior to it's sales date sold for 1 to 1.75 percent less, on average. This impact, however, is insignificant in most specifications that were tested and insignificant in all specifications reported here. Estimates also indicate that direct impacts of living in a neighborhood with greater housing density are negative, while higher housing density of one's neighbors has a positive impact on emerging transactions prices. The total impact of housing density is negative and statistically significant. There appears to be an added premium placed on properties in the wildland-urban 'interface' relative to properties in the wildland-urban 'intermix', but these impacts are insignificant in most specifications. The model yields several interesting results regarding the comparison between desirable and undesirable amenities. For example, every 10 additional houses per square kilometer in a property's census tract will cancel out the percentage increase in sales price from an additional square foot. Depending on the preferred definition of nearest neighbors, it can also be calculated that approximately every 9 recent wildfires within 1.75 miles cancels out the percentage increase from living in the wildland-urban interface. Table 2 summarizes the model results.

Table 2 – Model Results

N =5000 Dependent variable: ln(SalesPrice)	Total impacts = Direct impacts + Indirect impacts of 5 nearest-neighbors' characteristics	Total impacts = Direct impacts + Indirect impacts of 10 nearest-neighbors' characteristics	Total impacts = Direct impacts + Indirect impacts of 15 nearest-neighbors' characteristics	Total impacts = Direct impacts + Indirect impacts of 20 nearest-neighbors' characteristics
(intercept)	-15.279 (8.9750)	-18.06 (11.6720)	-27.37 (14.0760)	21.11 (16.01)
Age of the home	0.00049 + 0.0017* (0.0003) (0.0004)	-0.0004 + 0.0018* (0.0003) (0.0004)	0.0003 + 0.0019* (0.0003) (0.0004)	0.0003 + 0.0018* (0.0003) (0.0005)
Total Finished Square Footage	0.00024* – 0.0001* (<0.00001) (<0.0001)	0.0003* – 0.0002* (<0.0001) (<0.0001)	0.0003* – 0.0002 (<0.0001) (<0.0001)	0.0003* – 0.0002 (<0.0001) (<0.0001)
Number of Bedrooms	0.0510* – 0.0577* (0.0057) (0.0097)	0.0600* – 0.0831* (0.0056) (0.0118)	0.0602* – 0.0920* (0.0057) (0.0133)	0.0613* – 0.0934 (0.0057) (0.0144)
Number of Bathrooms	0.0851* – 0.0152 (0.0067) (0.0117)	0.0808* – 0.0145 (0.0066) (0.0142)	0.0818* – 0.0153 (0.0066) (0.0170)	0.0838* – 0.0141 (0.0067) (0.0177)
Wildfire Count	0.0003 – 0.0177 (0.0078) (0.0088)	-0.0031 – 0.0144 (0.0076) (0.0091)	0.0047 – 0.0147 (0.0075) (0.0090)	0.0052 - 0.0141 (0.0074) (0.0090)
Housing Density of the neighborhood	-0.00007* + 0.00005* (<0.0000) (<0.0000)	-0.00009* + 0.00008* (<0.0001) (<0.0001)	-0.00009* + 0.00008* (<0.0001) (<0.0001)	-0.00009* + 0.00008 (<0.0001) (<0.0001)
Interface Dummy	0.0277 + 0.1327* (0.0403) (0.0414)	0.0598 + 0.0578 (0.0369) (0.0385)	0.0416 + 0.0619 (0.0075) (0.0435)	0.0189 + 0.0750* (0.0337) (0.0362)
Intermix Dummy	0.0391 + 0.0768 (0.0392) (0.0439)	0.0573 + 0.0004 (0.0366) (0.0429)	0.0311 + 0.0011 (0.0356) (0.0435)	0.0073 + 0.0070 (0.0350) (0.0460)
Year of Transaction	0.0199* – 0.0143 (0.0019) (0.0042)	0.0200* – 0.0090 (0.0019) (0.0056)	0.0200* – 0.0052 (0.0020) (0.0068)	0.0203* – 0.0088 (0.00219) (0.0078)
ρ: Log-Liklihood:	0.6446* -878.1291	0.7324* -777.5930	0.7707* -770.2087	0.7934* -791.8037

Note: Standard Errors for estimated parameters are given in parenthesis and "*" indicates significance at the 0.05 level

Discussion

This method for capturing landowner perceptions of fire risk counted nearby wildfire activity within 1.75 miles of each residential property sold within the sample to estimate the negative total impact of recent fire activity on percentage changes in sales prices. The negative total impacts of this wildfire risk factor indicates that homeowners experience a loss from both their own proximity to recent fires and their neighbor's exposure to recent fires. However these impacts are insignificant, which indicate that homeowners may not take this risk factor into account when purchasing residential properties. This could be due to the long-run nature of the chosen risk factor which yields a much smaller percentage decrease in subsequent sales prices than what is found in prior research. Incorporating only more recent wildfires may change the significance of the parameters of wildfire count. It may also be more insightful to isolate the impact of wildfire risk factor's only on homes in the WUI, rather than on homes in both WUI and non-WUI areas. The model considers the value of open space amenities through both the housing density of the neighborhood and the level of vegetation density in a neighborhood and found that interface properties are worth more on average than intermix properties (medium density of vegetation). These results are consistent with prior case studies which find that recent wildfires have a negative impact on land prices and that homeowners prefer medium levels of vegetation density over higher levels of vegetation density in their neighborhood.

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References

Bivand R, Piras G (2015) Comparing Implementations of Estimation Methods for Spatial Econometrics. *Journal of Statistical Software* **63**(18), 1-36.

Bivand R, Hauke J, Kossowski T (2013) Computing the Jacbobian in Gaussian spatial autoregressive models: An illustrated comparison of available methods. *Geographical Analysis* **45**(2), 150-179.

Donovan G, Champ P, Butry D (2007) Wildfire Risk and Housing Prices: A Case Study from Colorado Springs. *Land Economics* **83**(2), 217-233.

Huggett RJ, Murphy EA, Holmes TP (2008) Forest disturbance impacts on residential property values. In 'The Economics of Forest Disturbances: Wildfires Storms, and Invasive Species'. (Eds. TP Holmes, JP Prestemon, KL Abt) pp. 209-228. (Springer: The Netherlands)

Kim Y-S, Wells A (2005) The Impact of Forest Density on Property Values. *Journal of Forestry* **103**(3), 146-151.

LeSage J, Pace RK (2009) 'Introduction to Spatial Econometrics.' (CRC Press: Boca Raton, FL)

Loomis J (2004) Do nearby forest fires cause a reduction in residential property values? *Journal of Forest Economics* **10**, 149-157.

Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefrey, JF (2005) The Wildland Urban Interface in the United States. *Ecological Applications* 1**5**, 799-805.

Surface Fuel Changes after Severe Disturbances in Northern Rocky Mountain Ecosystems

Christine Stalling*1[A]
Robert E. Keane 2[A]
Molly Retzlaff 3[A]

[A]USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 Hwy 10 West, Missoula, MT 59808, Phone: (406) 829-7386, FAX: 406-329-4877, Email: cstalling@fs.fed.us

Abstract:

It is generally assumed that insect and disease epidemics, such as those caused by the mountain pine beetle, predispose damaged forests to high fire danger by creating highly flammable fuel conditions. While this may certainly be true in some forests, these dangerous fuel conditions may only occur for a short time when evaluated at a landscape level. This study evaluates the effect that exogenous disturbance events, namely fire and beetles, have on future fire hazard. We measured surface fuel deposition rates several forest types after stand-replacement wildfire beetle outbreaks to quantitatively describe fuel dynamics in heavy mortality stands for up to 10 years post disturbance. Fuel deposition was measured using semi-annual collections of fallen biomass. This litterfall was collected using a network of seven, one meter square litter traps installed on sites located across the northern Rocky Mountains USA. We also measured stand and surface fuel characteristics of the plot using FIREMON techniques at the beginning, and yearly until the study's end. Results indicate that after the initial pulse of needlefall 2-3 years after disturbance, few fine woody fuels are actually deposited over the next 10 years.

Additional Keywords: Fire, fuels, litter, litterfall, fuel deposition, fuel accumulation

Introduction

Conventional wisdom in fire management holds that stands with trees that are killed by insects, disease, or fire have high fire hazard because the dead foliage and fine woody material is highly flammable while in the canopy (Axelson *et al.,* 2009; Hicke *et al.,* 2012) and then, when this material falls to the ground, it creates heavy fuel loads that may result in faster fire spread and greater intensities (Gara *et al.,* 1984; Jenkins *et al,* 2015). There is no doubt that the dying and dead needles are more flammable than green needles because of lower moistures and higher flammability (Jolly *et al.,* 2012), but these needles may remain in the canopy for a short time. Of more importance may be how fast the dead canopy material accumulates on the forest floor to increase fuel loadings and hazard. The dead fine woody material may fall quickly to the ground and create surface fuel conditions that could foster wildfires of high intensity and severity. This study evaluated through annual field collections, the effect that exogenous disturbance events, namely fire and beetles, have on future fuel conditions.

Materials and Methods

Study Sites

We selected fifteen sites in Montana and Idaho that were on flat ground, near a road, and had the potential for high tree mortality from a disturbance. Needles had to be present on the killed trees. We attempted to target only stands that had greater than 70% mortality from the disturbance, but it was difficult to evaluate future mortality at the inception of an outbreak, therefore, some selected stands had less than 70% mortality at study initiation. After an exhaustive GIS analysis and numerous reconnaissance trips, we established at least three sites of different forest types after major mortality events from three different disturbance agents: wildfire, Douglas-fir beetle, and mountain pine beetle outbreaks (Table 1). We wanted to select sites in just one forest type but that was nearly impossible under our site selection and disturbance selection criteria.

Table 1. List of all 15 study sites. Three stand-replacement disturbances are represented in this study: wildfire, Douglas-fir beetle, and mountain pine beetle. Sampling period ranged from year established to 2015.

Site Name	Acronym	Overstory Mortality (%)	Forest Type	Elevation (m)	Year Established
			Wildfire		
Jocko Lake	JL2	100	Mixed larch, Douglas-fir, lodgepole pine	1426	2008
Marias Pass	MP1	100	lodgepole pine	1715	2007
Merriwether 1	MW1	25	ponderosa pine (thinning unit)	1231	2007
Merriwether 2	MW2	98	ponderosa pine	1200	2008
			Douglas-fir Beetle		
Morgan Creek	MC1	50	Douglas-fir	2179	2009
Lost Trail	LT1	90	Douglas-fir	1882	2007
Flesher Pass	FP1	90	Douglas-fir	1839	2009
			Mountain Pine Beetle		
Galena Summit	GS1	100	whitebark pine	2737	2007
Bull Run	BR1	98	ponderosa pine	1429	2010
Red River 5	RR5	100	lodgepole pine/subalpine fir	1653	2001
Red River 6	RR6	100	lodgepole pine/subalpine fir	1670	2001
Red River 7	RR7	100	Mixed lodgepole pine, spruce	1328	2001
Homestake Pass	HP1	70	lodgepole pine	1938	2007
Twin Peaks 1	TP1	80	whitebark pine	2828	2009
Twin Peaks 2	TP2	70	whitebark pine	2679	2009

Field Methods

We measured surface fuel deposition and decomposition rates for a number of forest types after severe wildfire, Douglas-fir beetle, and mountain pine beetle events to quantitatively describe fuel dynamics for up to 10 years after the disturbance. Fuel deposition was measured using semi-annual collections of fallen biomass sorted into six fuel components (fallen foliage, twigs, branches, large branches, logs, and all other material) from a network of seven, one meter square litter traps installed on all plots. We took a monitoring approach to describing fuel dynamics after severe disturbances on the 15 selected sites. Fuel accumulation was documented from annual fuel loading measurements at each site. Fuel deposition was measured from litter that fell into wooden traps and were collected twice a year. We measured loadings of all fine woody, shrub, and herbs using the visual Photoload estimation method (Keane and Dickinson, 2007) (Figure 1).

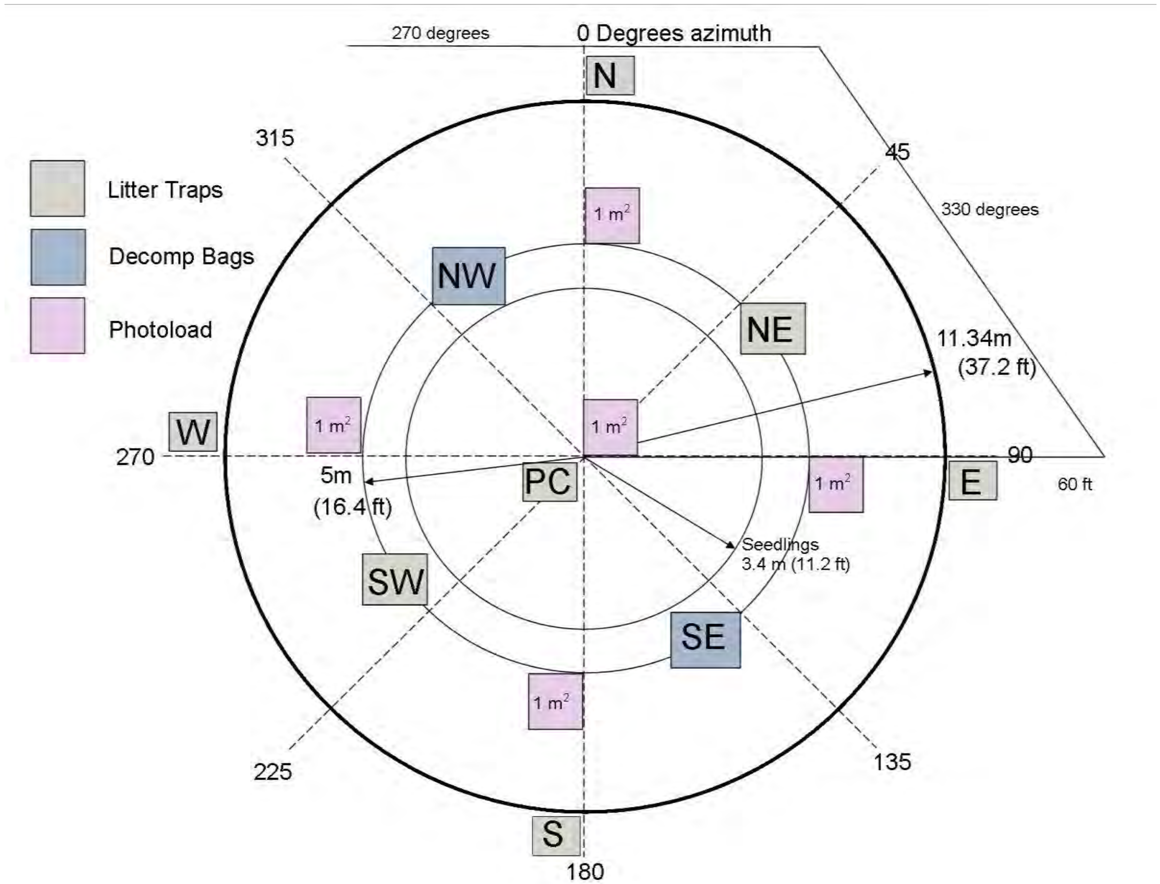

Figure 1. Plot Layout

Analysis

We performed an analysis of variance for litterfall across all fuel components on each plot to determine if we had statistically significant changes by year. We summarized fuel loadings and deposition rates by fuel component for each plot to create an annual time series of box-whisker plots (Sokal and Rohlf, 1981) to display temporal changes, and then pooled these data to create a time series by disturbance agent. For the loading time series, we calculated the trend (increasing, decreasing, same) and rate of fuel accumulation over the sampling time by plot and then summarized to disturbance agent. For the litterfall analysis, we visually estimated three parameters from each plot: (1) number of years it took for dead foliage to fall to ground, (2) number of years it took before substantial amounts of FWD to fall to the ground, and (3) number of years in which CWD was detected. We then summarized these statistics by disturbance agent.

Results & Discussion

Analysis of box-whisker plots of measured litterfall indicate that deposition of foliage across all 15 study sites occurred during the first 1-4 years post-disturbance, independent of site location or forest type. When site data was pooled by disturbance type these trends were repeated across all sites, foliage deposition took place within 1-4 years of disturbance regardless of disturbance type. Initial analysis of the fuel loading time series showed mostly constant, unchanging fine and coarse woody debris levels across nearly all study sites. A minor increase in coarse woody debris was noted on the Red River site but it is likely negligible. Fallen snags were rare on all of the study sites during the entirety of the study and did not contribute to overall fuel deposition. Preliminary analysis of litterfall rates and loading following stand-replacement disturbance on Northern Rocky Mountain ecosystems indicate there is little change to surface fuels regardless of forest or disturbance type. While the majority of foliage tends to fall within the first 1-4 years following disturbances on all sites, generally we do not see any substantial increases or decreases to surface fuels over the long term. Generally, there was little fuel accumulation during the first 5 years after severe disturbances.

References

Axelson, JN, Alfaro, RI, Hawkes, BC (2009) Influence of fire and mountain pine beetle on the dynamics of lodgepole pine stands in British Columbia, Canada. *Forest Ecology and Management* **257**, 1874-1882.

Gara, RI, Littke, WR, Agee, JK, Geiszler, DR, Stuart, JD, Driver, CH (1984) Influences of fires, fungi and mountain pine beetles on development of a lodgepole pine forest in south-central Oregon. In: Baumgartner, DM, Krebill, RG, Arnott, JT, Weetman, GF (Eds.), Lodgepole pine: the species and its management. Washington State University, Spokane, WA, 153-162.

Hicke, JA, Johnson, MC, Hayes, JL, Preisler, HK (2012) Effects of bark beetle-caused tree mortality on wildfire. *Forest Ecology and Management* **271**, 81-90.

Jenkins, MJ, Page, WG, Hebertson, EG, Alexander, ME (2012) Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management. *Forest Ecology and Management* **275**, 23-34.

Jolly, WM, Parsons, RA, Hadlow, AM, Cohn, GM, McAllister, SS, Popp, JB, Hubbard, RM, Negron, JF (2012) Relationships between moisture, chemistry, and ignition of Pinus contorta needles during the early stages of mountain pine beetle attack. *Forest Ecology and Management* **269**, 52-59.

Keane, R.E., Dickinson, L.J., 2007. The Photoload sampling technique: estimating surface fuel loadings using downward looking photographs. In. USDA Forest Service Rocky Mountain Research Station, p. 44.

Sokal, RR, Rohlf, FJ (1981) Biometry. W.H. Freeman and Company, San Francisco, CA USA.

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Towards Efficient Large Fire Management: Monitoring, Modeling, and Accountability

Matthew Thompson
US Forest Service, Missoula, Montana, USA, mpthompson02@fs.fed.us

Christopher Dunn
Oregon State University, Corvallis, Oregon, USA, chris.dunn@oregonstate.edu

Erin Belval
Colorado State University, Fort Collins, Colorado, USA, mccowene@gmail.com

Keith Stockmann
US Forest Service, Missoula, Montana, USA, kstockmann@fs.fed.us

Crystal Stonesifer
US Forest Service, Missoula, Montana, USA, csstonesifer@fs.fed.us

Yu Wei
Colorado State University, Fort Collins, Colorado, USA, yu.wei@colostate.edu

David Calkin
US Forest Service, Missoula, Montana, USA, decalkin@fs.fed.us

Introduction

Context and Purpose

This extended abstract summarizes six interrelated presentations organized together under a special session on wildland fire management in the U.S. The objective of the special session is to synthesize recent and ongoing research focused on quantifying and improving the efficiency of incident response, with a focus on the rare but large fires that typically account for the majority of socioeconomic and ecological impacts. This body of work embraces a primary focal area of the National Cohesive Wildland Fire Management Strategy – safe and effective wildfire response – and is premised on the idea that how fires are managed, not just how landscapes are managed before and after fires occur, is a key determinant of long-term landscape resiliency (Thompson et al. 2015).

In recent decades, the risks and complexities of the U.S. wildland fire management environment have increased dramatically, driving increased losses and elevated response costs (Calkin et al. 2015). A multitude of factors are likely responsible, including historical forest and fire management practices resulting in increased forest density and fuel loads, climatic changes resulting in warmer, drier, and longer fire seasons, and significant expansion of the wildland urban interface resulting in increased exposure of communities and homes. It is becoming increasingly apparent that a business-as-usual approach to fire management is unsustainable (Olsen et al. 2015). Suggested alternative management paradigms identify a need to learn to live with fire, and deemphasize fire exclusion while promoting expanded application of prescribed and managed natural fire (Moritz et al. 2014; North et al. 2015).

While the need to transition to a new fire management paradigm is well-recognized, significant knowledge gaps constrain our ability to clearly and comprehensively describe how changes in the way agencies plan for and respond to fires may lead to improved outcomes. Hence a need to better monitor fire management actions and outcomes, to better model and evaluate alternative management strategies, and to ensure agencies are accountable for acquiring and basing decisions on best-available information. These three concepts – monitoring, modeling, and accountability – are essential elements of risk analysis and management, and are the primary topics of our special session and of this extended abstract.

Organization

The remainder of this extended abstract is organized into three sections that tie back to our main concepts. Each section contains simply the title, lead author, and abstract for all individual presentations. Monitoring is the first topic we address, as a critical element for performance measurement and program review, as well as for ensuring models are accurately parameterized and calibrated. Both presentations in this section focus on aerial firefighting, which is dangerous and costly, and which remains the subject of analysis and deliberation regarding fleet modernization strategies. We next turn to modeling, presenting descriptive as well as prescriptive approaches that focus on the ordering, use, and movement of ground and aerial firefighting resources. Models such as those presented are critical for helping managers better evaluate alternative management strategies across a range of decision contexts. Lastly, we briefly review the notion of accountability, how it relates to monitoring and modeling efforts, and how it relates to risk management principles. While by no means exhaustive, we note that the topics discussed here are representative of the breadth and depth of analyses necessary to improve fire management efficiency.

Monitoring

Large airtankers in US fire management: describing historical use and discussing implications related to efficiency

Crystal Stonesifer

Airtankers are widely used in suppression of wildfires in the United States. While Federal guidance suggests that they are best reserved for initial attack (IA) of new wildfire ignitions, our past work analyzing drop records from 2010-2012 has shown that the Federal large airtanker (LAT) fleet was used in IA approximately half of the time. Further, nearly three-quarters of IA drops were on fires that escaped containment efforts during the first operational period, suggesting that LATs are used on fires that are inherently difficult to contain, and that there are often potential objectives at play beyond basic incident containment (e.g., point protection). Additionally, our analysis demonstrated frequent LAT use in conditions where their effectiveness may be limited by a combination of environmental factors conducive to extreme fire behavior (e.g., late afternoon, steep slopes, timber fuel models). These patterns demonstrating widespread use under conditions when all suppression resources are known to be less effective suggest that LATs may be viewed as a resource of last resort. Here, we briefly summarize our previous findings, and then discuss the implications of utilizing LATs under fire conditions when all else fails. We present ideas for an alternative system that emphasizes targeted use of LATs under conditions where they are known to be most effective through thoughtful preplanning, efficient deployment, and utilization of the best available fire activity and behavior forecast tools. The Aerial Firefighting Use and Effectiveness (AFUE) study currently underway will provide valuable additional information regarding environmental conditions of use, drop intent as it relates to the larger strategic fire suppression plan, and associated outcomes, which will greatly enhance our ability to improve the efficient use of the federal LAT fleet in the future.

Meaningful translation of aerial firefighting objectives, context and outcomes into effectiveness across the range of fire sizes for the Aerial Firefighting Use and Effectiveness Study
Keith Stockmann

A 2013 Government Accountability Office (GAO 2013) report critiqued interagency inability to characterize use, effectiveness and needs for aerial assets in wildfire suppression, which justified a long-term study to improve our understanding of the role and contribution of planes and helicopters in firefighting efforts. The current project takes a leap of complexity past previous investigations by designing a study that untangles the wide range of aircraft uses, focusing on expensive aircraft delivering suppressants and retardant to assist fire managers. The Forest Service's Technology and Development Centers are working with partners in fire and aviation management, USFS Research, National Interagency Fire Center information technology and the BLM. The AFUE Study has four operational modules across the western US, each with three experienced firefighters, a field coordinator, a data manager and an analyst. Collectively they developed an ESRI Collector instrument that classifies use into one of various objectives, captures drop tactics, plans, terrain, weather, and complementary resource availability/actions and also assesses outcomes at multiple scales. After refining this approach for several seasons and observing thousands of drops, it is time to translate the combinations of objectives and outcomes into a meaningful assessment of effectiveness. This is an inside look at the mechanics of this translation, anchored in firefighter perspective, but flexible enough to scale across the range of fire sizes and supported with limited quantitative analysis of fire growth and retardant survival modeling. This translation of outcomes to effectiveness is a key step towards classification and regression tree diagnosis of factors explaining success and future cost effectiveness analyses, both of which should lead to more informed and efficient use of aircraft in wildfire suppression.

Modeling

Firefighting Resource Use and Movement in the United States
Erin Belval

Examining the efficiency and effectiveness of wildland firefighting resource use is becoming increasingly crucial in light of rising suppression expenditures; however, there has been little research to date that has been designed to understand and quantify the patterns of resource ordering and movement in the US. Archived records from the Resource Ordering and Status

System (ROSS) provide data that support the task of quantifying national fire suppression resource use for large fire suppression. An initial analysis of ROSS data compares team assignments recorded in ROSS to the team type recorded in the set of incident status summary reports; this analysis found differences between the two sets of data and indicates that additional efforts may be needed to more accurately track team use. We also used ROSS data to study suppression resource utilization and resource movements between geographic regions during fire seasons. These analyses used linear regression techniques to examine crew, engine, dozer, and helicopter utilization on large fires. The results indicate significant variation in resource assignment frequency and assignment length on large fires based upon fire complexity and the region of fire occurrence. Additional multinomial regression analyses are used to model crews responding to fires outside their home region. The results demonstrate that the probability of a crew response from a specific home region to fires outside of its home region is significantly correlated with factors such as the region in which the crew is based, fire activity and resource scarcity in crew's home region, the region in which the incident occurs, national level resource scarcity, seasonality, and the proximity of the crew's home region to the region in which the incident occurs.

Develop a simulation/optimization procedure to study the daily suppression resource reassignments during a fire season in Colorado
Yu Wei

Sharing fire engines and crews between fire suppression dispatch zones over a fire season improves the utilization of these resources and allows managers to meet suppression demand in each zone during time of high fire activity. Using data from the Resource Ordering and Status System (ROSS) and the Predictive Service 7-day Outlook from 2010 through 2013, we studied daily fire crew and engine demand in Colorado's six dispatch zones and designed a simulation/optimization procedure to transfer crews and engines into Colorado and to move them between these zones. Management assumptions and policies may influence resource assignment patterns and related efficiencies; we compared the effect of several different assumptions and policies using our model. We also compared several model-suggested crew and engine reassignment patterns with historical ROSS records to identify potential improvements in efficiency.

A framework for optimal incident management: safe and effective response in a new fire management paradigm
Christopher Dunn

Transition to the new fire management paradigm will require adaptation and innovation from fire management organizations so they can manage risk and uncertainty while minimizing decision biases. This requires alignment of a hierarchy of decisions beginning with pre-suppression planning and continuing through the development of optimal response tactics. In this talk, we propose a new dynamic, multi-response optimization model of large fire management that considers uncertainty in land management objectives, environmental conditions and suppression resource availability, safety and efficiency. The most pressing and potentially important decision for large-fire incident response is the establishment of means-based objectives that are specific, measureable, achievable, realistic and time-constrained. Without means-based objectives there is limited opportunity to utilize modern analytical methods for decision support. Identified control lines, resources and assets requiring point protection, and logistical-features requiring construction should be included as part of the tactical response objectives utilized by incident managers that ultimately lead to the objective function and constraints within the dynamic optimization model. The next step in the dynamic optimization model is to integrate long-term fire behavior simulations with resource production models to determine the likelihood of controlling a fire at the identified control boundary. Following identification of intended control lines, three umbrella decisions are necessary to manage large-fire incidents and therefore need to be accounted for in the dynamic optimization model: resource acquisition, resource allocation, and resource demobilization. Each umbrella decision includes several sub-level decisions specific to individual resources and tasks, and all interact to determine the final solution. These large-fire management decisions are constrained by interactions between the operational environment and resources assigned to the incident, including variables related to operational standards and environmental constraints, which largely relate to interactions between fire behavior and firefighter safety. The framework we have described integrates decisions made at multiple levels within land and fire management organizations. Pre-suppression planning and use of modern analytical tools with expert knowledge has the potential to improve the large-fire management decision making process, provide the opportunity to develop optimal incident response tactics, and improve the safety and efficiency of large fire management. The dynamic optimization model requires improved data and modeling capacity, both of which require investment and support from agency leadership. Integrating these modeling efforts with expert knowledge will help fire management organizations more effectively adapt to the new fire management paradigm.

Accountability

Infusing Accountability and Risk Management Principles into the Fire Management System
Matthew Thompson

Adoption of core risk management principles is important to improve wildland fire management decisions and outcomes. Embracing risk management for instance means investing time and resources in upstream assessment and planning to reduce the uncertainties and time-pressures of the incident decision environment. It also means embracing various facets of accountability: committing to generating and using the best available information, developing robust systems to monitor performance, and using that information to facilitate continual improvement. Absent a data-driven system of accountability, fire management organizations have no basis for tracking or correcting behavior, even when such corrections would help better attain objectives. Similarly, without accountability organizations have difficulty connecting decisions to outcomes and evaluating how alternative courses of action may lead to improved outcomes. The analyses related to monitoring and modeling presented in this special session highlight pathways forward for improved adoption of risk management and accountability principles.

References

Calkin, D. E., M. P. Thompson, and M. A. Finney (2015), Negative consequences of positive feedbacks in US wildfire management, Forest Ecosystems, 2(1), 1-10.

GAO (2013) Improvements needed in information, collaboration, and planning to enhance federal fire aviation program success, Report GAO-13-684. Available at http://www.gao.gov/products/GAO-13-684 [Verified 06 August 2015]

Moritz, M. A., E. Batllori, R. A. Bradstock, A. M. Gill, J. Handmer, P. F. Hessburg, J. Leonard, S. McCaffrey, D. C. Odion, and T. Schoennagel (2014), Learning to coexist with wildfire, Nature, 515(7525), 58-66.

North, M., S. Stephens, B. Collins, J. Agee, G. Aplet, J. Franklin, and P. Fulé (2015), Reform forest fire management, Science, 349(6254), 1280-1281.

Olsen, R.L., Bengston, D.N., DeVaney, L.A., and T.A.C. Thompson (2015), Wildland Fire Management Futures: Insights from a Foresight Panel, USDA Forest Service General Report NRS-152, Newtown Square, PA.

Thompson, M., C. Dunn, and D. Calkin (2015), Wildfires: Systemic changes required, Science 350(6263), 920.

University of Wisconsin-Stevens Point Fire Crew: Approaching Tomorrow's Problems with Today's Education and Training

Paul Priestley
University of Wisconsin-Stevens Point, Stevens Point, Wisconsin, USA,
Paul.S.Priestley@uwsp.edu

Jacob Livingston
University of Wisconsin-Stevens Point, Stevens Point, Wisconsin, USA,
Jacob.J.Livingston@uwsp.edu

Ethan Robers
University of Wisconsin-Stevens Point, Stevens Point, Wisconsin, USA ,
Ethan.S.Robers@uwsp.edu

Introduction

The University of Wisconsin-Stevens Point (UWSP) Fire Crew is a student organization and a wildland firefighting organization. Our membership includes a diverse group of UWSP students, with majors in a variety of disciplines but predominantly; Forest Management, Ecosystem Restoration and Management, Wildlife Ecology, and Wildland Fire Science. The purpose of our presentation is to showcase the interactive relationship between theFire Crew, the Wildland Fire Science Program, Wisconsin Department of Natural Resources and other partners and stakeholders. We also provide details about training activities, in the field experiences and how integrating science and management equips students for the challenges we will face as wildland fire professionals. .

Fire Crew Organization

The crew has a set of officer positions that include a Crew Leader and his or her Assistant, Secretary, Cache Manager, Public Information Officer, Fire Effects Officer, Treasurer, and two Faculty Co-advisors. The crew has other positions with task books, which include Squad Boss and Burn Boss for crew members. Though officers act as the leadership on the fire line, the task books are open to anyone on the crew who seeks to help with leadership. We do have set requirements that must be met for member involvement on the fire line. Members who hope to burn with us must acquire their basic FFT2 certification, perform a shelter deployment, and complete an arduous level Pack Test. Currently we hold around 40+ members that can participate in operations. Our crew structure is set up to give students the maximum amount of experience that is available.

Activities

UWSP Fire Crew provides multiple opportunities such as performing prescribed fire operations for private landowners and the Wisconsin Department of Natural Resources (WI DNR) and has participants in various fire related faculty research projects.

Other activities include, writing prescribed burn plans, performing said burns during spring and fall, going on educational trips during winter and Spring Breaks, hosting professional speakers, and other miscellaneous workshops. The Fire Crew holds workshops dedicated to teaching students how to write effective burn plans which are frequently utilized for private landowners and also on public land such as state parks or nature reserves. We write burn plans with specific objectives that have clear ecological purpose. The window for opportunity to burn in central Wisconsin is fairly short, as we may only have three months of the school year without snow. While most of the burns we perform are in Wisconsin, we also get a chance to burn in different states. We have an annual trip to Florida every winter break where we burn with the Gold head State Park in Longleaf pine (*Pinus palustris*) dominated ecosystems. We also make a trip every spring break to Pushmataha Wildlife Management Area in Oklahoma which provides academic credit to participating students. On this trip, students are asked to determine ignition patterns, measure fuel loads and consumption, monitor fire behavior, examine fire effects, make weather observations, and also write a reflection paper about their experiences. We also do trips to the Cook County Forest Preserve District in the Chicago area to assist in operations for the city during spring break. These trips give students the opportunity to network, gain experience before applying for fire jobs, and understand variations of prescribed fire within several fuel types. The Fire Crew also hosts professional speakers including those from private companies, government organizations, and non-profit organizations such as the Nature Conservancy.

Other activities held include radio operation workshops, chainsaw projects, scouting trips to future burn plots, boot care, packing essentials for the fire line, resume and USAJOBS workshops, sand table exercises, tool sharpening, and flag fires. The officer core and students are constantly coming up with creative activities to prepare our firefighters for the field and getting them ready to fill professional positions. We also offer the opportunity for students to expand their knowledge of fire management and ecology by attending conferences around the country each year.

Mutual Aid

The Fire Crewhas a mutual aid agreement with the Wisconsin DNR that provides us with federally certified instructors to enhance our training as students while they are receiving a local firefighting resource to assist them with wildfire suppression and prescribed burn operations. We provide basic fire certification training twice a year with student lead sections at our outdoor hands-on training sessions. The fall class allows for credit through the university and spans 16 weeks while the spring course is offered over two weekends of class work, totaling 80 hours. Once participants complete the course, the DNR can then benefit from their training by allowing them to work on wildfire suppression assignments and prescribed burns. The fire crew acts as a local dispatch center for the Whiting and other Ranger districts near Stevens Point that need extra staffing during high fire danger. Each crew member that works with the DNR must log their own mileage and time and fill out an activity log for all duties performed on shift. The Fire Crew also provides several other NWCG fire certification courses throughout the school year including; S - 212 Wildland Fire Chain Saw, S – 211 - Portable Pumps and Water Use, S-131- Firefighter Type 1 Training, S-133 Look Up, Look Down, Look Around, S-230 Crew Boss Training, S-219 Firing Operations, S-270 Air Operations, and S-290- Intermediate Wildland Fire Behavior. These courses allow students to have a competitive advantage in the field before they graduate.

We not only have an emphasis on technical training, but scientific training as well, by bringing the classroom to the field through hands on experiences such as fire effects monitoring using pre and post burn vegetation surveys, seed bank analysis, fire behavior monitoring including fuels measurements, fire intensity, flame lengths, and smoke impacts on fire fighters.

Similarly, we bring the field to the classroom by inviting professionals from the fire science community to present new research, techniques, and improvements at our weekly meetings.

Fire Ecology

Combining the hands on experience acquired with field training, the Fire Science curriculum at UWSP is educating the future fire managers of America with a strong emphasis on ecology and restoration. Our program has recently been accredited by the Association of Fire Ecology (AFE) and therefore allows our graduates to become AFE certified fire managers and ecologists. The core courses of the Wildland Fire major listed belowincorporate a strong understanding of the ecological role of fire within various ecosystems.

Courses* such as;

- FOR224 - Fire Operations which is our basic certification course (S-130,S-190,L-180)
- FOR324 - Fire Management and Ecology - Phenomenon of fire; its physical and chemical effects and historical significance. Behavior and effect of wild and prescribed fire in temperate forests. Techniques for planning, conducting, and evaluating prescribed burns.
- FOR450 - Fire Policy Suppression and Use - History of wildland fire policy development in the U.S. and selected other countries. Fire suppression strategies, wildland fire use including smoke management, wildfire education strategies, and fire in the wildland urban interface. Use and limitation of computer models for fire danger information systems, suppression, and management.
- NRES454 - Fire Behavior and Fuels - Combustion process and physics of fire related to various fuels in the fire environment. Fire behavior, fuel measurement, and fuel modeling systems. Ecology of fuels, including moisture dynamics related to weather.
- NRES 455 - Advanced Fire Ecology - Fire as a fundamental ecological process emphasizing ecosystem dynamics in North American grasslands, shrublands, and forested systems with selected global examples from other ecosystems. Fire adaptations, regimes, seasonally and fire frequency effects on animal and plant communities, air, soils, and water and the role of fire in the environment.

- NRES 459 - Ecosystem Restoration and Management - Methods for managing and restoring ecosystems for biological diversity and sustainable use. Understanding the role of disturbance, such as fire, as an integral part of ecosystem health and function.

*Class descriptions acquired from the UWSP course catalog

Outside of the classroom, UWSP Fire Crew has a dedicated fire effects officer (FEO) position to monitor and study the ecological impacts of prescribed burns performed by the Fire Crew. The duties of this position include collecting pre and post burn vegetation surveys, fuel consumption data, and monitoring fire behavior characteristics such as intensity, flame lengths, rate of spread, and smoke dispersal. Another responsibility of the FEO is to coordinate member attendance at fire ecology conferences, such as this one, through our student chapter of AFE, which awards travel grants to Fire Science students. When our members attend conferences the information learned will be shared with other students through a presentation given at our weekly meetings. This keeps us updated on new topics being introduced in the wildland fire community.

Another key responsibility of the FEO is to establish and coordinate various research projects with the help of interested students. He or she also must collaborate with other student organizations such as the Society of Ecological Restoration to assist in research goals and data collection. Research topics include effects of prescribed fire on: encroachment of woody vegetation into an oak savanna, habitat restoration for the federally endangered Karner Blue butterfly *(Lycaeides melissa),* and seed bank composition changes under varying treatments of prescribed fire. Experimental design is generated by students under the guidance of faculty advisors to create complete scientific reports with viable data to present at our undergraduate research symposium. Having this experience to produce professional research at this level is preparing students for a graduate level degree in fire ecology. Currently, there is also research being done by the chemistry department at UWSP on the risk of different levels of exposure to smoke on wildland firefighters.

The overall goal of the Fire Crew and the UWSP Wildland Fire Science program is to promote student education and training to become wildland fire professionals that lead by example and support fire management decisions with scientific data. This is being achieved by students, faculty members, and current professionals working collaboratively to approach tomorrow's problems with today's education and training.

We are on the precipice of a dynamic future that will need fire managers and fire ecologists as much as firefighters and here at UWSP we are developing students of fire to approach upcoming issues in new and inventive ways.

Using McArthur model to predict bushfire prone areas in New South Wales

Liran Sun*
University of New South Wales, Sydney, NSW, Australia, haruhanasun@hotmail.com

John Trinder
University of New South Wales, Sydney, NSW, Australia, j.trinder@unsw.edu.au

Chris Rizos
University of New South Wales, Sydney, NSW, Australia, c.rizos@unsw.edu.au

Introduction

Fire intensity is a key component of bushfire regimes and its assessment has been widely used for mapping of bushfire prone areas. The basic factors which determine whether a bushfire will occur include the presence of fuel, oxygen and an ignition source. The goal of this research is to examine the potential of a spatial model of fire intensity, which is based on McArthur forest fire behaviour model and Byram's fire-line intensity, to detect and map state wide bushfire prone areas in NSW, Australia. The evaluation was based on historical burn data recorded from 2001 to 2013 using logistic regression. Digital elevation model(DEM) data were used to generate the maximum slope for assessing bushfire propagation susceptibility. Fuel load and weather index were also used to model potential fire intensity.

Bushfire is one of the major threats to the environmental and human systems in the state of New South Wales (NSW), Australia. It located in southeastern Australia, with a total area of approximately 809,444 km^2, is one of the most bushfire prone areas in the world. There are approximately 16,500 vegetation fires across NSW every year, according to the Australian Productivity Commission report. The principal timing of bushfires in NSW varies according to the weather condition, and is commonly linked to periods of drought. The most adverse bushfire weather occurs in the summer months of November, December and January in most areas, whereas for the North Coast and the Northern Rivers regions, fires most typically also occur during spring. .Statistical data from 2004 to 2014 indicate that the main bushfire season is from October to February, and 70% of the total yearly burned areas occur in December, January and February. From 1993 to 2003 bushfires in NSW collectively caused 10 deaths, the loss of 411 houses, with over 2,200,000 ha burned. In this paper, historical burn data for 2001 to 2013 were provided by the Rural Fire Service (RFS) of New South Wales.

Materials and methods

In the current study, a new methodology is proposed that combines the McArthur forest fire behaviour model with Byram's fire-line intensity to estimate potential fire intensity and map bushfire prone areas in New South Wales. This methodology has incorporated potential fuel load, landscape slope and forest fire danger index to determine the fire intensity.

The potential fuel load, which is represented by the approximate mass (measured in tonnes/ha) of combustible fuel material, is a key driver of fire behaviour and fire intensity. To estimate potential fuel loads for each vegetation category as shown in Table 1, reference was made to the 'Overall Fuel Hazard Assessment Guideline' and 'Vegetation Formations of NSW 'and applied fuel load estimates to each Vegetation Hazard Class.

Table 1: Vegetation Hazard classes and Potential Fuel loads

Vegetation Hazard Class	Vegetation Hazard Class description	Potential Fuel Load (tonnes/ ha)
1	Cleared	0
2	Rainforest	8
3	Wet sclerophyll forests (shrubby subformation)	27
4	Wet sclerophyll forests (grassy subformation)	25
5	Grassy woodlands	15
6	Grasslands	5
7	Dry sclerophyll forests (shrubby/grass subformation)	26
8	Dry sclerophyll forests (shrubby subformation)	19
9	Heathlands	8
10	Freshwater wetlands	3
11	Forested wetlands	5
12	Saline wetlands	1
13	Semi-arid woodlands (shrubby subformation)	10
14	Semi-arid woodlands (grassy subformation)	8
15	Arid shrublands (chenopod Subformation)	1
16	Arid shrublands (acacia subformation)	9

Topographic factors included elevation, slope and aspect. We used the one second smoothed digital elevation model (DEM-s) data at a spatial resolution of 30m to create the landscape slope maps. The 1 second DEM, derived from the SRTM data is not suitable for fire spread application due to various artefacts and noise, while the DEM-s has been adaptively smoothed to reduce random noise typically associated with the SRTM data in low relief areas. DEM-s data were provided by Geoscience Australia (GA), which was resized, re-projected, and re-sampled to match the coordinates of the fuel load data. The maximum slope was then derived from the DEM-s data.

The McArthur Forest Fire Danger Index (FFDI) is used to represent the complexity of weather variables including wind speed, temperature, relative humidity and recent precipitation in measuring bushfire risk. The following equation is used to calculate daily FFDI values:

$$\boldsymbol{FFDI = 2 * exp(0.987In(DF) - 0.45 + 0.0338T + 0.0234W_s - 0.0345RH)} \quad (1)$$

where DF is the drought factor calculated using the procedure in Griffiths(1999), T is the daily maximum temperature, Ws is the 3pm 10-minute average wind speed and RH is the 3pm relative humidity. In this research we made use of the weather data from 16 stations across New South Wales covering the period June 1972 to December 2009 to calculate the spatial distribution of

FFDI. The indicator of fire weather conditions is assessed by calculating the return period of extreme values by fitting extreme value distributions to records of FFDI (Sanabria et al. 2013). According to the extreme value theory, the return period (RP) of an event is related to the probability P of not exceeding this event in one year (Makkonen 2006):

$$\boldsymbol{RP = \frac{1}{1-P}}, \qquad (2)$$

Return period of FFDI for a range of years (1 year, 5 years, 20 years, 50 years and 100 years) were calculated for the data using the Generalized Extreme Value Distribution (GEV). However, this sparse discrete location data is not suitable for a spatially continuous environment. Therefore an advanced interpolation algorithm was used to generate 30m grid spatial distribution data based on the discrete points FFDI data in the next step. The Inverse Distance Weighting (IDW) algorithm was used to calculate the spatial distribution of point-based values.

Fire-line intensity is a standardized measure of the rate of fire suppression and can be used to estimate the potential flame length, radiant heat and other fire metrics to provide approximate estimates of risk to life and property(Byram 1959, Cheney et al. 2001, Zárate et al. 2008, Australia 2009, Alexander and Cruz 2012). It is calculated by combining estimates of the potential fire weather severity, landscape slope and potential fuel load, using formulae derived from established forest fire behaviour models:

$$\boldsymbol{FI = 0.62 * W^2 * FFDI * exp(0.069\theta)}, \qquad (3)$$

FI is fire-line intensity, W is total fuel load, FFDI is McArthur Forest Fire Danger index, and θ is the slope.

The final Bushfire Prone Area map is generated from potential fire-line intensity mapping by removing areas that do not meet a minimum potential fire-line intensity threshold, removing small and disconnected patches of vegetation that are less likely to be ignited or would not sustain a severe bushfire, adding a potential impact buffer, and smoothing map data to replicate naturally occurring boundaries.

Results

The potential fuel load map was generated by applying a fuel load estimate to each vegetation hazard class. As mentioned in the method section, this data set was developed by combining over 100 vegetation maps which vary in spatial resolution and currency. Therefore the map reliability needs to be assigned based on each image source. Specifically, 72% of western NSW have a low map reliability; 86% of the north coast area has a map reliability of medium or above; 92% of the central coast area has a map reliability of medium or above, and 98% of the south coast area has a map reliability of medium or medium-high.

Maps of FFDI return values from the 1985-2008 analysis dataset for a range of years are computed. In this case, a 20 year return period means a certain weather condition is exceeded with probalility 0.05 (1/20) on average once a year. For instance, if the average annual probability of exceeding a temperature of 32^{o} T at some location is 0.05, the 20 year return period (1/0.05) of a temperature at thatlocation is 32^{o} T, which means it is expected that the value 32^{o} T is exceeded, on average, once every 20 years. Generally speaking, 1 year RP represents the normal weather condition and the 100 years RP represents the extreme weather condition. In this study, it was found that the 20 years RP is most suitable for calculating the state-wide fire intensity.

Compared the 30m maximum landscape slope calculation method with others, the finite difference method identifies the steepest slope instead of an average. In this research the maximum value across the cell's eight neighbourhood slopes using cell statistics was adopted, and the final result gave a relatively smooth landscape slope, especially in high relief areas.

A 30m resolution state-wide mapping of potential bushfire prone areas was generated by applying the above three inputs into the McArthur fire intensity model, and is shown in Figure 2. As might be expected, bushfires mostly occurred in forestry areas with high elevations, while fewer bushfires occurred inland away from the coast and mountainous areas. High elevations also contribute to higher probability of ignition by electrical storms. Bushfire locations are found to be significantly influenced by the vegetation hazard class, and .most frequently occur in the Great Dividing Range, with the most flammable areas located in the Blue Mountains area.

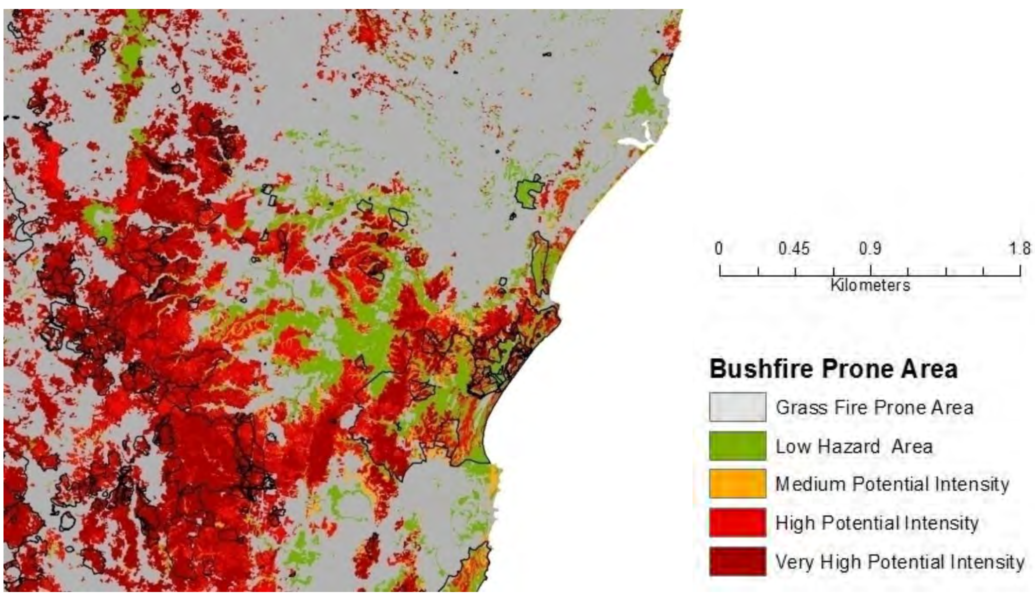


Figure 2: Bushfire prone area of NSW

The authors compared the high fire severity class with historical observations of burn data with a resulting overall accuracy of 72%, which indicates that this method is a reasonable predictor for bushfire prone areas in NSW (see Figure 3).

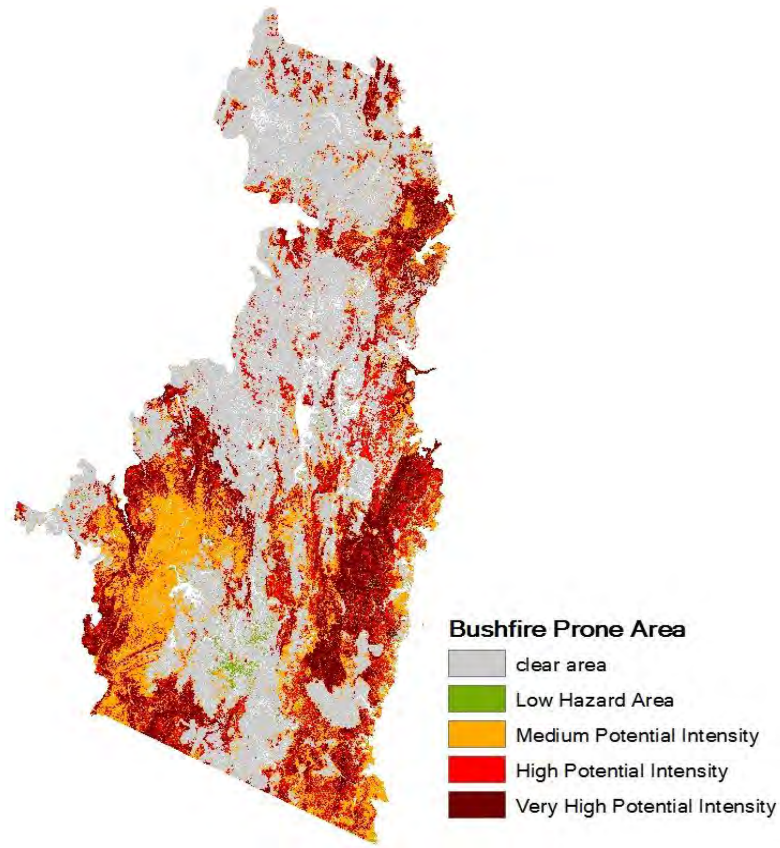


Figure 3: Bushfire prone areas in north coast area

Discussion

In this paper the authors studied the potential of a spatial model of fire intensity, based on the combination of McArthur forest fire behaviour model and Byram's fire-line intensity, to detect and map bushfire prone areas in the state of New South Wales, Australia. The McArthur model and Byram's fire intensity equation as the basis for modelling bushfire prone areas have been widely used in bushfire behaviour research in Australia. The results of this study provide an assessment of potential bushfire prone areas for the state of NSW and maybe useful for prediction purposes, and for the mitigation of potential bushfire impacts. But there are also some work need to do in the future. When the potential fuel load for vegetation hazard class is determined, a fixed value for each class is adopted, which was not really suitable in every case. For example, if 'freshwater wetlands' formation is assigned, this yields a low potential fuel load value of'3', but actually the bushfire fuel characteristics vary greatly between the vegetation classes within the freshwater wetland formation. In the freshwater wetlands class, Coastal Heath Swamps is a very flammable class due to its dense standing biomass of shrubs, while Coastal Freshwater Lagoons are very rarely flammable due to the low density of fuel, but they were all assigned a same potential fuel load '3'. As a result undervaluation of bushfire risk would occur in these areas. Therefore using a higher resolution fuel load data could improve the overall accuracy in future work.

Reference

Alexander, M. E. and M. G. Cruz (2012). "Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height." International Journal of Wildland Fire21(2): 95-113.

Byram, G. M. (1959). "Combustion of forest fuels." Forest fire: control and use1: 61-89.

Bond, W. and B. Van Wilgen (1996). "Fire and Plants (Population and Community Biology Series 14)." Chapmanand Hall, London, UK. Bond Fire and plants-population and community biology series 141996.

Buxton, M., et al. (2011). "Vulnerability to bushfire risk at Melbourne's urban fringe: the failure of regulatory land use planning." Geographical Research**49**(1): 1-12.

Chuvieco, Emilio. Wildland fire danger estimation and mapping: the role of remote sensing data. Vol. 4. World Scientific, 2003.

Clark, Andy, ed. Managing cover crops profitably. DIANE Publishing, 2008.

Cheney, P., J. Gould and L. McCaw (2001). "The dead-man zone—a neglected area of firefighter safety." Australian Forestry64(1): 45-50.

Chuvieco, E., I. Aguado and A. P. Dimitrakopoulos (2004). "Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment." Canadian Journal of Forest Research34(11): 2284-2293.

Chuvieco, E., I. Aguado, M. Yebra, H. Nieto, J. Salas, M. P. Martín, L. Vilar, J. Martínez, S. Martín and P. Ibarra (2010). "Development of a framework for fire risk assessment using remote sensing and geographic information system technologies." Ecological Modelling221(1): 46-58.

Environment, D. o. S. a. (2012). "Code of Practice for bushfire management of Public Land."

Gallant, J.C. and Wilson, J.P. (2000) Primary topographic attributes, chapter 3 in Wilson, J.P. and Gallant, J.C. Terrain Analysis: Principles and Applications, John Wiley and Sons, New York.

Gao, B.-C. (1996). "NDWI—a normalized difference water index for remote sensing of vegetation liquid water from space." Remote sensing of environment 58(3): 257-266.

Hussain, Mubushar, et al. "Emerging geo-information technologies (GIT) for natural disaster management in Pakistan: an overview." Recent Advances in Space Technologies, 2005.RAST 2005.Proceedings of 2nd International Conference on. IEEE, 2005.

Hurteau, M. D., G. W. Koch and B. A. Hungate (2008). "Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets." Frontiers in Ecology and the Environment6(9): 493-498.

Kalabokidis, K. D., N. Koutsias, P. Konstantinidis and C. Vasilakos (2007). "Multivariate analysis of landscape wildfire dynamics in a Mediterranean ecosystem of Greece." Area39(3): 392-402.

Leonard, J. and R. Blanchi (2014). Queensland Bushfire Risk Planning Project.

Makkonen, L. (2006). "Plotting positions in extreme value analysis." Journal of Applied Meteorology and Climatology45(2): 334-340.

Sanabria, L., et al. (2013). Mapping of Australian Fire Weather Potential: Observational and modelling studies. 20th International Congress on Modelling and Simulation (MODSIM 2013), Adelaide, December.

What is the Strategy? A Comparison of the Wildland Fire Decision Support System (WFDSS) and Incident Status Summary ICS-209

Morgan Pence*
USFS Wildland Fire Management RD&A, Salem, OR, USA, morganpence@fs.fed.us

Introduction

Home units provide direction for management of fires through Decisions created in the Wildland Fire Decision Support System (WFDSS). Decisions are required for federal wildland fires exceeding initial response or managed for multiple objectives. An optional strategy slider bar was added to the Course of Action section of Decisions in 2015. The slider scale is Monitor (value 0) to Suppression (value 100). The slider initiates at the mid-point (value 50) and must be saved to record a value. Users do not see the numerical values when using the slider.

The Incident Status Summary form (ICS-209) is required documentation for large fires, defined as 1) ≥ 100 acres in timber 2) ≥ 300 acres in grass/brush or 3) having a Type 1 or 2 Incident Management Team (IMT) assigned. Completed by local units or Planning Sections when IMTs are assigned, ICS-209s are submitted daily until containment with some variation. The ICS-209 form has four categories for strategy (Field 9D): Monitor, Confine, Point Zone Protection, Full Suppression. Users enter a percentage by category. This study compares the strategy directed in WFDSS by line officers to the one reported in the ICS-209 by fire managers.

Methods

This study focused on fires with WFDSS Decisions from January 1 through August 31, 2015. Optional use of the strategy slider bar was recorded for each fire. If the slider was used, the value, from 0 to 100, and the date it was saved was recorded. Then the strategy category and percent was recorded from the next available ICS-209 after that date (if none after that date then the latest available was used).

Line officers can change the WFDSS strategy over the life of a fire. Changes made within a day were assumed to be editing; recording the value at the end of the day. Changes made greater than a day were assumed to represent a change in strategy and were recorded separately, with the ICS-209 strategy for the next available date thereafter captured.

Results

General Data

There were 598 fires with WFDSS Decisions (1/1-8/31/2015); for a total of 669 strategies. Sixty fires changed the strategy in WFDSS one or more times. Strategies by Geographic Area are shown in Figure 1. Although the strategy slider bar was optional, it was widely used by all Geographic Areas; none had less than 80% use, with 85% use overall.

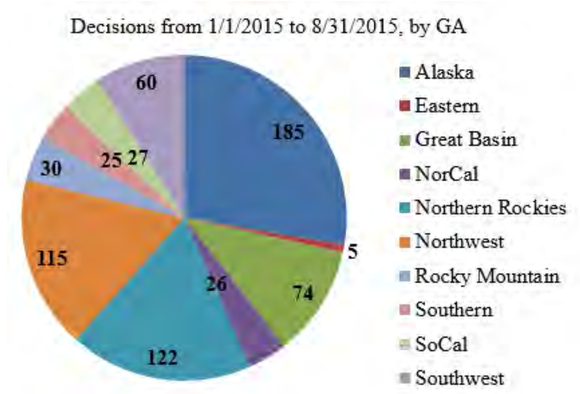


Figure 1 Number of strategies by GA for fires with Decision 1/1-8/31/2015.

Strategy Overall
Comparing strategies from WFDSS (directed) to the ICS-209 (reported) indicates: suppression is directed less than reported, monitor is directed less than reported, a mixed strategy is directed more than reported. Figure 2 shows a comparison between WFDSS and ICS-209 strategies for the fires overall. In WFDSS the directed strategy is less black and white compared to the ICS-209; a "mixed" strategy is directed more than double the amount than is reported.

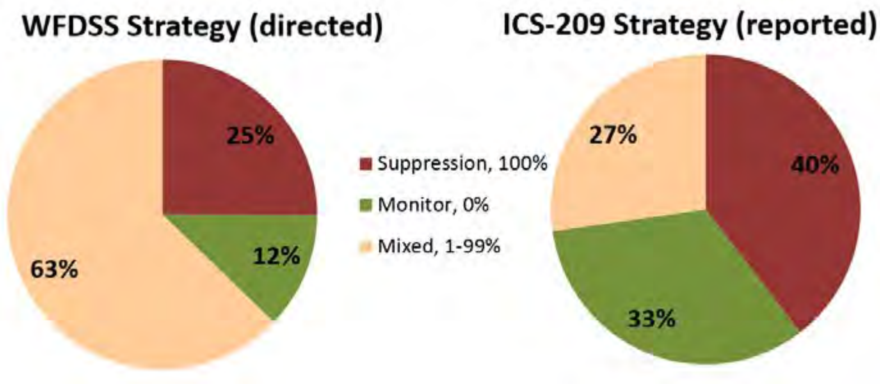


Figure 2 Comparison of strategy in WFDSS to ICS-209 overall.

Strategy by Geographic Area
Comparing strategies from WFDSS to the ICS-209 by area yields interesting nuances, Figure 3. For example, Northern (NorCal) 100%, and Southern California (SoCal) 85%, had the highest

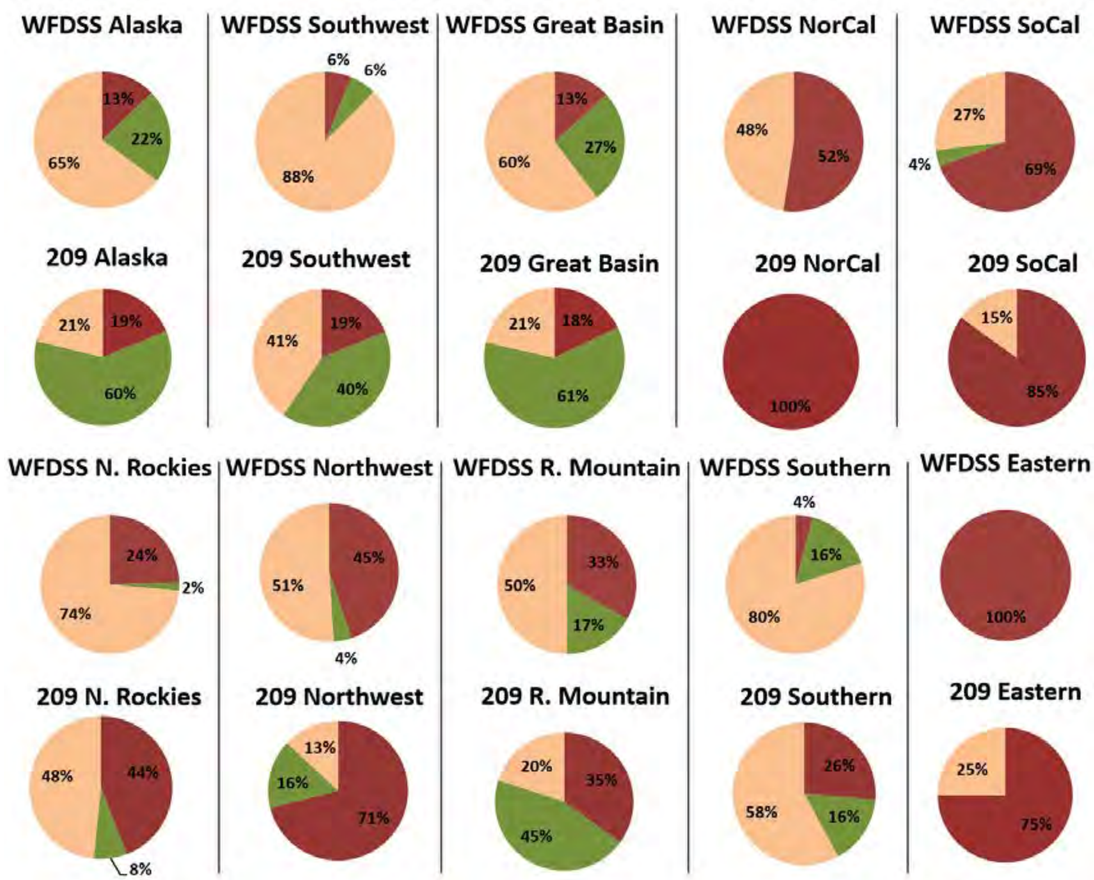


Figure 3 Comparison of strategy in WFDSS to ICS-209 by Geographic Area.

percentages of reporting Suppression; Great Basin had the lowest at 18%. Great Basin had the highest percentage of reporting Monitor at 61%. All NorCal fires reported Suppression but it was only directed 52% of the time. The Southwest directed Monitor 6% of the time but was reported almost 7-fold more at 40%. Despite intricacies in the data, the overall trend of directing Monitor and Suppression less often than reported holds true for all areas except Eastern.

Comparing Fire by Fire

Fire by fire comparisons were made nationally and by Geographic Area for the following scenarios, Table 1.

- The percent of time a WFDSS strategy for a specific incident directed Suppression when the ICS-209 reported Suppression.
- The percent of time a WFDSS strategy for a specific incident directed Monitor when the ICS-209 reported Monitor.
- The percent of time an ICS-209 reported Suppression when WFDSS directed anything other than Suppression.

These scenarios indicate the level of agreement between directed and reported strategy.

Table 1 National and Geographic Area comparisons of strategy fire by fire.

Geographic Area	% of time WFDSS directed Suppression when ICS-209 reported Suppression	% of time WFDSS directed Monitor when ICS-209 reported Monitor	% of time ICS-209 reported Suppression when WFDSS directed anything other than Suppression
Nationally	54%	28%	25%
Alaska	35%	31%	14%
Eastern	100%	N/A[1]	N/A[2]
Great Basin	50%	32%	10%
NorCal	58%	N/A[1]	100%
Northern Rockies	51%	14%	29%
Northwest	63%	27%	51%
Rocky Mountain	71%	44%	0%
Southern	20%	0%	22%
SoCal	65%	N/A[1]	100%
Southwest	17%	8%	17%
	High % = greater agreement	High % = greater agreement	Low % = greater agreement

Nationally, when ICS-209 reported Suppression it was only directed in WFDSS roughly half of the time (54%). Eastern Area had the greatest agreement on strategy reported in ICS-209 and directed in WFDSS, when ICS-209 reported Suppression, at 100%. Whereas Southwest, Southern, and Alaska Areas had the least agreement at 17%, 20%, and 35% respectively.

Agreement between WFDSS and ICS-209, when ICS-209 reported Monitor was low nationally (28%) and for all areas (excluding Eastern, NorCal, and SoCal[1]). Southern Area had the least

[1] Eastern, NorCal, and SoCal did not have any ICS-209s reporting Monitor as the strategy

agreement with respect to Monitor at 0%; the area with the greatest agreement was Rocky Mountain at 44%.

When an ICS-209 strategy reported Suppression but WFDSS directed anything other than Suppression the agreement in strategy differed greatly between Geographic Areas. Nationally this occurred 25% of the time, however in two areas, NorCal and SoCal, it happened 100% of the time, while in Rocky Mountain 0% of the time.[2]

Discussion

A Closer Look

Looking further at the details yields more insight and questions. Table 2 displays the value of the WFDSS slider (0% = monitor, 100% = suppression) and the reported Suppression strategy by category in the ICS-209 for some example fires in the dataset. If you were the line officer on these fires and you saw what the reported strategy was in the ICS-209, how confident would you be that the direction you provided in the WFDSS Decision with regard to strategy was followed?

Table 2 WFDSS strategy slider values vs. ICS-209 percent by category

Incident	**WFDSS Strategy Slider %** (0%=monitor, 100%=suppression)	**ICS-209 Category and %**
Bridge	61%	100% Suppression
Mount Emma	19%	100% Suppression
SA Hill	27%	100% Suppression
Thursday Creek	31%	100% Suppression
Tween	22%	100% Suppression
Barnaby	32%	100% Suppression
Jay Pt	80%	100% Suppression
Little Devil	79%	100% Suppression
Peters	100%	100% Confine
Card Street	44%	95% Suppression, 5% Monitor
Juneau Lake	69%	100% Suppression
Deepbank Creek	58%	100% Monitor
Rock	22%	100% Suppression
Golsovia #3	100%	100% Monitor
Village Creek	100%	100% Point Zone Protection
Keefer Cutoff	100%	100% Monitor
Mission Creek	100%	100% Point Zone Protection
Medicine Creek	100%	100% Confine
Pontag	100%	100% Monitor
Wolf Creek	79%	100% Suppression
Saddle Lakes	82%	100% Suppression

[2] All Eastern Area fires directed a Suppression strategy in WFDSS

Now let's flip that question around, imagine you are the Incident Commander for the fires in Figure 4 and 5. If you saw the direction provided on strategy in WFDSS for these fires, how would you direct your firefighters on the ground and how would direct your team to fill out the ICS-209 for strategy?

Figure 4 shows the strategy in a WFDSS Decision in which the author wrote that the strategy is "Full Suppression" but placed the slider at a value of 82%.

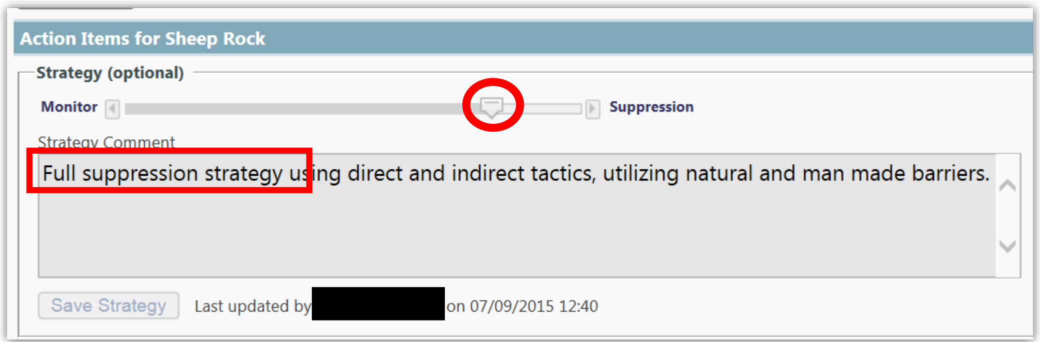


Figure 4 Strategy slider for a fire set to 82% while written direction says "Full Suppression."

Figure 5 shows the WFDSS strategy for a fire in which the author wrote the strategy is "100% Suppression" but also adds it is "point protection" and "contain/confine tactics." There is no way to represent a strategy in ICS-209 in three categories if one of them is listed at 100%.

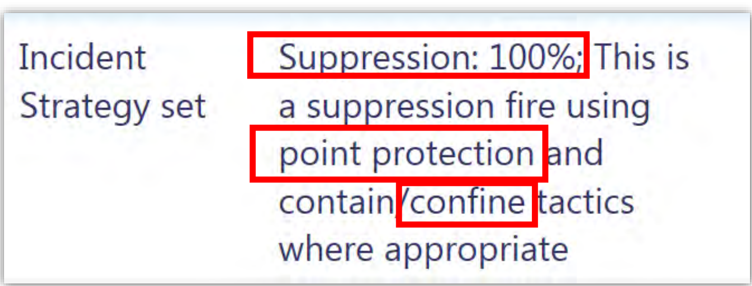


Figure 5 This fire's WFDSS strategy states 100% Suppression, but also lists point protection and confine.

What Does This Mean?

Clearly there are some disconnects between the directed strategy for a fire in WFDSS to what is reported as the strategy in ICS-209 and it varied by Geographic Area in 2015. More than one factor may be the cause:

- Differences in user interfaces. In WFDSS users are presented with a scale for selecting strategy, but in ICS-209 they are presented with categories. Does the manner in which the user is presented with options impact the selection? Does presenting a scale (WFDSS) lead users to select a value in the middle more often than presenting by category (ICS-209)?

- A result of the 2015 fire season. Are the nuances in the strategies by each Geographic Area a result of the 2015 fire season specifically or a reflection of direction and management for the area in general regardless of the type of fire season an area experienced in 2015?
- Misunderstanding/unintended use of the WFDSS strategy slider. There were clear instances in WFDSS where user entered data regarding strategy did not match the numeric value saved on the strategy slider. Either, users did not realize or did not care that selecting *Save Strategy* in the WFDSS strategy section would save a value on the slider, which by default is set in the middle, at a value of 50. Of the 23% of fires in which the strategy value was 50 some represent unintended use of the slider, but it would be impossible to say that all 23% were unintended use without verifying with each decision author.

The same question is posed to two different audiences in different ways. Does this inherently increase opportunities for misunderstanding of strategy? Line officers get a slider bar with two distinct strategies at either ends of a continuum, while fire managers get four categories. Furthermore, just because WFDSS and ICS-209 do not always match does not mean a misunderstanding happened between line officers and fire mangers with regard to strategy. It is possible the slider did not match the direction provided in the Incident Objectives and Requirements and through inbriefing, or perhaps the ICS-209 reporting is not reflective of what is occurring on the ground. Because directing and reporting of strategy do not use the same system and terms it is not even possible to have an exact match on strategy anytime the strategy is something other than Suppression or Monitor.

Why are managers asked to indicate strategy in different ways? Perhaps WFDSS should present strategy in a similar manner as ICS-209? Or maybe ICS-209 the same as WFDSS? What if WFDSS prepopulated the ICS-209 strategy via the Integrated Reporting of Wildland Fire Information (IRWIN) for fires with Decisions? Would that force a conversation between line officers and fire managers when there is a disconnect on directed and reported strategy?

Recommendations

To enable line officers and fire managers to communicate clearly with regard to strategy the fire community needs a data standard for the strategy on a fire. IRWIN should be used to populate the strategy throughout fire systems to reduce inaccurate and duplicate data entry. An authoritative data source (ADS) would need created to indicate which fire reporting/information/decision system was the authoritative source for strategy under different circumstances (i.e. when there is a published decision, when there is not a published decision).

Further research could be completed comparing the Strategic Objectives and Management Requirements from the Land and Resource Management Plan (LRMP) and the Incident Objectives and Requirements providing leader’s intent to both the WFDSS strategy slider bar and ICS-209 to evaluate if decision making and actions on the ground are in alignment with the LRMP direction.

When there's Fire there's Smoke: Linking Wildfire to Distant Urban Airsheds. A 10 Year Health Economic Assessment of the Western US, 2005-2014

Benjamin A. Jones[A]
Robert P. Berrens[B]

[A]Postdoctoral Researcher, University of Oklahoma, Center for Risk and Crisis Management/Center for Energy, Security & Society, 5 PP, 201 Stephenson Parkway, Suite 2300, Norman, OK, USA 73019, bajones@ou.edu
[B]Professor of Economics, MSC 05 3060, 1 University of New Mexico, Albuquerque, NM USA 87131, rberrens@unm.edu

Abstract:

Wildfire smoke is increasingly affecting air quality in urban areas distant from flame zones, particularly in the Western US. At present, little is known about the aggregate health costs of smoke across this increasing highly urbanized region. To address this knowledge gap, this study provides the first regional time series estimates of morbidity incidence and associated costs of wildfire smoke across the 18 largest metropolitan areas (>750,000 population) in the Western US over 2005-2014. A benefit transfer methodology is applied using the US EPA Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE). Results suggest that wildfire smoke over western airsheds is becoming more frequent. Over the past 10 years, health incidence has increased by an average of 9.8%/yr and health costs by 4.7%/yr. Aggregate health costs range from a low of $4.5 million in 2006 to a high of $19.7 million in 2013. There is substantial spatial and temporal heterogeneity in smoke health impacts across years and urban areas. A policy application of this work is that individuals in Western communities, consistent with their economic preferences, may be willing to pay for distant mitigation efforts in order to reduce the variability and severity of disruptions to their airsheds caused by wildfire.

Additional Keywords: wildfire smoke; economic costs; health; risk mitigation

Extended Abstract:

Introduction

There is concern that wildfire smoke is increasingly affecting urban airsheds distant from the flame zone, particularly in the Western US. Climate change, drought, and continued fuels build-up are expected to increase the magnitude and severity of Western wildfire smoke events. However, little is known about the aggregate health costs of smoke across this geographically expansive and increasingly, highly urbanized, region.

This is particularly troublesome in light of recent and ongoing discussions surrounding wildland fire management, broadly defined, and mitigation budgets, in which a complete picture of the full costs of wildfire is presently lacking. For example, the recent joint-position statement by the IAWF, Association for Fire Ecology, and The Nature Conservancy on wildfire risk and costs,[1] argues that there is a large disconnect (sometimes by orders of magnitude) between the actual costs of wildfire events and the measured costs that appear in official damage assessments. Wildfire smoke health costs are one source of disconnect given our limited understanding of the spatial and temporal distribution of health impacts during a wildfire event.

Methods

To address this knowledge gap, this study provides the first regional time series estimates of morbidity incidence and associated costs of wildfire smoke across the 18 largest metropolitan areas (populations greater than 750,000) in the Western US over 2005-2014. A benefit transfer methodology is applied using the US EPA Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE).[2] In a benefit transfer, available information from studies already completed are transferred to another location or context to estimate economic values for ecosystem services. This is a commonly used approach for estimating wildfire smoke health damages (e.g., Jones et al., 2015).

Wildfire-specific health incidence functions from Resnick et al. (2015) and Delfino et al. (2009) are used to capture relationships between smoke and health. A wildfire-specific willingness to pay measure ($130.79/wildfire event lasting 4.5 days) is used from Jones et al. (2015) – how much are you willing to pay to avoid a wildfire smoke health impact? The pollutant PM2.5 is focused on and air quality data used comes from the US EPA AirData network.[3] A wildfire smoke day is identified as a day at a monitoring site where PM2.5 > 99^{th} percentile of the previous five-year daily moving average.

Results

Results suggest that the health costs of wildfire smoke in the Western US are substantial and on the rise. Incidence is increasing at a rate of 9.7%/yr. on average over the past 10 years (Figure 1). Costs are increasing at an average rate of 4.7%/yr. (Figure 2), though are highly variable depending on the severity and duration of the smoke event. Aggregate health costs range from $4.5 million in 2006 to $19.7 million in 2013 for the 18 urban areas investigated (Figure 3). There is significant spatial and temporal variability in incidence and costs across the landscape

[1] http://www.iawfonline.org/Reduce-WIldfire-Risk-16-April-2015-Final-Print.pdf
[2] https://www.epa.gov/benmap
[3] https://www3.epa.gov/airdata/

that is only marginally associated with the size of the burn area. Some areas (e.g., southern California) are routinely affected by wildfire smoke, while other areas (e.g., Salt Lake City, UT) experience almost no wildfire smoke impacts. There is a degree of randomness as to whether a given city will experience a smoke event or not in a particular year, depending on weather patterns and distance to the flame zone.

Conclusion

This research establishes the first trend and reference point of the magnitude of economic costs of health impacts associated with large-scale airshed events precipitated by wildfire smoke. Given the ongoing implementation challenge of finding sustainable mitigation funding mechanisms, a policy implication of this research is to expand the scope of potential funding sources to communities, distant from the flame zone, who nonetheless can be significantly impacted by wildfire. Individuals in Western communities, consistent with their economic preferences, may be willing to pay for distant mitigation efforts in order to reduce the variability and severity of disruptions to their airsheds caused by wildfire smoke.

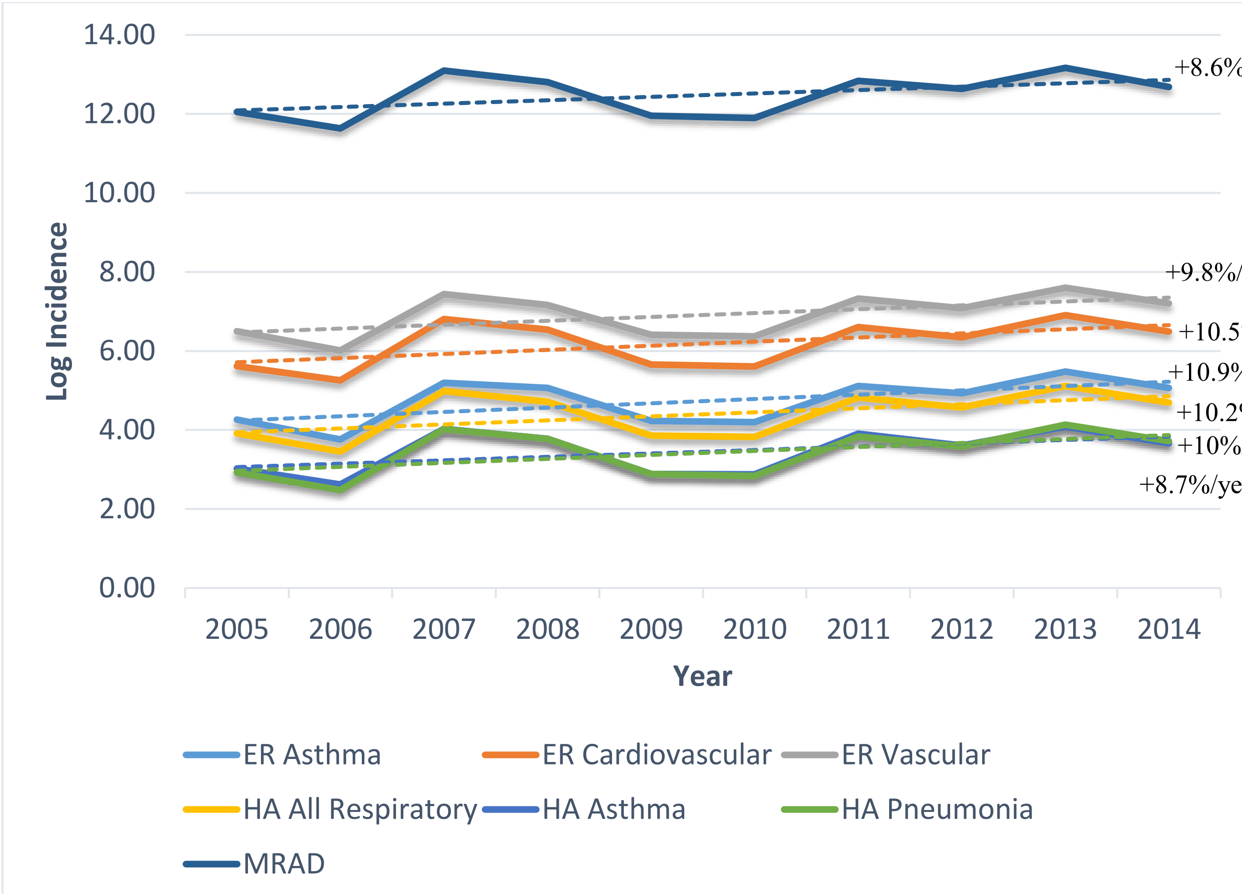
References:

Delfino, R. J., Brummel, S., Wu, J., Stern, H., Ostro, B., Lipsett, M., ... & Gillen, D. L. (2009). The relationship of respiratory and cardiovascular hospital admissions to the southern California wildfires of 2003. *Occupational and Environmental Medicine*, *66*, 189-197.

Jones, B. A., Thacher, J. A., Chermak, J. M., & Berrens, R. P. (2015). Wildfire smoke health costs: a methods case study for a Southwestern US ‘mega-fire’. *Journal of Environmental Economics and Policy*, 1-19.

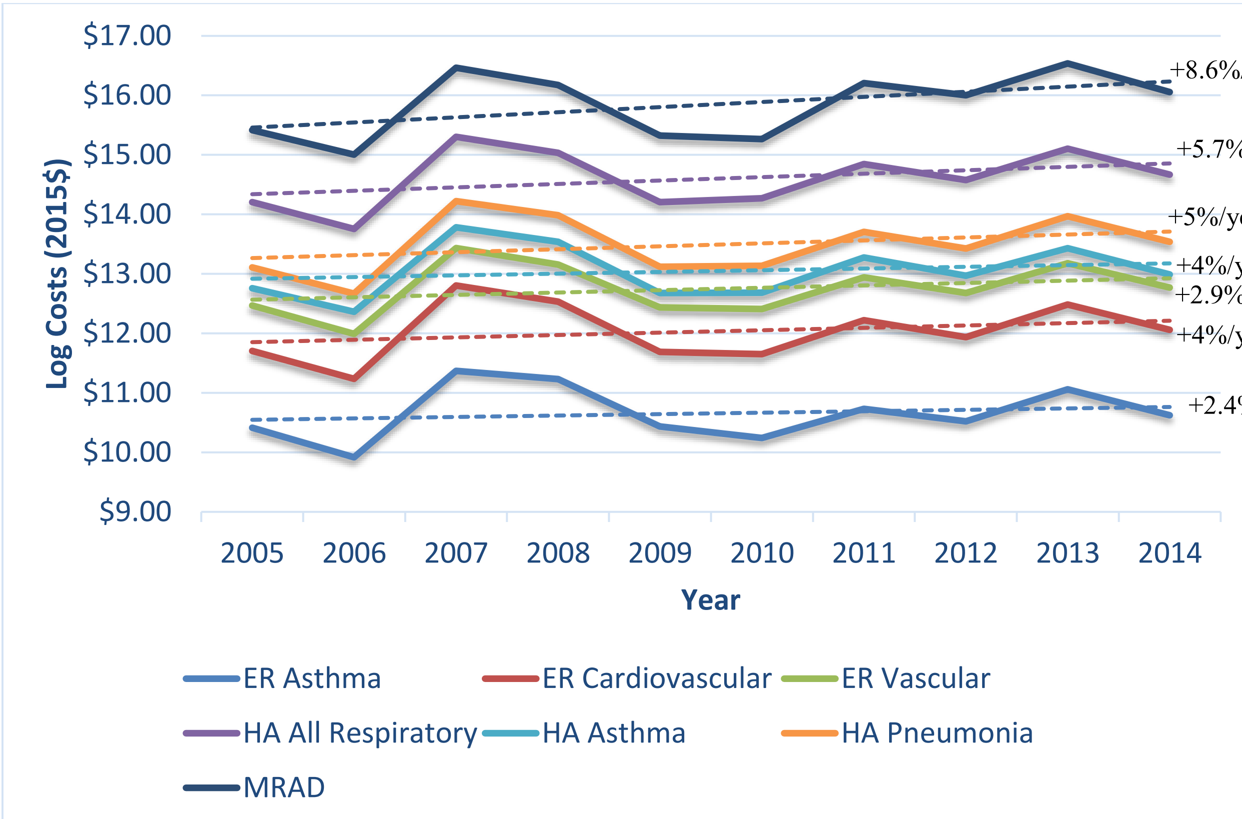
Resnick, A., Woods, B., Krapfl, H., & Toth, B. (2015). Health outcomes associated with smoke exposure in Albuquerque, New Mexico, during the 2011 Wallow fire. *Journal of Public Health Management and Practice*, *21*, S55-S61.

Figure 1: Wildfire Smoke (Log) Incidence for Western US MSAs >750k population, 2005-2014



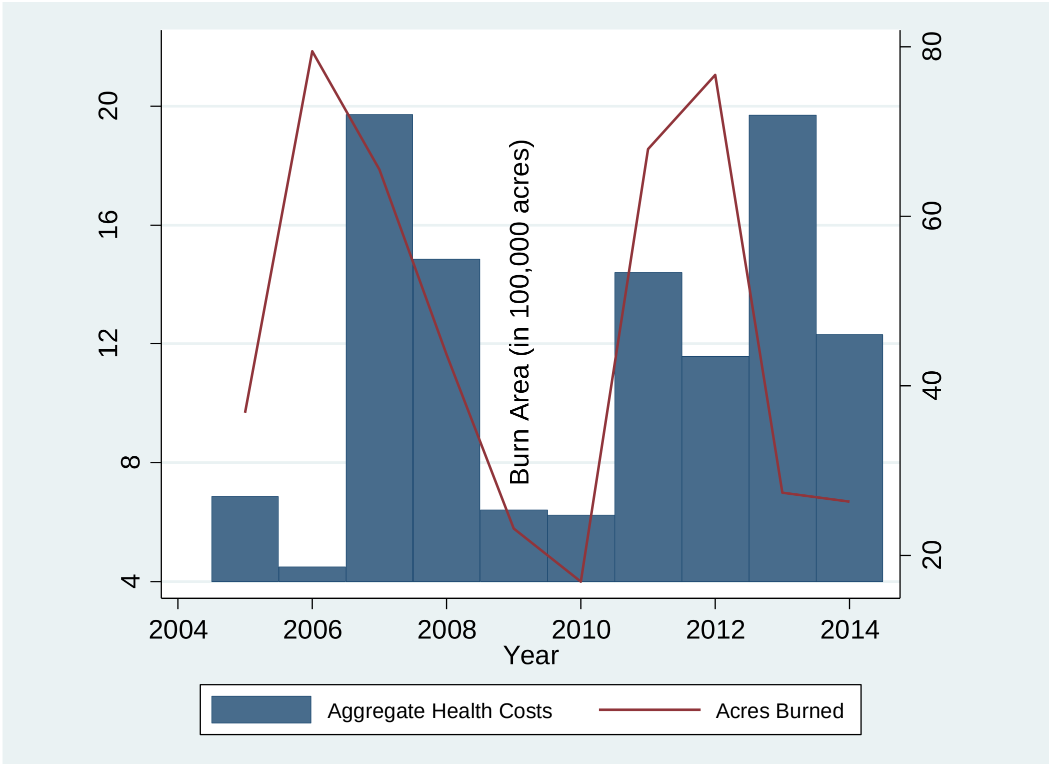
Average annual growth rates given per health endpoint. ER=emergency room, HA=hospital admissions, MRAD=minor restricted activity days.
Urban areas investigated are: Phoenix, AZ; Tucson, AZ; Bakersfield, CA; Fresno, CA; Oxnard, CA; Sacramento, CA; San Jose, CA; San Francisco, CA; San Diego, CA; Los Angeles, CA; Riverside, CA; Denver, CO; Albuquerque, NM; Las Vegas, NV; Portland, OR; El Paso, TX; Salt Lake City, UT; Seattle, WA.

Figure 2: Wildfire Smoke (Log) Costs for Western US MSAs >750k population, 2005-2014



Average annual growth rates given per health endpoint. ER=emergency room, HA=hospital admissions, MRAD=minor restricted activity days.
Urban areas investigated are: Phoenix, AZ; Tucson, AZ; Bakersfield, CA; Fresno, CA; Oxnard, CA; Sacramento, CA; San Jose, CA; San Francisco, CA; San Diego, CA; Los Angeles, CA; Riverside, CA; Denver, CO; Albuquerque, NM; Las Vegas, NV; Portland, OR; El Paso, TX; Salt Lake City, UT; Seattle, WA.

Figure 3: Aggregate Health Costs & Acres Burned across Western States with MSAs >750k population, 2005-2014



Health costs for non-overlapping endpoints (ER asthma, ER cardiovascular, ER vascular, HA all respiratory, and MRADs). Annual burn area data (acres) from National Interagency Fire Center. 9 states included are: AZ, CA, CO, NV, NM, OR, TX, UT, WA

A model of ember risk for improved bushfire risk management in the peri-urban fringes
5th International Fire Behaviour and Fuels Conference

Melanie E. Roberts*, Andrew Rawlinson and Ziyuan Wang
IBM Research – Australia, Carlton Victoria, Australia, and University of Melbourne, Parkville, Victoria, Australia, melanie.roberts@au1.ibm.com
IBM Research – Australia, Carlton Victoria, Australia, arawlins@au1.ibm.com
IBM Research – Australia, Carlton Victoria, Australia, ziwang@au1.ibm.com

Introduction

The management of bushfire risk in peri-urban communities maintains a strong focus on risk factors associated with the fire front, namely the risk to properties from radiant heat and direct flame contact. With embers a contributing factor in the majority of property damage and loss cases from bushfires in Australia, further consideration to the risk posed by embers is required for effective bushfire risk management. Although consideration is given to embers from a property perspective, for example with building codes to prevent gaps through which embers can enter a property, or via fire preparedness material from local agencies, bushfire risk management tends not to explicitly consider the localised ember risk and the contributions to ember risk from local bushland.

Following the Warrangine Park bushfire, in Hastings, Victoria, the Mornington Peninsula Shire Council and Country Fire Authority (CFA) commissioned a report into the fire, including a determination on the effectiveness of the existing Fuel Management Zones (FMZs) in achieving "no potential for flame or radiant heat ignition of houses and other key assets" (Terramatrix, 2015, p.1). The report concluded that

> "Although a number of dwellings were ignited, this was from ember attack or from combustible material burning within the private property such as garden vegetation, planter boxes and decking. The FMZ was considered to have achieved the objective of preventing radiant heat and flame ignition of houses from a fire in the reserve."(Terramatrix, 2015, p.3)

and while it is clear that the FMZs did achieve their stated aim, this approach indicates a lack of consideration for the contribution of government managed land on the ember risk to properties. Such an approach is not unique to the Mornington Peninsula Shire, see for example the fire management plans of the City of Gold Coast and Great Lakes Council, which likewise focus on direct impacts of the fire without specification for ember attack.

Whilst it is readily acknowledged that the Mornington Peninsula Shire actively considers the risk of embers in their fire management plans, such consideration appears to be restricted to building codes and the requirement for minimum Bushfire Attack Level (BAL) ratings. A BAL greater than or equal to 12.5 is considered to provide protection against ember attack (Terramatrix, 2015), however of the six properties (BAL >12.5) in the Warrangine Park bushfire report (Terramatrix, 2015), four of these sustained damage to either the house or surrounding structures. The contribution of embers to house damage in the Warrangine Park bushfire is not atypical. Within the Australian context, embers are a leading contributor to house damage and loss. For

*Melanie Roberts
IBM Research – Australia
Lvl 5, 204 Lygon St, Carlton Vic 3053, Australia
melanie.roberts@au1.ibm.com

example, in their survey of the Duffy region following the Canberra 2003 bushfire, Blanchi *et al.* (2006) found that embers only and embers with some radiant heat were the dominant causes of house loss and damage. With embers a leading contribution to house loss and damage in the Australian context, it is prudent to directly consider ember risk in any understanding of bushfire risk to properties.

Property level models of bushfire risk

Examination of property and environmental contributions to risk is well-established, with numerous models having been developed within the Australian and other contexts, such as Wilson and Ferguson's (1986) House Survival Likelihood Function, based on an examination of 450 houses affected by the 1983 Ash Wednesday fire at Mount Macedon, Victoria; Tolhurst and Howlett's (2003) House Ignition Likelihood Index, which is focussed on the contribution of weather and local fuel levels to risk; and the previously mentioned Bushfire Attack Level (NSWRFS, 2012). These models all seek to provide a quantification of bushfire risk at the property level, however are limited in their ability to be applied at scale.

The BAL is a static measure of risk invariant with changing fire-weather conditions. Focused on town planning and the application of construction standards, the BAL may be considered a poor-weather ranking, with little relevance during the winter months. The House Survival Likelihood Function incorporates factors of the weather, via the potential fire intensity, with some functions of defensibility such as occupant presence, garden vegetation, slope and construction. Presented both as an equation and via a circular meter (Wilson, 1988), the function provides a simple way to quantify risk, however the use of piecewise discontinuous functions results in step changes to risk that are not physical, a feature also of the BAL formulations. The House Ignition Likelihood Index is focussed on the impact of weather and local fuel supplies, providing a detailed understanding of the available fuel load in the vicinity of the home. This Index however requires expert knowledge to implement, which is not typically available within a community, as acknowledged by the authors (Tolhurst and Howlett, 2003).

The value of quantifying bush fire risk is well established, as it enables Government, communities, and individuals to understand and pro-actively manage this risk. Current methods of quantifying bush fire risk are however either applied across large regional areas, e.g. the Forest Fire Danger Index, or are limited in their application at scale due to the required information sources.

This research seeks to address these limitations through the development of a dynamic risk function based primarily on publicly available data sources, where the risk index can be refined through the inclusion of additional data sources, for example from direct entry of information by a home owner. In this work the ember contribution to this risk is explored, which is one component of the total risk index.

Ember risk

A property's ember risk has three components; the ember load impacting a property, the likelihood of ignition at the property, and the likelihood that embers will not be extinguished,

Table 1: Example factors contributing to bushfire risk in peri-urban environments.

Environmental Factors	Property Factors	Occupant Factors
• topography • proximity to bushland • bushland load • fuel load • vegetation type • temperature • humidity • windspeed and direction	• house construction • garden vegetation • nearby structures • access • water availability • maintenance and tidyness • defensive mechanisms	• preparedness • resilience • capability of occupants • occupant experience • care requirements of occupants

where these components are themselves functions of many factors. Table 1 provides a summary of key factors for ember risk, from the local environment, the property, and of the occupants.

In this analysis we consider the first component: the contribution of local bushland to the potential ember load experienced by a property during a bushfire. The characteristics of the fire, local weather as well as variations in vegetation type, fuel loads and the location and distribution of bushland in the vicinity of homes affects the number of embers that can be expected to impact a property in the event of a bushfire.

Guided by the results of Thurston *et al*. (2014) we introduce a number density function (NDF) to describe the distribution of embers originating from a point source. This NDF is composed of four factors; a 2D probability density function (PDF) modelled on the normal distribution to reflect the underlying behaviour of the ember spread, a fire-intensity based correction on the available ember load at the source, a correction to account for the time-dependent component of ember viability due to burnout or blowout, and the fuel load available at the source.

The underlying behaviour identified by Thurston *et al*. (2014) is captured in the PDF

$$\frac{1}{2\pi\sigma_x \sigma_y/\mu_x}\exp\left[-\frac{1}{2}\left(\left(\frac{x-\mu_x}{\sigma_x}\right)^2+\left(\frac{y-\mu_y}{\sigma_y x/\mu_x}\right)^2\right)\right], \qquad (1)$$

which is the two-dimensional normal distribution centered at the origin *(x,y) = (0,0)* with a modified standard deviation in the lateral *y* direction, subject to a background windspeed of u $m.s^{-1}$ in the positive *y*-direction. The standard deviations and means are given by σ_x and μ_x in the horizontal *x,* and σ_y and μ_y in the lateral *y* directions, respectively. The standard deviation σ_y is modified to account for the increase in spread with distance from the source observed in Thurston *et al*. (2014). In their analysis, Thurston *et al*. identified the distribution of embers originating from a point source subject to a varying background wind, without consideration for the impact of fire intensity on this distribution or on the number of embers released into the plume.

It is well understood that large fires have a considerable impact on ember behaviour beyond that accounted for by the background windspeed. In large fires the threat of spotting ignition increases in line with the scale of the fire, with larger fires producing enhanced plume behaviour capable of lifting larger embers and carrying embers further from the source (Koo *et al*., 2012).

As fire intensity is quadratically proportional to the background windspeed, we assume a quadratic dependency on the windspeed for the number of embers able to be lofted by the fire activity, by introducing the correction to Eq (1) of $1+(u/u_{ref})^2$, where u_{ref} is the reference windspeed, thus not only does a greater windspeed correspond to a greater mean and standard deviation in the horizontal direction of the available embers, but an increase in the number of embers produced by the fire.

A second correction to Eq (1) is introduced to account for the effective lifespan of the embers. Following Dold *et al*. (2011) we assume that the number of effective embers decreases linearly with time, which is reflected through distance from the origin. The correction is given by

$$\left(1-\frac{\sqrt{x^2+y^2}}{d_{\max}}\right)H\left(d_{\max}-\sqrt{x^2+y^2}\right), \qquad (2)$$

where H is the Heaviside Function, and d_{max} is the applied maximum distance embers can theoretically be transported. Thus the distribution of embers from a point source located at the origin subject to a background windspeed u is given by

$$\rho_E(x,y)=\frac{1+\left(u/u_{ref}\right)^2}{2\pi\sigma_x\sigma_y/\mu_x}\exp\left[-\frac{1}{2}\left(\left(\frac{x-\mu_x}{\sigma_x}\right)^2+\left(\frac{y-\mu_y}{\sigma_y x/\mu_x}\right)^2\right)\right]\left(1-\frac{\sqrt{x^2+y^2}}{d_{\max}}\right)H\left(d_{\max}-\sqrt{x^2+y^2}\right), \qquad (3)$$

and by convolution the cumulative ember load at a property is given by

$$\eta_{EF}\left(x,y\right)=\left(\rho_E*\eta_F\right)\left(x,y\right)=\int dx_1\int dy_1\rho_E\left(x_1,y_1\right)\eta_F\left(x-x_1,y-y_1\right), \qquad (4)$$

where η_F is the fuel load at the point of origin in $t.ha^{-1}$. The ember distribution for a range of background windspeeds between 2.5 and $15m.s^{-1}$ is shown in Figure 1. While a single NDF for the ember distribution has been introduced, where sufficient information is available different fuel types may be considered independently.

Application to communities

The presented ember load model, whilst simplifying a number of physical processes of ember spread, is constructed in such as way as to enable application at scale. A key limitation of previous models for property level risk has been the reliance on expert or personalised information. The developed model for bushfire risk, of which the ember model presented is one component, uses publicly available data sources to identify the baseline risk, where localised data sources can be incorporated to provide improved accuracy.

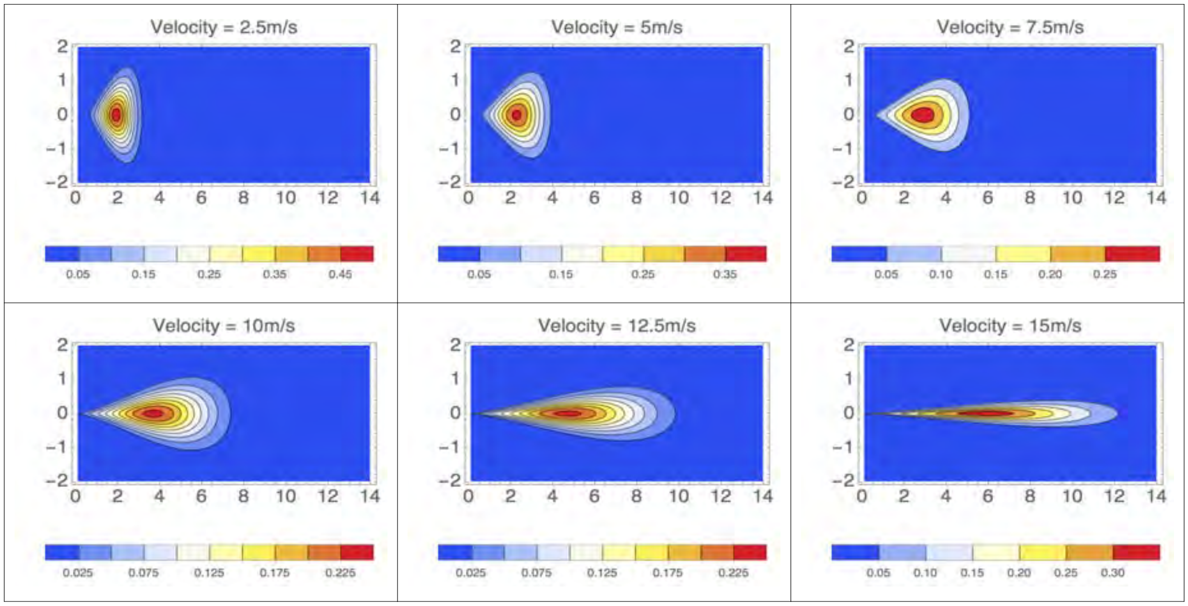


Figure 1: Two –dimensional spatial distribution of ember load for background windspeeds of 2.5, 5, 7.5, 10, 12.5 and 15 $m.s^{-1}$ corresponding to an unit available ember load at the origin (0,0), with u_{ref} = 150, d_{max} = 30 and 0.1*km* discretisation.

This ember model is demonstrated through an example scenario, shown in Figure 2, of a housing estate bordering bushland. The fuel load is indicated through the green heat map, with the risk score shown in red (darker colours correspond to higher fuel load and risk) for two background wind scenarios, 2 and 10 $m.s^{-1}$. The parameters used in this example are as for Figure 1. The footprint of ember risk is seen to increase significantly with the greater windspeed, as is the risk score experienced by the properties. It should be noted that the relative risk scores between the different wind scenarios is controlled by the choice of parameters, and that further analysis is required to understand appropriate values for different scenarios. Nonetheless, these results illustrate the key features of ember risk identified in previous research; an increased ember load and greater horizontal and reduced lateral reach of the ember storm with higher windspeeds.

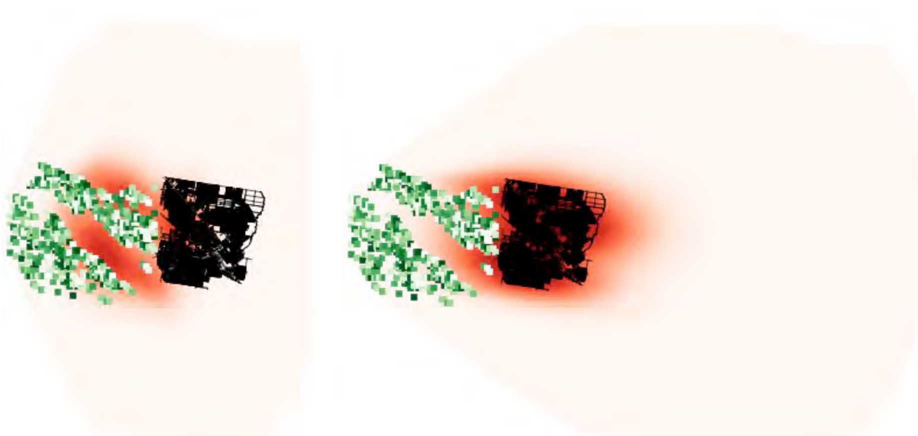


Figure 2: Illustrative risk profile for a community adjacent to bushland for background windspeeds of 2 (left) and 10 $m.s^{-1}$ (right). Darker greens correspond to a higher fine fuel load, with darker red shades corresponding to a higher risk index.

Conclusion

Analysis of bush fire impacts on properties demonstrates that embers are a dominant cause of property damage and loss in the Australian context, yet management of bushland in the peri-urban environment remains focussed on the radiant heat and direct flame contact risks. This work presents a model for the ember risk to a property, based on the distribution of embers from surrounding bushland. Through this model, the contribution of embers to property-level risk can be identified and communicated, empowering individuals and communities to pro-actively manage their risk

Identification of dynamic property-level risk is an important step in empowering home owners to reduce their risk. Together with mobile technologies, the developed model of risk, of which ember load is one component, provides the input to a personalised risk advisor, which assists homeowners in understanding their local risk and exploring mitigative options.

Further work in this area will focus on parameterising the model using available data of bushfire impacts on properties, and of incorporating additional features of ember risk such as the sheltering effect of houses and other structures in the windpath of the target property.

References

‘BAL Risk Assessment Application Kit. New dwellings and alterations and additions to existing dwellings.’ (2012). NSW Rural Fire Service.

Blanchi RM, Leonard JE, Leicester RH (2006) Bushfire risk at the rural/urban interface. http://bushfirecrc.com/sites/default/files/managed/resource/bushfire_risk_at_the_rural_urban_interface_-_brisbane_2006_0.pdf.

Dold J, Scott K, Sanders J (2011) The processes driving an ember storm. *Proceedings of the 19th International Congress on Modelling and Simulation, Perth, Australia, 12 – 16 December 2011.*

Koo E, Pagni, PJ, Weise DR, Woycheese JP (2010) Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire* **19** 818 – 843.

Terramatrix (2015) ‘Hastings Bushfire Case Study Warringine Park (Coastal Section) 3rd January 2015’. Terramatrix Wildfire Management Services. Report commissioned by Mornington Peninsula Shire & CFA. (Victoria, Australia).

Thurston W, Tory KJ, Kepert JD, Fawcett RJB (2014) The effects of fire-plume dynamics on the lateral and longitudinal spread of long-range spotting. *Proceedings of the Research Forum at the Bushfire and Natural Hazards CRC & AFAC Conference, Wellington, 2 September 2014.*

Tolhurst KG, Howlett KA (2003) House Ignition Likelihood Index – An Hazard Assessment Method for Land Management in the Wildland-Urban Interface. http://www.fire.uni-freiburg.de/summit-2003/3-IWFC/Papers/3-IWFC-075-Tolhurst.pdf

Wilson AAG (1988) A simple device for calculating the probability of a house surviving a bushfire. *Australian Forestry* **51** (2), 119 – 123. doi:10.1080/00049158.1988.10674524.

Wilson AAG, Ferguson IS (1986). Predicting the probability of house survival during bushfires. *Journal of Environmental Management* **23**, 259 – 270.

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A New Fire Spread Model for Spinifex Grasslands

Neil Burrows*
Parks and Wildlife, Perth, Western Australia, Australia, neil.burrows@dpaw.wa.gov.au
Malcolm Gill
Australian National University, Canberra, ACT, Australia, malcolm.gill@anu.edu.au
Jason Sharples
University of NSW, Canberra, ACT, Australia, J.Sharples@adfa.edu.au

Introduction

Spinifex grasslands are characterised by the dominance of perennial hummock grasses, primarily of the genus *Triodia*. They cover about 2.1 million km^2 (~27%) of the Australian continent including pastoral, Aboriginal and conservation lands as well as large tracts of unallocated crown land (Allan and Southgate 2002). The combination of accumulations of flammable vegetation, and the often extreme fire weather conditions makes spinifex grasslands highly flammable (Griffin 1984; Gill *et al*. 1995; Allan and Southgate 2002). With the departure of traditional Aboriginal burning practices, the fire regime throughout much of the spinifex grasslands has changed from predominantly small patchy low intensity cool season fires to large, intense summer fires (Latz and Griffin 1978; Burrows and Christensen 1991). This 'boom and bust' fire regime is largely driven by rainfall, which drives the rate of fuel accumulation (Griffin 1984; Allan and Southgate 2002), with lightning as the dominant ignition source in remote areas. Changed fire regime has been implicated in the decline of mammals and some bird species, as well as the contraction of fire sensitive plants such as cypress pine (*Callitris* spp.) and mulga (*Acacia aneura*) (Burbidge and McKenzie 1989; Start 1986; Bowman and Latz 1993; van Leeuwen *et al*. 1995; Ward *et al*. 2014).

Being remote, suppression capability is limited or non-existent, so fires generally burn until they run out of fuel or the weather changes. In addition to potentially harmful ecological, environmental and cultural consequences, wildfires are increasingly impacting remote communities and mining and other infrastructure. Therefore, there is a need for pro-active fire management to mitigate the impacts of wildfires. This includes planned burning. Fundamental to successful fire management is the need to have a firm understanding of fire behaviour. To this end, this paper builds on the work of others (Griffin and Allan 1984; Gill *et al*. 1995; Burrows *et al*. 2009; and Sharples *et al.* 2015) by presenting a revised spinifex grassland fire spread model based on experimental fires conducted over almost three decades.

Methods

The current fire spread model was developed from 159 experimental fires carried out at various locations in four arid 'Interim Bioregionalisation for Australia' (IBRA) regions (Thackway and Creswell 1995) in Western Australia. Additional data from 7 fires in spinifex grasslands near Mt Isa, Queensland, were kindly provided by Dr Paul Williams (Williams *et al*. 2015). Latest modelling incorporated original data from 83 experimental fires reported by Burrows *et al*. (1991 and 2009) as well as new data from 76 experimental fires conducted since 2009, of which 24 were conducted in 2015.

Field sites
Fire behaviour studies were conducted in hummock grasslands since the 1980s in the following Australian desert IBRAs; Gibson Desert (95 fires), Great Sandy Desert (22 fires), Great Victoria Desert (11 fires), Murchison (24 fires) and Mt Isa Inlier (7 fires). The location and biophysical descriptions of these regions is provided by Burrows *et al*. (1991 and 2009), Williams *et al*. (2015) and at http://www.environment.gov.au/land/nrs/science/ibra.

Experimental fires
The experimental method used to develop the current model is similar to that published by Burrows *et al*. (1991 and 2009). Post 2009, experimental fires were lit by a line of fire ~100 m long set at right angles to the wind direction. Spreading fires were monitored for distances ranging from 60 m to 200 m. Fires that ignited but did not sustain spread were allocated a rate of spread and flame height values of zero.

Data analysis
For discontinuous fuels such as spinifex grasslands, Gill *et al*. (1995) suggest three stages in the formulation and application of fire spread models; (i) a domain analysis for the applicability of, and limits to, inputs to a fire spread model, (ii) a likelihood of fire spread analysis (likelihood of go or no-go) and (iii) application of a spread model to predict rate of spread once ‘go’ thresholds were met. Generally, it was difficult to ignite spinifex when the clump profile moisture content (including live and dead material) exceeded about 35-40% so analysis focussed on determining the probability of a fire spreading once ignition was achieved. A logistic regression procedure (SAS v9.3), which attempts to predict the likelihood of an event was used to model rate of spread as a binary outcome variable; for those fires that did not spread (58 fires), rate of spread was set as zero (no-go) and those that did spread (101 fires), rate of spread was set as 1 (go). The second step in model development was to analyse only those fires that spread, setting rate of spread and flame height as outcome (fire behaviour) variables and the other measured fuel and weather variables as potentially predictor variables.

Results and Discussion
Once fuels were sufficiently dry to ignite (spinifex clump profile moisture content <~40%), wind speed, fuel moisture content and fuel cover were found to be the most important variables determining whether or not fire would spread. Using these variables, the probability, or likelihood of fire spreading was best estimated by the applied logistic function of the form;

$$SI = 0.32(U)+0.27(c)-0.53(m)-4.23$$

Once thresholds for fire spread were exceeded (SI>0), then the relationship that best explained variation in rate of spread was the linear function:

$$ROS = 140.26(U) + 35.14(l) + 27.44(c) - 185.11(m) + 1005 \ (R^2=0.84) \ldots Eq.1$$

A more elegant but slightly less accurate model was one of the form:

$$ROS = (l*c)^{1.21} *(U/m)^{2.2} \ (R2 = 0.82) \ldots Eq.2$$

Where:
SI = Spread Index (likelihood of spread).
ROS = head fire rate of spread (m/h).
U = wind speed at 1.8 m-2 m (km/h) (exp. range 4-36 km/h).
l= fuel load (t/ha) (exp. range 1.1-17.7 t/ha).
c= Fuel cover (live and dead spinifex) (%) (exp. range 5-80%).
m = Profile fuel moisture content (spinifex clump profile) (exp. range 12-31%).

Based on an earlier data set (that did not include the 2015 fires) Sharples *et al*. (2015) reported slightly different forms of the SI and ROS models being;
SI (U,m,c) = 37(c) (U/m) and,
ROS(U, m, c) = 1.5SI(U, m, c) + 600.

The current ROS models, which include the additional (24) 2015 fires, incorporate fuel load and fuel cover, improving predictions in circumstances where cover alone is not a reliable surrogate for fuel load.

If SI ≤ 0 then flames are unlikely to breach fuel gaps, the fire is unlikely to spread and the prediction processes ceases, with the predicted ROS=0. If SI > 0, then flames are likely to breach the fuel gaps and the fire is likely to spread. The relationship between SI and observed rate of spread, including fires that did not spread, is shown in Figure 1. The 'likelihood of spread' model mis-classified 19% of non-spreading fires and 13% of spreading fires.

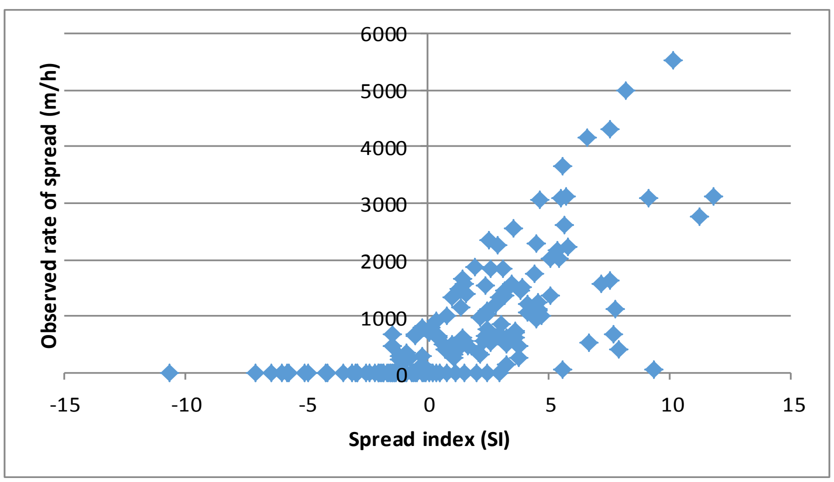

Figure 1: Relationship between the likelihood of fire spread and observed rate of spread for all experimental fires in spinifex grasslands, including fires that did not spread.

As to be expected, wind speed was the most influential variable, explaining about 60% of the variation in rate of spread. As indicated above both fuel load and fuel cover are now included in the ROS model because the most recent experimental fires (conducted in 2015) showed that meadows with similar cover often varied in fuel load depending on the height and bulk density of the clumps; fuel load directly influenced flame dimensions therefore fire spread across discontinuous fuel. Ambient temperature and relative humidity *per se* were not found to be statistically significant factors affecting rate of spread, but influenced fire behaviour by affecting the moisture content of the dead fuel component, which in spinifex meadows, varies significantly with time since fire. Figure 1 also illustrates the importance of the two-step process in predicting rate of spread in discontinuous fuels such as spinifex grasslands. The ROS model will perform poorly when applied to *all* fires (i.e., 'go' and 'no-go' fires) by; a) predicting that fire will spread when it won't and b) predicting high negative rates of spread under conditions when fires will not spread. Figure 2 shows the relationship between observed and predicted rates of spread for spreading fires only, showing that, tested against the experimental data, the model performs well with no apparent bias. Figure 3 shows the relationship between predicted rate of spread and SI for all fires (go and no-go), illustrating the importance of the two-step process in predicting rate of spread in discontinuous fuels with multiple spread thresholds (i.e., other than moisture content).

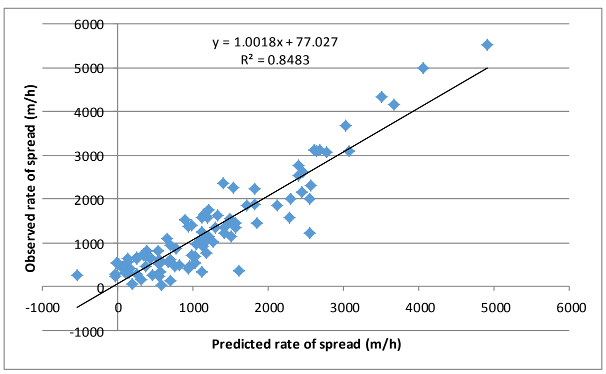

Figure 2: Observed (experimental fires) and predicted (Eq.1) rate of spread for spreading fires.

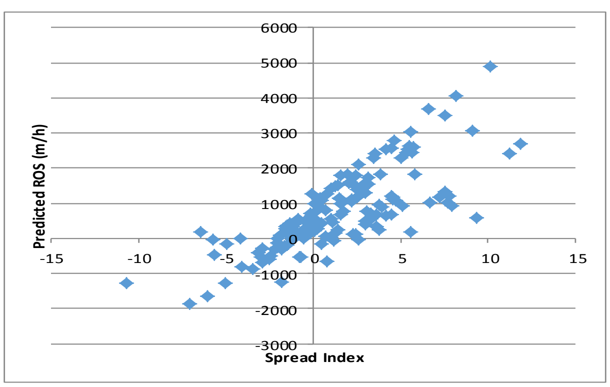

Figure 3: Relationship between predicted rate of spread (Eq.1) and the spread index (SI) for all fires. Note the large number of fires with predicted 'negative' rates of spread when the SI is negative.

Predicting head fire flame height

Head fire flame height was related to rate of spread by the saturation equation shown in Figure 4. Flame height saturated at about 3-4 m above a rate of spread of about 2,000 m/h. In a fire burning in dry, heavy fuels, flame height reached about 6 m, but generally flames were less than 4 m. Spotting (spot fires) was rare in the experimental spinifex fires with occasional short distance spotting to 50 -100 m associated with high intensity fires burning under hot, dry conditions with a mallee overstorey.

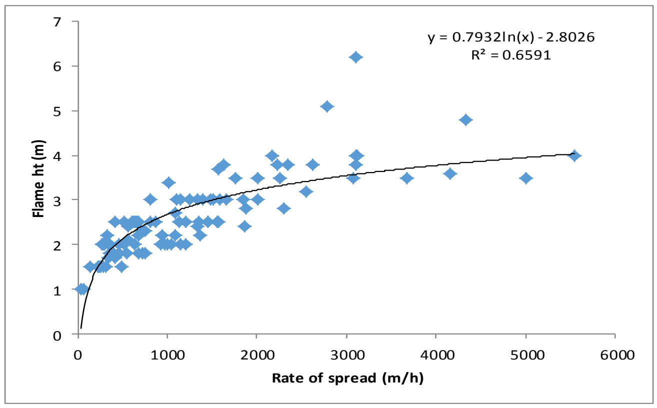

Figure 4: Relationship between flame height and rate of spread. Maximum flame heights of 5-6 m were recorded in heavy fuels (>12 t/ha).

Conclusion

Once fuels are sufficiently dry to ignite, predicting whether fire will spread, and rate of fire spread, in discontinuous fuels such as spinifex grasslands is necessarily a two-step process. The relatively simple models presented here have been derived from 159 experimental fires and provide accurate predictions over the range of experimental conditions. Further research is focussing on developing remote sensing tools to enable fire managers to effectively estimate fuel cover, load and moisture content in remote spinifex grasslands.

References

- Allan GE and Southgate RI (2002). Fire regimes in the spinifex landscapes of Australia. In 'Flammable Australia: Fire Regimes and Biodiversity of a Continent'. (Eds RA Bradstock, JE Williams, AM Gill)pp. 145-176. Cambridge University Press, Cambridge, U.K.
- Bowman DMJS and Latz PK (1993). Ecology of *Callitris glaucophylla* (Cupressaceae) on the Macdonnell Ranges, Central Australia. *Australian Journal of Botany* **41**, 217-225.
- Burbidge AA and McKenzie NL (1989). Patterns in the modern decline of Western Australia's vertebrate fauna: causes and conservation implications. *Biological Conservation* **50**, 143–198.
- Burrows N and Christensen PES (1991). A survey of Aboriginal fire patterns in the Western Desert of Western Australia. In 'Fire and the Environment: Ecological and Cultural Perspectives' (Eds SC Nodvin, TA Waldrop) pp297-306. General Technical Report SE-69, US Department of Interior.

- Burrows ND, Ward B and Robinson A (1991). Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia. *Journal of Arid Environments* **20**, 189-204.
- Burrows ND, Ward B and Robinson A. (2009). Fuel dynamics and fire spread in spinifex grasslands of the Western Desert. *Proceedings of the Royal Society of Queensland* **115**, 69-76.
- Gill AM, Burrows ND and Bradstock RA (1995). Fire spread in hummock grasslands. *CALM Science Supplement* **4**, 29-34.
- Griffin GF (1984). Hummock grasslands. In 'Management of Australia's Rangelands' (Eds GN Harrington, AD Wilson and MD Young) pp. 271-284. CSIRO, Melbourne.
- Griffin GF and Allan GE (1984). Fire Behaviour. In 'Anticipating the inevitable: A patch burn strategy for fire management at Uluru (Ayres Rock-Mt Olga) national park' (Ed EC Saxon) pp. 55-68. CSIRO Australia, Melbourne.
- Latz PK and Griffin GF (1978). Changes in Aboriginal land management in relation to fire and to food plants in Central Australia. In 'The Nutrition of Aborigines in relation to the Ecosystem of Central Australia'. (Eds BS Hetzel, HJ Frith) pp. 75-85. CSIRO, Melbourne.
- Sharples JJ, Gill AM and Burrows ND (2015). A rate of spread index for fires in spinifex fuels. 21st International Congress on Modelling and Simulation, Gold Coast, Australia, 29 Nov to 4 Dec 2015 www.mssanz.org.au/modsim2015.
- Start AN (1986). Status and management of Mulga in the Pilbara region of Western Australia. In 'The Mulga Lands'. (Ed P Sattler) pp. 136-138. Royal Society of Queensland, Brisbane.
- Thackway R and Cresswell I (1995). An Interim Biogeographic Regionalisation for Australia: A Framework for setting Priorities in the National Reserves System. Cooperative Program Version 4, Australian Nature Conservation Agency, Canberra.
- van Leeuwen, S.J., Start, A.N., Bromilow, R.B. and Fuller, P.J. (1995). Fire and the floristics of Mulga woodlands in the Hammersley Ranges, Western Australia. In 'Ecological Research and Management in the Mulgalands'. (Eds MJ Page, TS Beutel) pp. 169-175. University of Queensland, Gatton.
- Ward BG, Bragg TB and Hayes BA (2014). Relationship between fire-return interval and mulga (*Acacia aneura*) regeneration in the Gibson Desert and Gascoyne–Murchison regions of Western Australia. *International Journal of Wildland Fire* **23**, 394-402.
- Williams PR, Collins EM, Blackman M, Blackman C, McLeod J, Felderhof L, Colless L, Masters K, Coates S, Sturgess A, and Martin G. (2015). The influence of ignition technique on fire behaviour in spinifex open woodland in semiarid northern Australia. *International Journal of Wildland Fire* **2015**, 607–612.

A Spatial DSS for the Understanding and Reduction of Long-Term Wildfire Risk

Graeme A. Riddell*
University of Adelaide, Adelaide, SA, Australia, graeme.riddell@adelaide.edu.au
Hedwig van Delden
Research Institute for Knowledge Systems, Maastricht, the Netherlands, hvdelden@riks.nl
Simeon Telfer
DEWNR, Keswick, SA, Australia, simeon.telfer@sa.gov.au
Mike Wouters
DEWNR, Keswick, South Australia, Australia, mike.wouters@sa.gov.au
Roel Vanhout
Research Institute for Knowledge Systems, Maastricht, the Netherlands, rvanhout@riks.nl
Holger R. Maier
University of Adelaide, Adelaide, South Australia, Australia, holger.maier@adelaide.edu.au
Aaron C. Zecchin
University of Adelaide, Adelaide, South Australia, Australia, aaron.zecchin@adelaide.edu.au

Introduction

The challenges facing fire and land managers grow increasingly wicked as more factors that impact on their ability to manage wildfires need to be considered. Large numbers of influencing environmental and anthropogenic factors influence wildfire risk, and their number and impact only grow when longer time scales are considered. There is a need however to consider longer time scales than a seasonal or annual planning horizon as a mix of risk reduction options (e.g. suppression capabilities, land management, community awareness and education programs, and land use planning) operate at different scales but all play their part in managing and reducing the threat of wildfires.

This paper introduces a spatial decision support system (SDSS) that has been developed for the Greater Adelaide region in South Australia through collaboration between researchers at the University of Adelaide, the Research Institute for Knowledge Systems (RIKS), and the South Australian Department of Environment, Water and Natural Resources. The SDSS is designed to understand the spatial and temporal dynamics of wildfire risk over extended planning horizons (20-50 years) by exploring the factors that influence the natural hazard, society's exposure to the hazard and how vulnerable society is to it.

The SDSS conceptualises, and subsequently models, risk as the combination of the natural hazard, exposure and vulnerability (UNISDR, 2009). This extended abstract will provide details on how each of these factors is modelled within the DSS, the consideration of risk as a function of these components and the risk reductions included together with their influence on the factors of risk. Finally, we will discuss the value and application of this approach, along with improvements for its future development and use.

Wildfire risk modelling
The modelling of risk is considered across three factors, hazard, exposure and vulnerability, also called the risk triangle (Crichton, 1999). Treating each of these individually and simulating their spatial and temporal dynamics improves the understanding of long term wildfire risk. It also allows for the consideration of risk reduction options to be implemented across each of these factors, targeting specific aspects of the risk.

Exposure modelling
Within the SDSS exposure is considered dynamically with the inclusion of a land use allocation model (RIKS, 2015) and building stock information retrieved from the NEXIS database (REF). The land use model operates on a square grid of 100m cells. The model is cellular automaton (CA) based and calculates the state of each cell within the overall growth of the region of interest (Greater Adelaide for this study), driven by population and economic demands (White and Engelen, 1993). The CA model stochastically allocates the land use demands at an annual time step based on the land uses in the previous time step and the spatially dependent, attractive and repulsive forces that land uses exert on each other within a close neighbourhood. There are three additional site specific factors that influence the potential for a land-use to change, namely suitability, zoning status and accessibility (van Delden et al., 2007).

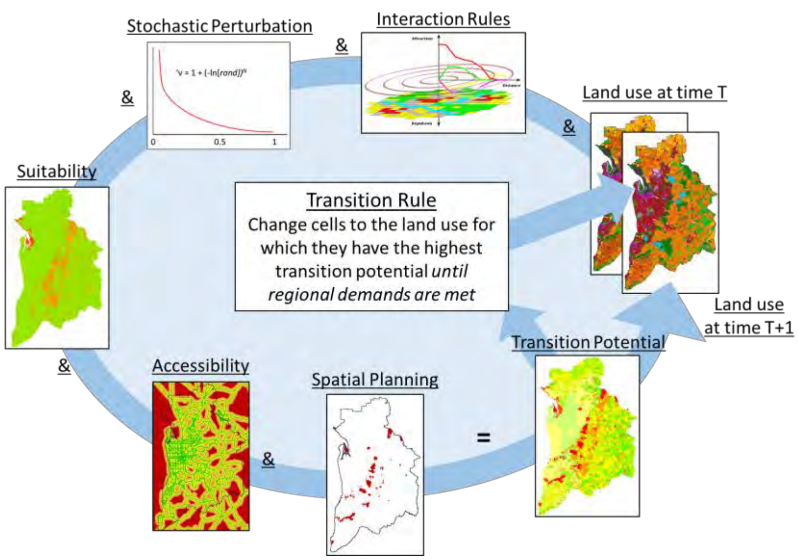

Figure 1 Main drivers of the Greater Adelaide land use model, adapted from van Delden et al., 2011

Suitability relates to the physical aptness of a cell to support a particular land use and its activities. Examples of this include soil type or slope. Suitability is represented as one map per land use function modelled. Zoning, similarly represented as one map per land use function, specifies when a cell can or cannot be changed to a particular land use for various planning periods and how strict or flexible the policy is. Accessibility expresses the ease with which the activities associated with each land use can fulfil its requirements for transportation, mobility or any other infrastructure need based on its proximity to networks (van Delden and Hurkens, 2011).

To allow differentiation between building types and the density of the building stock, the land use information is complemented with building stock data extracted from the NEXIS database. Building types from NEXIS are linked to urban land uses, *residential, rural residential, commercial, public institutions including education, and industrial,* for Greater Adelaide. To consider building standards and bushfire risk, a split in the NEXIS database between pre and post 1980 is used with all buildings built prior to 1980 considered not built to standard, and all buildings built post 1980 are assumed built to a standard based on the bushfire attack level (BAL, AS-3959:2009). All post 1980s buildings are built to one of three of the BAL, and as such would withstand that design intensity in a fire event. This results in each cell having a number of buildings of a specific construction type (BAL) for each urban land use class. Modelling into the future involves parameters that account for changes in the number of buildings and their BAL value. The change in buildings is driven by a *renewal rate (%, per building type, per year, per Local Government Area (LGA)),* representing the rate with which the building stock will be renewed, and the *expansion* of the building stock due to socio-economic developments as modelled by the land use model. All new builds are assumed to meet the standards for the year they are built, and hence are assumed to be constructed to a BAL value depending on the fire intensity at that location at the previous time step.

Also contained within the building stock model are the exposed value (the total structural value for all urban land uses, and total contents value for the two residential classes). These values come from NEXIS and are aggregated across LGAs. The building stock model then divides the total values by the total number of buildings per LGA to determine the exposed value per cell which is subsequently used in the assessment of risk. Agricultural values are also considered by using NEXIS information regarding the value of agriculture, horticulture and livestock land across Greater Adelaide, and associating these values with their respective land use cells.

Hazard modelling

The wildfire hazard modelling builds on the TASBRAM approach (Taylor and Wallace, 2011) and considers the likelihood of an event occurring in a particular cell based on three main components: ignition potential, fire behavior, and suppression. Ignition potential is calculated based on a combination of human factors and vegetation types. Fire behavior consists of head fire intensity, fuel load and rate of spread. Suppression capabilities relate to how quickly a fire can be detected and suppressed.

Fire behavior is expressed as energy intensity per cell (kW/m). The calculation of fire behavior is carried out differently for grassland and woodland fire. Fire behavior for grassland fuels considers the heat of combustion (H), fuel load and rate of spread (ROS) (for particular grass types (Cruz et al., 2015)). Woodland fire behavior is based on the forest fire danger index FFDI, the fuel load and the rate of spread (Cruz et al., 2015). Climatic factors that influence ROS, such as relative humidity and temperature are linked to long term climate scenarios.

Suppression is an input layer within the model that accounts for the time taken for resources (ground and air) to reach an area and apply initial attack derived from overlays of weighted factors such as aircraft and brigade response time, accessibility and detection. In its current form for Greater Adelaide, this is a static layer (Figure 2) with the option to update it to account for increased suppression capabilities into the future. It is considered as a probability map of the initial attack being successful and therefore having no significant consequence, the higher values indicating greater suppression capability.

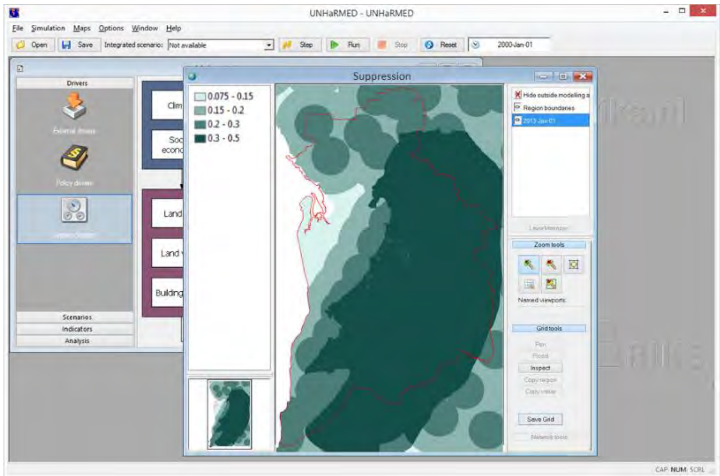

Figure 2 Suppression layer for Greater Adelaide SDSS

The ignition potential consist of three contribution factors, which are summed to obtain an overall ignition potential (i.e. road proximity, land use, and vegetation type). For each of the three aspects, a value is attributed to the classes on the map. The ignition potential of vegetation types and land use have been statistically derived from comparison between the mapped factors and historic fire data. This allows each cell to be given a value of land use and vegetation type factors that contribute to ignition potential. Land use information is obtained from the dynamic land use change model, while vegetation types are taken from a (static) vegetation map. Furthermore, a one cell (100 m) band along the road network is taken to calculate the impact of road proximity on ignition potential.

Vulnerability modelling

The vulnerability of buildings is based on the standard they are built to. This information, as discussed previously in the building stock model, considers the bushfire attack level the assets would have been constructed to, based on their age and the modelled fire intensity at that location. The vulnerability calculation considers the constructed strength versus the modelled intensity in a cell to determine whether the asset would be subject to damage. If the intensity is greater than constructed strength it is assumed that the entire asset is lost. For agricultural land it is assumed that the entire value would be lost to a fire event.

Long-term risk modelling

Risk is modelled as the average annual loss which is calculated by multiplying the bushfire likelihood (hazard model), the exposed assets and their associated vulnerabilities (from exposure and vulnerability modelling). This produces dynamic maps showing the changing risk from year to year based on the dynamics of bushfire likelihood, influenced by climate and anthropogenic ignition potential and exposure, driven by economic and population demands. Figures 3a – 3c show outputs for the Greater Adelaide SDSS, Figure 3a shows the risk in 2013 (start date of simulation), Figure 3b, the risk in 2050 for a scenario of central urban growth, reducing risk in peri-urban and rural zones, and Figure 3c, the risk in 2050 for a scenario of agricultural and rural residential growth.

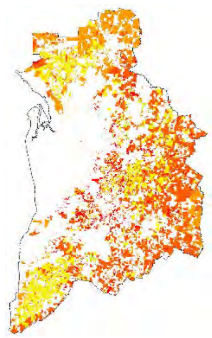

Figure 3a – Risk in 2013

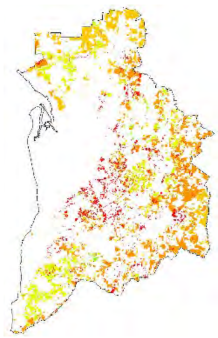

Figure 3b – Risk in 2050 (Scenario 1)

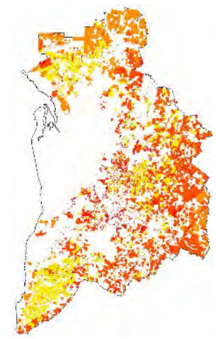

Figure 3c – Risk in 2050 (Scenario 2)

Risk reduction options

Several risk reduction options are also considered, and can be implemented within the SDSS to test their effectiveness in reducing risk, along with considering their impact on other policy indicators, including benefit cost assessments. Risk reduction options occur across the components of risk, allowing planners to consider various options or a mix of options to achieve risk reduction targets. Table 1 highlights the options currently considered within the SDSS, and where they influence the calculation/modelling of risk.

Table 1 – Included risk reduction options

Risk Reduction Option	Description	Influence on Model
Planned burns	Planned burns can be implemented within the model, allowing the modeler to set the location and frequency of burns. This alters the time since last burn, and subsequently the fuel load and intensity of wildfire in a cell for a particular year.	Change time since last fire, decrease fuel load.
Land use planning	Several options through the land use model can influence overall wildfire risk. The magnitude and location of developments can be influenced through zoning, changing the assets at risk. The ignition potential can also be influenced by land use planning.	Implement zoning policy restricting or redirecting development. Influences exposure and ignition potential.
Building Code Changes	Building codes changes can decrease the vulnerability of buildings. This shifts the vulnerability curve, requiring a greater intensity to create the same damage and can be applied to new developments and retrofitted within LGAs with an associated cost.	Change shape of vulnerability curve for certain developments.
Suppression Capabilities	Increase brigade or aircraft capabilities with an associated cost. This is considered as a new input map for suppression.	Updated suppression layer
Arson reduction	User has the option to enter cost of program per inhabitant as well as expected benefit in terms of reducing ignition potential in rural residential land use.	Reduces values of land use ignition factor

Policy indicators

Several policy indicators are also included to allow for a consideration of long term risk, and the effectiveness of risk reduction measures. Currently most indicators focus on risk and cost, however, the SDSS is set up as a modular framework, and there is the option to expand this further, and consider a broader definition of risk (incorporating more factors of exposure and vulnerability particularly social and environmental), along with broader strategic indicators relevant to land use planning.

The SDSS currently provides indicators reflecting the annual cost of wildfires in a spatially explicit manner such as Figure 3 and aggregated across LGAs displayed with plots of costs into the future along with tables for each LGA and year. With the implementation of risk reduction measures similar tables and graphs report the difference between a reference scenario (with no reduction measures) and the implemented policies. Total cost of risk reduction measures annually are also reported, on along with a cost benefit analysis considering the direct annual costs of wildfires and the annual cost of risk reduction methods.

Conclusion

This abstract provides a brief overview of a wildfire risk SDSS currently being developed for Greater Adelaide. The SDSS takes wildfire risk analysis into a more complex and comprehensive space. The analysis of risk reduction can be coupled with cost-benefit analysis and socio-economic-environmental values and impacts to provide a more holistic view of the various mixes of risk reduction options. Given wildfire risk management has very strong social and environmental dimensions, it is hoped the SDSS can lead to more transparent and robust policy settings and decision making.

Several improvements are also being considered to provide a better representation of wildfire risk. These include the dynamic modelling of vegetation, and hence fuel load based on climate change and management practices and the dynamic modelling of planned burns based on risk indicators instead of manual inputs. Also considered as a significant improvement would be the integration of more advanced fire spread dynamics for improving the modelling of fire behavior and the spatial dependency of wild fire risk. Inclusion of a wider range of wildfire risk mitigation actions (e.g. community engagement) will make the SDSS more relevant to policy decision analysis.

References

Crichton, D, 1999. The Risk Triangle. Natural Disaster Management. Ingleton J pp. 102–103. Eds. London, UK:Tudor Rose.

Cruz, M.G., Gould, J.S., Alexander, M.E., Sullivan, A.L., McCaw, W.L., Matthews, S., Land, C., Flagship, W., Alberta, U.o., Parks, W.A.D.o., Wildlife, M., Fire, A., Limited, E.S.A.C., 2015. A Guide to Rate of Fire Spread Models for Australian Vegetation.

United Nations International Strategy for Disaster Reduction (UNISDR), 2009. 2009 UNISDR Terminology on Disaster Risk Reduction. United Nations, Geneva, Switzerland.

van Delden, H., Hurkens, J., 2011. A generic Integrated Spatial Decision Support System for urban and regional planning, 19th International Congress on Modelling and Simulation: Perth, Australia.

van Delden, H., Luja, P., Engelen, G., 2007. Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management. Environmental Modelling & Software 22(2) 223-238.

White, R., Engelen, G., 1993. Cellular Automata and Fractal Urban Form: A Cellular Modelling Approach to the Evolution of Urban Land-Use Patterns. Environment and Planning A 25(8) 1175-1199.

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A Tasmanian Case Study of Fire Weather Behaviour Using Visual Weather.

Paul Fox-Hughes*
Bureau of Meteorology, Hobart, Tasmania, Australia, p.fox-hughes@bom.gov.au
Alex Melitsis
Bureau of Meteorology, Hobart, Tasmania, Australia, a.melitsis@bom.gov.au
Melanie Webb
Bureau of Meteorology, Hobart, Tasmania, Australia, m.webb@bom.gov.au

Introduction

Meteorologists have understood for many decades the importance of upper atmospheric (here taken to mean the upper half of the troposphere) processes at a synoptic scale in driving surface weather, for example the development and movement of surface low pressure systems is closely dependent on upper level dynamics (e.g., amongst very many others Dowdy et al 2013). In the last several decades, it has become more widely apparent that mesoscale (scale of kilometres to tens of kilometres) surface features are intimately linked to the activity of such upper level features as the jet stream. It is now understood that severe thunderstorm development often occurs in conjunction with the movement aloft of the right exit region of a jet (Uccellini and Johnson 1979), as can other wind and precipitation extremes (Browning and Golding 1995, Skerlak et al 2015 and references therein). There has been substantially less published work relating upper tropospheric patterns and activity to surface fire danger. Schaefer (1957) and Schroeder et al (1964) drew a connection between high fire danger or "blow-up" fire conditions and the proximity of the jet stream, while some other studies (Brotak and Reifsnyder 1977, Newark 1975, Numchuk 1983) linked other, sometimes related, upper tropospheric synoptic patterns to the occurrence of dangerous fires. In the last decade, in particular, a number of studies have documented the role of upper tropospheric processes in mesoscale weather relevant to fire activity and fire danger. Mills (2008a and 2008b) highlighted the importance of water vapour dry bands as an indicator of possible heightened fire danger due to descent to near-surface levels of dry, high-momentum air. Other studies (Zimet et al 2007, Kaplan et al 2008, Fox-Hughes 2012) have examined the processes operating to bring such airmasses to the surface in fire weather events.

This paper discusses a set of guidance tools used to assist in the decision to update forecasts on the morning of 06 October 2015, a decision that observations of the weather on the day showed to be well-founded. The guidance tools were based on research cited above documenting the connection between upper tropospheric and surface phenomena.

Event description

Tasmania historically has experienced a summer-autumn fire season (Luke and McArthur 1978), but has been subject to increasing numbers of dangerous springtime fire weather events in recent decades (Fox-Hughes 2008). Three such events occurred during October 2015, including 06 October, the most serious of the three.

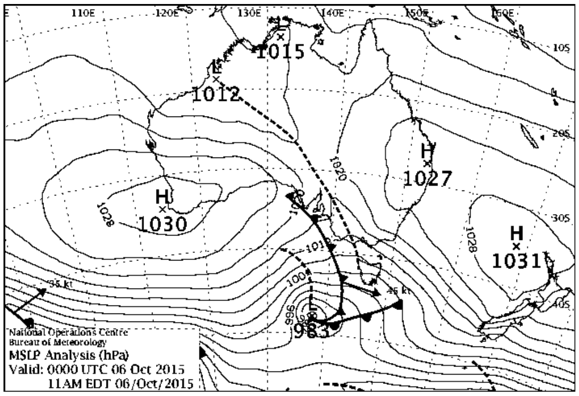

Fig. 1. Australian region mean sea level pressure chart at 0000 UTC 06 October 2015.

Severe to locally extreme fire danger occurred in southern Tasmania on 06 October 2015, with the passage of a cold front (Figure 1). Forecasts issued the previous day indicated that fire danger was expected to be Very High across most of eastern Tasmania and Severe in eastern and southeastern districts (Figure 2), consequently fire weather warnings were issued by the Hobart office of the Bureau of Meteorology. Examination of the modelled upper atmosphere on the morning of the 6th, however, suggested strongly that conditions would be worse than those forecast the previous afternoon. As a consequence, forecasts and warnings were updated, an action that proved correct in the light of events.

Discussion

Visual Weather (VW), a software package from IBL, is the visualisation tool introduced into the Bureau of Meteorology in the last several years. Among numerous other capabilities of VW is the capacity to plot vertical cross-sections of atmospheric fields from numerical weather prediction (NWP) models and to overlay different types of data. One of the authors (MW) has developed VW "maps" (displays) allowing moveable cross-sections of potential vorticity, wind speed, relative humidity and vertical motion. These assist forecasters to diagnose the possibility of transport of upper tropospheric, and possibly stratospheric, air closer to the surface, where processes such as thermal or turbulent mixing can act to further transport the air to the surface, influencing fire activity if any fires are present (Mills 2008a). Another author (AM) has developed maps visualising the dynamic tropopause, allowing comparison of model forecasts with satellite water vapour imagery, thereby validating the performance of numerical model guidance.

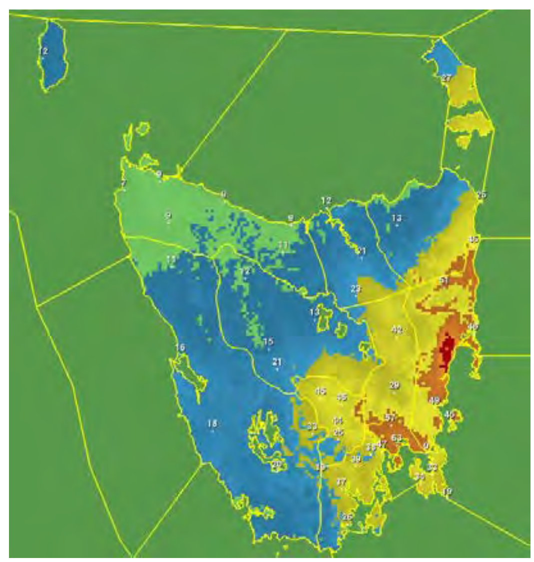

Figure 2. Forecast forest fire danger ratings for 06 October for Tasmania, issued on the afternoon of 05 October. Green= Low-Moderate, blue= High, yellow = Very High, orange = Severe and red = Extreme.

Two of the authors (AM, PFH) were on duty in the BoM Hobart office early on the morning of 06 October as a cold front approached Tasmania. Satellite water vapour imagery (Figure 3) clearly indicated the presence of a dry band associated with the front, suggesting the possibility of a period of further increased fire danger near the passage of the cold front. Overlaying the

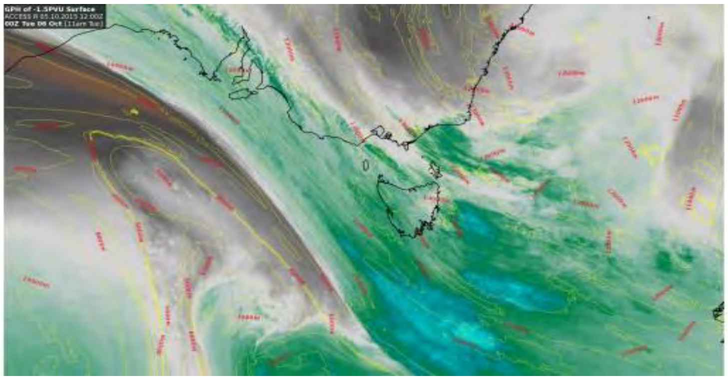

Figure 3. Himawari-8 water vapour image at 0000 UTC 06 October 2015. A dry band (grey-orange) lies west of Tasmania, approaching the state. Superimposed are contours (in yellow) of height of the 1.5 PVU surface in thousands of metres.

dynamic tropopause diagnostic from the 1200 UTC run of ACCESS-R, (the operational Australian region NWP model of the Bureau of Meteorology) showed a good overlap of the modelled tropopause depression with the WV image location of the dry slot, suggesting that ACCESS-R had captured essential aspects of the event. Cross-sections of the fields discussed above through the line shown in Fig.4 were then examined to assess the likely impact of the dry slot on the surface weather (Fig. 5). Fig. 5(a) displays potential vorticity (PV) in PVU ($10^{-6}m^2s^{-1}kg^{-1}$), with values greater than 2 PVU shaded purple, and the 2 PVU contour (often used to delineate the tropopause) shown as a thick black line. Stratospheric air has high PV, and a tropopause depression corresponding to the approaching trough west of Tasmania is clear in Fig. 5(a), with a fold extending towards Tasmania. The fold extends to at least 700 hPa, and there is evidence of high PV air extending to 850 hPa. Further, Fig. 5(b) shows strong descent on the eastern side of Tasmania, in the lee of the westerly airflow, the result of mountain wave activity. An ascent-descent couple can also be seen corresponding to the tropopause fold. Dry air has descended to around 850 hPa at this point. Finally, Fig. 5(c) (showing wind speed in knots) indicates the approach of the jet associated with the trough. It also indicates that high momentum air has likely descended in the tropopause fold, with a lobe of 55 kt air evident as low as 825 hPa. Subsequent time steps (not shown) displayed similar, and supporting, information. This information strongly suggested that dry, high momentum air had descended in the tropopause fold to low levels in the atmosphere to the west of Tasmania, and that there was a high likelihood that it would be transported to the surface over southeastern Tasmania via mountain wave activity during the afternoon. While we believed ACCESS-R had in general, captured the state and development of the atmosphere well, modelled surface dewpoint temperature and wind did not reflect a rapid and substantial change that the upper level modelling suggested. We believed that the model surface parametrisations had not sufficiently represented the changes aloft. On the basis of the upper level

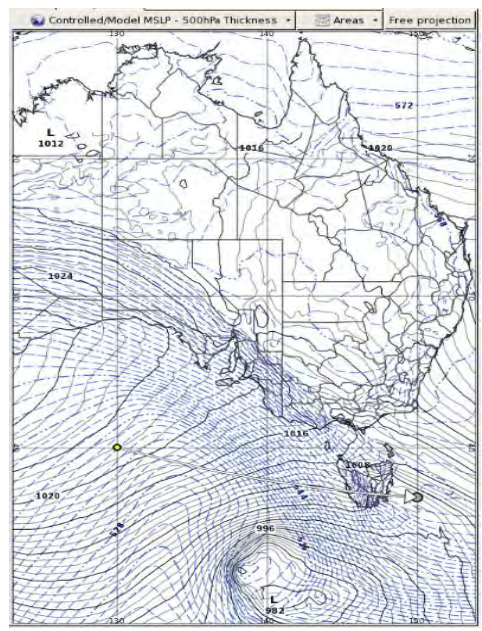

Fig. 4. ACCESS-R modelled MSLP (black solid lines, in hPa) at 0300 UTC 06 October, from the 1200 UTC run of 05 October, with MSLP-500 hPa thickness (blue dashed lines in geopotential dm). The arrow defines the cross-sections displayed in Fig. 5.

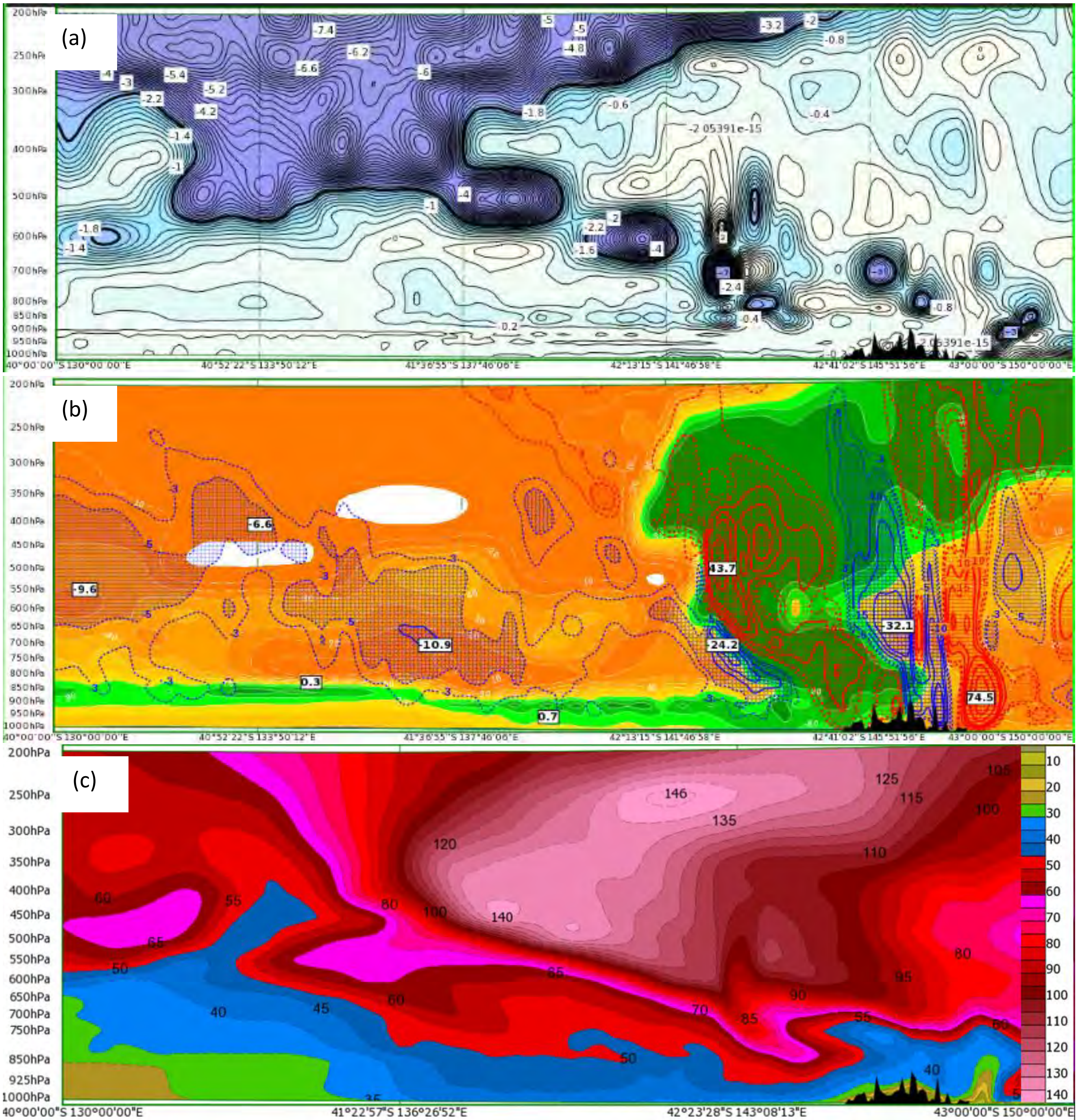

Fig.5. ACCESS-R cross-sections, valid 0300 UTC on 06 October from the 1200 UTC 05 October model run, through the region defined by the arrow in Fig. 4 of (a) PV (units PVU) (b) RH (shaded: orange=dry, green=moist) and vertical motion (red=up, blue=down, units cms^{-1}) (c) windspeed in kt, with a legend inserted on the right of the image. The (model) topography of Tasmania is displayed in black, on the bottom-right of the cross-sections.

diagnostics, we updated the forecast to indicate an increase in wind and significant decrease in surface moisture during the early afternoon ahead of the change. Subsequent events showed this to have been a good decision. Dewpoint temperature at Hobart Airport fell to as low as -9 ^{0}C for a period in the early afternoon, with ten minute mean wind speed increasing to 52 kmh^{-1} (28 kt) at times, resulting in an Extreme forest fire danger rating. Several other southeast Tasmanian weather stations reported Extreme fire danger, and Very High to locally Severe fire danger occurred across eastern Tasmania.

Conclusions

Not one diagnostic or even set of diagnostics can ever completely characterise the state of the atmosphere, and provide guidance to forecast even a limited range of weather phenomena. When a forecaster has in mind a conceptual model of how the atmosphere may evolve, however, particular sets of diagnostics can provide very useful guidance, and assist greatly in the decision to warn or not warn for phenomena. The diagnostic tools presented in this paper provide a useful way of visualising the possible influence of the upper troposphere on surface weather conditions, and help in the decision to warn for dangerous fire weather. Certainly, these diagnostics assisted greatly in the decision to upgrade fire weather warnings in Tasmania on 06 October 2015.

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David James and Alan Wain assisted with data plots, and John Bally and Robin Hicks helpfully reviewed drafts of the manuscript.

References

Brotak EA, Reifsnyder WE (1977) An investigation of the synoptic situations associated with major wildland fires. *Journal of Applied Meteorology* **16**, 867-70.

Browning KA, Golding BW (1995) Mesoscale aspects of a dry intrusion within a vigorous cyclone. *Quarterly Journal of the Royal Meteorological Society* **121**, 463-93.

Dowdy AJ, Mills GA, Timbal B (2013) Large-scale diagnostics of extratropical cyclogenesis in eastern Australia. *International Journal of Climatology* **33**, 2318-27.

Fox-Hughes P (2008) A fire danger climatology for Tasmania *Australian Meteorological Magazine*. **57**, 109-20.

Fox-Hughes P (2012) Springtime fire weather in Tasmania, Australia: two case studies. *Weather and Forecasting.* **27**, 379-95.

Kaplan ML, Huang C, Lin YL, Charney JJ (2008) The development of extremely dry surface air due to vertical exchanges under the exit region of a jet streak. *Meteorology and Atmospheric Physics* **102**, 63-85.

Luke RH and McArthur AG (1978) Bushfires in Australia. (Australian Government Publishing Service: Canberra)

Mills GA (2008) Abrupt surface drying and fire weather Part 1: overview and case study of the South Australian fires of 11 January 2005. *Australian Meteorological Magazine* **57**, 299-309.

Mills GA (2008) Abrupt surface drying and fire weather Part 2: a preliminary synoptic climatology in the forested areas of southern Australia. *Australian Meteorological Magazine* **57**, 311-328.

Newark M (1975) The relationship between forest fire occurrence and 500 mb longwave ridging. *Atmosphere* **13,** 26-33.

Nimchuk N (1983) 'Wild fire behavior associated with upper ridge breakdown.' Alberta Energy and Natural Resources, Forest Service Technical Report. (Edmonton, Alberta)

Schaefer VJ (1957) The relationship of jet streams to forest wildfires. *Journal of Forestry* **55**, 419-25.

Schroeder MJ, Glovinsky M, Henricks VF, Hood FC, Hull MK (1964) 'Synoptic weather types associated with critical fire weather.' USDA Forest Service, Pacific Southwest Forest and Range Experiment Station Technical Report. (Berkeley CA)

Škerlak B, Sprenger M, Pfahl S, Tyrlis E, Wernli H (2015) Tropopause folds in ERA-Interim: Global climatology and relation to extreme weather events. *Journal of Geophysical Research: Atmospheres* **120**, 4860-77.

Uccellini LW, Johnson DR (1979) The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective storms. *Monthly Weather Review* **107**, 682-703.

Zimet T, Martin JE, Potter BE (2007) The influence of an upper-level frontal zone on the Mack Lake Wildfire environment. *Meteorological Applications* **14**, 131-47.

An Integrated Bushfire Risk Decision Support Tool for Land Use Planning

Laura Gannon
Hawksley Consulting (MWH Global), Brisbane, Queensland, Australia,
laura.gannon@hawksley.com

Introduction

Bushfire risk across Australia continues to grow despite the application of planning, building, land management and emergency management measures aimed at protecting our communities. Australians have historically maintained a strong desire to settle in bushland environments and this behaviour is unlikely to change into the future, particularly with recent demographic trends resulting in increasing population growth at the metropolitan fringe and within townships. Decision making frameworks have been developed in the areas of building construction as well as land and emergency management however, our approach to land use planning lacks the application of a consistent and effective decision support framework. The National Strategy for Disaster Resilience identifies land use planning as the most potent policy leaver available, whilst the Council of Australian Governments' (COAG) 2004 bushfire enquiry ranks it the single most important mitigation measure in preventing future disaster losses (COAG, 2009; Ellis et al., 2004). The methods adopted in applying land use planning approaches varies between local governments, regions and States. This, coupled with the challenges and conflicting interests confronting contemporary planning activities underscores the need for a rigorous national approach to the manner in which bushfire risk is assessed with regard to the formation of planning policy, planning strategy (planning schemes and other planning instruments) and development assessment. This paper introduces the Bushfire Risk Rating System for Land Use Planning which seeks to fill this gap and effectively enhance community bushfire resilience across Australia, both with respect to existing and future development risk.

Land Use Planning in PPRR

There remain a number of resilience and mitigation measures which play a role in the prevention, preparation, response, recovery (commonly referred to as PPRR) process as it relates to bushfire risk. The formation of legislation and regulation provides the legal framework that guides activities across the PPRR spectrum whilst governance approaches often set the tone within which PPRR processes are executed. Land use and infrastructure planning, regulating the use of land and the manner in which communities and people are placed across the landscape, maintains a strong influence on community exposure to natural hazard risk. Building control measures (such as the bushfire attack level (BAL) assessment framework), land (fuel) management and emergency management likewise sustain critical elements. Along this pathway, the deferral of residual risk is distributed which eventually ends with our communities and the insurance industry, refer to Figure 1. Shared responsibility is a notion present within much dialogue surrounding risk and resilience processes. The intrinsic linkage between each of these elements when implemented in combination dramatically increases the ability of communities to withstand bushfire.

Figure 1: The role of land use planning in the PPRR spectrum

Context of Land Use Planning

The role of land use planning in contemporary contexts is many and varied however, there is an established framework to guide the implementation of planning policy, strategy and development assessment. These can be divided into three overarching categories including policy frameworks and principles, (strategic) plan preparation processes and importantly, resilience planning techniques (MWH Global, 2015). The tools which aid the implementation of these approaches includes risk / hazard mapping, spatial controls (such as zoning) and precincts, local plans, overlays, structure planning and infrastructure provision (MWH Global, 2015). In addition to these land use planning instruments are the risk treatment approaches of maintaining the status quo (do nothing), defend, accommodate and retreat, each of which involves a varying level of action such as risk avoidance, risk reduction or mitigation, risk transfer or risk acceptance (MWH Global, 2015).

In recognising the value-add of land use planning within the above contexts, it is likewise pertinent to consider the various drivers and challenges which often come to bear in planning policy, strategy and development assessment processes. Norman et al. (2014) identifies that further development is continuing in high-risk bushfire prone areas across Australia. The reasoning behind this lies in the drivers and challenges with which land use planning is involved. Existing use rights and community expectation for example, are critical political issues which planning activities commonly encounter and which influence the nature of planning approaches in many instances. Existing use rights are commonly conferred via spatial controls such as zoning, and decisions regarding zoning across Australia are continuing to be made without acceptable consideration of bushfire risk. Zoning controls guide the manner in which communities are expected to expand, the decisions made with regard to where and how growth takes place are done so on the basis that natural hazard or ‘constraint’ overlays within planning instruments will effectively mitigate risk.

This approach continues to defer much of the consideration of risk to the development assessment (site-based) stage of the process, by which time the powerful ability of land use planning controls to mitigate community exposure to risk, and enhance bushfire resilience, are significantly fettered. These current approaches perpetuate an over-reliance on site-based assessment to the detriment of the implementation of more effective spatial controls which regulate how, where and why we place people and land uses across the landscape (QRA, 2012). The extent to which this pattern prevails varies across the country, on a State-by-State basis as well as between municipal / local governments. Notwithstanding, it is a consistently prevailing issue which must be addressed if we are to appropriately utilise land use planning tools to leverage community bushfire resilience. There remains a gap between understanding the need for risk assessment and the implementation of spatial controls, recognising that an overlay approach in isolation can only achieve a finite level of resilience, and excludes consideration of existing community risk. One of the more significant causes responsible for the continued increase in bushfire risk exposure includes the absence of a decision support framework which provides land use planners the ability to justify and rationalise spatial controls to respond to risk using an evidence-based approach.

A Decision Support Framework: The Bushfire Risk Rating System (BRRS)

A decision support framework to support land use planning activities to reconcile bushfire risk will substantially improve the application of land use planning policy and strategy mitigation measures. The Bushfire Risk Rating System (BRRS) approach seeks to fill the current gap between undertaking risk assessment practices and implementing a suite of appropriate land use controls aimed to reduce risk exposure to both existing and new communities.

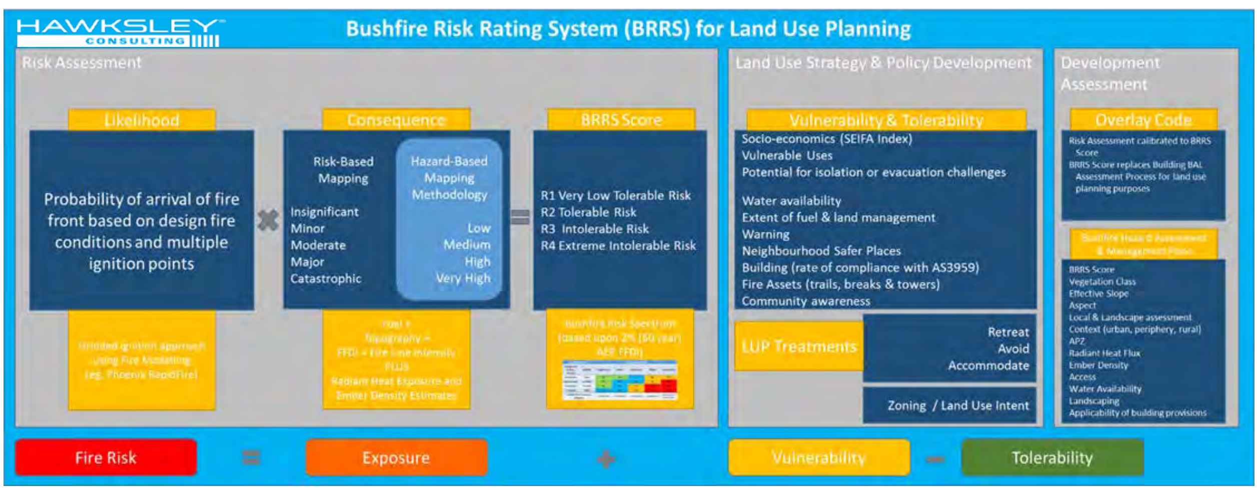

Figure 2: The process concept of the Bushfire Risk Rating System (BRRS) for Land Use Planning

The decision support framework comprises three components which consider bushfire risk specifically in a land use planning context. At present, the approach adopted across Australia relies on an assessment of bushfire attack level (BAL) classifications for certain buildings and structures. Whilst this approach allows land use planners in some cases to understand the risk profile as it applies to buildings, there remain a host of planning-related issues which contribute to that risk profile which a BAL assessment and overlay code do not address. The issue in this respect is that whilst building provisions provide 'how' development may occur, it does not consider if development 'should' occur – this is the role of the planning system. The BRRS approach commences with an understanding of the risk context both in terms of the fundamental characteristics of the community as well as the related fire history of the region. An assessment of likelihood is then conducted based upon the probability of arrival of the fire front based on desire fire conditions and utilising multiple ignition points in a gridded ignition approach using fire modelling software, such as Phoenix RapidFire. The likelihood or probability of ignition at this point in time is not a concept which can be reliably estimated. Another alternative would be the adoption of an annual exceedance probability (AEP) approach based on forest fire danger index (FFDI) data at designated intervals such as 20 per cent, 5 per cent, 2 per cent and 1 per cent, similar to that adopted for flood. However, as this approach is weather-based rather than event-based, it may not be considered a true reflection of likelihood.

Consequence assessment relates to the scale of impact if a bushfire were to occur. This is variable across Australia as the characteristics of fire weather and fuel loads vary. To this end, an assessment of fire line intensity, incorporating fuel load and type, topography and FFDI, can derive a somewhat reliable picture of hazard, as opposed to risk. The CSIRO-developed bushfire hazard mapping methodology for Queensland is representative of such an approach and incorporates categories of hazard described as low, medium, high and very high and incorporates a standardised 100m wide hazard 'buffer' surrounding the hazard source (CSIRO, 2014). There remains a direct correlation between this hazard-based mapping approach and potential consequence. The 100m wide buffer reflects the methodology of AS3959-2009 Construction of Buildings in Bushfire Prone Areas, principally in terms of the potential extent of radiant heat exposure and ember attack (CSIRO, 2014; Standards Australia, 2011). Ember density remains a challenging issue. It is estimated that ember attack is responsible for between 80 to 90 per cent of buildings lost as a result of bushfire, with an estimated 80 per cent occurring within 100m of the hazard source (CSIRO, 2014). In a building context, it may be acceptable to focus on that 80 per cent in terms of regulating building responses however, land use planning assessments maintain the scope to cast a wider net in terms of considering the potential impact of ember attack and how land use planning policy and strategic decisions are made in response. The two processes can and should function independently, but maintain important points of correlation where required to maintain synergy across regulatory frameworks.

A BRRS score, similar in concept to that of a BAL classification, can then be derived as a result of the likelihood and consequence equation. This score is intended to be represented spatially (i.e. mapped to support policy and strategic planning processes), highlighting the proportion and location of development occurring in the various risk exposure classifications. In this sense, the BRRS classifications include R1 (Low Risk), R2 (Moderate Risk), R3 (High Risk) and R4 (Extreme Risk).

As previously highlighted, fuel type and fuel load as well as fire weather varies across the country and as such, the BRRS classifications also must vary based upon prevailing 2 per cent (50 year) AEP of FFDI. This approach maintains consistency with that of AS3959-2009 whereby the

Likelihood Level		Consequence Level				
Fire Ignition & Burn History	NERAG	Insignificant	Minor	Moderate	Major	Catastrophic
Infrequent	Rare	R1	R1	R2	R3	R3
Intermittent	Unlikely	R1	R2	R2	R3	R4
Occasional	Possible	R1	R2	R3	R4	R4
Frequent	Likely	R2	R2	R3	R4	R4
Radiant Heat Exposure Category		<12.5kW/m²	<19kW/m²	<29kW/m²	<40kW/m²	40kW/m² + (Flame Zone)

Figure 3: DRAFT Risk Spectrum Table for FFDI 40-80, for example purposes

application of varying risk spectrums based on FFDI categories is then applied. This approach recognises the risk profile context which may exist.

Following the risk assessment component, the land use strategy and policy development component of the decision support framework includes an analysis of the risk assessment outcomes. Where risk is a function of exposure, vulnerability and tolerability, there remain a number of important social contexts which must be considered. Those characteristics which indicate vulnerability at a community level is but one of these. This may include the economic profile of the community, demographic characteristics such as the proportion of infirm, elderly or young people, car ownership (important for self-evacuation), etc. Likewise, the extent and nature of any vulnerable land uses should be considered and may include hospitals, nursing homes and retirement facilities as well as child care and educational facilities to name a few. In addition, the vulnerability of populations to self-evacuate must be examined which includes potential for isolation or other evacuation challenges.

A tolerability assessment then analyses the level of tolerance a community may sustain with regard to responding to bushfire risk. This includes the level of community awareness which can be captured by community survey of appropriate sample size as well as matters such as exposure to past bushfire events, water availability, extent of fuel and land management practices routinely undertaken, ability for early warning, access to neighbourhood safer places, extent of compliance with building construction and landscaping provisions (relevant in the consideration of house-to-house ignition) and fire assets such as firebreaks, trails and towers. The exposure, vulnerability and tolerability context of the BRRS decision support framework is supplemented by the input of the 'risk evaluation tool', which has been developed to support the analytical integrity of the assessment. The analytical approach adopted allows for a 'traffic light' assessment approach of data relating to exposure, vulnerability and tolerability across individual townships and communities, as illustrated at Figure 4. This risk evaluation tool has been successfully applied in a flood context and is equally capable of addressing bushfire risk is the same capacity, but has not yet been formally tested.

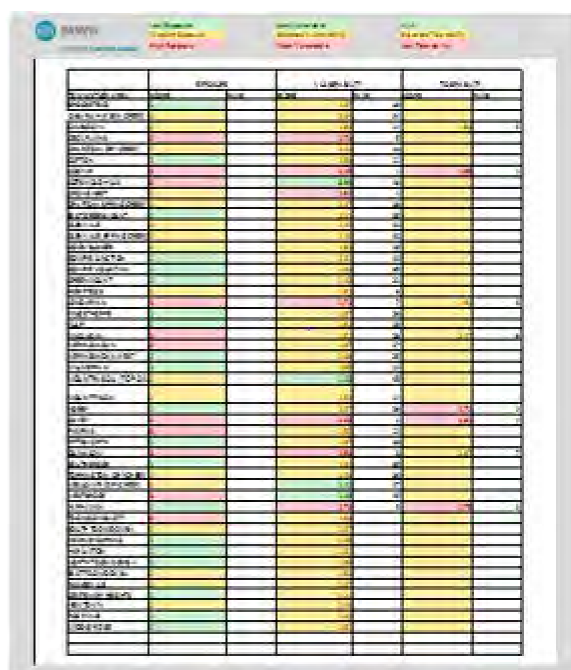

Figure 4: An Excerpt from the Exposure, Vulnerability and Tolerability Evaluation Tool

The analytical capability of this tool as an input to the BRRS decision support framework provides the necessary level of rigour to quantify and qualify land use decisions in response to community and political sensitivities. It also offers the capacity to adjust the degree of mitigation approaches required depending on the individual nuances of community-based vulnerability and / or tolerability and so builds-on from the one-size-fits-all methodology currently being used.

The output of the evaluation process enables the identification of a suite of potential spatial controls under the categories of retreat, avoid and accommodate. Included within this suite of potential controls to avoid, mitigate, transfer or accept the level and type of risk that has been identified. A suite of zoning, risk precincts, local area planning, overlay and structure planning recommendations are then produced for analysis by planning authorities. Specifically, we must move away from the concept that an overlay code in isolation is a sufficiently robust approach to reconcile bushfire risk. As evidenced above, there is a considerable body of work that must be undertaken in advance of overlay code compilation to address the manner in which our communities are forecast to grow and expand.

Conclusions

The land use planning system is Australia currently lacks a decision support framework to evaluate and guide the spatial context of our communities in the face of bushfire risk. This paper presents a sound framework capable of national-level application to support land use planning decision-making to enhance community-level resilience, using data analytics and risk metrics to inform spatial responses. Noting that development in high risk locations continues to occur across the country and with a substantial level of existing risk, the need for a quantified support framework to guide planning decisions is essential. The BRRS framework seeks to deliver in the application of such a process using a risk and evidence-based approach.

References

Council of Australian Governments (2009) 'National Strategy for Disaster Resilience: Building our Nation's Resilience to Disasters' (Commonwealth Government: Canberra)

CSIRO (2014) 'A new Methodology for State-wide Mapping of Bushfire Prone Areas in Queensland' (Queensland Government: Brisbane)
Ellis. S, Kanowski. P, Whelan. R (2004) 'National Enquiry on Bushfire Mitigation and Management' (Council of Australian Governments: Canberra)

MWH Global (2015) 'National Land Use Planning Guidelines for Disaster Resilient Communities' (Planning Institute of Australia & Attorney-General's Department: Canberra)

Norman. B, Weir. J, Sullivan. K, Lavis. J (2014) 'Planning and Bushfire Risk in a Changing Climate: Final Report for the Urban and Regional Planning Systems Project' (Bushfire CRC / University of Canberra: Melbourne)

Queensland Reconstruction Authority (2012) 'Planning for Stronger, More Resilient Floodplains – Part 2: Measures to Support Floodplain Management in Future Planning Schemes' (Queensland Government: Brisbane)

Standards Australia (2011) 'AS3959-2009 Construction of Buildings in Bushfire Prone Areas' (Standards Australia Limited: Sydney)

Analysing the Impacts of Vegetation and Topography on Wind Fields over Complex Terrain

R. Quill*[1,2], J.J. Sharples[1,2], L.A. Sidhu[1]
[1] School of Physical, Environment and Mathematical Sciences, UNSW Canberra, Australia
[2] Bushfire and Natural Hazards CRC, Melbourne, Australia

Introduction

The importance of understanding uncertainty in the fire modelling process has been highlighted and discussed in the literature for a number of years (Preisler *et al.*, 2004; Cruz, 2010; Finney *et al.*, 2011). However, probabilistic modelling frameworks such as FireDST (French *et al.*, 2013) or SABRE (QFES, 2015) have only recently begun development. Understanding the uncertainty of input variables to these ensemble-based frameworks enables a better understanding of uncertainties in fire prediction. Since much of the variability of fire spread can be attributed to the variability of wind flow (Cruz and Alexander, 2013), recasting wind fields in a probabilistic light will not only better suit emerging ensemble-based fire prediction methods, but will also provide more comprehensive information for the fire modelling and decision making processes.

To develop probabilistic approaches to wind modelling that will complement the current physics-based models, we must understand the impacts of physical features such as surface roughness on the statistical representation of wind fields. Surface roughness may be characterised at different scales, from vegetation to topography. The impacts such features have on wind flow are well studied in the physics literature using computationally demanding mathematical models (Finnigan, 2000; Wood, 2000; Simpson *et al.*, 2013), but complex dynamics are not captured in current operational models (Forthofer *et al.*, 2014) due to the constraints of real-time (or near real-time) fire prediction. For instance, it has been shown that wind direction prediction errors of up to 180° can occur in certain areas of complex terrain. Moreover, the deterministic models currently used are not capable of capturing the inherent probabilistic nature of wind flow, particularly in areas of complex terrain where small variations in wind speed or direction can have significant impacts on fire spread and behaviour.

In this paper, wind fields are recast in probabilistic terms by considering the distribution of wind directions observed at points in the landscape. Unconditional wind direction distributions, i.e. all possible wind directions observed at a point under all conditions, are considered as well as conditional distributions – wind direction distributions observed at a point in the landscape under a specified prevailing wind direction.

Data and methods

The Kolmogorov-Smirnov (KS) statistical comparison test (Gosset, 1987) is used to compare wind direction distributions observed across different vegetation and topographic conditions.

Two case studies are presented in this paper. Firstly, the KS test is used to compare wind direction distributions observed across the fire-affected Flea Creek Valley, Brindabella National

Park NSW. Distributions observed after four years of regrowth are compared with similar observations after eleven years of regrowth. The second case study, at the National Arboretum Canberra, is used to determine whether there is a significant difference between wind directions observed on similar topography but with contrasting vegetation, and those observed in similar vegetation but with varying topography. The results will provide insights into the impacts of varying surface roughness on wind fields across complex terrain.

Results

Despite visually similar wind direction distributions, results of the KS test suggest that post-fire regrowth across Flea Creek Valley has induced a significant change in the wind fields experienced at the surface. A single exception to this result occurs on the valley floor when considering conditional wind directions, that is, given a WNW prevailing wind. In this case, the seven years of further post-fire regrowth has had no significant effect on the conditional wind direction distribution experienced at this point.

At the National Arboretum Canberra, the results of the KS test show a significant difference between wind fields observed on a clear leeward slope to those experienced on the same topographical aspect but with vegetation. Inspection of the wind direction distributions suggest that this difference is highly structured, and indicates the prevalence of lee-slope eddies in the presence of vegetation.

Significant KS test results are also obtained from the National Arboretum Canberra when considering wind fields in a uniform Radiata pine stand, but across varying topography. Visual inspection of the wind direction distributions suggests the presence of topographical thresholds to forming dynamic wind behaviour across the landscape.

Conclusion

Despite its sensitivities, results from the Kolmogorov-Smirnov test have shown that both vegetation and topography have significant impacts on wind direction in areas of complex terrain. However, in areas where wind direction is sufficiently varied, this impact becomes less obvious. The introduction of sufficient vegetation, i.e. surface roughness, on leeward slopes appears key to the development of wind reversals. Furthermore, topographical thresholds in relation to prevailing wind direction also appear to exist when considering the generation of lee-slope eddies.

These findings have important implications for bushfire modelling, particularly in light of recent research into extreme fire behaviours, when current deterministic modelling approaches are less capable of capturing key wind dynamics. This paper also highlights the potential for hybrid wind modelling approaches, which complement current deterministic physics-based models with probabilistic information. Such hybrid approaches enable quantification of the potential for the occurrence of dynamic or extreme fire behaviour in areas of the landscape, without any increase in the computational demand of modelling frameworks.

References

M. G. Cruz (2010) Monte Carlo-based ensemble method for prediction of grassland fire spread. *International Journal of Wildland Fire*, **19** (4), 521-530.

M. G. Cruz and M. E. Alexander (2013) Uncertainty associated with model predictions of surface and crown fire rates of spread. *Environmental Modelling and Software*, **47** (0), 16-28.

M. A. Finney, I. C. Grenfell, C. W. McHugh, R. C. Seli, D. Trethewey, R. D. Stratton, and S. Brittain (2011) A method for ensemble wildland fire simulation. *Environmental Modelling and Assessment*, **16** (2), 153-167.

J. Finnigan (2000) Turbulence in plant canopies. *Annual Review of Fluid Mechanics*, **32** (1), 519-571.

J. Forthofer, B. Butler, and N. S. Wagenbrenner (2014) A comparison of three approaches for simulating fine-scale surfaces winds in support of wildland fire management. Part I. Model formulation and comparison against measurements. *International Journal of Wildland Fire*, **23**, 969-981.

I. French, B. Cechet, T. Yang, and A. Sanabria (2013) FireDST: Fire Impact and Risk Evaluation Decision Support Tool - model description. In J. Piantadosi, R. S. Anderssen, and J. Boland, editors, *MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand Inc*., 2013.

E Gosset (1987). A three-dimensional extended Kolmogorov-Smirnov test as a useful tool in astronomy. *Astronomy and Astrophysics*, **188** (1), 258-264.

H. K. Preisler, D. R. Brillinger, R. E. Burgan, and J. W. Benoit (2004) Probability based models for estimation of wildfire risk. *International Journal of Wildland Fire*, **13** (2), 133-142.

Queensland Fire and Emergency Services (2015) 2014-2015 Annual Report. Technical report, The State of Queensland, Queensland Fire and Emergency Services 2015.

C. C. Simpson, J. J. Sharples, J. P. Evans, and M. F. McCabe (2013) Large eddy simulation of atypical wildland fire spread on leeward slopes. *International Journal of Wildland Fire*, **22** (5), 599-614.

N. Wood (2000). Wind flow over complex terrain: A historical perspective and the prospect for large-eddy modelling. *Boundary-Layer Meteorology*, **96** (1/2), 11-32.

Australia's New National Guidelines for Prescribed Burning

Paul de Mar*
GHD Pty Ltd, Sydney, NSW, Australia   paul.demar@ghd.com
Dominic Adshead
GHD Pty Ltd, Sydney, NSW, Australia   dominic.adshead@ghd.com

Extended Abstract

The Australasian Fire and Emergency Service Authorities Council (AFAC) and Forest Fire Management Group (FFMG) have over the last three years been undertaking a major project called the National Burning Project (NBP). Under this project, GHD recently completed preparation of National Guidelines for Prescribed Burning. These guidelines are focussed on the operational planning and burning operations implementation phases of prescribed burning. Due to the great variety in climate, landscape, vegetation and fuel types across Australia, the guidelines are necessarily developed at 'principles' level , establishing 17 principles which cover the process of planning a burn, preparing for its implementation, executing the burn, and conducting post-burn assessment. Each principle is supported by some guidance material on considerations and practice. The guidelines contain 9 case studies from around Australia, showcasing the systems and techniques applied by Australian land and fire managers in planning and conducting burning operations in diverse range of fuel types, from savannas and spinifex grassland in north and central Australia, to a range of forests (including those at the urban-bushland interface), shrublands and button grass moorlands in southern Australia. These case studies illustrate how tools such as fire behaviour prediction guides are used and how operational knowledge-based systems are applied. The case studies provide knowledge-rich, practically-focussed resource material for those developing burning guides for local fuel types and landscape settings. The guidelines are being used by AFAC as a framework for the development national prescribed burning training materials, and are already being used in WA as a framework for State-level prescribed burning guidelines development. In this conference paper I outline the key features of the national prescribed burning guidelines and case studies.

Prescribed burning in Australia – some context

Deliberate, purposeful biomass burning by humans has a history spanning more than 40,000 years in Australia. For Aboriginal people throughout Australia, the use of fire was central to their way of life and obligatory to meet their spiritual and cultural obligations to care for country. The use of fire was their principal means of shaping and managing local environments to sustain a diversity of food sources which were abundant, predictable (in time and space) to locate, and convenient to access and acquire through the year and despite inter-annual climate variability[1]. Their use of fire also provided safe areas for living, facilitated navigation and travel, was a means of communication, facilitated tracking of animal movement/location and hunting methods, and provided heat for a range of purposes and light. These traditional burning practices only continue in certain areas where knowledge of

[1] There is a significant body of literature examining the issue of traditional Aboriginal burning practice, including a range of studies conducted at regional and sub-regional scales. Among the more comprehensive works on the subject is *The Greatest estate on Earth - How Aborigines made Australia* (2011) by historian Bill Gammage (Adjunct Professor at the Australian National University) which brings together a wide array of evidence on the subject of how, where and why Aboriginal people modified and maintained Australian landscapes with fire.

traditional practices has been retained, and where traditions involving burning remain a part of contemporary lifestyles of the traditional owners. There is widespread acknowledgement that Indigenous Australians continuous and frequent use of fire in the landscape contributed significantly to shaping the biodiversity of Australia as it existed prior to European settlement. In southern Australia, Indigenous burning practices have been extinguished, in most places for more than a century. They have been replaced by very different burning practices – different in scale, frequency and timing - instituted by European settlers, changes which have been evolving and changing to the present day.

Prescribed burning for community and asset protection has been used by Australian public land management agencies since about the 1960s, when the development of systematic science-based approaches gained momentum. Prior to that, burning to reduce fuels around properties was principally an activity undertaken for self-protection by people living in rural or forested areas, acting individually or in local groups (it is noteworthy that the majority of private and leasehold rural land burning undertaken was by pastoralists for native pasture management and shrub control). The use of prescribed fire specifically for ecological purposes has been a relatively recent practice emerging mostly since the 1990s, principally on public land and some privately owned reserves managed for conservation. In most places the scale and frequency of prescribed burning since European settlement never reached anything close to the traditional burning practices undertaken by Aboriginal people prior to settlement.

Undertaking prescribed burns is not risk-free – there are unavoidable uncertainties (sources of risk) associated with weather, fuel condition variability, undetected burn escape vectors, and the potential for human error to be managed when implementing prescribed burn programs, but a level of residual implementation risk will inevitably remain. Communities expect that those undertaking prescribed burns will diligently manage the associated risks. Further, community understanding of, and attitudes to the use of prescribed fire varies widely, from those with substantial doubts about its benefits along with concerns about its impacts, through to those who advocate that it is an essential bushfire risk reduction tool and expressing strong criticisms that it is insufficiently used by land managers and fire services among others.

With our expansive continental area and large latitudinal range, Australia has a great variety of different climatic zones, vegetation communities and land-use patterns. Hence there is vast range of different physical operating environments and contexts in which prescribed burning is applied. These range from high risk urban interface areas abutting vast areas of fire-prone forests; to rural landscapes with an intermix of townships, agricultural land and retained bushland areas; to vast tropical savanna landscapes; alpine and sub-alpine landscapes with limited access; vast semi-arid rangelands; to areas containing complex vegetation mosaics including rainforest, tall wet forests, dry open forests, woodlands, shrublands and grasslands. Accordingly, a diverse range of prescribed burning practices and tools have been developed.

National Prescribed Burning Guidelines

While a necessarily wide range of different prescribed burning planning and operating practices have been developed in response to the range of different operating environments, practices can be said to follow a similar staged planning and implementation process and founded on some common operating principles. The National Prescribed Burning Guidelines therefore focussed on establishing a logical common operating framework for the prescribed burn planning and implementation process, founded around a suite of key principles with which good burn planning and implementation practice should conform. Supporting each principle are some brief general guidance notes explaining the key considerations, analyses and decision points typically involved in implementing a good practice approach.

The end-to-end prescribed burning process within which the operational planning and implementation work phases sit is depicted at Figure 1.

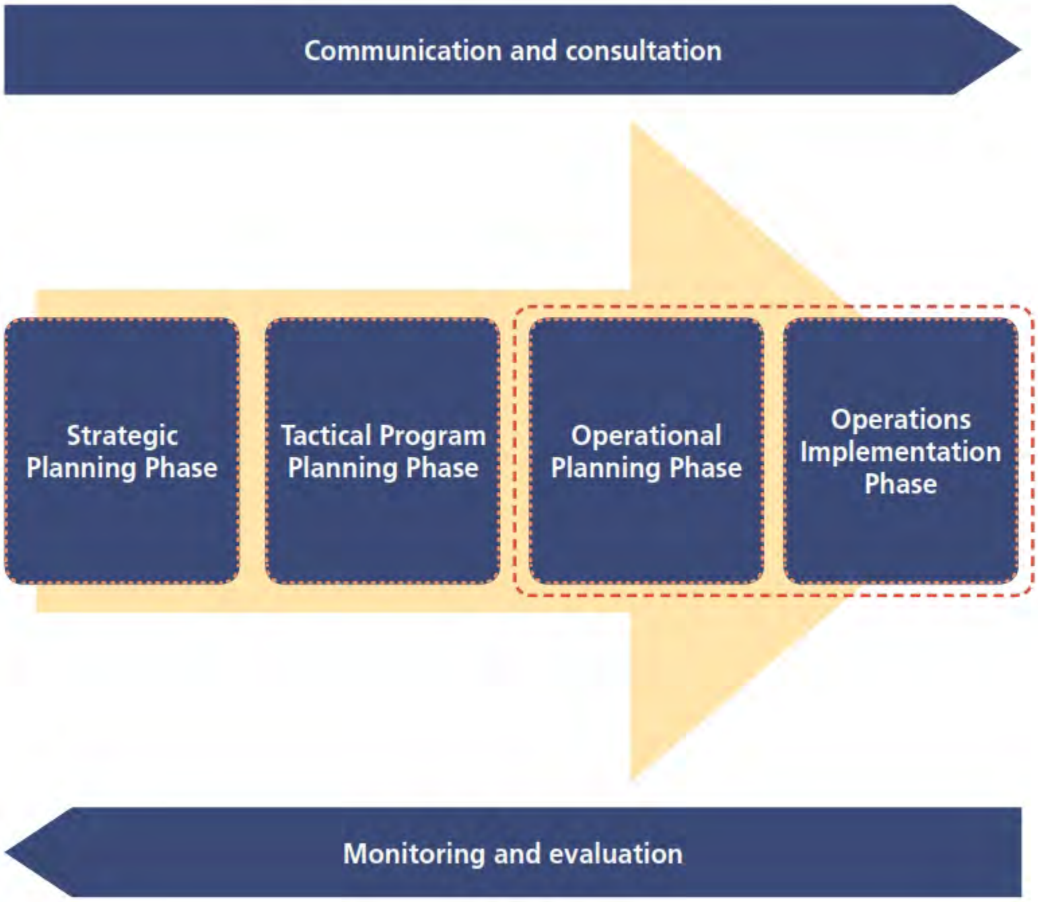

Figure 1 High-level end-to-end process model for prescribed burning

Operational planning progresses prescribed burn planning from the strategy and scheduling phases of strategic and tactical planning (setting location, area, burn type and season) through to the stage where a specific burn activity is planned and made ready to implement.

The operational planning phase has three key stages:

1. Burn site and risk analysis
2. Deciding the burn execution and risk management strategies

   [The principal output of operational planning phases 1 and 2 is Prescribed Burn Plan

3. Burn preparation

The burn implementation phase also has three key stages:

1. Conduct burn-day checks
2. Light and control the burn and manage associated risks
3. Assess and decide scale-down (or scale-up) and patrol requirements

Following completion of the burn a post-burn assessment phase is implemented.

A prescribed burn planning and implementation process model is depicted at Figure 2.

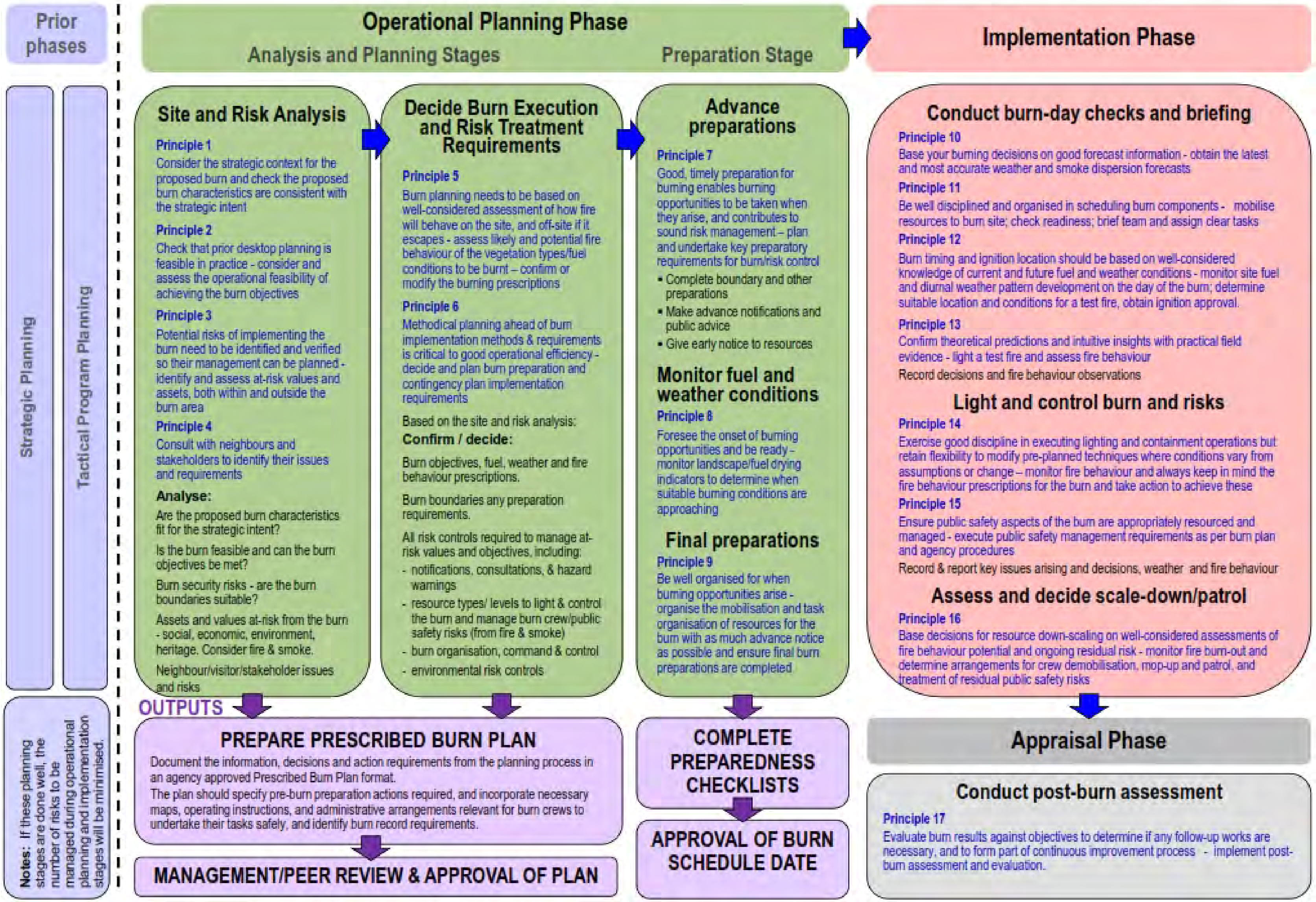

Figure 2 Process model of prescribed burning: operational planning, implementation and appraisal phases

Prescribed Burning Principles

As captured within the process model, 17 best-practice principles for successful and efficient prescribed burning have been identified. Chapter 4 of the national guidelines provides general guidance in relation to each of the principles.

The guidelines provide an explanation of why each principle is important, some general practice notes providing guidance on what considerations need to be addressed to meet the broad requirements of each principle, and the nature of key decision points involved.

Recognising that the range of prescribed burning operating contexts around Australia varies greatly, the guidelines are intentionally not prescriptive. They are more focussed on what needs to be considered, decided and done, not the detail of how. The detail of how things are done is by necessity left open to agencies to determine given that each will have its own unique combination of institutional arrangements; regulatory obligations; policies and management priorities; organisation and resourcing levels; different capabilities, limitations, and risk appetite; and systems maturity for prescribed burn planning and implementation.

Prescribed Burning Case Studies

Chapter 5 of the national guidelines provides nine case studies from around Australia that document how an agency, or group of agencies in a particular jurisdiction, undertake planning for, and implementation of prescribed burns for a particular vegetation type or operating environment.

The case studies incorporated in the national guidelines are:

Case Study 1	Bush-urban interface burns – Blue Mountains (NSW)
Case Study 2	Burning young Silvertop Ash regrowth forests (NSW)
Case Study 3	Low intensity burning in tall moist Karri forests (WA)
Case Study 4	Multi-year landscape mosaic burning in forested mountain terrain using natural boundaries (VIC)
Case Study 5	Semi-arid mallee and mallee-heath burning (SA)
Case Study 6	Button grass moorland burning (Tasmania)
Case Study 7	Savanna burning for greenhouse gas abatement (NT)
Case Study 8	Spinifex hummock grassland burning in the arid interior of WA (WA)
Case study 9	Burning for eucalypt forest health in SE Queensland / Northern NSW

The case studies provide a valuable resource providing such things detailed planning and implementation procedural information, tools for assessing whether fuels are in a suitable condition for burning within prescription, fire behaviour prediction guides, decision-support systems and ignition/burn-control techniques specific to each particular burn scenario. The case studies integrate operational knowledge and practice gained through years of implementing burning operations with scientific knowledge and tools developed through research to support burning implementation. The national guidelines report contains only a one page synopsis of each case study, however weblinks are provided to the full case studies on the AFAC website.

Intended use for the National Guidelines

The national guidelines have been developed with a view to providing a nationally consistent framework to guide prescribed burn planning and implementation by agencies. Development of the national guidelines was informed by extensive input from fire and land management agencies around Australia and thus can be considered industry-developed guidelines.

For those agencies embarking on a process of reviewing and improving their prescribed burn planning and implementation practices, the guidelines can provide a useful reference document facilitating alignment with a nationally adopted framework and process model.

For those agencies preparing or reviewing existing procedural documentation relating to different phases of burn planning and/or implementation, the guidance notes can provide a useful frame of reference for considerations to cover and matters to address in developing a best-practice approach.

For those seeking to develop or improve prescribed burning guides for specific burning applications or fuel types, the range of case studies showcase a range of innovative approaches to developing practical guidance tools for burn practitioners.

For those seeking to commission or undertake fuels or fire behaviour research work to improve the knowledge and systems basis for prescribed burning in particular applications or fuel types, the case studies show a range of different ways in which research findings have been translated into operational tools that support prescribed burn planning and implementation.

AFAC has recently reviewed its competency standards and training resource materials for prescribed burning. These have been aligned to the framework and principles set out in the national guidelines.

Further Reading

AFAC (2016) National Guidelines for prescribed burning operations. Report for National Burning Project – Subproject 4. Australasian Fire and Emergency Service Authorities Council Limited (Melbourne: Victoria). http://www.afac.com.au/initiative/burning

de Mar P, Kingswood R, Meade G, Henry A and Scott-Lawson D (2016) Case Study 1 - Bush-urban interface burning in the Blue Mountains of NSW

de Mar P, McGuffog T and Linehan M (2016) Case Study 2 - Burning young silvertop ash regrowth forests in NSW

de Mar P, Adshead D, McCaw L, Keppel P, Bennett J and Moss B (2016) Case Study 3 - Low intensity burning in tall moist Karri forests in Western Australia

de Mar P, Caddell R and Jamieson D (2016) Case Study 4 - Multi-year landscape mosaic burning in forested mountain terrain using natural boundaries in Victoria

de Mar P, and Wouters M (2016) Case Study 5 - Semi-arid mallee and mallee-heath burning in South Australia

de Mar P, and Pyrke A (2016) Case Study 6 - Button grass moorland burning in Tasmania

de Mar P (2016) Case Study 7 - Savanna burning for greenhouse gas abatement in Northern Australia

de Mar P, Burrows N, and Butler R (2016) Case Study 8 - Burning of spinifex grasslands in the arid interior of Western Australia

Adshead D, Burnham M and Kington D (2016) Case Study 9 - Burning for eucalypt forest health in Southeast Queensland / Northern NSW

Note: All the above case studies are available at http://www.afac.com.au/initiative/burning

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Building a Comprehensive Fuel Map – From Research to Operational Use

Belinda Kenny* and Levi Roberts
NSW Rural Fire Service, Lidcombe, NSW, Australia, * Belinda.Kenny2@rfs.nsw.gov.au

Introduction

Having a comprehensive fuel map provides input for a wide range of fire management planning and operational applications. The NSW fuel type map has recently been revised to incorporate years of research on fuel accumulation.

Knowledge of fuel type and fuel load is required operationally for fire behaviour predictions, and a state-wide data layer is an essential input into fire behaviour simulators. With adequate fuel type and fire history mapping, fuel load maps can be produced, showing current and maximum predicted fuel load. These maps are an invaluable resource for fire behaviour analysis and other applications such as risk management planning and hazard reduction prioritisation.

Methods

Bushfire Fuels Research

In order to gather the best available information on bushfire fuels in NSW, the Rural Fire Service (RFS) commissioned the University of Wollongong (UoW) to conduct a comprehensive fuel modelling project. This project examined multiple aspects of fuel development for the forest and grassy woodland vegetation types of NSW:

- Literature review (Watson, 2009)
- Collation of existing fuel load dynamics research (Watson 2012)
- Fuel hazard field study including comparison of methodologies and provision of Overall Fuel Hazard (OFH) and Vesta hazard score information for selected vegetation classes (Watson *et al.* 2012a)
- Bark fuel assessment (Horsey and Watson 2012)
- Synthesis of work including collation of fuel accumulation curve parameters and identification of information gaps (Watson *et al.* 2012b)
- Literature review of canopy fuels (CERMB 2013)

Further work has been conducted to provide information on fuels in some heath and forested wetland vegetation classes (Gordon and Price 2015).

Fuel Map Development

The approach used to create a fuel map was to first construct a fuel type map (Figure 1). As coverage of the entire state of NSW was required, state-wide data sets were needed as inputs. A composite raster map was created from a native vegetation map ('Vegetation Classes of NSW v3.03b' dataset using the classification of Keith (Keith 2004, Keith and Simpson 2010)) in-filled in cleared areas with vegetation cover ('NSW Native Vegetation Extent MODIS/FPC' dataset from OEH) and overlayed with land use (e.g. urban, plantations, agriculture, etc. from various Land and Property Information and land management agency datasets).

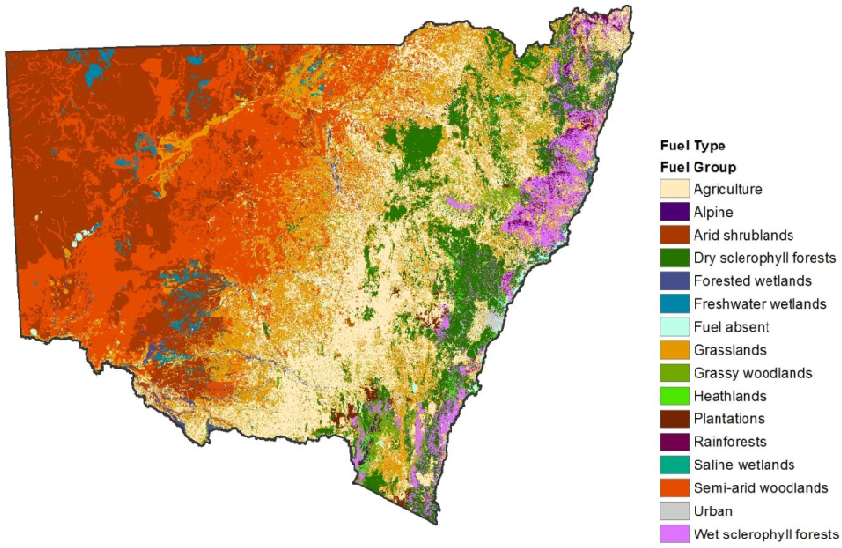

Figure 1. Fuel type map; grouped into broader fuel groups

Fuel types were classified within this map based on the level of available fuel accumulation data. The UoW fuels research (Watson *et al.* 2012b; Gordon and Price 2015) provided fuel parameters at formation level for rainforest, and at class level for wet sclerophyll forests, dry sclerophyll forests, grassy woodlands, and some heathlands and forested wetlands. Remaining native vegetation classes and non-native vegetation were grouped into types with similar structures and assigned fuel parameters based on other sources (Tolhurst 2005, Metcalf and Price 2013).

To produce the predicted fuel load map, the fuel type map was overlayed with fire history to calculate the current fuel load level based on the fuel accumulation parameters (Figure 2). A state-wide fire history map was converted to a time since fire raster, then a series of raster calculations performed to give fuel load per strata (surface, elevated, bark) and a total fuel load (Figure 3).

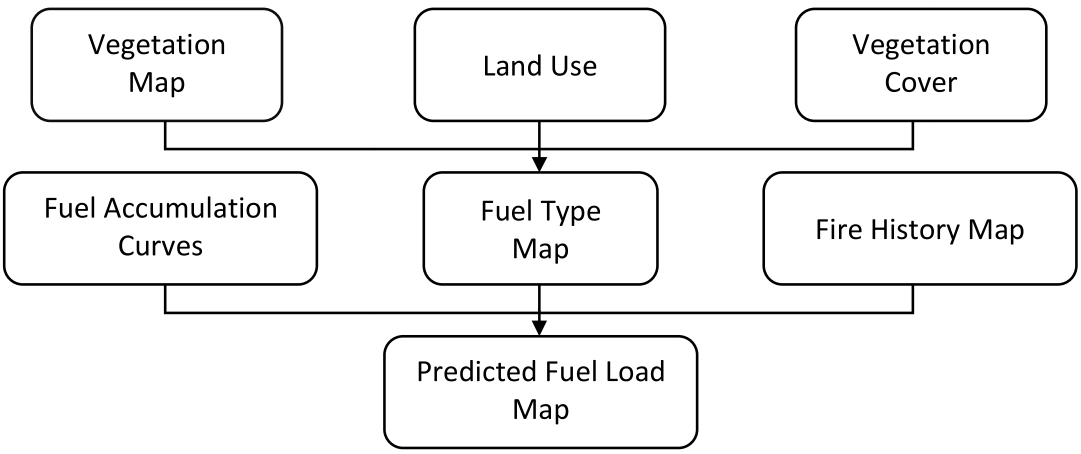

Figure 2: Fuel map construction process

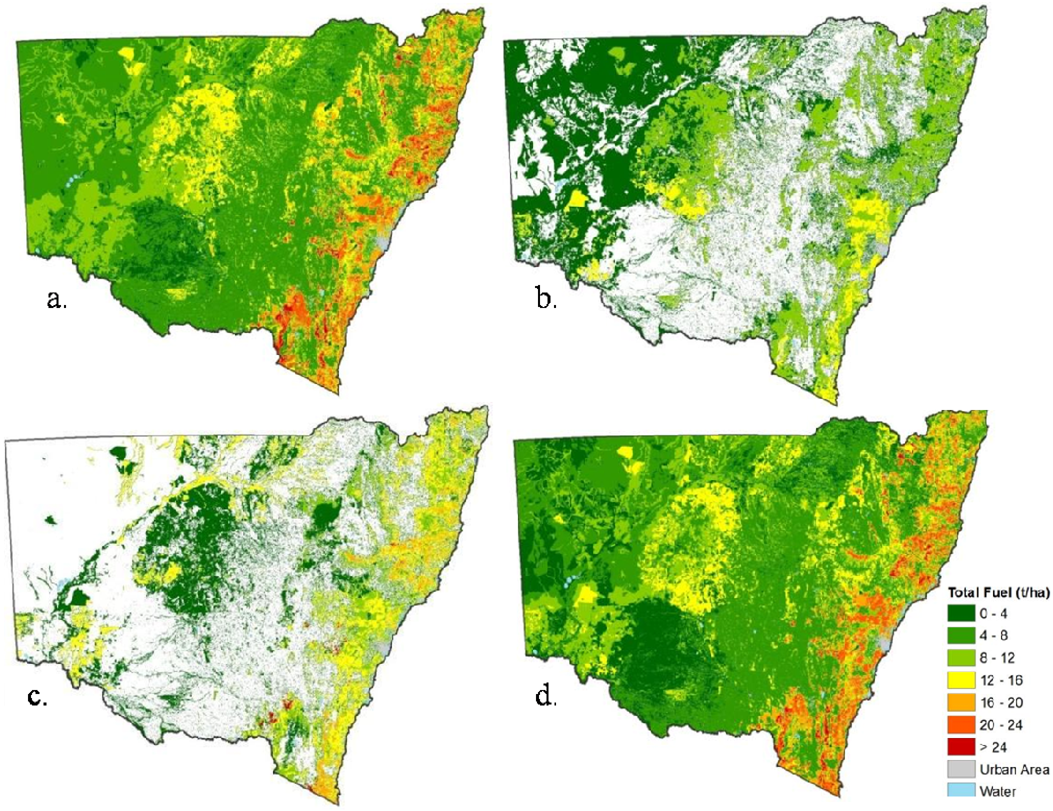

Figure 3. Predicted fuel load by fuel strata: (a) Surface fuel; (b) Elevated fuel; (c) Bark fuel; (d) Total fuel load.

Discussion

Operational Application of Research Data

The value of research to an operational agency is realised when it can be applied for operational use, allowing best practice through the use of the best available information.

Output from the UoW fuels modelling project is being applied by the RFS in multiple ways including fuel tables in the 'Fire Behaviour Analyst Handbook', interactive fuel curves in the 'Forest and Woodland Fuel Dynamics Calculator', and compilation of fuel type and predicted fuel load maps. These applications have required different levels of development by RFS staff to make them suitable for operational use. Having well collated, defined, and fit for purpose research output makes it possible to develop these operational applications.

Fuel Map Products and Applications

The initial intent of updating the NSW fuel type map was to provide a better input data layer for use in the Phoenix Rapidfire (Tolhurst *et al.* 2008) fire spread simulator. Phoenix requires a map of fuel types, a look up table of fuel curve parameters, and a fire history map. The appropriate classification of fuel types, the accuracy of the fuel curves applied and the spatial accuracy of the fuel and fire history mapping all affect the accuracy of the fire behaviour outputs from Phoenix (Metcalf and Price 2013).

By updating the Phoenix fuel input data to reflect current best knowledge of fuel dynamics, greater confidence is gained in the output, and hence operational use, of this simulator. As the RFS is starting to use Phoenix for scenario modelling and risk management planning applications (see Wells and O'Halloran in these proceedings), the use of the best available input data is increasingly important.

The fuel type and predicted fuel load maps can be displayed in numerous ways for operational and planning applications. For use in manual fire spread predictions by Fire Behaviour Analysts (FBANs), having both the fuel type map (to choose the appropriate fie behaviour model) and predicted fuel load maps (to estimate current fuel quantity) available as GIS data layers makes a quick and convenient way to obtain this essential information.

There are multiple ways to present the predicted fuel load map (Figure 4), for example as maximum fuel (fuel load calculated for long unburnt state), current fuel (calculated based on fire history at a point in time), or proportional (calculated as the current fuel as a proportion of maximum fuel). These maps provide a good strategic overview of areas where fuel load is currently high and may need to be considered in hazard reduction planning.

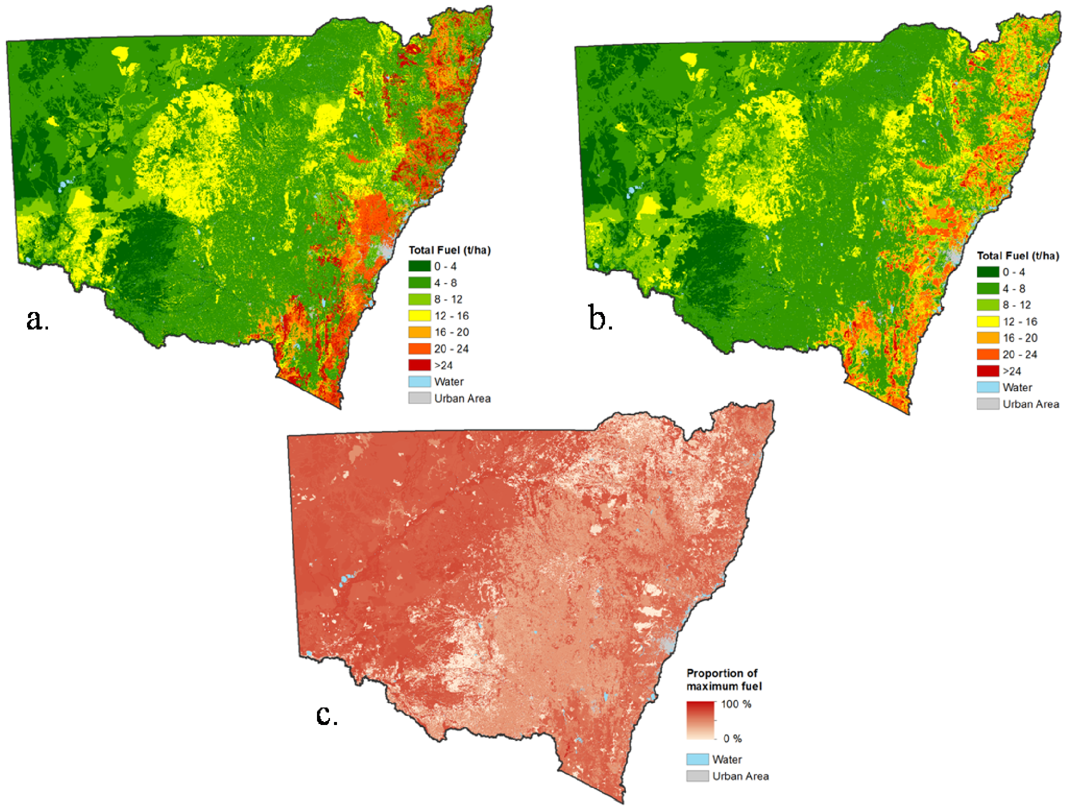

Figure 4. Predicted total fuel load displayed as (a) Maximum fuel (t/ha); (b) Fuel at 1-Jan-2015 (t/ha); (c) Fuel at 1-Jan-2015 as a percent of maximum fuel.

Other applications of information provided by the UoW fuels modelling project include categorising spotting hazard (Figure 5) from the information provided on the proportion of species with specific bark types (Horsey and Watson 2012). This is another valuable operational data source for FBANs, and provided one of many data inputs used in the RFS Fire Danger Rating trial (see Matthews *et al.* in these proceedings).

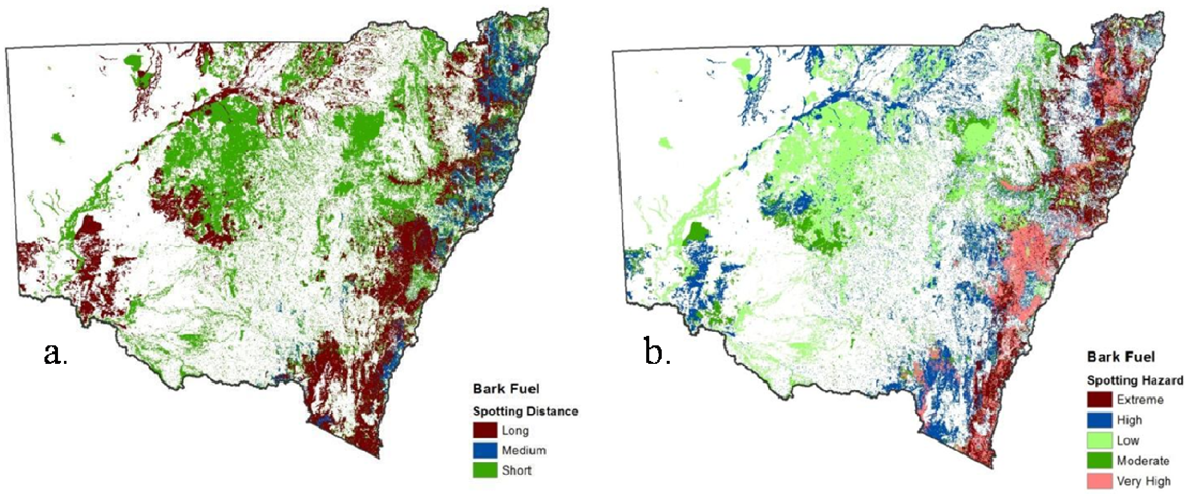

Figure 5. Bark fuel information expressed as (a) Potential spotting distance; (b) Spotting hazard (potential ember density).

Future Developments
The quality and hence value of modelled fuel data is limited by the quality of the input data sources. Hence, an ongoing improvement process is required to incorporate new and improved data as it becomes available.

Opportunities for validation of the predicted fuel load map (e.g. cases where FBAN or Phoenix fire spread predictions have been inaccurate; fire spread reconstructions; or comparison to field observations of fuel hazard) can help to identify issues in the underlying data. Consistent issues found with a particular fuel type would indicate the need for better fuel dynamics data. Spatial accuracy issues can be addressed by identifying better map source data to use in construction of the fuel type map.

Future developments might include finding newer data sources for mapping fuel type or characterising fuel structure (e.g. LiDAR or other remote sensing data), inclusion of biophysical modelling to describe fuel dynamics, or alternate fuel classification systems.

Current projects include a validation of predicted fuel load against field fuel hazard data being run by the ACT Parks and Conservation Service (Adam Leavesley, personal communication), and re-classification of the fuel type map into the draft national Bushfire Fuel Classification system being developed through the Australasian Fire and Emergency Service Authorities Council (Hollis *et al.* 2014).

References

CERMB (2013) 'Canopy Fuels: Literature Review.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Gordon C, Price O (2015) 'A Review of Fuel Load Dynamics in Heathlands and Forested Wetlands of New South Wales.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Hollis J, Gould J, Cruz M, Doherty M (2014) 'Development of a Framework for a Bushfire Fuel Classification.' CSIRO, Canberra and AFAC, Melbourne.

Horsey B, Watson P (2012) 'Bark Fuel in New South Wales Forests and Grassy Woodlands.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Keith D (2004) 'Ocean Shores to Desert Dunes: Native Vegetation of New South Wales and the ACT.' NSW Department of Environment & Climate Change, Hurstville.

Keith D, Simpson C (2010) 'Vegetation Formations of NSW (Version 3.0). A Seamless Map for Modelling Fire Spread and Behaviour.' Report to the Rural Fire Service. NSW Department of Environment & Climate Change, Hurstville.

Metcalf S, Price O (2013) 'Performance of the Phoenix Fire Characterisation Model.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Tolhurst K (2005) 'Conversion of Ecological Vegetation Classes (EVCs) to Fuel Types and Calculation of Equivalent Fine Fuel Loads with Time Since Fire, Victoria.' University of Melbourne, Victoria.

Tolhurst K, Shields B, Chong D (2008) Phoenix: development and application of a bushfire risk management tool. *Australian Journal of Emergency Management* **23**, 47-54.

Watson P (2009) 'Understanding Bushfire Fuels. A Report for the NSW Rural Fire Service.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Watson P (2012) 'Fuel Load Dynamics in NSW Vegetation. Part 1: Forests and Grassy Woodlands.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Watson P, Penman S, Horsey B (2012a) 'Data from the UoW Fuel Hazard Study, by Vegetation Type and Time-since-fire.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Watson P, Penman S, Horsey B (2012b) 'Bushfire Fuels in NSW Forests and Grassy Woodlands. Fuels Modelling Project Final Report.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

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Characterising Fire Weather for Victorian Fire Risk Landscapes

Sarah Harris*[a], Graham Mills[a] and Tim Brown[ab]

a. School of Earth, Atmosphere & Environment, Monash University, Melbourne, VIC, Australia
b. Desert Research Institute, Reno Nevada, USA

Background

Weather and climate are essential components in understanding bushfire characteristics and for informing fire management. A high spatial and temporal resolution climatology of fire weather is vital for examining relationships and determining bushfire risks upon which to base fire management decisions. A homogeneous 41-year (1972–2012) hourly 4-km gridded climate dataset for the fire-prone state of Victoria, Australia has been generated using a combination of mesoscale modelling, global reanalysis data, surface observations, and historic observed rainfall analyses. Outputs include the surface weather variables hourly temperature, relative humidity, wind speed and wind direction. Combined with daily drought indices these data have been used to calculate a commonly used fire danger index. This extended abstract describes how the dataset is used to characterise the fire weather of Victoria and highlights its use and relevance for fire management.

Methods

To characterise the fire weather of Victoria data were analysed on differing spatial and temporal scales. The mean, minimum, maximum and percentiles were calculated for each variable on temporal scales include hourly, monthly, seasonally and annually. The average of the grid points within Victoria and for each Bushfire Risk Landscape were also calculated to further analyse and highlight the spatial and temporal differences (Figure 1). Further analysis calculated trends for each of the variables and timescales along with anomalies. The discussion in this extended abstract primarily focuses on characteristics of the FFDI.

To understand the variability in extreme fire weather across Victoria 23 representative stations were chosen. The nearest grid point to each station was found and timeseries data extracted for each candidate station. The data were sorted by FFDI and the top-ten days extracted along with the corresponding weather variables (temperature, relative humidity, wind speed, wind direction, KBDI and DF). The variability, range and trends in extreme FFDI were analysed.

*Sarah Harris, sarah.harris@monash.edu
School of Earth, Atmosphere and Environment, Faculty of Science, Monash University, Clayton, VIC, Australia 3800

Figure 1. The outline of Victoria and the Bushfire Risk Landscape, and 23 candidate stations.

Results

Diurnal cycles

There is a clear diurnal cycle for the FFDI in January. The highest mean FFDI hour for Victoria occurs in the late afternoon. The hour with the lowest mean FFDI is near dawn, which is followed by a steeper increase of FFDI following sunrise. The Mallee & Murray Goulburn region has the highest mean hourly January FFDI. The Alpine & Greater Gippsland, Barwon Otway and East Central regions all have the lowest hourly averaged FFDI values in January. Information on the spatial variability of diurnal cycles may be important in preparing for active fires as well as planning for prescribed burns.

Seasonal variability

There is large variability spatially across Victoria and between seasons as revealed by the 99th percentile of daily maximum FFDI (Figure 2). As expected, the summer (December, January and February) reveals the highest FFDI values overall with the most extreme occurring in the north west of the state and the lowest values in the Alpine area. Also, as expected, the lowest values across the state are found in the winter months (June, July and August). Autumn (March, April and May) reveals a slight contrast between the east and west of the state with higher average values in the north west and lower in the south and east. For the FFDI 99th percentile in spring there is a large contrast between the northwest of the state and the rest of the state. This type of spatial and seasonal variability may reveal important information for planning fuel reduction burns and also for preparing for a fire season.

*Sarah Harris, sarah.harris@monash.edu
School of Earth, Atmosphere and Environment, Faculty of Science, Monash University, Clayton, VIC, Australia 3800

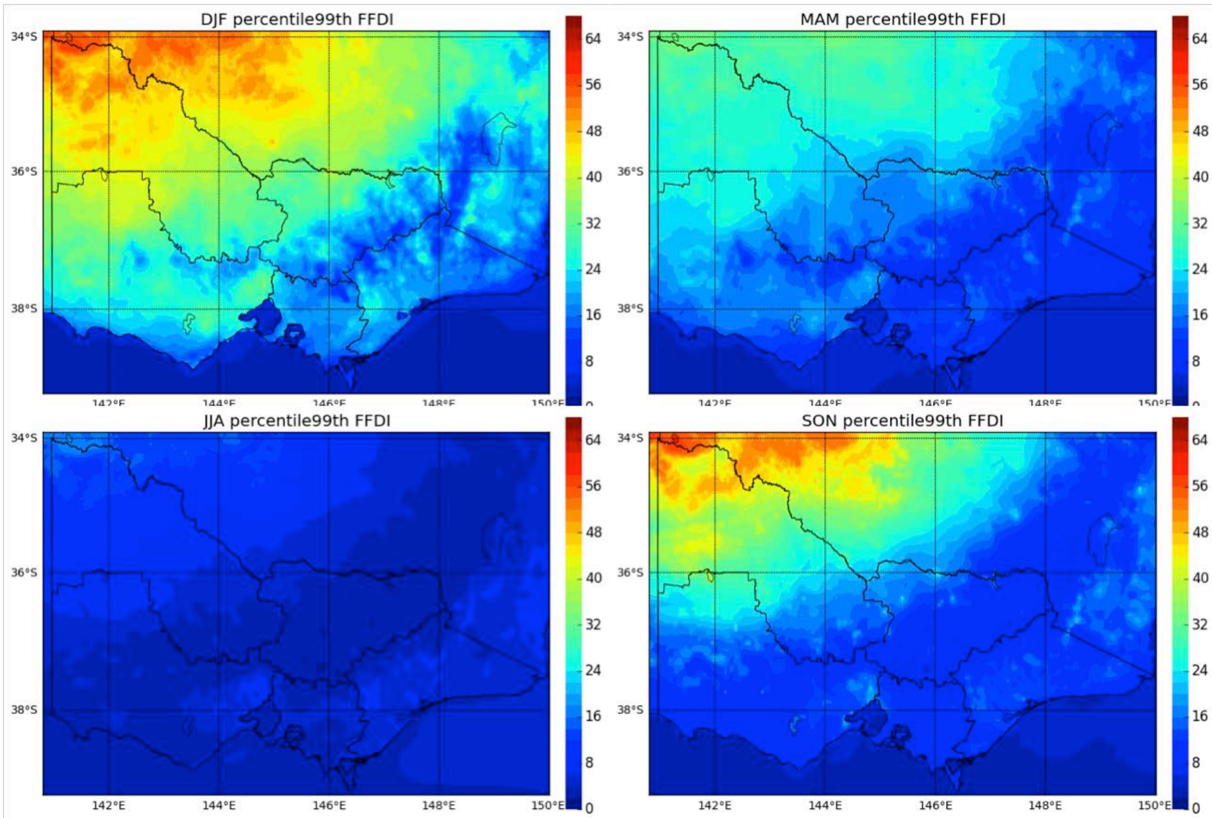

Figure 2. The FFDI 99th percentile (1972-2012) for each season – March, April, May (MAM), June, July, August (JJA), September, October, November (SON) and December, January, February (DJF)

Annual anomalies

The Victoria mean maximum annual FFDI anomaly reveals broad interdecadal variability. The cycle begins with a mostly positive anomaly from 1972 to 1983 and then for the extended period of 1984 to 2000 the FFDI anomaly remains mostly negative. Following this (from 2001 until 2012) the FFDI anomaly has been positive (with the exception of 2010-11). The highest positive anomalies generally coincide with years that have resulted in extreme fire activity or seasons.

Variability of extreme fire weather

There is large variability between candidate stations in the FFDI values for the top ten FFDI events. Stations in the warmer and drier north west of the state have the highest median FFDI values. Stations in areas with high elevations that are commonly cooler than surrounding areas reveal the lowest median FFDI values for the top ten events. Further work investigates the climate variables that contribute to this variability and also the trends in this variability.

*Sarah Harris, sarah.harris@monash.edu
School of Earth, Atmosphere and Environment, Faculty of Science, Monash University, Clayton, VIC, Australia 3800

Discussion and Conclusion

There is significant spatial and temporal variability in fire weather across Victoria and between each Bushfire Risk Landscape and this has implication for fire management. Furthermore, there is variability and range in the most extreme FFDI events and the associated weather elements driving the FFDI.

The opportunities to use the dataset described and the outputs produced are limitless. Examples include, as base line information for climate change studies, to inform fire management plans and assist in identifying regions of greatest risk and where fuel hazard reduction burns will be the most effective in reducing risk. The opportunities to advance bushfire research for these regions and thereby provide information to improve risk analysis and fire management are immense.

Acknowledgments

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References

Brown T, Mills G, Harris S, Podnar D, Reinbold H, Fearon M (2015) A fire weather climatology data set for Victora. Final Report to the Department of Environment, Water, Land and Planning. September 2015. 129pp.

Jones DA, Wang W, Fawcett R (2009) High-quality spatial climate data-sets for Australia. Australian Meteorological and Oceanographic Journal **58**, 233–248

*Sarah Harris, sarah.harris@monash.edu
School of Earth, Atmosphere and Environment, Faculty of Science, Monash University, Clayton, VIC, Australia 3800

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Community Protection Planning in New South Wales, Australia - Tailoring Bush Fire Risk Management to Individual Communities

Patrick Schell* and Andrew Nicholls
New South Wales Rural Fire Service, Lidcombe, New South Wales, Australia,
patrick.schell@rfs.nsw.gov.au

Introduction

One of the key themes that arose during the Royal Commission Inquiry into 2009 Victorian 'Black Saturday' Bush Fires was the importance of educating the community on bush fire risk as well as the most appropriate actions to take prior to and during a bush fire (VBRC 2010). Following the delivery of the Royal Commission's final report and recommendations, community level bush fire planning programs have been established in a number of State jurisdiction across Australia.

In New South Wales (NSW), the Community Protection Plan initiative was developed in direct response to the recommendations from the Victorian Bush Fire Royal Commission. Recommendations 1-5 of the final report, which relate to bush fire safety policy, have provided a basis and impetus for the development of this program (NSW Government 2010).

The Community Protection Plan program is now in its fourth year of operation. Over this period, it has become an integral part of the bush fire risk management framework for the State and evolved into a valuable education tool for communities at risk of bush fire. This paper will provide a brief overview of Community Protection Plans in NSW and outline some examples of how the process has been used to engage communities, resolve issues and generate positive bush fire protection outcomes for an area.

Bush Fire Risk Management Arrangements in NSW

A comprehensive bush fire risk management framework currently exists in NSW, which is supported by legislation and State policy. The framework is governed by the Bush Fire Coordination Committee (BFCC), which is a multi agency body formed under the *Rural Fire Act* 1997 that has a pivotal role in planning in relation to bush fire prevention and coordinated fire fighting (BFCC 2006).

Local Bush Fire Management Committees (BFMC) are formed by the BFCC and have representation from the land management and fire agencies for the area. A BFMC typically covers a broad geographic area and can consist of one or multiple local government authorities. One of the main legislative responsibilities of a BFMC is to prepare a Bush Fire Risk Management Plan (*Rural Fire Act* 1997).

The Bush Fire Risk Management Plan is a strategic document that identifies the level of bush fire risk across the BFMC area and records the treatment strategies specified by the BFMC. The document also outlines who is responsible for the risk treatments and when they will be implemented (BFCC 2008). Community participation forms a key component of preparing a Bush Fire Risk Management Plan in NSW. Members of the community are actively engaged and given an opportunity to have input on the bush fire risk management process. This provides an avenue for concerns and perceptions of risk to be identified, better understood, documented and addressed (BFCC 2008).

Whilst the Bush Fire Risk Management Plan provides an effective tool for managing bush fire risk across a BFMC area, in the majority of cases, engaging members of the community in the development of the document has been a challenging exercise. Experience has shown that this is partially due to the scale at which the Bush Fire Risk Management Plan is prepared and presented. The maps that accompany the plan cover broad areas and are often used as visual tools in engagement activities. However, it has become clear that most people find it difficult to relate to or connect with this type of information.

Therefore, the creation of improved visual tools that have greater appeal to members of the community and compliment the strategic Bush Fire Risk Management Plan is an important element that underpins the Community Protection Plan initiative (NSW RFS 2013).

Community Protection Plans in NSW

In NSW, Community Protection Plans have developed into a tactical bush fire planning document that incorporates a range of aspects relevant to bush fire risk management into a single document. They provide the public, fire services and land management agencies with easy to understand information that is specific to a community. For the purpose of the Community Protection Plan program, a community is defined by geographic location (NSW RFS 2013).

Community Protection Plans have been integrated into the State policy and currently forms a treatment option in a Bush Fire Risk Management Plan. This treatment is generally applied to human settlement assets that have a very high to extreme risk rating. The plans are prepared by the NSW Rural Fire Service (RFS) who work closely with the BFMC agencies and local community groups. Under State policy, the responsibility for approving a Community Protection Plans rests with the BFMC (BFCC 2008).

Through the development of the Community Protection Plan framework, linkages have also been established with other existing bush fire planning activities such as:

- Personal Bush Fire Survival Plans for residents of the community
- Local brigade operations and pre-incident planning
- Evacuation planning undertaken by Local Emergency Management Committees
- Land manager / owner Plans of Management / Fire Management Strategies

(NSW RFS 2013)

The Planning Process

As part of the framework, guidelines were established to outline the process for developing, implementing and maintaining a Community Protection Plan. Essentially, the planning process involves the following eight steps:

1. Initial Consultation with Key Stakeholders (which includes the development of a communication strategy)
2. Information Collection and Desktop Analysis
3. Field Investigations
4. Review of Existing Bush Fire Treatments
5. Preparation of Draft Community Protection Plan Maps
6. Community Consultation
7. Promoting and Implementing the Plan
8. Monitor and Review

(NSW RFS 2013)

Communication and consultation with stakeholders is a critical aspect of preparing a Community Protection Plan and must occur throughout the process. This will be vital to the development of a plan that is relevant, practical and addresses the specific issues of the community. The level of involvement of the community, particularly in the development phase, will influence the overall success of the process. (NSW RFS 2013)

The Community Maps

The maps produced as part of a Community Protection Plan in NSW appear to have a number of common elements with similar programs that exist in other State jurisdictions. Three community maps are prepared each with a different purpose and target audience. These maps attempt to reflect the Prepare.Act.Survive messaging used by fire agencies throughout Australia. A brief description of the three maps are outlined below.

- Bush Fire Survival Map (see Figure 2) - includes information on the potential bush fire threat, the safety of access / egress provisions, early relocation options and contingency shelter options. This map provides information that can be used by members of the community when preparing their personal Bush Fire Survival Plan.
- Bush Fire Preparation Map - provides information for land managers, fire agencies and community members on details of the existing and proposed bush fire risk treatment works for the community. The map will also provide information that will prompt home owners / occupiers to take action to reduce their bush fire risk.
- Operational Brigade Map - provides brigades and other emergency services with important data relevant to the community and is to be used for operational purposes only.

(NSW RFS 2013)

Perhaps a unique aspect of Community Protection Plans in NSW that differs from similar bush fire planning programs developed in other States is the content of the Bush Fire Survival Map. A key feature of this document is the Bush Fire Impact areas (see Figure 2). These are polygons on the map that extend from the bush land interface into the built up areas of the community. Key messages are linked to each of the Bush Fire Impact areas that aim to improve community understanding of bush fire risk and the nature of bush fire attack. There are four Bush Fire Impact categories:

- Flame Impact (Red) – Captures all areas of the community that may be subject to flame attack, deadly levels of radiant heat and embers.
- Radiant Heat Impact (Orange) – Extends from the outer edge of the Flame Impact area and includes areas of the community that may be subject to deadly levels of radiant heat and ember attack.
- Ember Impact (Yellow) – Extends from the outer edge of the Radiant Heat Impact area and capture areas of the community that may be subject to low levels of radiant heat and ember attack. This area extends 350m from the bush land interface where approximately 99% of house losses occur (Chen and McAneny 2010).
- Be Aware (Green) – Captures the remaining area of the community that may still be subject to some mechanisms of bush fire attack (e.g. smoke and embers).

(NSW RFS 2013)

The scale of the map enables members of the community to identify the bush fire threat to their property, any landmarks or assets within the community and the main access / egress roads. This information can then be used in the preparation of personal Bush Fire Survival Plans and inform the triggers or actions people will take when faced with a bush fire.

Applying the Process

To date, Community Protection Plans have been developed in more than seventy communities across NSW. The communities vary from coastal hamlets situated in forested landscapes to more isolated villages west of the Great Dividing Range that are surrounded by grass and woodland vegetation. In each case, the planning process has been adapted to suit the individual circumstances of each community in order to optimise its relevance and ensure it addresses the specific issues of the area.

The NSW RFS experience to date indicates that the scale and specific nature of Community Protection Plans generates greater community interest than the strategic Bush Fire Risk Management Plans. As such, it provides a more effective platform for the engagement of the community. The Community Protection Plan prepared for the Batlow Township provides an example of the increased level of interest created by the program.

Batlow (population 1200) is at an elevation of 780 metres and nestled in the South West Slopes of NSW, midway between Canberra and Wagga Wagga. The area is located between much drier country to the west and the significantly higher, damper and cooler Snowy Mountains to the east. The community contains a number of vulnerable facilities such as schools, child care, a hospital, tourist accommodation and aged care. Outside of the township area, the gentle sloping landscape is dominated by a mixture of grazing properties, plantation pine forest and apple orchards. The Hume Highway lies approximately 40 kilometres to the west of the township.

The Bush Fire Risk Management Plan, approved in June 2009, for the area identified Batlow village as a medium bush fire risk. However, the perceived bush fire risk within the community was altered during the Victorian Bush Fire Royal Commission into the 'Black Saturday' event. With a broader perspective, some community advocates started to compare the Batlow situation and threat from large scale fire to that of Marysville and Kinglake. There were also growing concerns within the community on the bush fire risk to economic assets, such as the agricultural industry.

The best way to address these issues was through the development of a Community Protection Plan for the area. The process gave residents and fire authorities an opportunity to talk openly about bush fire risk, fire season preparations and coordinated bush fire management arrangements in place. The level of interest amongst the community exceeded expectations and at a meeting in December 2015, 70 people attended (see Figure 1).

Figure 1 – The Batlow Community Meeting

By working through the process, the issues raised by the community are able to be formally recognized, discussed and addressed appropriately. The Community Protection Plan gave residents a shared knowledge of the bush fire threat for the area and the strategies in place to manage the risk. Individual property inspections were arranged with residents, hazard reduction proposals were generated as a result of the consultation and residents better understood the limitations of fuel management as well as the important role they have in reducing the risk to their property. Overall, the Community Protection Plan assisted in establishing cohesion amongst the community on bush fire risk and its management.

Another example of where the Community Protection Plan was successful in engaging people on bush fire risk was in Eucumbene Cove. Situated on the western edge of the Snowy Mountains, Eucumbene Cove is identified as an extreme risk asset in the Bush Fire Risk Management Plan. Rugged terrain surrounds the community, particularly to the west with the only road to and from the area traversing forested land. As part of the development of the Community Protection Plan, a meeting was held with the community to discuss bush fire risk and the options currently available to residents when faced with a bush fire. The Bush Fire Survival Map (see Figure 2) was used to help facilitate these discussions and proved to be a powerful education tool on this occasion.

By using the Bush Fire Survival Map, the significant threat of bush fire for the community could be clearly communicated with the residents. During the discussions, some of the older residents came to the realization that leaving early was the best option for them. The map was once again used to emphasize the need for these people to have appropriate triggers that identified when it was possible to leave and the circumstances where it was unsafe to do so. In addition, it highlighted that there may be situations where they are unable to 'leave early' and it was critical to have a number of contingency options in place.

The group as a whole came to the conclusion that regardless of what an individual planned to do prior to and during a bush fire, it was important that all homes and properties were well prepared and maintained. This would reduce the risk of structure loss and house to house ignitions, enhance the ability of fire fighters to defend properties and provide a shelter option if a fire were to impact with little warning. Whilst work will continue in improving the preparedness of this community for bush fire, it was apparent that the attendees were in a better position to prepare a well thought out Bush Fire Survival Plan as a result of the Community Protection Plan.

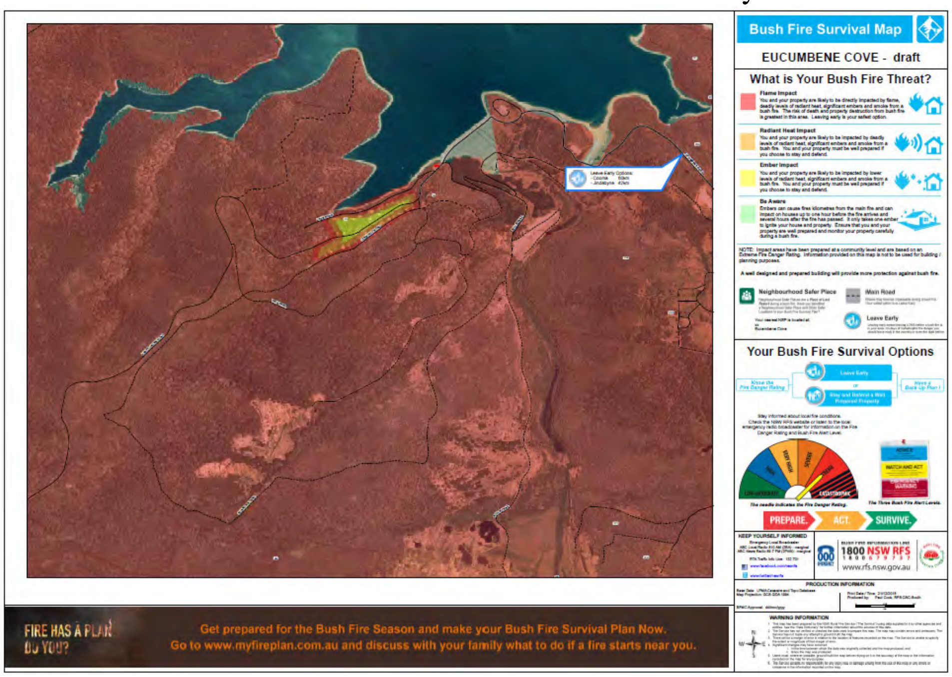

Figure 2 – Eucumbene Cove Bush Fire Survival Map (Draft)

Conclusion

Over a four year period, Community Protection Plans have become an important element of the bush fire risk management framework in NSW. The process and maps provide a valuable engagement tool that can be adapted to suit individual communities at risk of bush fire. In particular, the Bush Fire Survival Map and the identification of Bush Fire Impact areas has proven to be an effective way to increase community understanding of their bush fire risk, the safety of access / egress provisions, early relocation options and contingency shelter options. With this knowledge, members of a community are in a better position to prepare a practical Bush Fire Survival Plan that is appropriate for their circumstance.

References

Bush Fire Coordinating Committee (BFCC), 2006, *Bush Fire Management Committee Handbook - Edition 1*. - http://www.rfs.nsw.gov.au/

Bush Fire Coordinating Committee (BFCC), 2008, *Policy No. 1/2008 Bush Fire risk Management*. http://www.rfs.nsw.gov.au/

Chen K and McAneney J, 2010, *Bush Fire Penetration into Urban Areas in Australia: A Spatial Analysis*, Bush Fire CRC

NSW Government 2010, *NSW Government Response to the Final Recommendations of the 2009 Victorian Bush Fires Royal Commission*.

NSW Rural Fire Service (RFS), 2013, *Community Protection Planning Guideline*

Victorian Bushfires Royal Commission (VBRC), 2010, *Final Report – Summary*.

Rural Fire Act 1997 - http://www.legislation.nsw.gov.au

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DEVELOPING A NEW MODEL FOR BUSH FIRE RISK MANAGEMENT IN NSW

Melissa O'Halloran
New South Wales Rural Fire Service, Lidcombe, New South Wales, Australia,
Melissa.OHalloran@rfs.nsw.gov.au

Abstract

Bush Fire Risk Management Planning in NSW is undertaken in accordance with the Bush Fire Coordinating policy developed in 2007. This policy provides local planning committees with a consistent approach to risk planning and has influenced risk management in many States of Australia. The current policy does not consider the extensive research in this area over the past decade.

A new modelling methodology is being developed to incorporate recent research in fire behaviour and risk vulnerability. This research, improved data and the development of operationally applicable models will improve our ability to quantify bush fire risk. The model will incorporate advancements in mapping and understanding bush fire fuels allowing a continuous assessment of bush fire risk across the landscape.

Modelling will evaluate bush fire risk and the effectiveness of treatments across a range of weather scenarios that will include an understanding of the effectiveness of existing risk controls. This will assist with an understanding of mitigation and response activities across all fire management business not just for extreme weather events.

The aim is to produce a model that values all aspects of fire management beyond the current risk based priority for hazard reduction activities used to allocate funds. Trade-offs between treatments will be considered that modify the exposure, the likelihood or the vulnerability of assets. The analysis should allow the comparison of treatments such as, for example implementing building design to improve the ability for structure to withstand bush fire exposure with programmes that influence the likelihood of ignitions from arson.

Background

Bush fire risk management in NSW has legislative support within the *Rural Fire Act* 1997. The Act outlines the development, timeframes and content of Bush Fire Risk Management Plans. The plans are undertaken by local planning committees in accordance with the Bush Fire Coordinating Committee policy developed in 2007.

This policy has provided local committees from a range of stakeholder agencies with a consistent approach to risk planning. The policy provides for the development of a Bush Fire Risk Management Plan, a strategic document which spatially identifies assets at risk from bush fire and provides a methodology for undertaking a risk assessment for each of these. The plans also records treatment strategies identified by the Bush Fire Management Committees and the agencies responsible the implementing them.

A survey conducted in 2014 of NSW RFS District Managers asked about their perceptions of the current bush fire risk modelling process. The most favourable aspect of the plan was the spatial elements and the maps generated as part of the process for discussion and consultation. The development of a prioritisation of risk mitigation treatments, setting a clear works programme for all participating agencies based on a risk management approach was also a well liked feature. The part of the process they liked the least was the format of the text based document, and the tools and processes provided for community engagement were considered to be ineffective.

A technical review of the policy and tools identified a number of weak points:

- Inconsistency in how each Bush Fire Management Committee interpreted and applied individual components of the model. The risk differentiation within a plan area was usually good, however there is often poor correlation with risk assessments undertaken in adjoining areas. Therefore it was difficult to develop a State-wide view by amalgamating local level plans.
- While a register of risk mitigation treatments is developed, there is no evaluation of the risk reduction that results from these treatments. This is a significant step in the risk assessment process as outlined in ISO31000 and therefore the existing process does not fully comply with the standard. This was acknowledged in the development of the current model, however at the time there was inadequate science to support the valuation of risk treatments.
- One of the key outputs of the risk management process is the treatments register, it currently has poor links to tactical and operational planning processes. Additional tools and linking processes are needed to better identify how strategic priorities are programmed.
- The current model for bush fire risk management planning is asset centric and works well where assets can be grouped with defined spatial boundaries. It is less effective for assets that are spatially discrete and cannot easily be spatially described or grouped. As a result the model does not support rural areas as well as more urbanised areas.

A Case for Change

In the decade since the current policy was developed, significant effort has been invested to improve the underlying datasets, the models and research to support the values applied to the model elements. In 2009, NSW Rural Fire Service commissioned an evaluation of the performance of Phoenix Rapidfire for a number of recent fire case studies (Cook et al 2009). One of the key results was the poor performance of the models due to the underlying fuels and fuel accumulation information. NSW RFS subsequently commissioned development of fuel accumulation curves for priority vegetation types (Watson 2012). The operational implementation of the Fire Behaviour Analyst role (Heemstra and McCoy 2016) and ongoing commitment to improve the underlying data (Kenny 2016) has provided confidence that a quantified risk assessment model is achievable.

A modelling approach is required that can integrate the fire behaviour elements with the factors that describe and influence the vulnerability of people and property. Penman *et al.* (2011) explored the use of Bayesian Networks to assess risk reduction from fire management practices including prescribed burning, initial attack and suppression. The model successfully combined existing data and expert opinion to demonstrate the potential use of Bayesian Networks to provide a comprehensive analysis of all fire management strategies. An expansion of this model was used in the national fire danger rating probabilistic framework project (Penman et al 2015) and this has been incorporated into the NSW 2015/16 Fire Danger Rating Trial project (Matthews et al 2016).

The NSW RFS Bush Fire Household Assessment Tool accessible via the NSW RFS public website (NSW RFS 2016) is an operational implementation of a Bayesian Network. The model combines information about the radiant heat exposure of a property and qualitative judgements (Penman et al. 2013b) on personal capability, available equipement and property preparedness to provide advice regarding the circumstances related to the fire danger ratings where it may be safe for a resident to safely stay and defend their home. This model considers many elements immediately surrounding residential structures and is likely to provide input to bush fire risk management planning or more detailed risk analysis in community protection plans.

Designing a New Model

A project has been initiated to develop and evaluate a modelling framework suitable for bush fire risk management in NSW. The objectives of the project are to develop a model that:

- incorporates a risk assessment methodology that is applied consistently across the State
- is scalable and can be equally applied at State and community level
- provides a locally relevant assessment of the population and the assets in line with the values of the community
- has the ability to evaluate the effectiveness of treatments to assist in identifying the most valuable suite of treatment strategies
- integrates with appropriate business processes across NSW RFS to incorporate a consistent risk based approach
- can readily update risk profiles to accommodate changes in risk analysis and risk treatments
- provides new products to better communicate risk

A conceptual model (Figure 1) has been developed that incorporates the three key elements: hazard modelling, the values at risk from bush fire, and the risk mitigation treatments. These elements provide the basis of the risk model for contemporary settings as well as future planning.

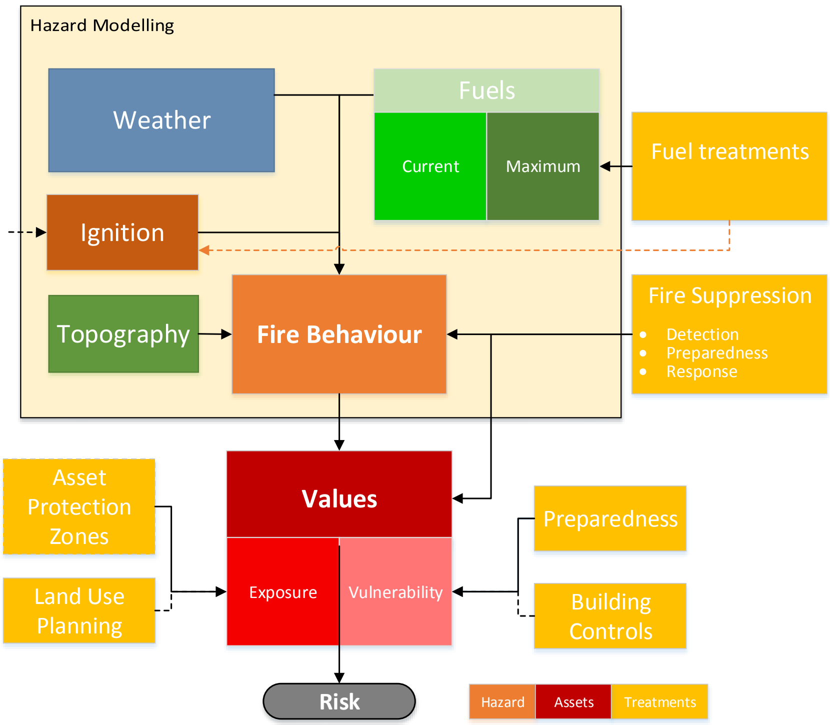

Figure 1 - Conceptual model of NSW Risk Management Model

The proposed approach will consider three baseline risk scenarios, the first with theoretical maximum fuels assuming there have been no fires in the landscape and no other treatments applied, the second with current fuels considering bush fires and existing fuel treatments but no additional treatments applied and the third will consider current fuels and existing response and suppression arrangements.

Hazard Modelling

The majority of life and property losses are experienced in Extreme or Catastrophic fire danger ratings (Blanchi 2012), however these events occur infrequently. The majority of fire management effort occurs on days of lower fire danger and without existing mitigation and suppression efforts greater life and property damage would be anticipated. The NSW model will test a range of weather scenarios based on the fire return intervals developed by Louis (2014). Fire weather return intervals will be considered for 1,5,10, 20, 50 and 100 years. The aim is to better represent all aspects of fire management business and allow treatments to be valued for the types of fires they are designed to support.

The fire danger index value for each weather return interval will be represented as a probability weighted ensemble of weather scenarios derived from a fire weather reanalysis dataset for that local area. Weather scenarios representing Extreme and Catastrophic fire danger ratings are most likely to have weather patterns dominated by a single weather scenario, however fire lower return intervals (for example a 1 year return interval) could have a larger distribution of possible events.

The weather scenarios for each fire danger index value will be weighted by the probability of occurrence. Figure 2 shows a proposed product from Phoenix RapidFire of residential house loss from ignition source for a theoretical weighted ensemble of weather scenarios.

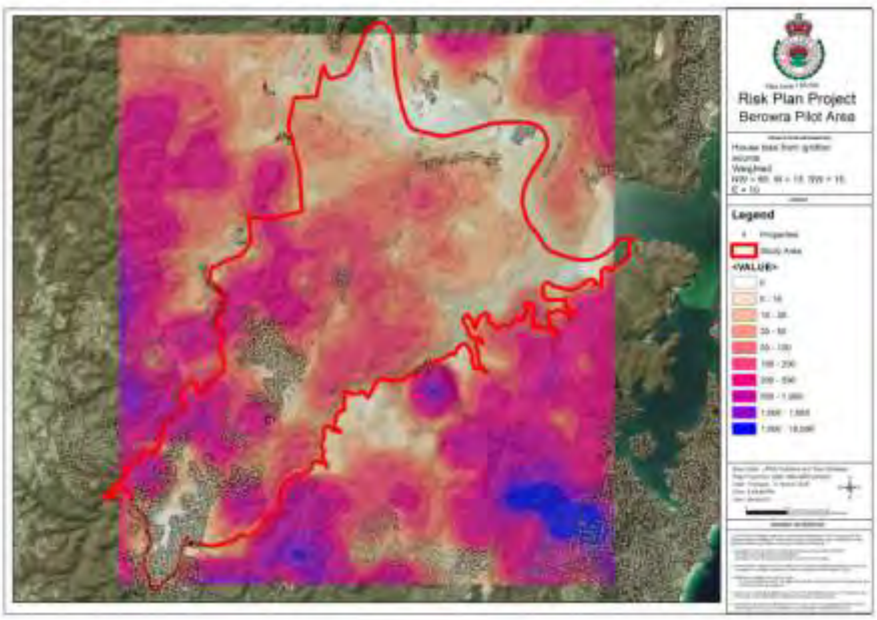

Figure 2 – House loss using weighted weather ensemble - One of the proposed analysis products from bush fire risk modelling

A number of case studies using the proposed methodology for bush fire risk modelling have been developed in NSW to model the effectiveness of specific treatment options for local management committees (Wells and McCoy 2016). The results have been well received and have improved our understanding of how the potential products can be interpreted and used for strategic planning.

The analysis of likelihood will be enhanced by consideration of ignition patterns and frequency. In the Sydney Basin arson ignitions are more likely to be associated with human infrastructure (Penman 2013a). Population density and road networks will be used as inputs to determine the influence of increased or fewer ignitions.

Valuing assets and asset specific treatments

Threat to life and property has traditionally been focused on protecting residential properties to protect people, however fire agencies are increasingly focused on management actions that remove people from potential impact areas on days of heightened fire risk. We will explore whether human behaviour can be modelled independently of residential assets to match current management practices linked to fire danger ratings.

The concept of community profiling will be explored using demographic data to highlight areas where the population is at an increased vulnerability to bush fires due to factors such as age, mobility, education, awareness, or social economic status. This will be used in the development of the risk profile but also in the identification of appropriate treatments that can be tailored specifically to the community.

Improved spatial data will allow a more detailed analysis of a range of assets. Where available, information on bush fire specific construction standards will be used. For over a decade property development in bush fire prone land in NSW has required consideration of Planning for Bushfire Protection 2006. These areas will have a different risk profile to existing development areas in bush fire prone land. For existing developments assumptions will be made about the structural vulnerability based on the average age of housing stock and typical construction for the area. Special purpose facilities such as schools, nursing homes and hospitals will consider the population size and vulnerability, the availability of on-site refuges as well as the built structures.

Treatments that influence preparedness can be related to the people or the structures they inhabit. Community engagement increases resident's awareness and also encourages improvements to structural preparedness by maintaining landscape features and removing fuels and hazards from around the home. Community engagement, pre-incident planning, alerts and warnings and neighbourhood safer places are examples of risk management treatments that are traditionally applied to reduce risk to particularly vulnerable people and assets.

Landscape Treatments

Fires may start under a range of conditions however most do not impact properties or threaten lives as they are extinguished before they spread to areas where they cause damage. Extending work developed for centralised dispatch the probability of first attack success for all weather scenarios at all ignition points across the landscape will be assessed. Fire detection, response time and number of resources available will be considered based on the location of suppression resources for each of the fire fighting agencies. The model will be tested to establish if it can measure the effectiveness of fire trial construction and maintenance. The effectiveness of aircraft, remote area fire fighting teams and pre-emptive resourcing on days of heightened fire danger will be evaluated for first attack success where data is available.

Fuel management strategies will be modelled to provide a profile of risk over the planning timescale. The pilot studies will explore the process for developing and testing an effective and achievable mitigation programme. The hazard assessment modelling will determine the modification to potential fire behaviour and the asset assessment module will ensure that the most vulnerable assets are treated as a priority.

Conclusion

The project to deliver a new risk modelling framework is still in the early stages. A conceptual model has been developed based on knowledge and experience gained through the assessment and application of elements across a number of business areas.

We are currently developing a case study for a single community to test the parameters of the model. It is anticipated that this will provide initial model values to be tested on a larger scale bush fire management committee pilot area.

Pilot studies will be developed under the direction of the project steering committee to test the model in a range of environments. It is anticipated pilot studies will be selected to represent an urban interface, an area dominated by grassland and agriculture and potentially a coastal community. This will assist in testing how each of the model elements works together in different environmental to ensure the parameters for hazards, assets and treatments are relevant for each landscape.

References

Blanchi R, Leonard J, Haynes K, Opie K, James M, Kilinc M, Dimer de Oliveira F, Van den Honert R (2012). Life and house loss database description and analysis. CSIRO, Bushfire CRC report to the Attorney-General's Department. CSIRO EP-129645

Cook, B, Price, O, Chong, D, Tollhurst, K (2009) Review of Potential Applications for Bushfire Behaviour Models for Bushfire Management in NSW Centre for Environmental Risk Management of Bushfire, University of Wollongong, Wollongong.

Heemstra S, Mc Coy L (2016) Evolution of Fire Behaviour Analysis into Operational Business as Usual – The NSW Experience. Proceedings for the 5th International Fire Behaviour and Fuels Conference.

Kenny, B.J, Roberts, L (2016) Building a Comprehensive Fuel Map – From Research to Operational Use Proceedings for the 5th International Fire Behaviour and Fuels Conference

Louis SA (2014) Gridded return values of McArthur Forest Fire Danger Index across New South Wales. *Australian Meteorological and Oceanographic Journal* **64**, 243–260.

Matthews S, Roberts L, Louis S, Heemstra S, Kenny B, McCoy L (2016) Exploring Physical Measures of Fire for Calculating Fire Danger. Proceedings for the 5th International Fire Behaviour and Fuels Conference.

NSW RFS (2006) Planning for Bush Fire Protection

NSW RFS (2016) NSW RFS Bush Fire Household Assessment Tool. Accessible at assessmyrisk.rfs.nsw.gov.au

Penman TD, Price O, Bradstock RA (2011) Bayes Nets as a method for analysing the influence of management actions in fire planning. *International Journal of Wildland Fire* **20**, 909-920.

Penman TD, Bradstock RA, Price O (2013a) Modelling the determinants of ignition in the Sydney Basin, Australia: implications for future management. *International Journal of Wildland Fire* **22**, 469-478.

Penman, TD, Eriksen, C, Blanchi, RM, Chladil, M, Gill, AM, Haynes, K, Leonard, J, McLennan, J, Bradstock, RA (2013b) Defining adequate means of residents to prepare property for protection from wildfire, *Int. J.Disaster Risk Reduct*. **6**67–77.

Penman TD, Parkins KA, Mascaro S, Chong D, Bradstock RA (2015) 'National fire danger rating system probabilistic framework. Report for year 3'. Bushfire and Natural Hazards CRC report (Melbourne, Vic)

Watson P (2012) 'Fuel Load Dynamics in NSW Vegetation. Part 1: Forests and Grassy Woodlands.' Centre for the Environmental Risk Management of Bushfires, University of Wollongong, Wollongong.

Wells J, McCoy L (2016) Evaluating Bush Fire Treatment Effectiveness Using Phoenix RapidFire Gridded Ignition Case Studies. Proceedings for the 5th International Fire Behaviour and Fuels Conference.

Developing Fuel Maps for Predicting Smoke Dispersion for Forests of Victoria, Australia

Liubov Volkova* [1], C.P. (Mick) Meyer [2], Andrew Mellor [3] and Christopher J. Weston[4]

1. The University of Melbourne, Department of Ecosystem and Forest Sciences, the Faculty of Science, Creswick, Vic, Australia, lubav@unimelb.edu.au
2. CSIRO, Oceans and Atmosphere Flagship, Aspendale, Vic, Australia, carl.meyer@csiro.au
3. Department of Environment, Land, Water and Planning, East Melbourne, Vic, Australia, andrew.mellor@delwp.vic.gov.au
4. The University of Melbourne, Department of Ecosystem and Forest Sciences, the Faculty of Science, Creswick, Vic, Australia, weston@unimelb.edu.au

*Corresponding author

Introduction

Smoke pollution during fires (wild and prescribed burns) is a serious issue affecting health, environment, economics which concern public and fire managers alike. Fuel maps increase accuracy of predicting fire related emission and smoke dispersion and became an essential part for land management agencies around the world and Australia.

Type and amount of fuels affect combustion and emissions during wildfires and prescribed burns. Fine fuels (litter) usually burnt in flaming combustion and affect progression of a surface fire's flaming front. This makes them inadequate for estimating fire effects associated with post-frontal, smouldering combustion, a characteristic of heaver, woody fuels. Burning of fine fuels produce more oxidised gaseous species (e.g. CO_2) while smouldering of woody fuels will release more potent gases (CO, CH_4 and particular matter [PM])(Cook and Meyer, 2009)

In south-eastern Australia fuel characterization and classification approaches have focused on providing inputs for predicting fire spread (McCartur Meter and Phoenix fire spread model) and as such only fine fuels were considered (Gould *et al.*, 2007; Tolhurst *et al.*, 2008). The contribution of heavy fuels (i.e. coarse woody debris [CWD]), especially large woody fuels to surface fire intensity is likely underestimated in fire behavior models (Brown *et al.*, 2003). These fuels can hold smouldering fire for an extended period and can contribute to the development of convection column and thus fire severity (Sullivan *et al.*, 2002). In megafires, CWD smouldering contribute significantly to total fire emission (Volkova *et al.*, 2014). Despite their important contribution to fire severity and smoke development, CWD fuels remain understudied in SE Australia.

Several approaches are used for fuel mapping, including remote sensing, field measurements, as well as modelling fuels from a set of biogeochemical parameters or vegetation classes. In this study we used an innovative approach to develop fuel maps for fine and CWD fuels based on a combination of field measurements, biogeochemical modelling (BIOS2) and vegetation classification (fuel classification used in the Phoenix Rapidfire model)

Field measurements were extracted from several empirical fuel datasets for Victoria which recently emerged in the literature. Volkova and Weston (2015) provide a range of forest fuel loads measured across a range of forest sites. The Victorian Forest Monitoring Program (VFMP), initiated by the Department of Environment and Primary Industries (DEPI) of Victoria, provide a comprehensive set of measurements of forest biomass, including litter and CWD (DEPI, 2013; Haywood *et al.*, 2016). Additional field measurements across a range of sites in Victoria, were conducted as a part of this Bushfire CRC project “Smoke and Transportation modelling for Victoria”

The biogeochemical model, BIOS2, is a process-level, ecosystem simulation model that calculates the cycling of carbon through forest ecosystems (Haverd *et al.*, 2014). BIOS2 uses 0.05 degree grid which is too coarse to predict fire behaviour, but can be used for modelling smoke dispersion and estimation of emission release. Kean *et al* (2001) concluded that maps with small polygon sizes are too detailed for use in most land management projects.

Phoenix Rapidfire model (Tolhurst *et al.*, 2008) is used for prediction of wildfire spread and widely used across south eastern Australia; the model uses an unpublished dataset developed by Tolhurst (2005). The database includes fine fuel components and the fuel beds that are classified by an aggregation of the Ecological Vegetation Group. The fuel components are aggregated into 27 groups and include surface fuels (litter and duff), elevated fuels (live shrubs), and bark. The fuel load for each component is defined either as a class average, or by parameters of the fuel accumulation curves, which, when combined with fire history data, define the mean fine fuel load in the year of the fire. Fuel dataset has not been confirmed by empirical measurements.

Both of the models require verification and possible calibration before they can be used for smoke and emission modelling purposes. This study assesses applicability of available carbon cycle model (BIOS2) and a fuel dataset used in fire spread prediction (Phoenix) against field observations. The rational of the project was to 1) analyse field observations with models predictions and based on analysis 2) produce comprehensive maps of fine and CWD fuels for the State of Victoria, Australia

Materials and Methods

Field measurements

Both BIOS2 and Phoenix models estimate fuels in their steady state, and therefore all field measurements were assessed against fire history for Victoria; plots where measurements were conducted within 5 year since fire (wildfire or planned burn) were excluded from further analysis.

Models used in fuel map development

BIOS2 model requires daily data for standard meteorological conditions, maximum-minimum temperatures to simulate the dynamics of the canopy, live and dead woody pools and the live and dead grass pools. We used data for the period of 1983-2013 to extract CWD and fine fuel loads. Maximum values of the monthly mean (hereafter BIOS2_max); the 30 year mean of the annual monthly max (hereafter BIOS2_mean) were extracted as raster layers to ArcMap 10.2.2 (Esri, Redlands, CA, USA).

Phoenix surface fuel loads (Tolhurst 2005) were used to assess field measurements and BIOS2 predictions. Fuel codes of Phoenix were used to group field data by vegetation classes. Near surface and elevated fine fuels were not included in the analysis.

Linear model of R Studio (R Core Team, 2016) was used to assess performance of BIOS2 and Phoenix in predicting fuel loads. Each model was ranked based on the least difference between observed and predicted fuel loads; a model with the least difference was used as a prototype for the development of fuel maps.

Results

BIOS2_max was ranked first out of three models (BIOS2_mean, BIOS2_max, Phoenix) based on the smallest sum of the difference between observed and predicted fine fuel loads and therefore was used as a prototype for developing a fine fuel map. Phoenix surface fuel loads and BIOS2 predictions were significantly higher than field measurements (t-test, $P<0.001$, both models). Overall, BIOS2 predictions were more uniform than spatially variable field measurements, but generally were close to the mean of field measurements.

Predicted and observed fine fuel loads based on BIOS2 calibration using the ratio of averages produced least mean difference and smallest 95% confidence interval. It was used as a final map for fine fuel loads (Fig. 1).

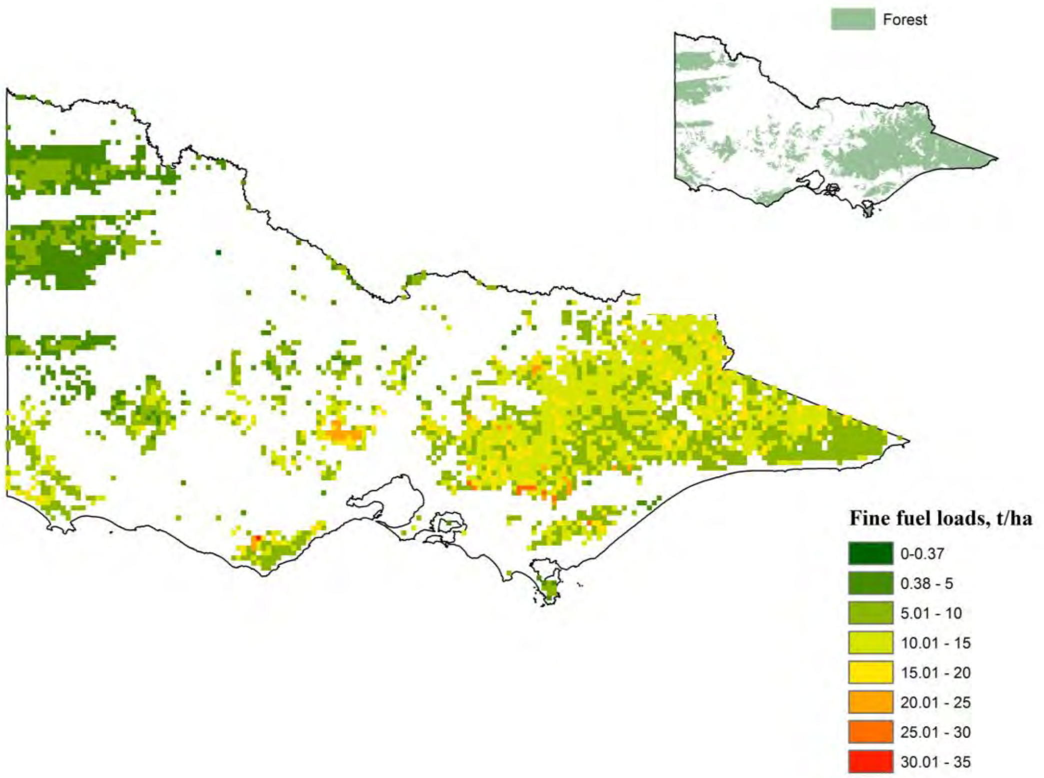

Figure 1. Map of fine fuel loads for Victoria. Fine fuels include duff, and litter and twigs with diameter <6 mm

BIOS2_mean was ranked first in predicting CWD loads and produced the smallest sum of the absolute difference between observed and predicted CWD loads. It was used as a prototype for development of the CWD map.

A total of 435 data points were available for final analysis of CWD. Fuel code and IBRA each explained between 21% and 34 % variations in CWD loads respectively. BIOS2 predictions differ significantly from observed measurements ($P<0.001$). In contrast to fine fuel, CWD loads were not evenly distributed which resulted in low prediction of BIOS2 based on the ratio of medians. Predicted values based on the ratio of averages produced similar results to the observed values ($P=0.9$) and was used as the final fuel map for CWD loads (Fig. 2).

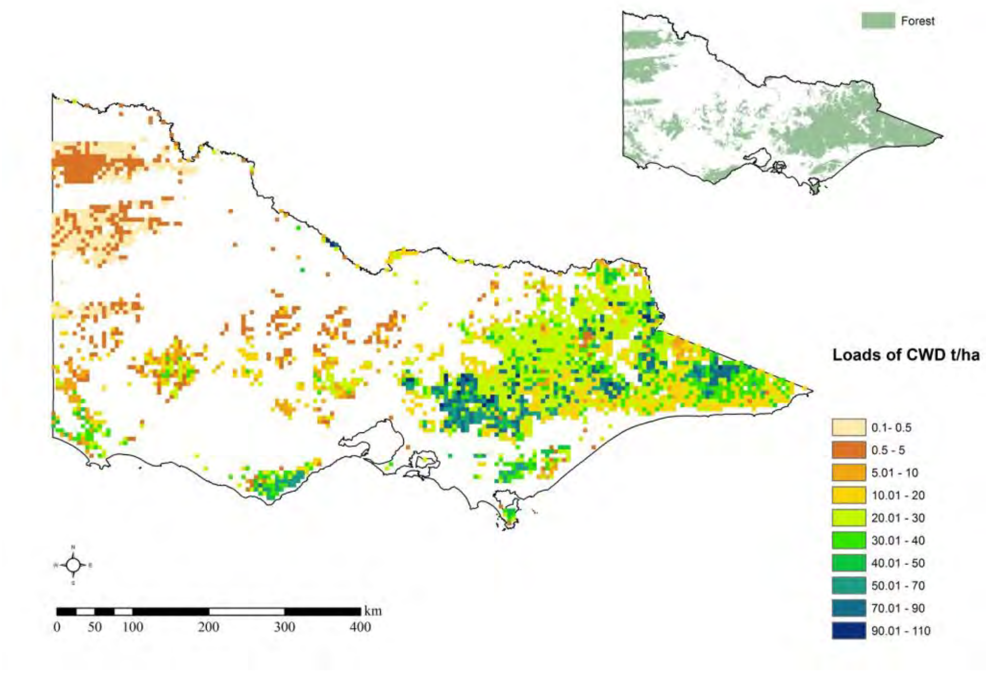

Figure 2. Map of CWD fuel loads for Victoria. CWD fuels include twigs and logs >6 mm

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References

Brown J. K., Reinhardt E. D., and Kramer K. A. (2003). Coarse Woody Debris: Managing Benefits and Fire Hazard in the Recovering Forest. General Technical Report RMRS-GTR-105. Rocky Mountain Research Station, Fort Collins, CO, USA.

Cook G. D., and Meyer C. P. (2009). Fire, fuels and greenhouse gases. In J. Russell-Smith, P. J. Whitehead & G. D. Cook (Eds.), *Culture, ecology and economy of fire management in Northern Australian savannas: rekindling the Wurrk tradition*: CSIRO, Collingwood Victoria.

DEPI. (2013). Victoria's State of the Forests Report, Department of Environment and Primary Industries, Melbourne. Melbourne, Victoria.

Gould J. S., McCaw W. L., Cheney N. P., Ellis P. F., Knight I. K., and Sullivan A. L. (2007). Project Vesta: Fire in Dry Eucalypt Forest. Collingwood: CSIRO Publishing.

Haverd V., Smith B., Nieradzik L. P., and Briggs P. R. (2014). A stand-alone tree demography and landscape structure module for Earth system models: integration with inventory data from temperate and boreal forests. *Biogeosciences,* **11**(15), 4039-4055.

Haywood A., Mellor A., and Stone C. (2016). A strategic forest inventory for public land in Victoria, Australia. *Forest Ecology and Management,* **367**, 86-96.
Keane R. E., Burgan R., and van Wagtendonk J. (2001). Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. *International Journal of Wildland Fire,* **10**(3-4), 301-319.
R Core Team. (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.
Sullivan A. L., Knight I. K., and Cheney N. P. (2002). Predicting the radiant heat flux from burning logs in a forest following a fire. *Australian Forestry,* **65**(1), 59-67.
Tolhurst K. (2005). Conversion of ecological vegetation classes (EVCs) to fuel types and calculation of equivalent fine fuel loads with time since fire, in Victoria, pp 1–7, *Unpublished.*
Tolhurst K., Shields B., and Chong D. (2008). Phoenix: Development and Application of a Bushfire Risk Management Tool. *Australian Journal of Emergency Management,* **23**(4), 47-54.
Volkova L., Meyer C. P., Murphy S., Fairman T., Reisen F., and Weston C. J. (2014). Fuel reduction burning mitigates wildfire effects on forest carbon and greenhouse gas emission. *International Journal of Wildland Fire,* **23**(6), 771-780.
Volkova L., and Weston C. J. (2015). Carbon loss from planned fires in southeastern Australian dry Eucalyptus forests. *Forest Ecology and Management,* **336**(0), 91-98.

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Effective prescribed burning strategies for eucalypt forests in Australia

Owen Price
Centre for Environmental Risk Management of Bushfire, University of Wollongong
(oprice@uow.edu.au)

Introduction

In 2003 Fernandes and Bothello wrote an influential review of prescribed burning practice around the world. They concluded that while there was strong theoretical evidence that prescribed burning moderated fire behaviour, most of the empirical evidence relied on anecdote and there was a need to conduct thorough research on the influence of prescribed fire on all aspects of fire behaviour. Since then, our empirical knowledge of how and when prescribed burning is effective has improved. Here, I review our current understanding for eucalypt forest and woodlands, the focus for much of this new research.

Prescribed burning is a common practice in Australia, the USA and Mediterranean Europe. The objective is to reduce vegetation fuels so that subsequent wildfires are less likely to ignite, and will stop, slow or burn with reduced intensity. Usually the express intention is to aid suppression by slowing or reducing the intensity to give firefighters some 'advantage'. Prescribed burning is a major component of the fire management arsenal, although suppression is the biggest budget item in almost all areas of the world. In the USA, approximately 8000 prescribed burns covering an area of >1m ha are implemented each year. The Victorian state Government implemented a 5% annual treatment target at an annual cost of $70m as recommended by the 2009 Victorian Bushfires Royal Commission, though this strategy was abandoned in 2016. Treatment levels in Western Australian eucalypt forests are ~ 7% per year , while in New South Wales, they are much lower (~1%) .

Prescribed burning removes fuel making it unavailable to subsequent fires. While this is a straightforward effect in theory, there are many criteria that must be achieved in order for practice to match the theory.

1) The burn must achieve sufficient fuel reduction to moderate subsequent fire behavior across a range of weather conditions;
2) The fuel recovery period should be long enough to allow a reasonable chance of encountering a wildfire while reduced (see also 4), otherwise the effort is wasted;
3) The burn should not change the vegetation community or fuel structure in a way that increases fire behaviour (for example by substantially increasing air-flow, encouraging shrub growth or replacing shrubs with grasses) or eliminates ecologically important species;
4) The burn should be placed in an area where wildfire is sufficiently common to allow a reasonable chance of encounter (while fuel is reduced, see 2), otherwise the effort is wasted;
5) And it should be placed where the consequence of wildfire is not negligible.

Ultimately, to be effective, prescribed burning must affect fire behaviour. For example, the nature of fuel reduction is not so important as the reduction in subsequent fire intensity. Hence, most of the research focuses on one or more aspects of fire behaviour and addresses the criteria listed above indirectly.

1) The Nature of Fuel Reduction

In Australia fuels are generally divided into five strata: surface (or litter), near surface, elevated (or shrub), crown and bark, and also the particle sizes are divided into fine, coarse and woody elements. I only consider fine fuels (< 6mm thick) since they are most important for fire behaviour and the most affected by prescribed burning but I will review each stratum.

Surface fuels usually comprise the majority of the fuel load. Normally, a fire will consume all litter fuel where it actually burns, but there is considerable patchiness in fires (Price *et al.* 2003; Penman *et al.* 2007). This means that the average litter fuel remaining can be quite high (mean 3.2 t/ha from 8 studies used in Thomas (2014), ~6 t/ha in (Penman *et al.* 2008)). We can generally assume near-surface fuel to be completely consumed except in unburnt patches, as with surface fuels (as assumed, for example by Gould *et al.* (2011)). Depending on the height of the shrub layer and the flame lengths of the fire, some parts of the elevated fuels may be consumed, scorched or unaffected. Gould et al (2011) found 1/3 of fuel remained after fires in the VESTA program. Tree crowns are rarely affected by prescribed burning because the flame heights are intentionally low. Bark fuel can promote fire spotting and ‘laddering’ of flames into the tree crown. Only fires above a threshold flame height consume bark fuel so low intensity prescribed fire does not affect bark. Where the tree trunks are burned, fire usually reduces the thickness of the bark layer by about 65% (Horsey and Watson 2012). McCaw et al 2012 reported that the outer layer of bark between 5-12 mm was consumed in the VESTA experimental fires. Ribbon bark is usually unaffected by fire because it is high in the trees (Horsey and Watson 2012).

The amount of fuel reduction is complicated because it depends on the weather and the pattern of fuel present at the time of the prescribed burn, aspects lacking systematic research.

2) Fuel recovery

Fuels recover to pre-fire levels over time, but the rates of recover differ among the fuel strata and among vegetation types. Litter fuels accumulate to 8 tons/ha (equivalent to a High hazard rating) within 2 years of fire in wet sclerophyll forests and within 4 years in dry sclerophyll forests in the productive regions of south-eastern Australia (Thomas *et al.* 2014). In less productive forests which never reach 8 t/ha, fuel recovers to 50% of maximum within 4 years (Gould *et al.* 2011). Near surface recovery follows a similar trajectory to surface fuels (Gould *et al.* 2011; Watson 2011). Elevated fuels can recover very quickly because the fire stimulates recruitment . Generally elevated fuel will be at least 50% of pre-fire levels within 2 years (Gould *et al.* 2011). Bark fuel recovery is slow and continues for decades (Grant and Wouters 1993; Horsey and Watson 2012).

To some extent the recovery of fuel depends on the nature of the original fire. A severe fire might reduce the canopy by killing fire sensitive trees and top-killing re-sprouting trees. The same fire promote the recovery of elevated fuels because many seeds are stimulated to germinate and the reduction of the canopy relieves the competitive pressure. Hence, there may be a tradeoff between strata: a mild fire may produce rapid litter and slow elevated recover and a severe fire may do the opposite.

Many studies of fire severity have measured the effect of fuel reduction and recovery on subsequent fire behavior. Most find severity is reduced for several years (Bradstock *et al.* 2010; Price and Bradstock 2012; Tolhurst and McCarthy 2016), though in some cases the effect was slight (Clarke *et al.* 2014). Weather has a profound effect on fire behaviour and extreme weather can essentially overwhelm the effect of fuel reduction. While recent burning reduced fire severity in the alpine fires of 2003, this effect was reduced at FFDI > 50 (Tolhurst and McCarthy 2016). In the Black Saturday fires of 2009, the effect was entirely absent at FFDI > 100 (Price and Bradstock 2012) (Figure 1a). The limited evidence suggests that recent burning has only a small effect on the likelihood of ignition (Penman *et al.* 2013). Examination of patterns of spread in hundreds of fires have found a small but significant inhibitory effects of recent burning (Price and Bradstock 2010; Price *et al.* 2015a).

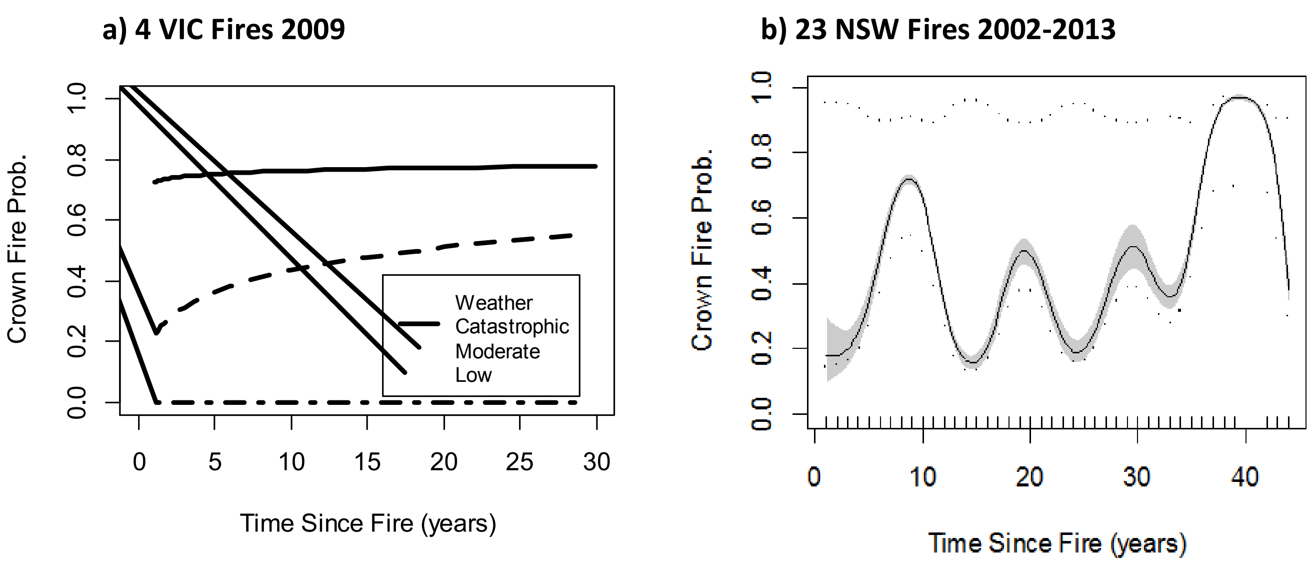

Figure 1: The probability of crown fire (high severity) as a function of time since the previous fire from two studies: a) Four fires in the Black Saturday fires of 2009 (including differences according to fire weather) (Price and Bradstock 2012); b) 23 forest fires across NSW (fitted with a generalized additive model) (Storey et al in review).

3) Changes to plant community

The available data suggests that elevated fuel cover does not asymptote in time but reaches a peak at around 10 years which is higher than the pre-fire levels and then declines (Conroy 1993; Watson 2011) as shrubs die (senesce or are outcompeted by trees or other shrubs). Recent examination of elevated fuel cover using Lidar has shown similar pattern (author's unpublished data). This pattern is reflected in a peak in fire severity across recent NSW fires (Storey *et al.* in review)(Figure 1b). Long-term high frequency burning has the potential to replace shrub understory with grass, as has been proposed for the creation and maintenance of grassy patches in Queensland (Gammage 2011) and Tasmania (Butler *et al.* 2014), and savanna (Bowman *et al.* 2004), though this phenomenon is far from proven. Over the medium term, a series of four fires in the Wombat forest (Victoria) had little effect on the structure of the understorey (Anon 2003). Several repeat fires have not resulted in species being lost from affected areas (Anon 2003; Penman *et al.* 2008), but there is evidence of gradual decline in abundance for many species (Penman *et al.* 2008; Russell-Smith *et al.* 2012)

4) Placement in High Risk Areas

In most biomes, wildfires are rare events: in Australian forests, the mean percentage of the forest burnt each year is less than 5% (Boer *et al.* 2009; Price and Bradstock 2011; Price *et al.* 2015c). In arid environments it is less than 2%. Similarly in Mediterranean and forest environments elsewhere less than 4% burns each year (Price *et al.* 2012b; Price *et al.* 2015b). This means that a randomly placed prescribed burn has a maximum 4% chance each year of being encountered by a randomly located wildfire. Only in savanna biomes with a very high fire activity (between 20% and 40% burnt per year (Price *et al.* 2012a)) is there a high chance of encounter. Given the fuel recovery rates, most prescribed burn patches do not encounter a wildfire within their useful life and are essentially wasted effort. In the Sydney region, 80% of prescribed burns do not encounter a wildfire within 5 years of treatment (Price and Bradstock 2010). Strategic placement of the treatment patches can increase the encounter rate (Finney 2007). The most obvious spatial strategy is to target areas with high ignition rates. Generally, this is near the urban interface (Penman *et al.* 2013; Price and Bradstock 2013b) because most fires are caused by arson or accident .

5) Placement in High Consequence Areas

House loss in wildfire is strongly influenced by fuels near the houses (30-40 m)(Cohen 2000; Gibbons *et al.* 2012) and the influence decreases as distance increases. Maximum return on effort occurs by placing prescribed burns where they will directly protect important assets by moderating fire behavior (Price and Bradstock 2010, 2012; Penman *et al.* 2014). However, there is evidence that embers from forests have contributed to house damage from as much as 1 km away (Price and Bradstock 2013a). Realistically placement should either be adjacent to those assets or in some place where suppression advantage can help prevent a wildfire from spreading to an asset (e.g. a road near the urban interface). Treatment is not necessary in remote areas where the occurrence of a wildfire is either inconsequential or is actually beneficial (from an ecological perspective).

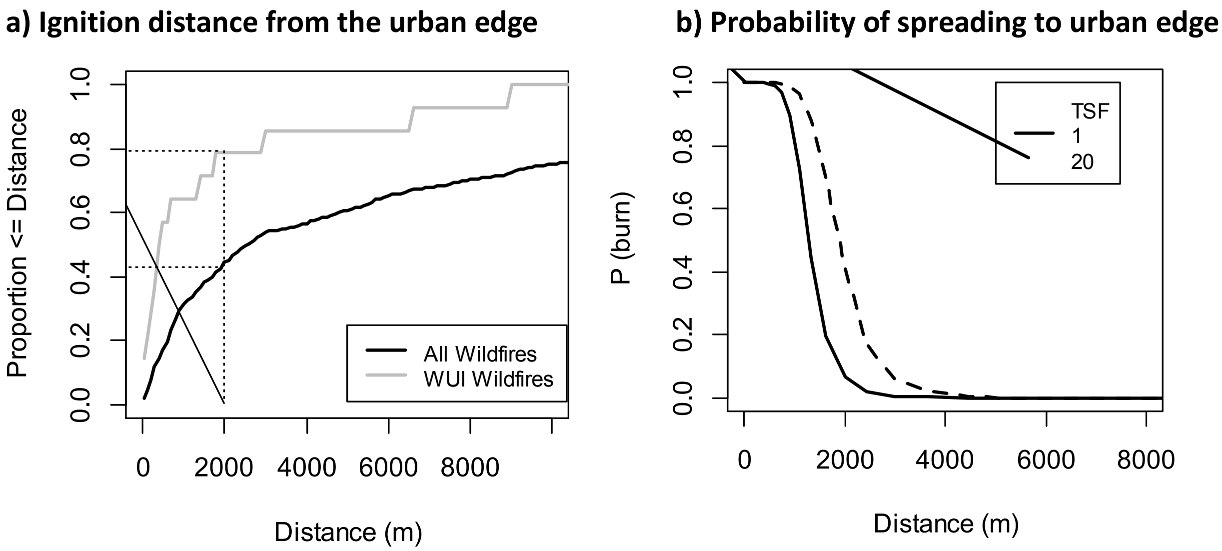

Figure 2: a) The distribution of ignition distances from the urban edge in Sydney, showing that 40% of all wildfires and 80% of fires that actually burn the edge in severe fire weather originate < 2 km away (Price and Bradstock 2013b); b) The effect that recent burning has on the likelihood of a fire reaching the urban interface in Sydney (Price *et al.* 2015a).

Conclusion

Research since Fernandes and Bothello (2003) has found that prescribed burns achieve a considerable but variable fuel reduction, which moderates fire behavior for several years. However, this is unlikely to be of advantage when the weather is extreme and of no advantage for the many treated areas that recover their fuels before a wildfire occurs. Over the long run, 3-4 ha of treatment is required for each ha reduction in wildfire area (Boer *et al.* 2009; Price and Bradstock 2011; Bradstock *et al.* 2012). This implies that treatment increases the overall area burnt, and hence may lead to other problems including reduction in biodiversity, increased pollution and reduction in carbon storage. From the perspective of risk reduction, prescribed burning offers an uncertain protection. General conclusions are:

1) Prescribed burning in remote areas offers little benefit to asset protection;
2) Prescribed burning provides maximum advantage when co-located with suppression activities. Therefore, it works best next to assets and/or fuel breaks such as roads.
3) Even the most effective prescribed burning program leaves a considerable residual risk. Hence, a range of other risk reduction strategies are needed (e.g. rapid response, strengthening house/garden, householder preparedness, evacuation);
4) Prescribed burning effectiveness varies geographically according to predictable patterns. It is most effective in regions where wildfires are common, fuels recover slowly and fire weather is not extreme.

Selected References

Anon (2003). Ecological effects of repeated low-intensity fire in a mixed eucalypt foothill forest in south-eastern Australia - Summary report (1984–1999). Department of Sustainability and Environment, Melbourne.

Boer, MM, Sadler, RJ, Wittkuhn, R, McCaw, L, Grierson, PF (2009). *For. Ecol. Manag.* **259**, 132-142.

Bowman, DMJS, Walsh, A, L.D., P (2004). *J. Biogeogr.* **31**, 207-223.

Bradstock, RA, Cary, GJ, Davies, I, Lindenmayer, DB, Price, O, Williams, RJ (2012). *J. Environ. Manag.* **105**, 66-75.

Bradstock, RA, Hammill, KA, Collins, L, Price, O (2010). *Landsc. Ecol.* **25**, 607-619.

Butler, DW, Fensham, RJ, Murphy, BP, Haberle, SG, Bury, SJ, Bowman, D (2014). *J. Biogeogr.* **41**, 1492-1505.

Clarke, PJ, Knox, KJE, Bradstock, RA, Munoz-Robles, C, Kumar, L (2014). *J. Veg. Sci.* **25**, 1033-1044.

Cohen, JD (2000). *Journal of Forestry* **98**, 15-21.

Conroy, B J Ross (Ed.) (1993) 'Fuel management strategies for the Sydney region, The burning question: fire management in NSW.' Coffs Harbour. (University of New England)

Fernandes, PM, Botelho, HS (2003). *Int. J. Wildland Fire* **12**, 117-128.

Finney, MA (2007). *Int. J. Wildland Fire* **16**, 702-711.

Gammage, B (2011) 'The biggest estate on earth: how aborigines made Australia.' (Allen and Unwin)

Gibbons, P, van Bommel, L, Gill, AM, Cary, GJ, Driscoll, DA, Bradstock, RA, Knight, E, Moritz, MA, Stephens, SL, Lindenmayer, DB (2012). *PLOS one* **7**, e29212.

Gould, JS, McCaw, WL, Cheney, NP (2011). *For. Ecol. Manag.* **262**, 531-546.

Grant, SR, Wouters, MA (1993). The effect of fuel reduction burning on the suppression of four wildfires in western Victoria. Department of Conservation and Natural Resources No. 41.

Horsey, B, Watson, P (2012). Bark fuel in New South Wales forests and grassy woodlands. Uni. W'gong.

Penman, TD, Binns, DL, Shiels, RJ, Allen, RM, Kavanagh, RP (2008). *Austral. Ecol.* **33**, 197-210.

Penman, TD, Bradstock, RA, Price, O (2014). *Environmental Modelling and Software* **52**, 166-175.

Penman, TD, Kavanagh, RP, Binns, DL, Melick, DR (2007). *For. Ecol. Manag.* **252**, 24-32.

Penman, TD, Price, OF, Bradstock, R (2013). *Int. J. Wildland Fire* **22**, 469-478.

Price, O, Russell-Smith, J, Edwards, A (2003). *Int. J. Wildland Fire* **12**, 227-236.

Price, O, Russell-Smith, J, Watt, F (2012a). *Int. J. Wildland Fire* **21**, 297-305.

Price, OF, Borah, R, Bradstock, R, Penman, T (2015a). *Int. J. Wildland Fire* **24**, 597-606.

Price, OF, Bradstock, R (2010). *Int. J. Wildland Fire* **19**, 35-45.

Price, OF, Bradstock, R (2012). *J. Environ. Manag.* **113**, 146-157.

Price, OF, Bradstock, R (2013a). *Plos One* **8**, e73421.

Price, OF, Bradstock, R, Keeley, JE, Syphard, AD (2012b). *J. Environ. Manag.* **113**, 301-307.

Price, OF, Bradstock, RA (2011). *Int. J. Wildland Fire* **20**, 142-151.

Price, OF, Bradstock, RA (2013b). *Natural Hazards and Earth System Sciences* **13**, 3385-3393.

Price, OF, Pausas, JC, Govender, N, Flannigan, M, Fernandes, PM, Brooks, ML, Bird, RB (2015b). *Int. J. Wildland Fire* **24**, 297-306.

Price, OF, Penman, TD, Bradstock, RA, Boer, M, Clarke, H (2015c). *J. Biogeogr.* **42**, 2234-2245.

Russell-Smith, J, Watt, F, Edwards, A, Price, O (2012). *J. Biogeogr.* **39**, 1303-1317.

Storey, M, Price, O, Tasker, E (in review). *Int. J. Wildland Fire*

Thomas, PB, Watson, PJ, Bradstock, RA, Penman, TD, Price, OF (2014). *Ecography* **37**, 827–837.

Tolhurst, KG, McCarthy, G (2016). *Aust. For.* **79**, 1-14.

Watson, P (2011). Fuel load dynamics in NSW vegetation. Part 1: forests and grassy woodlands. University of Wollongong.

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Eight case studies: effectiveness of prescribed burning in Mallee, heathy, and forest fuel types during the 2013 and 2014 fire seasons in Victoria

Nicholas Gellie[1], Nicholas Bauer[2], and Glenn Rudolph[3]

[1]Ecofuego, 83 Highton Lane, Mansfield, Victoria, 3772, Australia, nic@ecogis.com.au
[2]DELWP, 8 Nicholson St, Melbourne 3002 nicholas.bauer@delwp.vic.gov.au
[3]DELWP, Private Bag 260, Horsham, 3402, glenn.rudolph@delwp.vic.gov.au

Introduction

Prescribed burning, also known as planned burning, is 'the planned application of fire to the vegetation in a preselected land area' (McArthur 1962). Its primary aim according to McArthur is to 'reduce fuel accumulation and so reduce the intensity and damage of bushfires'. Within Victoria, and other fire-prone regions of the world (Fernandes and Botelho 2003), there have been a limited number of studies that examine the effectiveness of prescribed burning in reducing the severity and extent (equating to damage in McArthur's definition) under severe-extreme fire danger conditions

Recommendation 56 of the 2009 Victorian Bushfires Royal Commission (VBRC) stated "The State fund and commit to implementing a long-term program of prescribed burning based on an annual rolling target of 5 per cent minimum of public land.". In response to the VBRC the Victorian Government, the Department of Environment, Land, Water, and Planning (DELWP), committed itself to a significantly larger program of prescribed burning on public land. In 2015 the Victorian Government adopted a risk based approach to bushfire management, via 'Safer Together' which has replaced the original 5% annual area target recommended by the VBRC amounting to 395,000 ha of public land (7,916,000 ha) in Victoria.

This paper presents findings of the effectiveness of recent planned burns in mitigating the extent and severity of bushfires under severe and extreme Forest Fire Danger Index (FFDI)ratings. Eight case studies in three different regions of Victoria, were prepared. These include:

- *Mallee region of Victoria (Mallee low open woodlands)*: Pheenys Track, Rocket Lake, and Red Bluff in the Mildura District, and McDonalds Highway in the Wimmera District.
- *Grampians Region of Victoria (heathy and grassy woodlands and forests)*: the Victoria Range bushfire in 2013 and the Northern Grampians Complex bushfire in 2014.
- *East Gippsland (dry and damp eucalypt forests)*: the Jack River-Egans Roads bushfire and the Jacksons Crossing-Moorsford Road bushfire north of Orbost, both in 2014.

In this study, the effectiveness of prescribed burning is examined using two key indicators: (1) the reduction in fire severity of the bushfire; and (2) the potential reduction in areal extent of the bushfire based on expert or software derived estimates of area burnt if prescribed burns had not been conducted.

Methods and Data

The method used in the case study approach involved a three-step process:

(1) collection of a range of fire intelligence and fire environment data;
(2) reconstruction of fire spread based on methods derived for the Black Saturday bushfires (Gellie *et al*. 2010)
(3) estimation of fire severity within and adjoining planned burns in the critical sections of ab bushfire (Gellie and Mattingley 2014); and
(4) estimation of potential fire spread of the bushfire in the absence of the prescribed burns (i.e. maximum potential fuel hazard and load). The final extent of the bushfire in each case study was determined using either expertly derived fire spread or Phoenix Rapid-fire fire simulations.

Data collected for this analysis in the first step included: the history of recent planned burns both within and adjacent to the bushfire; the vegetation and fuels and terrain; and the fire weather immediately before, during, and after the bushfire event.

These in more detail were:

(1) *Fuel treatment details*:
(a) location: when the burn was completed, coverage and severity, photos of fuel types and results of burn (if possible); and
(b) general context for the treatment based on DELWP's fire operations plans (2013–2015);
(2) *Planned burn fire severity maps*: accurate maps of fire severity classes;
(3) *Fuel type information***:**
(a) vegetation maps, fuel type descriptions and photographs; and
(b) fine fuel data: fine fuel loading, fuel continuity, depth, and fuel age;
(4) *Seasonal fire climate and fire weather data*: in the lead up to, during, and after the fire from the nearest representative Bureau of Meteorology weather stations; and
(5) *Details about the bushfire run*: when it started, photos of the fire run, photos of its interactions with the planned burns, times and position of fire fronts based on the above or from situation reports or aerial observations:
a) Fire linescans: the day before, during the fire run, and the day afterwards,
b) *Aerial and ground photos* taken during and after the bushfire
c) *post-fire aerial photography* or *Landsat TM* images to assess fire severity of the areas within and adjoining planned burns affected by the bushfire

In the third step, aerial photography and ground and aerial photographs combined with the fire spread reconstruction in step (2) of the process were used to analyse the potential reduction in fire severity and fire spread.

In the fourth step Phoenix fire simulations were run using the closest available weather stations during the period interaction between the planned burn or burns and bushfire. If the Phoenix fire simulations were not realistic, an expertly derived fire extent model was created using empirical fire models available for each fuel type combined and fire weather data from the nearest representative weather station (Cruz *et al*. 2015).

Results and discussion

The data available for each case study is presented in Table 1. Fire linescan data was not always in most of the case studies. The study relied heavily on pre-and post-aerial photography and field fire intelligence to support the planned burn effectiveness findings in this study.

The summary of effectiveness of the planned burn or burns in each case study is presented in Table 2. These are described in more detailed below.

Mallee: Mallee low open woodlands and heathlands

The 2011 prescribed burn strategically located to the east of the Pheenys Track proved very effective in halting the forward spread of the bushfire under the Very High to near Extreme FFDIs (40–50) in Mallee heath fuel types in the centre of Murray Sunset National Park.

Similarly, the 2010 planned burn to the south of the Rocket Lake bushfire stopped the head fire of the Rocket Lake bushfire from spreading into 40 plus-y-old Mallee Low Woodland fuels to the south on three consecutive days when the FFDI range between 40 and 80. It is estimated that Rocket Lake prescribed burn prevented possibly 68,000–85,000 ha destructive bushfire, bringing about a likely 78–98% reduction in the bushfire area and a possible 90% reduction in total perimeter.

In the case of the Red Bluff bushfire the combined effect of 2008 and 2009 prescribed burns to the north and east of the bushfire, restricted the Red Bluff bushfire to a moderate sized bushfire within conservation reserves and away from private land. It is estimated that there was a ~27% reduction in area and the total length of fire perimeter by 18%. In addition, the five chain fuel breaks also supported the suppression effort between public and private land during severe–extreme FFDIs on 16 and 17 January 2014.

Under very high FFDIs, the 2011and 2007 prescribed burns restricted the McDonald Highway bushfire to being a moderately small bushfire in the Little Desert National Park with nearly 30 % of the fire perimeter naturally self-extinguishing. These prescribed burns reduced the areal extent of the bushfire by nearly 25%.

Grampians: heathy and plains woodland and heathlands

The planned burns conducted in the 2–3 years before the North Grampians complex bushfire, together with 2010 bushfire in the northern section of this bushfire, all combined to reduce its extent and severity while FFDIs remained severe-extreme in the early evening of 14 February 2014. The extent of the northern part of the 2014 Grampians–Northern Complex fire was reduced by 54% in area and 29% in terms of overall length of perimeter, and most likely preventing extensive damage to and economic loss in the communities of Dadswell Bridge and Ledcourt.

The 2007, 2010 and 2012 planned burns in the 2013 Victoria Range fire did not restrict the northern spread of the fire over the Victoria Range. They did however limit the spread along its western and southern flanks. This prevented the fire from becoming much larger and minimised potential impacts on adjoining private farmland; the southern end of the Victoria Range in the Grampians National Park; and stopped it from entering into the Rocklands Reservoir water catchment. Planned burns along the southern and western sides of the Victoria Range reduced the overall extent of the bushfire by 57%.

Table 1. Data and information available for case studies

Case study	Digital aerial photography		Remotely sensed imagery		Digital Map data						Fire weather		Fire linescans	Still photographs		
	Before	After	Before	After	Planned burn severity	Vegetation Map (EVCs)	Fire History	DEM	Tenure	Roads & Tracks	AWS Data	Radar		Vegetation and Fuel	During	After
Pheenys Track	●			●	●	●	●	●	●	●	●		●	+	●	+
Rocket Lake	●			●	●	●	●	●	●	●	●		●	+	●	+
Red Bluff	●			●	●	●	●	●	●	●	●		●	+	●	+
North Grampians Complex	●	●	●	●	●	●	●	●	●	●	●		●	+	●	●
Victoria Range	●			●	●	●	●	●	●	●	●		●	●	●	
Jacksons Crossing–Moorsford Road	●	●			●	●	●	●	●	●	●	●	●	+		
Jack River-Egans Road	●				●	●	●	●	●	●	●	●		+	●	
McDonalds Highway	●			●	●	●	●	●	●	●	●			●		●

Notes: (1) high resolution pre- and post-fire digital aerial photography (12 cm and 50 cm resolution) were available for all case studies

(2) fire weather was available at 1-min frequency for all the case studies. However, 0.5-hour data was used in the Pheenys Track, Rocket Lake, Red Bluff, and McDonalds Highway to simplify analysis and presentation of results

(3) the plus (+) sign indicates that the author took supplementary photographs in the field of the dominant fuel types found in the case study

Table 2 Summary of effectiveness of planned burns

Case study & year	Location	Fuel Types	Terrain	Fire Danger Index (FFDI)	Area burnt in bushfire (ha)	Simulated area without (ha)	Likely reduction in extent (%)	Summary of effectiveness
Pheenys Track (2013)	Mallee	Open Heath Mallee	Flat dune systems	40–50	1,570	5,320	70	A two-year-old planned burn conducted in 2011 stopped the wildfire's advance and significantly reduced the suppression difficulty in a remote area of Murray Sunset National Park.
Rocket Lake (2014)	Mallee	Open Heath Mallee	Flat dune systems	40–80	1,125	68,000–85,000	78–99	A highly effective 2010 strategic burn contained a possible major bushfire in the eastern section of Murray–Sunset National Park.
Red Bluff (2014)	Mallee	Heath Mallee, Arid Heathland	Flat dune systems	40–80	29,000	39,600	27	The planned burns to the north and east of the Red Bluff wildfire, as well the perimeter fuel breaks, contained the fire to a moderate sized bushfire.
McDonalds Highway (2014	Mallee	Heath Mallee, Broombrush Mallee, Arid Heathland	Flat dune systems	20-30 down to 15	855	1,100–2,700	22–33	The strategic location of the recent 2011 planned burn, close to the 2007 wildfire significantly reduced the extent of the bushfire
Grampians–Northern Complex (2014)	Grampians	Heathy Woodlands, Plains Woodland	Footslopes and plains	40–60	12,420	27,060	54	The mosaic of planned burns, and a previous bushfire significantly limited the severity and impact of the northern fire run of the Grampians–Northern Complex in the Dadswell Bridge area.
Victoria Range (2013)	Grampians	Heathy woodlands and forests & Plains Woodland	Footslopes and plains	20-50	36,500	63,800	57	The mosaic of planned burns conducted between 2007 and 2012 on the western flanks of the Victoria Range prevented the southern parts of the Grampians and adjoining private property from being burnt out.
Jacksons Crossing–Moorsford Road (2014)	East Gippsland	Dry and damp sclerophyll eucalypt forest	Dissected hills	60 down to 20	27,000	45,700	41	Although the 2011 ecological mosaic of planned burns burnt over during the south-east fire run did not retard the bushfire, the rest of it had a moderate effect on bushfire spread and spotting during the fire's north-east run.
Jack River–Egans Road (2014)	Southern Gippsland	Dry and damp sclerophyll eucalypt forest	Dissected hills	>100 down to 20	2,900	3,240	10	Despite being a small 100 ha planned burn, the burn blocked the spread of the bushfire in the south-east corner and reduced spot fires into adjoining grassland to the north

East Gippsland: Dry and damp sclerophyll eucalypt forest

During the severe fire weather conditions from 13:00–18:00, the 2011 Moorsford Road prescribed burn mosaic had limited impact on the fire severity and extent of the south–east fire run of the Jacksons Crossing–Moorsford Road bushfire under severe FFDIs. This was due to the relative low coverage and low fire severity of the planned burns done during a 'La Nina' phase. However, once estimated DFMC rose above 10% during its north-east fire run, another prescribed burning mosaic done in 2011 further to the north had a major impact in slowing fire spread and reducing the potential for further runs from fire spotting. It is estimated that with the limited amount of burning achieved at a landscape scale the burning limited the possible extent of this run by ~40% in terms of area and 24% in terms of final perimeter on the blow-up day of 9 February

In the Jack River–Egans Road bushfire, a relatively small 94 ha prescribed burn on its south-east corner served as an important anchor point for suppression along the north-eastern perimeter of State Forest and private land. Without it, there would have been another 2–3 km of edge suppression by ground crews and medium-range fire spotting into private property.

Conclusions

In the Mallee region prescribed burning can reduce the extent and impact of bushfires in Mallee and arid heathland for up to 3–5 years. In addition, 1-km-wide fuel breaks from prescribed burning can even halt the spread of bushfires burning under severe to extreme FFDIs. In the Grampians, the effectiveness of prescribed burns is limited to 1-2 years even if there is a 100% fuel treatment coverage. In dry and damp eucalypt forest, rapid post-fire fuel recovery after a planned burn reduced the possible time that a planned burn has an impact on fire severity and potential bushfire extent to 1–2 years, and was most effective when fuel treatment covered over 70% of the area treated and removed much of the surface, near-surface, and bark fuels. In these cases, prescribed burns of sufficient area (>300 ha) and high standards of coverage can greatly assist suppression effectiveness and hence the time to put out bushfires.

References

Cruz, M. G., et al. (2015). 'Empirical-based models for predicting head-fire rate of spread in Australian fuel types.' Australian Forestry 78(3): 3-3.

Fernandes, P. M. and H. S. Botelho (2003). 'A review of prescribed burning effectiveness in fire hazard reduction.' International Journal of Wildland Fire 12(2): 117-128.

Gellie, N. J. H., Gibos, K. E., Mattingley, G., Wells, T., & Salkin, O. 2010. Reconstructing the spread and behaviour of the February 2009 Victorian fires. 3rd Fire Behaviour and Fuels Conference. Spokane, Washington: International Association of Wildland Fire, Birmingham, Alabama.

Gellie, N. J. H. and G. Mattingley (2014). Effectiveness of recent prescribed burning in reducing fire severity of the Black Saturday fires in Victoria. 4th Fire Behavior and Fuels Conference, February 18 – 22, 2013, Raleigh, North Carolina, USA and July 1-4, 2013, St. Petersburg, Russia. Published by the International Association of Wildland Fire, Missoula, Montana, USA.

McArthur, A. G. (1962). 'Control burning in eucalypt forests'. Leaflet No 80. Canberra, Forest and Timber Bureau, Commonwealth Government: 43.

Victorian Bushfires Royal Commission (2010). Final Report, Volume 1: The Fires and the Fire-Related Deaths. Victorian Government, Melbourne, Parliament of Victoria. I: 361.

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Enhanced Weather Situational Awareness - Filling the Gaps Between the Modelled World and Reality

David Field,

New South Wales Rural Fire Service, Sydney, New South Wales, Australia

David.Field@rfs.nsw.gov.au

Abstract

Continually improving incident predictability and the accuracy of fire spread predictions requires an equivalent improvement in the specificity and validity of the weather data which is used to produce fire spread predictions. However, the monitoring of weather conditions and validation of a forecast for a fire burning in a rugged and remote location can be difficult given the constraints of Australia's existing observation network, a network which is designed to prioritise the coverage of the populated areas of Australia.

The NSW Rural Fire Service's *Enhanced Situational Awareness Project* has been designed to provide the State with an adaptive and portable observation capability. This paper outlines how the project seeks to fill the gaps in the state's existing observation network and satisfy the ever increasing need for incident specific fire and weather intelligence.

This paper outlines what the NSW RFS is doing to establish a network of portable and in-situ weather stations, establish the capacity to conduct portable atmospheric soundings, enhance the Service's reconnaissance capability and finally, to share this intelligence across a range of different platforms and with a broad range of stakeholders.

The Need for Increasingly Specific Observations to Improve Incident Predictability

For fire fighters, despite the accuracy (and continual improvement) of spatial weather forecasting there will always remain a need to validate a forecast against the observed weather. Validation enables the detection of differences between the forecast and actual weather conditions which may affect fire-fighter and public safety. It is also essential to prevent the amplification of errors as spatial forecasts are fed into subsequent fire spread modelling processes.

Validation of a forecast requires accurate observations. The consequences associated with a threatening and dynamic situation like a bush or grass fire means the observations need to be taken as close to the fire as possible. For fire-fighters in NSW this represents a challenge. Australia's observation network has been justifiably weighted towards servicing populated areas and arranged to address the requirements of aviation. Consequently, this means that there is a lower density of both surface and upper air observation sites in NSW's remote forested and grass country. Unfortunately often, these are areas where the State's more remote and challenging fires often occur.

However, as well as the challenges associated with validating a spatial weather forecast for a fire in a remote location, Incident Management Teams (IMTs), fire-fighters, Meteorologists and Fire Behaviour Analysts also need a means of detecting situations where localised weather-effects which occur on scales either not considered or smoothed-out by weather models may influence a fire's behaviour. These effects include (but are not limited to):

land/sea breeze convergence; frontal boundary locations and timings; thunderstorm outflow boundaries and gust fronts; and terrain induced variations to the wind field such as funnelling, foehn winds and anabatic and katabatic winds.

A necessary step of producing a spatial forecast is that the modelling process either homogenises (smooths) or does not model effects which occur on a scale smaller than the resolution of the forecast (sub-grid scale effects). However, these effects may influence fire behaviour and there is a need for them to be detected.

In addition to these sub-grid scale effects, if an intense fire develops it may also interact with the atmosphere. Currently it is not possible to model the effects of this, they can only be observed. Therefore, in order to detect this occurrence and the resulting effects (and thereby improve public and fire fighter safety) it is important to have an observational capability which can monitor the potential for; and effects of fire-atmosphere interaction.

Project Background and Initiation

On the 12th of January, 2013 a fire began in the Wambelong campground of the Warrumbungle National Park. Over the coming days the fire burnt over 56,000 hectares and destroyed 53 houses and 113 other buildings. The subsequent Coronial Inquiry recommended the New South Wales Rural Fire Service (NSW RFS) develop the capability to conduct atmospheric soundings and deploy portable weather stations to incidents.

Recently the Honourable David Elliot Minister for Emergency Services announced that in response to the Parliamentary and Coronial Inquiries the NSW Government would strengthen NSW's already robust capability to prevent and respond to bushfires by developing the capability to deploy portable balloon-based atmospheric soundings and provide additional portable automatic weather stations. To achieve this, the NSW RFS initiated the *Enhanced Situational Awareness Project* designed to establish this capability. The NSW RFS's *Enhanced Situational Awareness Project* aims to not only provide NSW with an integrated and adaptive weather observation capability but also to share this invaluable information across a broad range of platforms with a broad range of stakeholders.

The Enhanced Situational Awareness Project

The Enhanced Situational Awareness Project will seek to address situations where serious fires occur within observation "gaps" and address this issue by establishing a portable capability to provide high quality weather observations for these fires. To achieve this the NSW RFS will establish multiple regionally based weather observation units. These units will include a Portable Automatic Weather Station (PAWS), a Portable Balloon-Borne Atmospheric Sounding Capability and two personnel trained to deploy the weather observation equipment and take detailed fuel and field-based fire behaviour observations.

Portable Balloon-Borne Atmospheric Sounding Capability

The project will utilise World Meteorological Organisation (WMO) specified atmospheric sounding equipment and will provide high resolution incident specific observations which will remove the need to extrapolate the atmospheric conditions from either modelled data or fixed upper air observation sites which may be hundreds of kilometres away from an incident. The soundings will provide certainty about active (or potential) atmospheric instability effecting an incident. As well as definitively identifying dangerous abnormal conditions aloft, (conditions which may not be apparent from the surface) such as: strong winds aloft (low level jets); horizontal and vertical shear. The use of balloon-borne soundings will enable high resolution measurements of temperature and dewpoints in the atmosphere's boundary layer, providing accurate and relevant information about the strength and height of surface and subsidence inversions.

Although procurement of the equipment is not yet finalised it is intended that the equipment will be: dust, water and shock proof; simple and quick to deploy; and capable of pushing the derived data to multiple recipients.

Portable Automatic Weather Stations (PAWS)

The project will use Portable Automatic Weather Stations (PAWS) which are rugged, quick to deploy, simple to use and of a specification acceptable to Bureau of Meteorology.

Fuel and Fire Behaviour Reconnaissance

The project will train teams of reconnaissance personnel to provide location specific fuel observations and fire behaviour intelligence. This information will be shared with Incident Management Teams, fire fighters and Fire Behaviour Analysts to ensure it is instantly accessible and usable to all stakeholders.

The Future

This is the first phase of the project. It is currently intended that future phases of the project will enhance the fixed observation capability of NSW. In addition to this the project hopes to provide a range opportunities for future research and fire modelling. There is potential for the data the project collects to assist into research into future fire-atmosphere coupled modelling and for the sounding data to potentially feed into future domain specific modelling.

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Evaluating Bush Fire Treatment Effectiveness Using Phoenix RapidFire Gridded Ignition Case Studies

Jessica Wells*, Laurence McCoy
NSW Rural Fire Service, Lidcombe NSW, Australia jessica.wells@rfs.nsw.gov.au

Abstract

NSW Rural Fire Service has identified the need to move towards building bush fire risk assessment tools which quantify bush fire risk and evaluate treatment effectiveness using fire behaviour metrics.

Phoenix Rapidfire has been used to undertake some preliminary case studies. These studies explore how Phoenix can be used as a tool to assist in operational planning and evaluate the effect of potential hazard reduction treatments. It is envisaged that these case studies will provide a foundation for building quantitative risk assessment tools for the next generation of Bush Fire Risk Management Plans in NSW.

Preliminary work has identified there are challenges in representing complex weather scenarios, working with the model constraints, as well as finding meaningful ways of interpreting and communicating information.

Introduction

There is a need for fire managers to effectively understand the risk of bush fires to communities, assets and other values, so that risks can be suitably reduced. Identification of bush fire risks and the treatment of such risks is a core responsibility of the Bush Fire Management Committees in New South Wales, as outlined by the Rural Fires Act (1997). Bush Fire Risk Management Plans have been prepared for each Bush Fire Management Committee across NSW for the past 10 years. These plans identify assets, assess their risk from bush fire, and assign treatments to reduce this risk. The current process is largely qualitative, with an emphasis on local expert knowledge identifying sources of risk. Such an approach can be prone to bias in judgement, with regional variations in how risk is assessed.

Fire simulation tools are increasingly being used in operational contexts by most Australian fire jurisdictions. Phoenix RapidFire, developed by the Bushfire CRC and University of Melbourne is one of these bush fire simulation tools, which is currently used by most Australian jurisdictions in modelling potential fire behaviour for real-time bush and grass fire incidents.

Phoenix is currently being adopted by other states in a bush fire risk management planning context. Victoria and Tasmania have incorporated Phoenix into risk assessment and treatment evaluation products (Department of Environment and Primary Industries 2014, State Fire Management Council 2014). These approaches tend to be focused at a landscape level, rather than focusing on risk at a community based level.

* NSW Rural Fire Service, Locked Bag 17 Granville NSW 2142 Australia jessica.wells@rfs.nsw.gov.au

NSW RFS has integrated the use of Phoenix into supporting operational decision making for wildfire incidents, but is yet to embed use of fire simulation tools into bush fire risk management planning.

NSW RFS is currently in the early stages of building tools to improve future bush fire risk management planning. These tools will enable a more consistent and quantitative approach to assessing bush fire risk and evaluating treatments (O'Halloran 2016). NSW RFS has used case studies to explore the different applications of Phoenix as a bush fire risk management tool, and how these may be incorporated into the next generation of risk modelling in NSW. This paper will briefly outline the objective, methods and findings of two case studies which have been developed to date.

2016 Scout Jamboree

Context

In January 2016 the annual Australian scout jamboree was held at Cataract Scout Park, near Appin NSW. This event involved accommodating up to 15,000 patrons in a location considered to be of very high bush fire risk during the bush fire danger period. As part of the preparation for this event, the NSW RFS was involved in preparation of evacuation plans, as well as implementation of hazard reduction burns adjacent to the scout park to reduce fuels in the lead up to the event.

Objective

Explore the potential for Phoenix modelling to inform the preparation of evacuation plans, and assess the effectiveness of the hazard reduction burns in changing the time to impact of potential fires.

Methods

This scenario looked at how implementing burns around the scout park changed the time to impact under a variety of weather conditions and ignition start times. Three weather scenarios were built to simulate typical weather for days of Severe, Extreme and Catastrophic fire danger ratings (FDR). They replicated a typical fire weather day, and were based on return intervals of fire danger index (FDI) (Louis 2013). Each FDR scenario included the passage of a frontal system causing North Westerly winds to shift to South Westerly.

To assess the effectiveness of the prescribed burn, two fuel scenarios were modelled for each weather stream. One included contemporary fuels (all wildfire and hazard reduction before the burns were implemented), and the second included the reduction in fuels due to the recent hazard reduction burns.

Phoenix was run using a 1 km ignition grid to simulate numerous potential ignition points across the area to the west of the scout park. This was identified by local NSW RFS District staff as the area most likely to result in ignitions that would impact on the scout park. Ignitions were modelled with start times before (1000hrs) and after (1400hrs) the frontal change.

Python scripts were developed to identify the time from ignition that each fire first reached the polygon bounding the scout park.

Results

Model results suggested the time to impact changed as a result of implementing the proposed hazard reduction burn. These results do not account for the effect of suppression.

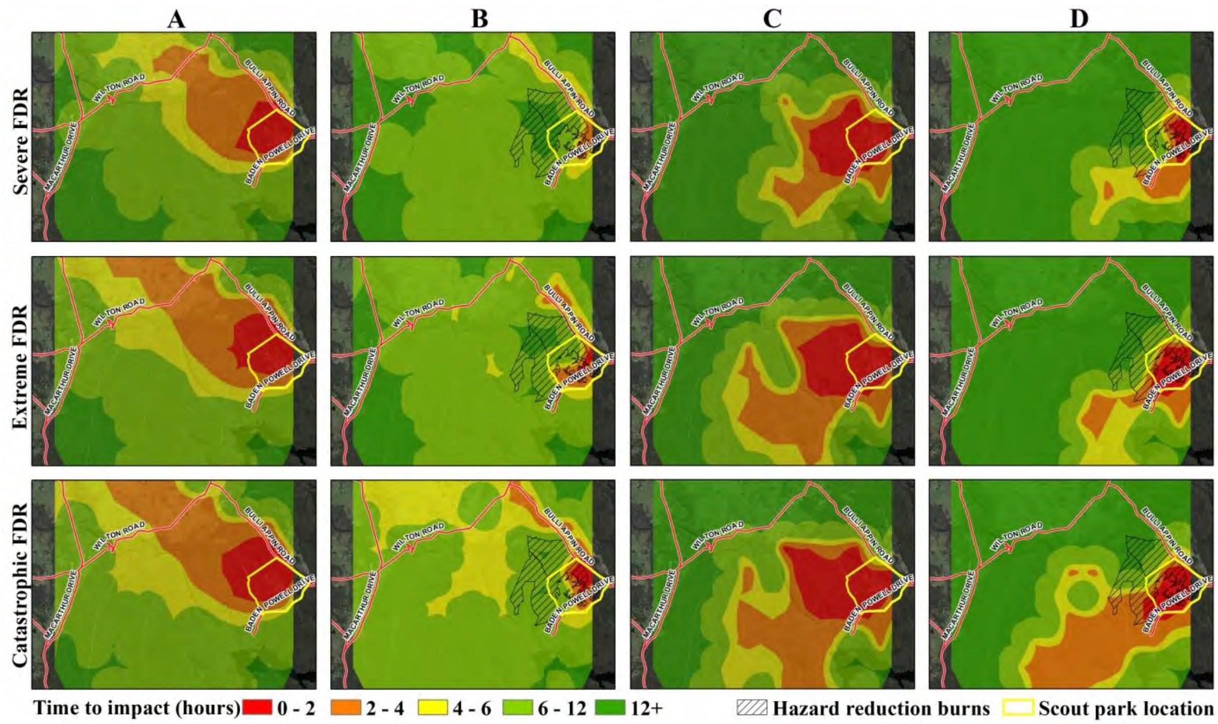

Figure 1. Time to impact from modelled fires igniting at 10:00 with the contemporary fuels A) and reduced fuels (B), and time to impact from modelled fires igniting at 14:00 with contemporary fuels (C) and reduced fuels (D). The yellow shape identifies the location of the scout park, and the hashed area in b and d identifies the location of the hazard reduction burn.

Comparing the pre-treatment and post-treatment maps, the model predicts that the hazard reduction significantly increases the time to impact to the north west of the park across all FDR/ignition time scenarios (Figure 1). The hazard reduction burn provides greatest value with ignitions starting in the 1000hrs scenario under a north westerly/south westerly change wind scenario. The effectiveness of the hazard reduction burn in modifying the time to impact reduces as the severity of the weather increases.

Lessons learnt

Time to impact is a useful concept in understanding the threat of fires to a particular asset. Time to impact is a consideration used in issuing of emergency warnings in NSW, as well as in preparation of evacuation plans for special fire protection places, vulnerable residents and event planning. This product may also have use as a strategic operational prediction tool.

Whilst time to impact can be a useful indicator of which ignitions are a concern for evacuation, the results are sensitive to weather scenarios, in particular wind direction, and ignition start time. Also identified through this case study was the importance of including multiple FDR scenarios in the analysis, as this shows that the effectiveness of hazard reduction treatment reduces with increasing severity of fire weather. This case study identified that results are sensitive to complex weather streams, and that there is a need to include multiple weather scenarios (e.g. variation in wind direction, or timing of frontal system passage) to produce ensemble risk products in future assessments.

Sutherland District bush fire risk analysis

Context

Fire managers in the Sutherland District are currently reviewing options and planning hazard reduction treatments in their area. As part of the review process, the local NSW RFS officers sought a science based approach to inform decision making on what treatments to include in the treatment register.

Objective

Identify the areas where ignitions cause the most house loss, and identify the most vulnerable assets under a range of possible weather conditions. This information can then form the basis for planning and prioritising hazard reduction treatments.

Methods

This scenario attempted to assess the risk of fires spreading under varied wind directions under one fire danger rating. As per the scout jamboree case study, a weather scenario based on return interval of 1 in 50 years was built (Louis 2013). This represented a Severe FDR, which formed the basis for 3 different weather scenarios. Each weather scenario used the same air temperature, relative humidity and wind speed series, but used a different wind direction (North-westerly, Westerly, South-westerly). A more robust method of developing appropriate weather streams will be developed in future.

Ignitions were simulated across the entire Sutherland Bush Fire Management Committee (BFMC) area, as well as 8km to the west in the neighbouring BFMC area to allow for the potential for fires to spread from other areas. Ignitions were located on a 1 km grid.
Address point data was used to infer the location of houses.

Python scripts were developed to identify the number of houses reaching house loss thresholds developed by Tolhurst and Chong (2014) for each fire. A second script identified how frequent each house was impacted by a different ignition. Both scripts were run for each weather scenario. A weighted score was then developed, based on local knowledge of how frequently this wind direction occurred.

Results

For the ignitions modelled in this case study, there was a high degree of variation in both the average house loss per ignition location, and average frequency of potential house loss per house amongst the 3 weather scenarios (Table 1).

Figure 2 shows the potential house loss from the source of ignition for fires igniting under each of the 3 weather scenarios. These results do not account for the effect of suppression, and assume that all houses have equal chance of loss. The map shows that each potential house loss for each ignition changes amongst the weather scenarios, with the most damaging fires usually occurring in the direction that the wind comes from. The weighted result is able to identify the most damaging fires under each of the 3 weather scenarios.

Table 1. Average house loss per ignition point, and average frequency of impact per house across the 3 weather scenarios, and weighted result.

	North-westerly	Westerly	South-westerly	Weighted
Average house loss per ignition	505	633	1626	892
Average frequency of impact per house	2.1	3.5	5.7	3.8

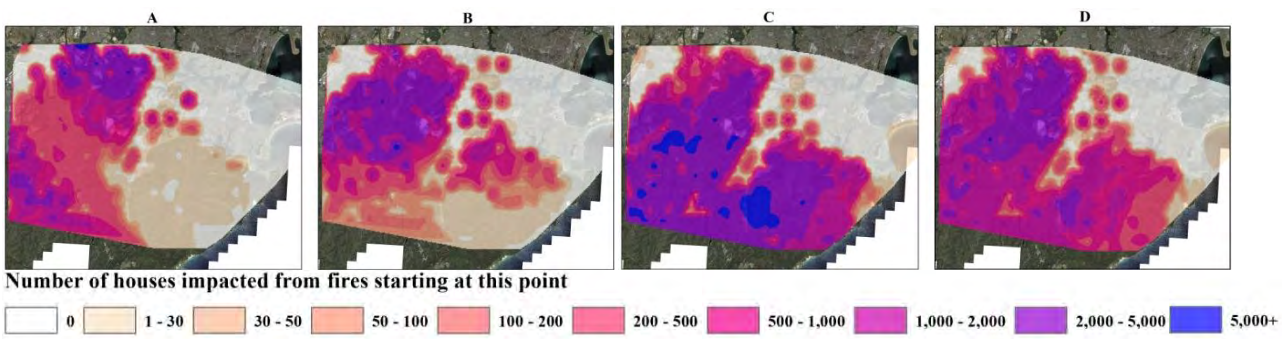

Figure 2. Number of houses impacted from ignition point of origin for the North-westerly (A), Westerly (B), South-westerly (C) and weighted results (D).

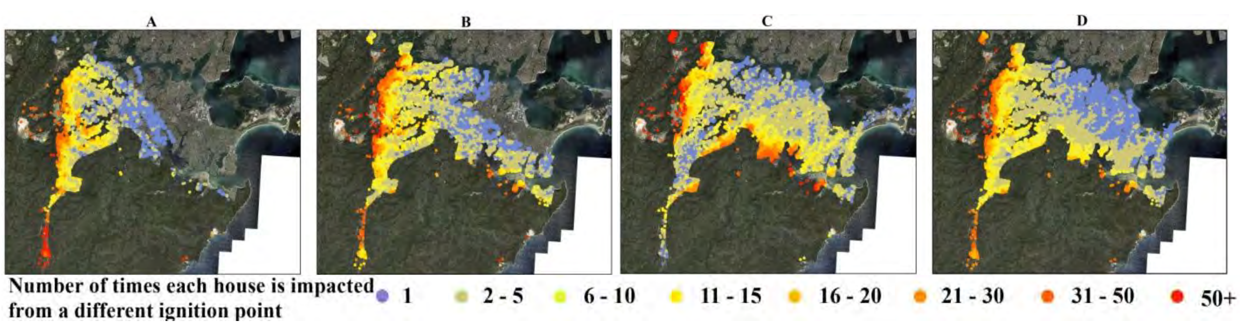

Figure 3. Frequency of impact per house for the North-westerly (A), Westerly (B), South-westerly (C) and weighted results (D).

Frequency of impact can infer how vulnerable a house is to fires starting in different parts of the landscape. Figure 3 identifies that assets have different frequency of impact depending on the wind direction. The weighted result shows the most commonly occurring vulnerable assets across the 3 different weather streams.

When determining where to place and how to prioritise treatments, the local fire managers will need to consider both where the most damaging fires originate, and where the most vulnerable assets are located. The next phase for this case study will be to determine which planned treatments result in the greatest reduction in house loss.

Lessons learnt

This case study has demonstrated the need to consider multiple weather scenarios, as sources of risk originate in different parts of the landscape, depending on the weather scenario used. The weighted approach provides a useful method of combining multiple scenarios into one product, although a more robust method of determining realistic weather streams, and combining results in a probabilistic approach, is needed.

Discussion

One of the greatest challenges that both case studies have identified is finding appropriate methods of communicating results to end users, who may not necessarily have capability in interpreting complex risk based information. Producing documents which show areas of high risk, without being misinterpreted or misused by the public provides a further challenge.

As with any modelling, limitations lie in the quality of underlying datasets, and accuracy of models. This may be overcome if results are analysed as being relative to each other across scenarios, rather than absolute.

Particular limitations may lie in the application of Phoenix in areas which adjoin the urban interface, where bush fires either extinguish, or behave as urban fires, which are outside the parameters of Phoenix's current underlying models.

References

Department of Environment and Primary Industries (2013) 'Victorian bushfire risk profiles: A foundational framework for strategic bushfire risk assessment.' (Victorian Government, Department of Environment and Primary Industries: East Melbourne)

Louis SA (2014) Gridded return values of McArthur Forest Fire Danger Index across New South Wales. Australian Meteorological and Oceanographic Journal 64, 243–260.
O'Halloran M (2016). Proceedings for the 5th International Fire Behaviour and Fuels Conference (International Association of Wildland Fire: Missoula)

State Fire Management Council (2014) 'Bushfire in Tasmania. A new approach to reducing our statewide relative risk.' (State Fire Management Council Unit: Tasmania Fire Service: Hobart)

Tolhurst K, Chong D (2014) 'PHOENIX RapidFire: User Manual - Introduction and Exercise Draft 9 May 2014.' (Bushfire CRC, University of Melbourne & Department of Sustainability & Environment: Melbourne)

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Evaluating dead fuel moisture models for Australian grasslands

Susan Kidnie* [A], Miguel G. Cruz [B], Stuart Matthews [C], Richard J. Hurley [B], Alen Slijepcevic[A], David Nichols [A], Jim S. Gould [B]

[A] CFA, Fire and Emergency Management, PO Box 701, Mt Waverley, Victoria, Australia
[B] CSIRO, GPO Box 1700, Canberra, ACT, Australia
[C] NSW Rural Fire Service, 15 Carter Street, Lidcombe NSW, Australia

Introduction

Grass represents the most widespread vegetation type in Australia. These fuels have a number of features that differentiate them from litter or fine woody fuels including their physical structure and how this structure affects the moisture exchange processes between fuel particles and the surrounding environment. Grass fuels are finer than other common wildfire fuels resulting in faster moisture response times to changes in the weather (Van Wagner 1972; Viney and Hatton 1989).

In Australia, a number of tools, such as tables, slide rules and derived equations, have allowed the estimation of dead grass fuel moisture content under sunny conditions in a typical south-eastern Australian summer (McArthur 1960, 1966, 1977, Noble *et al.*1980, Cheney *et al*. 1989). Models derived from the above studies are used to estimate dead grass fuel moisture content operationally in Australia (Cruz *et al*. 2015), although their predictive capacity has not yet been evaluated.

There are also a number of other models, some used to quantify fuel moisture in grassland fuels elsewhere in the world (e.g., Deeming *et al*. 1977; Van Wagner 1987) and newly developed process based ones (Wotton 2009; Matthews 2006). As is the case for other models and tables described in the paragraph above, there is a need to assess the accuracy of these models in Australian grasslands.

The main objective of this study is to test the predictive capacity of dead fuel moisture content models for grassland fuels under the dry environmental conditions typical of eastern Australia.

Methods

Data on dead fuel moisture content was collected within the scope of a grass fire behaviour study (see Kidnie *et al*. 2015 and Cruz *et al*. 2015). Dead fuel moisture content data was collected at five distinct grassland sites in eastern Australia: Wangaratta South (n=11) and Wendouree (n=16) in Victoria; Tamworth (n=8) and Braidwood (n=31) in New South Wales and Toowoomba (n=10) in Queensland between 2013 and 2016.

Samples (20 – 30 g each; 3 to 10 replicates) were collected and sealed in airtight metal tins, weighed, oven-dried for 24 hours at a nominal temperature of 105 °C and then reweighed (Matthews 2010).

*Susan Kidnie
Country Fire Authority
8 Lakeside Drive Burwood East VIC 3151, s.kidnie@cfa.vic.gov.au

Air temperature, relative humidity, and solar radiation 1.5 m above ground and wind speed and direction at 2-m height were measured continuously and averaged at 10-minute intervals. Rainfall was measured with a tipping bucket.

Key Results

Initial analysis suggest that the Cheney *et al* (1989) model (AM60), the Noble et al. (1980) model (MK5), and the Matthews (2006) model (Koba) to have the most consistent predictions. These models have the lowest mean absolute error (2.0%, per cent moisture points). Bias for these three models was relatively small, 16 and 36% of the mean error for Koba and MK5 respectively (under-prediction); and an over prediction bias of 34% of the mean error for the AM60.

Our results suggest that the assumption of instantaneous response to changes in environment conditions, as assumed by the AM60 and MK5 models, is reasonable for standing dead grass fuels, without loss of precision.

The good results obtained by Koba are encouraging. Its physical base, with explicit modelling of the main processes determining fuel moisture should allow for its reliable application to a wide range of conditions. Namely, for fuel configurations other than standing grass and environmental conditions characteristic of prescribed burning operations (e.g., low air temperatures, moderately high relative humilities). Due to its computational requirements, further work is required to make Koba an operational model.

The predictive capacity of these models suggests absolute errors around 2 oven dry weight percentage points. As a percentage, the average error was 25 to 30% of the observed fuel moisture content. Knowledge of this uncertainty is required to reliably apply ensemble simulation methods that take into account the uncertainty in environmental conditions.

The results from the current study have also implications for fire danger ratings in Australia. Predicting accurate grass fuel moisture subtleties will be critical for the development of improved Fire Danger Rating systems when relating the potential for rapid fire development, fire behaviour parameters, the difficulty of fire suppression, and potential impacts and consequences of grass fires.

References

Cheney NP, Gould JS, Hutchings PT (1989) Prediction of fire spread in grassland. Unpublished report, CSIRO National Bushfire Research Unit, Canberra, ACT.

Cruz MG, Gould J, Kidnie S, Bessell R, Nichols D, Slijepcevic A (2015) Effects of curing on grassfires: II. Effect of grass senescence on the rate of fire spread. *International Journal of Wildland Fire* **24**, 838–848.

Deeming JE, Burgan, RE, Cohen JD (1977) The National Fire-Danger Rating System--1978. Gen. Tech. Rep. INT-39. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 63 p

Kidnie S, Cruz MG, Gould J, Nichols D, Anderson W, Bessell R (2015) Effects of curing on grassfires: I. Fuel dynamics in a senescing grassland. *International Journal of Wildland Fire* **24**, 828–837.

Matthews S (2006) A process-based model of fine fuel moisture. *International Journal of Wildland Fire* **15**, 155–168.

Matthews S (2010) Effect of drying temperature on fuel moisture content measurements. *International Journal of Wildland Fire* **19**, 800-802.

McArthur AG (1960) Fire Danger Rating Tables for Annual Grasslands. Commonwealth of Australia, Forestry and Timber Bureau, Canberra, ACT.

McArthur AG (1966) Weather and grassland fire behaviour. Commonwealth of Australia, Forestry and Timber Bureau, Leaflet 100 (Canberra, ACT).

McArthur AG (1977) Grassland Fire Danger Meter Mk V. Country Fire Authority of Victoria, linear slide-rule. (Melbourne, Victoria).

Noble IR, Bary GAV, Gill AM (1980) McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecology* **5**, 201–203.

Van Wagner CE (1972) Equilibrium moisture content of some fine fuels in eastern Canada. Canada Department of Fisheries and Forestry, Information Report PS-X-36. (Chalk River, ON)

Van Wagner CE (1987) Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Information Report 35. (Chalk River, ON)

Viney NR, Hatton TJ (1989) Assessment of existing fine fuel moisture models applied to eucalyptus litter. *Australian Forestry* **52**, 82–93.

Wotton B (2009) A grass moisture model for the Canadian Forest Fire Danger Rating System. In 'Eighth Symposium on Fire and Forest Meteorology', 13–15 October 2009, Kalispell, MT. (American Meteorological Society: Boston, MA).

Evaluation of Operational Wind Field Models over Complex Terrain

R. Quill*[1,2], J.J. Sharples[1,2], L.A. Sidhu[1], N. Wagenbrenner[3], J. Forthofer[3]
[1] School of Physical, Environment and Mathematical Sciences, UNSW Canberra, Australia
[2] Bushfire and Natural Hazards CRC, Melbourne, Australia
[3] US Forest Service, Missoula Fire Sciences Laboratory, USA

Introduction

With emerging research into the dynamics of extreme fire behaviour, it is of ever-increasing importance that operational wind models capture areas of complex flow patterns across rugged terrain. Butler *et al.* (2015) highlight the limited nature of traditional broad-scale (4km resolution) weather prediction in understanding the variability of wind fields across complex terrain. Downscaling models are often used to predict finer-scale wind fields from these broader weather predictions, but there is a lack of wind datasets observed at the necessary scales to effectively evaluate these downscaling models for use in operational fire modelling (Butler *et al.*, 2015).

A limited number of studies have shown that, despite significant improvements in wind field predictions on those given by broad-scale weather models, a number of limitations of downscaling models such as WindNinja[1] remain, particularly in areas with complex terrain (Forthofer *et al.,* 2014; Wagenbrenner *et al.*, 2016). For example, poor performance is regularly observed on leeward slopes. The consequences of not capturing key wind features are significant in the fire modelling context, with characteristics such as flow separation on lee-slopes linked to extreme fire behaviour (Simpson *et al.*, 2013).

Many current operational models are also deterministic in their nature while fire spread (and wind fields) can be thought of as inherently probabilistic, with elements of random behaviour that are not currently understood or captured by physical modelling approaches. In order to better account for this random nature, probabilistic approaches to fire modelling have been introduced in a number of emerging ensemble-based frameworks (French *et al.,* 2013; QFES, 2015). These approaches aim to capture the inherent variability of fire spread across the landscape by sampling input data from random distributions. Wind fields, as an input variable to fire models, have been recast in a probabilistic light (Whiteman, 1993; Sharples *et al.*, 2010), and it has been shown that wind characteristics do not follow the Uniform or Normal distributions used in these ensemble models. In order to better understand and quantify the uncertainty in fire spread and behaviour predictions, particularly with respect to finer-scale spatial variability across the landscape, better statistical characterisation of input variables such as wind fields is required.

The aim of this study is to evaluate currently operational deterministic wind field models in the context of bushfire over areas of complex terrain. By considering wind fields in probabilistic terms, this study also aims to advance discussions of uncertainty in wind and fire modelling.

[1] http://www.firelab.org/project/windninja

Methodology

WindNinja 2.5.2 (referred to as the WindNinja-native solver) is the mass conservation wind modelling scheme currently used operationally within the state-of-the-art fire modelling framework Phoenix Rapidfire (Tolhurst *et al.*, 2008). This study compares the outputs of the WindNinja-native solver to wind data collected over complex terrain at scales from 10's to 100's of metres. A beta version of the next generation WindNinja 3.0 (referred to as the WindNinja-OpenFOAM solver) is also evaluated in this study. This newly developed version incorporates a momentum flow solution based on the OpenFOAM CFD toolbox.

Wind data were collected across a transect of Flea Creek Valley, Brindabella National Park, NSW. The focus of this investigation was to evaluate the ability of the above models to capture the variability of wind direction across the valley. Although wind speed was not the focus of the study, it is important to note that observed wind speeds were relatively weak throughout the study period (approx. 0 to 3m/s).

In contrast to previous studies, the wind direction data were recast in a probabilistic context so that the wind direction outputs from the deterministic models were compared to the full distribution of wind directions observed across the study period. Modelled wind fields were also recast in probabilistic terms by constructing distributions of wind direction output from the WindNinja-OpenFOAM solver.

Results

On modelling wind fields across Flea Creek Valley under a west-north-westerly prevailing wind direction, the WindNinja-OpenFOAM solver clearly captured more topographic impacts on wind flow across the valley, including recirculation through gullies on the lee slopes and larger scale channelling down the valley. On the ridge-tops, deterministic predictions from both models captured the observed wind direction modes that aligned with the prevailing winds across the valley.

Both models were limited by their deterministic nature, and both failed to register a high degree of agreement with the observed distributions, particularly in places with highly variable wind directions. Probabilistic prediction of wind direction distributions using the WindNinja-OpenFOAM solver was much more informative than single predictions, and it was able to capture many of the key modes in the distributions, such as those corresponding to wind reversals.

As in Forthofer *et al.*, (2014), it was found that the WindNinja-native solver generally performed least well on the lee-slopes of the valley. Probabilistic implementation of the WindNinja-OpenFOAM solver performed better on these lee-slopes, with the momentum solver being able to capture the observed lee-slope wind reversals.

On the windward slope, the deterministic WindNinja-native solver outperformed the WindNinja-OpenFOAM solver. On this slope, the new model suggested a northerly biased flow driven by channelling through the valley, but this was not observed. It is likely that smaller scale mechanical flows, caused by local topography at a higher resolution to that of the model, may be a significant factor in the discrepancies between the models and the observations. The probabilistic results showed that the WindNinja-OpenFOAM solver was still generally unable to capture the variability of wind flow across this region.

Conclusion

Across the broader topographic scale, the deterministic models were consistent with observations, however, within the complex landscape i.e. on the leeward and windward slopes, both deterministic models failed to capture dominant wind direction modes. The increased information available by using probabilistic approaches to modelling revealed important wind direction behaviours that were not captured using the current operational deterministic model. Deterministic predictions could at times produce errors of up to 180°, whereas probabilistic predictions more accurately captured multi-modal wind direction distributions.

In the fire context, lee-eddies and smaller scale variations in wind direction (and speed) can have volatile and dangerous impacts on fire behaviour. It is therefore vital to be able to capture these variations within wind models used for fire spread prediction. It is clear that the use of deterministic models alone is inadequate for capturing this variability. By incorporating probabilistic approaches into traditional physics-based models, wind field modelling frameworks can formulate a more informed view of wind flow across complex landscapes for fire modelling purposes.

References

B. W. Butler, N. S. Wagenbrenner, J. M. Forthofer, B. K. Lamb, K. S. Shannon, D. Finn, R. M. Eckman, K. Clawson, L. Bradshaw, P. Sopko, S. Beard, D. Jimenez, C. Wold, and M. Vosburgh (2015) High-resolution observations of the near-surface wind fields over an isolated mountain and in a steep river canyon. *Atmospheric Chemistry and Physics*, **15**, 3785-3801.

J. Forthofer, B. Butler, and N. S. Wagenbrenner (2014) A comparison of three approaches for simulating fine-scale surfaces winds in support of wildland fire management. Part I. Model formulation and comparison against measurements. *International Journal of Wildland Fire*, **23**, 969-981.

I. French, B. Cechet, T. Yang, and A. Sanabria (2013) FireDST: Fire Impact and Risk Evaluation Decision Support Tool - model description. In J. Piantadosi, R. S. Anderssen, and J. Boland, editors, *MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand Inc*., 2013.

Queensland Fire and Emergency Services (2015) 2014-2015 Annual Report. Technical report, The State of Queensland, Queensland Fire and Emergency Services 2015.

J. J. Sharples, R. H. D. McRae, and R. O. Weber (2010) Wind characteristics over complex terrain with implications for bushfire risk management. *Environmental Modelling and Software*, **25** (10), 1099-1120.

C. C. Simpson, J. J. Sharples, J. P. Evans, and M. F. McCabe (2013) Large eddy simulation of atypical wildland fire spread on leeward slopes. *International Journal of Wildland Fire*, **22** (5), 599-614.

K. G. Tolhurst, B. Shields, and D. Chong (2008) Phoenix: development and application of a bushfire risk management tool. *Australian Journal of Emergency Management*, **23** (4), 47-54.

N. S. Wagenbrenner, J. M. Forthofer, B. K. Lamb, K. S. Shannon, and B. W. Butler (2016) Downscaling surface wind predictions from numerical weather prediction models in complex terrain with WindNinja. *Atmos. Chem. Phys. Discuss.*, **2016**, 1-32.

C. D. Whiteman and J. C. Doran (1993) The relationship between overlying synoptic-scale flows and winds within a valley. *Journal of Applied Meteorology*, **32** (11), 1669-1682.

Evolution of Fire Behaviour Analysis into Operational Business as Usual – The NSW Experience.

Simon Heemstra
New South Wales Rural Fire Service, Sydney, New South Wales Australia.
simon.heemstra@rfs.nsw.gov.au

Laurence McCoy,
New South Wales Rural Fire Service, Sydney, New South Wales Australia.
laurence.mccoy@rfs.nsw.gov.au,

Abstract
Whilst fire behaviour models have been in operational use in New South Wales for many years, and following the release of the recommendations from the 2009 Victorian Bushfires Royal Commission, in 2010 the NSW Rural Fire Service (NSW RFS) commenced a project to develop a formal Fire Behaviour Analysis capability. In the five years since establishment, NSW has been able to develop a significant capability with procedures, training and assessment, a suite of tools, equipment and personnel (agency staff and NSW RFS volunteers) in place to support operations with predictions and analysis at a state an incident level.
The foundation of the system is the use of a split computer simulated and manual validation process and the use of a Fire Behaviour Supervisor at NSW RFS State Operations. This aims to increase confidence in the products and assist with triage and dissemination of predictions. Overall the project has been a remarkable success. Continuous improvement and innovation have been integral to the development of the service and will ensure predictive services continue to flourish within NSW.

Introduction
Whilst fire behaviour models have been in operational use in New South Wales for many years, following the release of the recommendations from the 2009 Victorian Bushfires Royal Commission, in 2010 the NSW RFS commenced a project to develop a formal Fire Behaviour Analysis Capability. In the five years since establishment, NSW has been able to develop a significant capability with procedures, training and assessment, a suite of tools, equipment and personnel (agency staff and NSW RFS volunteers) in place to support operations with predictions and analysis at a state and incident level.

Timeline
The report prepared by Cook *et.al*. (2009) provided the initial impetus for the current system in operations in NSW. It identified issues with the accuracy of the computer simulation predictions. They attribute much of these accuracy issues to the accuracy of input data and suggested that Phoenix should only be used in a trial in conjunction with traditional methods. They also suggested that it would be useful to use Phoenix and manual methods alongside each other.
In 2010, a 12 month project to develop a NSW RFS Fire Behaviour Analysis and Smoke Plume Modelling capability commenced. Two relatively quiet fire seasons associated with the La Niña events resulted in consecutive project extensions.
The two quiet seasons enabled a fire behaviour analysis system to be established (Figure 1). This system relies on independent preparation of predictions via manual and computer simulator (Phoenix) methodologies. Figure 1 presents a flow chart whereby a prediction is either requested or pre-emptively prepared by a Simulator Operator using Phoenix. This

prediction is independently manually validated by a Fire Behaviour Analyst (FBAN) via manual methodology. Both the simulated and manual predictions are compared by a Supervisor and if consistent the manual prediction is approved or published with an accompanying report. In the event of inconsistency, the Supervisor will investigate before making a decision as to whether to publish a prediction.

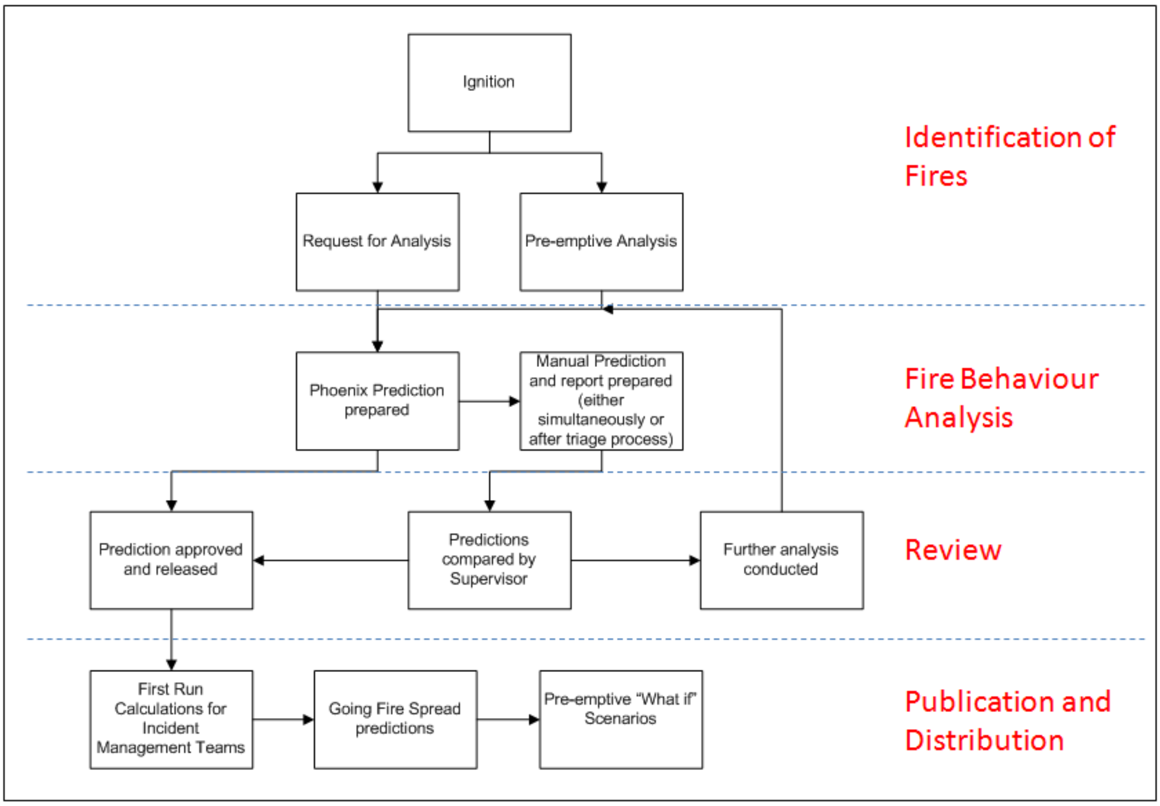

Figure 1 Flow chart for publishing a prediction in NSW

The prediction system is underpinned by a policy document called the "Fire Behaviour Analyst Handbook" (NSW RFS, 2015). This document provides policy and guidance for FBANs for preparing a prediction within the NSW RFS corporate environment. It is contained with an "FBAN kit". The kit is a digital repository for reference material, templates, tools and research.

The system is also underpinned by National Training lead by Dr. Kevin Tolhurst from the University of Melbourne. It is supported by a collaborative approach between each of the NSW fire fighting agencies.

Due to lack of accreditation, an early strategy was for FBANs to be located at state headquarters so that a Supervisor could review and approve a trainees work.

2012-2013 Fire Season

January 2013 saw the first major operational event for the unit. At its peak staffing (multi agency staff and NSW RFS volunteers) escalated from 2 to 26 members. Roles included Management, FBANs, and Mapping and Administrative Support. Around 370 predictions were prepared over the season.

Predictions for three major fire events were evaluated by Storey and Price (2014) from the University of Wollongong (UoW). Storey and Price (2014) found that wind forecasts played a big part in the accuracy of the predictions; on average direction error was around 30º. Despite quite accurate predictions for 2 of the 3 fires studied (one third of predicted distances were within 20% of actual distance), they found an average distance error of 45% (mostly under predicted). This was predominantly the result of predictions for the Wambelong Fire, where pyro convection probably played a significant role in prediction inaccuracy. Timing of fire "break outs" were also not predicted well.

A post project review by McCoy (2013) found that there was an ongoing need for education relating to the products and services provided by the unit. It also found that communication procedures were needed to ensure two way communications between customers and analysts. McCoy (2013) reported survey results indicating that there was broad support amongst Incident Controllers for the continuation of fire behaviour prediction products. Over 97% (48 of 49) of respondents indicated that they would request a fire behaviour prediction in the future. It suggested there was a need to proceed carefully to ensure ongoing support and utilisation of the service and the role within Incident Management Teams (IMTs).

2013-14 Fire Season

October 2013 saw a major weather event with significant fires escalating in the Blue Mountains and Southern Highlands areas. Once again the FBAN unit escalated significantly to a NSW multi agency (staff and NSW RFS Volunteers) unit with additional interstate and CSIRO resources helping with predictive services. At its peak the unit totalled 28 members split into two teams, one dedicated to the Blue Mountains event and the others supporting the remainder of the state. For the first time, formally trained FBANs were located within three IMTs in addition to the established capability in State Headquarters.

Following this event the NSW Government made a significant investment in Fire Behaviour Analysis in NSW. Staffing of the unit was enhanced with a total of 8 staff employed including an embedded Bureau of Meteorology Severe Weather Meteorologist.

Wambelong Fire

The Wambelong Fire occurred in January 2013. It burnt over 56,000 hectares and destroyed 53 houses and 113 other buildings. In 2015, a Coronial Inquiry was held into the fire at Wambelong Campground, Warrumbungles NSW. A number of reports were prepared including a draft report by Tolhurst (2014) evaluating the fire behaviour predictions created for the fire event.

Tolhurst (2014) found that some of the predictions being produced could have been quite useful for fire suppression planning, but their usefulness would have been significantly diluted by the large variation in the predictions and the accuracy of these predictions. Tolhurst also found that the FBAN unit proved that they could operate during an emergency event and that this was probably the most complex event to be analysed since the unit was established in NSW but there was a number of improvements that could be made.

The Wambelong Inquiry Coroners recommendations were released in 2015. These included recommendations for arrangements to deploy portable weather balloons for the purposes of assessing atmospheric stability, revisions to the Fire Behaviour Reports and a recommendation to consider including FBANs into IMTs for class 3 fires.

In response, the NSW RFS have initiated the "Enhanced Situational Awareness Project" (Field, 2016). This aims to establish a portable atmospheric sounding capability and packaged with other weather surveillance and fire behaviour reconnaissance capabilities.

The Wambelong inquiry created much debate as to the operational use of fire behaviour models. Primarily this involved the use of the modified MkV McArthur meter (McArthur 1967) as opposed to the Dry Eucalypt Forest Fire Model (Project Vesta) model (Cheney et. al. 2012).

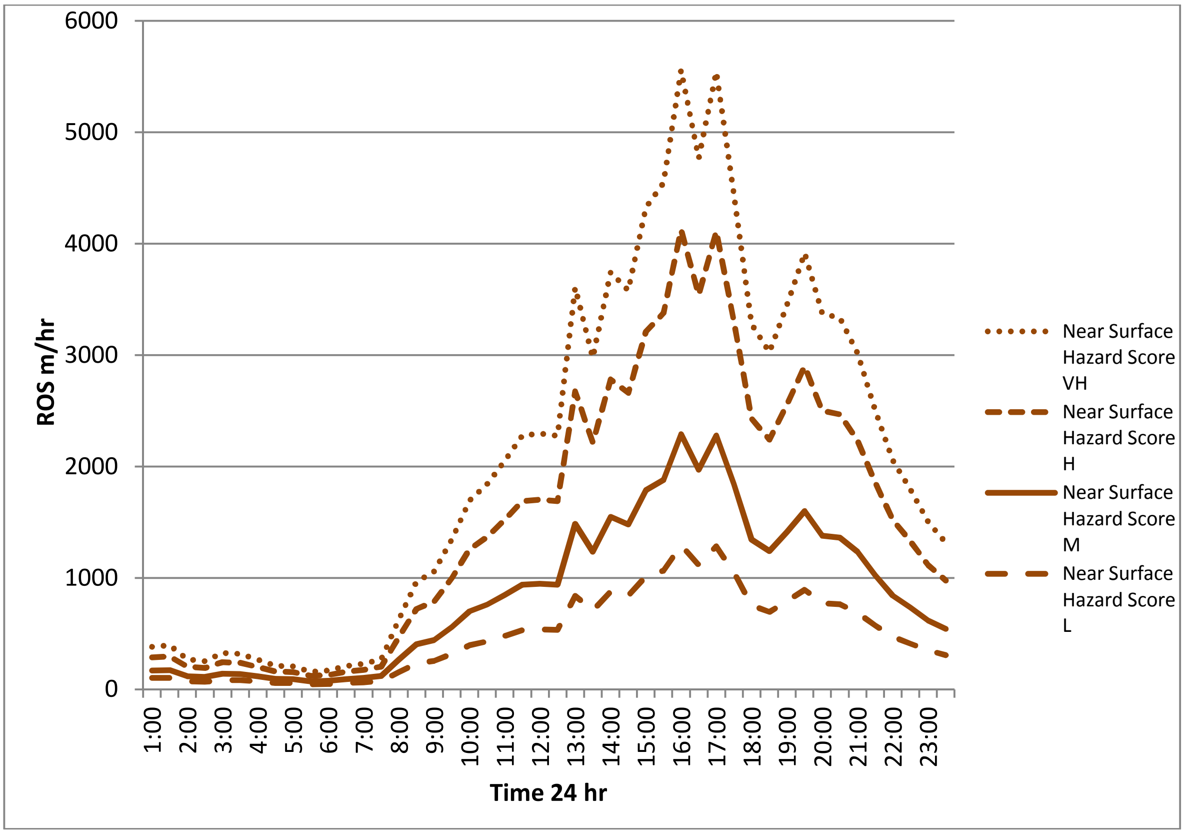

Figure 2 Chart from NSW RFS Sensitivity Analysis comparing variation to rates of spread predicted by the Dry Eucalypt Forest Fire Behaviour Model.

NSW RFS sensitivity analysis submitted as evidence to the inquiry found that reasonable predictions could be made for extreme fire behaviour (as experienced during the Wambelong event) using adjustments to the modified MkV McArthur meter. It found that the Dry Eucalypt Forest Fire Model was highly sensitive to changes in near surface fuel. It recommended that due to the subjective nature of the fuel assessment process, the Project Vesta model should only be used when the user is familiar or confident in the assessment of near surface fuels.

Discussion

A framework for fire behaviour analysis services was developed as part of an initial set up project. Major events and the ensuing post event reviews (either through University research or formal inquiries) have helped to refine policy and procedure and improve systems and processes. These events also helped shape future directions that have been incorporated into formal business planning.

In NSW, currently 6 FBANs (Agency staff and a NSW RFS volunteer) have been awarded national accreditation and FBANs have been sent on interstate and international deployments. There is a multi agency approach to the role, with each of the fire fighting agencies committing staff and volunteers to formal training.

Some critical lessons learnt along the way relating to operational forecasting and the importance of communication and situational awareness in addition to areas for future research.

Ongoing communication with customers is critical. The products need to meet the customers need. The products also need to incorporate timely intelligence.

In relation to operational forecasting, for going fires with reasonable intelligence reports such as Storey and Price (2013) and to a lesser extent Tolhurst (2014) have demonstrated that reasonable predictions can be made. However once a fire is contained within natural or created breaks, predicting the timing of breakouts or fire escapes is at best a guess and there is little science around the concept. Hard lessons have been learnt in this area and breakout scenarios are now routinely run.

The NSW RFS continues to develop new products; an example is an ensemble approach using Phoenix to address the break out scenario concept. In the past the use of single predictions from Phoenix have given unrealistic results, mainly because the whole fire perimeter was modelled in Phoenix as "going" or the FBAN had to predict where the fire would break out and model from an uncertain point of origin. At times, these predictions have been criticised for being alarmist or unrealistic or conversely being criticised for not predicting the correct breakout location. This has lead to the development of the ensemble prediction product (Figure 3).

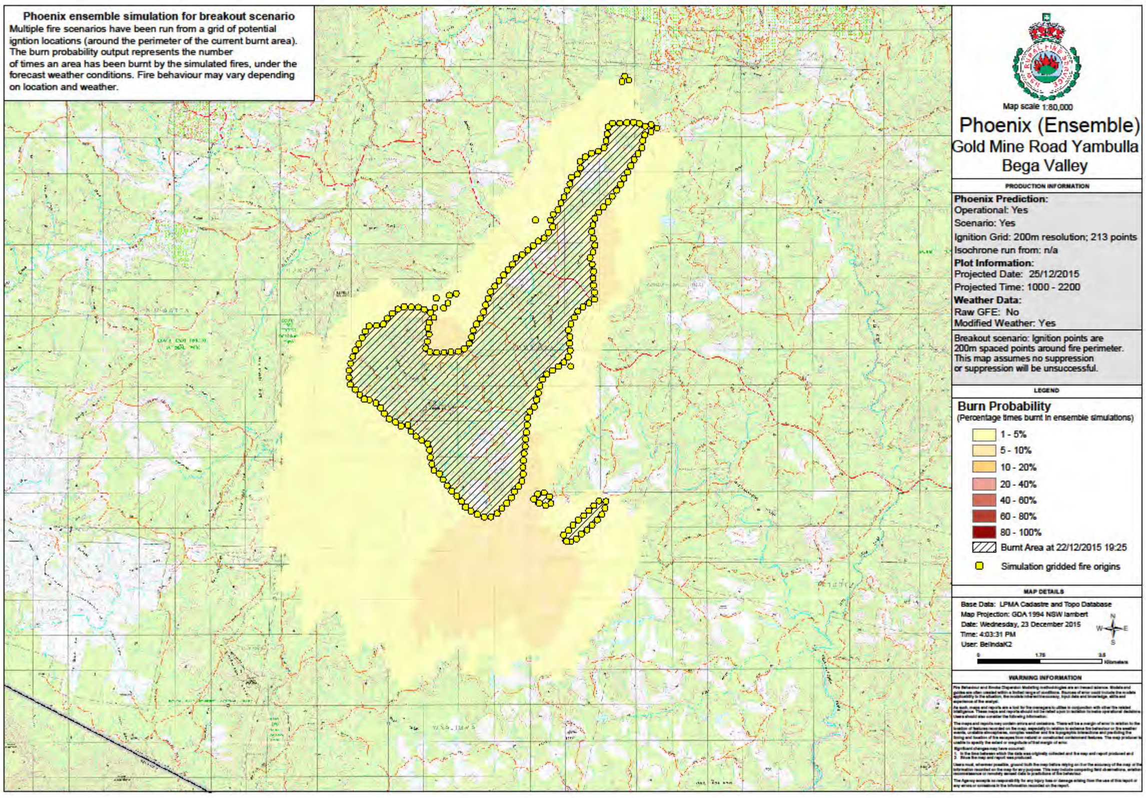

Figure 3 Example of product in development for a fire break out scenario

This starts fire from points at regularly spaced intervals 30m from a contained edge and aggregates the results to provide a probability map. This is a more realistic product as it starts the breakout from a point as opposed to a going fire edge and it simulates a fire starting anywhere along the perimeter. This reduces uncertainty in trying to determine where a fire may break out.

Further research is required into predicting blow up events. The NSW RFS is currently piloting "Blow up" forecasting (BUFO Project) with ACT ESA (McCrae et al 2016). The NSW RFS is also contributing to the BFNHCRC research cluster Next Generation Fire Modelling in addition to the University of Queensland Bushfire Convective Plume Experiment.

Projects such as the AFAC National Fuels Classification project have significant potential for FBANs operating remote from fire locations. Future products derived from this project could expand the use of fire behaviour models such as the Dry Eucalypt Forest Fire Model where obtaining fuel structure information is currently difficult when operating remotely.

With increasing competence and confidence NSW branched out into posting FBANs into IMTs during the 2013-14 season. These initial trials of posting FBANs into IMTs proved effective with anecdotal feedback suggesting that the FBAN's were able to access greater intelligence than those operating from remote locations. They were also able to interpret FBAN products for the IMT which aided uptake or use of the products within the IMT. This experience in combination with the recommendations from the Wambelong Coroner's inquiry and the experience gained from interstate and international deployments, is likely to result in the majority of FBAN's in NSW being located within an IMT as tactical FBANs. Tactical FBANs in IMTs will complement a more strategic capability at State Headquarters. This capability will be bolstered by the recent announcement for four Fire Behaviour Analyst positions to be located within NSW regions. Their primary role planned to support IMTs. The post project survey results (McCoy 2013) indicates there is broad support amongst Incident Controllers for the role. With continued engagement development and refinement of products, the role should continue to evolve to a point where it is considered a routine operational product.

References

Cheney NP, Gould JS, McCaw WL, Anderson WR (2012). Predicting fire behaviour in dry eucalypt forest in southern Australia. *Forest Ecology and Management*, ***280*** 120-131.

Cook B, Price O, Chong D, Tolhurst K. (2009) Review of Potential Applications for Bushfire Behaviour Models for Bushfire Management in NSW. University of Wollongong and the University of Melbourne. (Wollongong, NSW)

Field (2016) Enhanced Weather Situational Awareness - Filling the Gaps Between the Modelled World and Reality, these proceedings

McArthur AG (1967) 'Fire Behaviour in Eucalypt Forests'. Commonw. Aust. For. And Timber Bur. Leaflet 107 (Canberra, ACT)

McCoy L (2013) Fire Behaviour Analysis Project Final Report. NSW Rural Fire Service (Lidcombe, NSW)

McCrae R, Sharples J, McCoy L (2016) Results of a formal trial for predicting blow-up fire events, these proceedings.

NSW Rural Fire Service (2014) Sensitivity Analysis; Vesta and Modified McArthur (MkV) Fire Behaviour Models. Internal report NSW Rural Fire Service (Lidcombe, NSW)

NSW Rural Fire Service (2015) Fire Behaviour Analyst Handbook. NSW Rural Fire Service (Lidcombe, NSW)

Storey M, Price O (2013) Accuracy of Fire Spread Predictions for January 2013 Fires in NSW. Draft report for the NSW Rural Fire Service. Centre for Environmental Risk Management of Bushfires, University of Wollongong.(Wollongong, NSW)

Tolhurst K. (2014) Assessment of the Fire Behaviour Predictions for the Wambelong Fire, January 2013. Technical Report, University of Melbourne (Melbourne, Vic)

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Exploring Physical Measures of Fire for Calculating Fire Danger

Stuart Matthews[a*], Levi Roberts[a], Simon Louis[b], Simon Heemstra[a], Belinda Kenny[a], Laurence McCoy[a]
[a]NSW Rural Fire Service [b]Bureau of Meteorology
*NSW Rural Fire Service, Lidcombe, NSW, Australia, stuart.matthews@rfs.nsw.gov.au

Abstract
The National Fire Danger Ratings Working Group has recommended the development of a new national Fire Danger Rating (FDR) system for Australia including an index based on a physical parameter of fire. The new system will also be required to expand from a single measure of 'fire danger' to six factors describing fire weather, fuel condition, fire behaviour, ignition likelihood, fire suppression, and fire impact.

To explore the possibilities and challenges for this system, the NSW Rural Fire Service (RFS) has developed and trialled a demonstration system based on existing science and data sets. It was not clear what parameter should be used as the Fire Behaviour Index (FBI) and as such the system included seven candidate FBIs. These were based on simple estimates of rate of spread, intensity, and flame length for grass and forest landscapes as well as more exotic variables including power of fire, house loss probability derived from Phoenix RapidFire simulations, and house loss probability calculated using a Bayes net model. The system also includes 65 other variables that contribute to the six factors.

A complete set of outputs were calculated for the 2013/14 fire season in NSW from historical fuel and weather data. This historical data set was used to map candidate FBIs to categories of the current fire danger rating system (Low-Moderate, High, etc) to facilitate interpretation. A future system may not necessarily retain these categories for public messaging and decision making. Statistical analysis of fire occurrence, area, and decisions to issue Total Fire Bans was used to explore the predictive ability of the FBIs. Over the 2015/16 fire season, the system was trialed in parallel with operations to gain an understanding of the use of the system for daily operations.

Introduction
The current fire danger ratings (FDR) system used in Australia is based on simple fire danger indices calculated for forests (McArthur 1967), grasslands (McArthur 1966), and button-grass moorlands (Marsden-Smedley and Catchpole 1995). Following the 2009 Black Saturday fires, the National Fire Danger Rating Working Group (NFDRWG) was tasked with improving FDR systems used in Australia.

The NFDRWG has developed principles and requirements for a new FDR system (Cube Group 2015). To meet the needs of modern fire management a fire danger rating system with six modular factors has been proposed:

1. Fire weather
2. Fuel condition

3. Fire behaviour
4. Ignition likelihood
5. Fire suppression
6. Fire impact potential

The first three factors contain physical data and models for calculating fire behaviour, to answer the question 'if a fire reaches a particular location, what will its behaviour be?' Broadly, inputs are weather, fuels, and topography. Factors 4 to 6 use outputs from 1 to 3, along with inputs such as an ignition model, asset layers, suppression resources, community vulnerability, etc as inputs into multiple risk models. These models provides answers to questions such as 'what is the probability that a fire with given hazard will be ignited and reach a valued asset?', 'what is the chance that local suppression resources will be overwhelmed?', 'what is the probability that at least one house will be lost somewhere in Australia today?' These factors are inherently probabilistic.

A key requirement is that the new FDR must be based on a physical parameter of fire behaviour - something that can be measured or inferred from measurement - to be called the Fire Behaviour Index (FBI). It became clear during the requirements development that it was not obvious what the physical measure should be. To investigate potential FBIs, the NSW RFS developed a system to calculate 7 possible indices and examined the performance of these indices using historical data and an operational trial over the 2015-16 fire season.

Materials and methods

Trial Fire Behaviour Indices

Seven trial FBIs, 'methods' 1 to 7, were developed. All indices were calculated and presented as a 0.05° resolution grid aligned with Bureau of Meteorology weather forecast grids, and summarised into a single fire danger rating for each NSW fire weather area. Ratings were assigned by categorising fire behaviour metrics into classes aligned with the current system, i.e. Low-moderate, High, Very high, Sever, Extreme, Catastrophic. For some methods different metrics were used for cells classified as forest and grass fuel types. Fuel type classification was based on an existing classification used for calculation of FDR in NSW. Fire behaviour calculations were based on existing fire behaviour models and fuels data (NSW RFS 2015) and as a consequence were dependent on McArthur's fire behaviour model for forests (McArthur 1967). Newer models for fuel types other than grass or forest (e.g. heath) were not used as suitable classifications and data were not available within the scope of the project. All metrics were calculated for the head of a fully developed fire.

The seven methods were:

1. Rate of spread (m h^{-1}) for grasslands, intensity (kWm^{-1}) for forest
2. Intensity for both vegetation types, common scale for both vegetation types
3. Intensity for both vegetation types, separate scales for each vegetation type
4. Power (kW) calculated as intensity (kWm^{-1}) times flaming depth (m), common scale for both vegetation types
5. Flame length (m), common scale for both vegetation types

6. Probability of house loss, estimated using the Phoenix fire simulator (Tolhurst and Chong 2011) for a grid of ignitions, one per grid cell.
7. Probability of a fire starting and reaching a house with intensity >4 MW^{-1}, estimated using the Penman et al. (2015) Bayesian network model. This method was only available for the Sydney Basin region and was not classified into an FDR.

Calculations were performed for a historical period including January 2013 (A time of significant fire activity), August 2013 to March 2014, and the 2015-16 fire season from August 2015 to March 2016. Daily maxima of each FDR were calculated using current or archived weather forecasts and static fuel, topography, and asset grids, For historical analysis the fuel grid was updated monthly using fire history data to examine the effect of major fires such as the 2013 Blue Mountains fires on FBI.

To facilitate analysis of the data, FBI and all components required for their calculation were stored in hourly and daily netCDF grids. An SQLite database of ratings and selected fire behaviour metrics (rate of spread, intensity, etc) was also produced with one entry per day for each fire weather area using 90th percentile values. For the operational trial a web page was produced showing maps of daily maximum FBI (Figure 1) for each method and a table of ratings for each fire weather area for methods 1 to 6.

Historical analysis and calibration results

To explore the performance of the methods and determine baseline characteristics prior to the operational trial, all outputs, except Method 6 & 7, were calculated for Jan 2013 and the 2013/14 fire season. Initial categorisations of FBI metrics into ratings were performed using existing data analyses (e.g. Harris et al. (2012) house loss analysis) and operational experience. This historical analysis showed that ratings levels were set too low, with some methods recommending total fire bans (rating of Severe or higher) for most of NSW for most of January 2013. It is not clear whether this is due to deficiencies in our modelling approach (particularly the assumption of fully developed fires), errors in historical assumptions about fire behaviour (e.g. that 4 MWm^{-1} constitutes an unsuppressible fire), or both.

To produce a workable set of metrics for use in the operational trial the historical data set was used to adjust the rating categories to match the overall distribution of the existing system. The calibration further tied the trial methods to the existing system beyond the dependence on the McArthur fire behaviour models. Table 1 shows the rating categories derived from the analysis of historical data. In most cases the cut-off values for each category was higher than expected based on historical experience.

Table 1: Categorisation of fire behaviour metrics into ratings using calibration against existing distribution of ratings

	L-M	H	VH	S	E	C
Method 1: Forest intensity (kW m^{-1})	<5,400	<11,272	<25,000	<41,135	<53,541	>53,541
Method 1: Grass spread rate (m h^{-1})	<2,646	<4,598	<7,866	<11,703	<14,372	>14,372
Method 2: Intensity (kW m^{-1})	<5,280	<11,272	<22,2495	<37,285	<52,962	>52,962
Method 3: Forest intensity (kW m^{-1})	<5,400	<11,272	<25,000	<41,135	<53,541	>53,541
Method 3: Grass intensity (kW m^{-1})	<4,794	<10,575	<19,943	<32,303	<61,969	>61,969
Method 4: Power (MW)	<40	<148	<584	<1,689	<4,171	>4,171
Method 5: Flame length (m)	<4.8	<6.9	<19	<28	<33	>33

Operational trial

To gain an understanding of the feasibility of using an FBI and the supporting factors and other data in day-to-day use an operational trial was run over the 2015-16 fire season. On each day of the fire season participants:

1. Reviewed the FDR ratings website and supporting weather, fuels, and fire behaviour grids. They used these to make predictions about potential locations of damaging fires and summarise agreement and differences between FBI methods.
2. Made specific observations on individual fires with a particular focus on fire behaviour, property losses and public warnings along with a summary of fire activity and overall difficulty of fire containment and suppression
3. Summarised actual fire behaviour and number of fires at the end of the day and compared this with the prediction made in the morning.

These observations were recorded in an MS Access database. After a short initial period, observations were only recorded for days where at least one method was predicting significant fire behaviour.

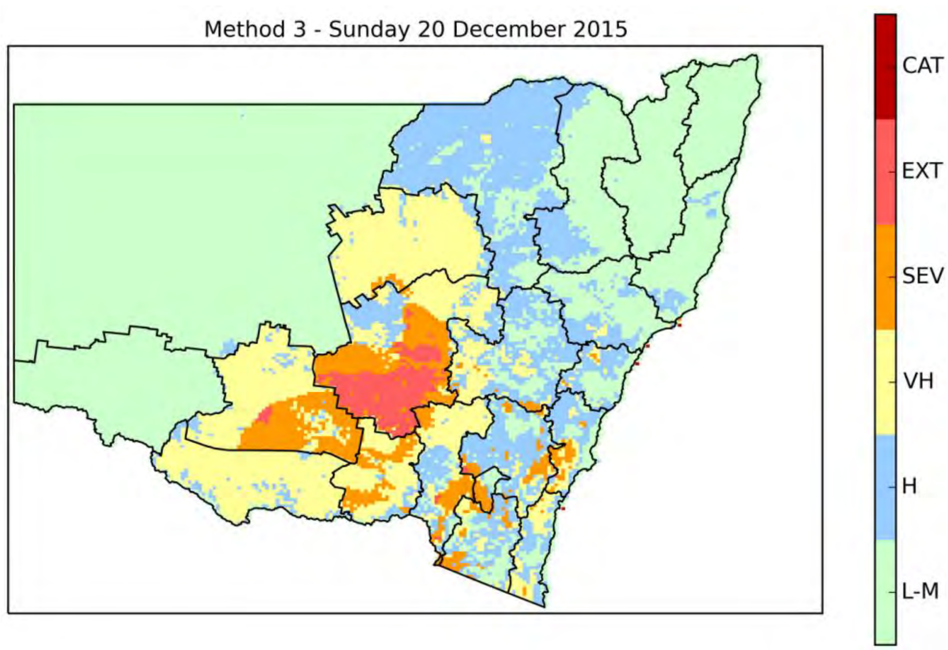

Figure 1. Sample fire danger rating map.

Results and Discussion

The 2015/16 fire season was relatively benign in NSW with few significant fires and no property losses. Using the current method 29 fire weather area-days with Severe or higher ratings occurred (Table 2), compared to 97 for the 2013/14 season. Method 1 generated a much higher number of events than the other methods because of the different mix of forest and grass driven events in the historical and operational data sets. This is a limitation of the small sample sizes of the trial data set.

Table 2. Number of events with Severe or higher FDR for the 2015-16 fire season

Method	Current	Method 1	Method 2	Method 3	Method 4	Method 5
Number of events	29	43	30	33	34	34

A detailed analysis of the trial results is still in progress but a few early lessons can be drawn from analysis of the historical data and data collected during the operational trial:

Fire behaviour measures and derived methods 1 to 5 were correlated due to their common dependence on weather and fuel parameters. This suggests indices based on them can be calibrated to give similar answers, with the probable exception of flame length for grass and forest. If a future FDR is based on one of these measures this may allow some flexibility in the choice of metric.

On the other hand, the similarity is at least partly due to the limitation of using only two fuel types. Two significant heath fires occurred in the Sydney basin during humid, windy weather conditions. In both cases the forest fire models under-predicted fire behaviour because of differences in the sensitivity of heath and forest to fuel moisture. This indicates a need for more fuel types to be considered in a new FDR system and suggests it is likely there will be more diversity between fuel types than our trial system showed.

Fully developed fires present a very different threat from those during the initial build up phase. These was most notable for grass fires which were almost always extinguished while a small. However, the volume of suppression resources required did increase with fire behaviour metrics. A fire escalation model will be an important component of a new FDR system.

Some methods were very biased to forest or grass due to dependence on rate of spread or intensity. Also, some of the methods tended to focus the elevated fire danger areas in a strip along the eastern part of the Great Dividing Range as a result of the combination of high fuel loads and complex terrain.

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References

Cube Group (2015) 'Requirements Summary. Report to National Fire Danger Rating Working Group' (Melbourne, VIC)

Harris S, Anderson W, Kilinc M., Fogarty L (2012). The relationship between fire behaviour measures and community loss: an exploratory analysis for developing a bushfire severity scale. *Natural Hazards* **63**, 391-415.

Marsden-Smedley JB, Catchpole WR (1995). Fire behaviour modelling in Tasmanian buttongrass moorlands. II. Fire behaviour. *International Journal of Wildland Fire* **5**, 215-228.

McArthur AG (1966) 'Weather and grassland fire behaviour'. Department of National Development, Forestry and Timber Bureau, Leaflet 100 (Canberra, ACT)

McArthur AG (1967) 'Fire Behaviour in Eucalypt Forests'. Commonw. Aust. For. And Timber Bur. Leaflet 107 (Canberra, ACT)

NSW Rural Fire Service (2015) 'Exploring Physical Measures of Fire for Calculating Fire Danger', Technical Report (Lidcombe, NSW)

Penman TD, ParkinsKA, Mascaro S, Chong D, Bradstock RA (2015) 'National fire danger rating system probabilistic framework. Report for year 3'. Bushfire and Natural Hazards CRC report (Melbourne, Vic)

Tolhurst KG, Chong DM (2011). Assessing potential house losses using PHOENIX RapidFire. In 'Proceedings of Bushfire CRC & AFAC 2011 Conference', pp. 74-86 (Melbourne, Vic)

FIRE AND WATER: NEW TOOLS FOR EVALUATING WATER SUPPLY IMPACTS OF FIRE

Joanna Wand*, Gary Sheridan**, Patrick Lane**, Christoph Langhans** and Craige Brown***

*Department of Environment, Land, Water and Planning, Knoxfield, Victoria, Australia, joanna.wand@delwp.vic.gov.au

**The University of Melbourne, Carlton, Victoria, Australia, sheridan@unimelb.edu.au, patrickl@unimelb.edu.au and christoph.langhans@unimelb.edu.au

***Melbourne Water, Docklands, Victoria, Australia, craige.brown@melbournewater.com.au

Introduction

Fire in catchments can result in severe water contamination in the short term and substantial water yield losses in the long term, compromising the water supplies of cities and towns. For example, most of the water for Melbourne's ca. 4 million residents is sourced from the Upper Yarra and Thomson reservoirs, Victoria, Australia. Research in the past decades has shown that the characteristics of the forests and soils in these catchments make them particularly susceptible to the impacts of fire, and water supply protection is therefore a critical component of fire management. Water yield impacts of fire are associated with the age profile of the forest, which in turn alters the partitioning of rainfall into evapotranspiration and streamflow. Forests that recover from fire by reseeding, resulting in even age stands (such as Mountain Ash *Eucalyptus Regnans*) are particularly important in this context. Mixed Eucalyptus species forests (e.g *Eucalyptus obliqua*) are drier forests that, when burnt at a high severity, can result in debris flow events which can reduce water quality and damage infrastructure. Protection of these forests is important for water supply, however these needs must be addressed in the context of the primary fire management goal of protecting life and property, and balanced against other values such as biodiversity conservation and timber production.

Problem statement

Planned burns occur annually over large parts of Victoria with the aim of protecting human life, infrastructure and ecological assets. In and around Victoria's catchments, planned burning is used to reduce forest fuel to create low fuel barriers which impede the development of fires. These low fuel areas also work to reduce fire intensity. Our objective is to manage the fire impact on fire sensitive Mountain Ash forests and vulnerable dry Mixed Species forests to protect both the environmental as well as non-environmental values.

Until recently, placement of planned burns has been based solely on the extensive experience of fire practitioners. In conjunction with The University of Melbourne (UoM) and Melbourne Water (MW), the Department of Environment, Land, Water and Planning, Victoria (DELWP) has applied Phoenix RapidFire (Tolhurst *et al.* 2008) bushfire simulation to predict where fires might reach critical impact thresholds to threaten water supply. This modelling has determined where bushfires might ignite, spread and impact on water assets, providing information on the extent to which an asset might be affected and how planned burns might reduce this impact. This

Joanna Wand - joanna.wand@delwp.vic.gov.au
609 Burwood Highway, Knoxfield, Victoria, Australia 3180
http://bushfire-planning.delwp.vic.gov.au

information has helped to inform practitioner development of planned burning regimes, however it does not give an indication of the probability of a debris flow occurring, the potential size of the debris flow event or the potential quantity of water yield lost in the catchment as forests regenerate.

Project Aims

This project has two key aims:

1. Improve current water risk analysis by developing algorithms that describe broad-scale, long-term water quality and quantity implications of both planned burns and bushfire events. Develop instructions for the use of these algorithms for practitioners to use on different modelling platforms (Langhans *et al.* 2016)
2. Apply these algorithms in the East Central bushfire risk landscape (DELWP, Victoria, Australia) to assist land managers to include water values in strategic fire management planning.

Developments in modelling fire regime impacts on water supply

The University of Melbourne has developed two new models to measure bushfire impacts on water supply.

Measuring impacts on water quality

In south eastern Australian uplands, large impacts on water quality after fire are mostly the result of post-fire debris flows. Two characteristics of post fire debris flows which are important for risk assessment include the probability of initiating a debris flow and the magnitude (volume) of the debris flow.

The probability of initiating a post-fire debris flow depends on a critical set of inter-dependent conditions. The slope must be steep enough, there must be sufficient "available" sediment on the hillslopes, the soils must be sufficiently impermeable, and the rainfall intensity high enough to generate runoff. The modelling approach developed estimates of debris flows probability based on 2ha headwaters within the larger catchment, as these are potential debris flow initiation areas. The critical rainfall intensity required to initiate a debris flow in each headwater depends on fixed properties such as slope, and other properties influenced by fire severity, and is pre-calculated for a wide range of slope, soil, and fire severity conditions using a detailed erosion model (Smith et al. 1995). The probability of initiating a debris flow depends on the probability of receiving a rainfall event that exceeds critical rainfall intensity. The probability of rainfall events is based on the intensity-frequency-duration (IFD) rainfall statistics of the headwater location provided by the Australian Bureau of Meteorology.

The volume (m^3) of a debris flow depends principally on the slope of the catchment, and on the amount of runoff and sediment available, which is often strongly related to the catchment area. Our modelling predicts the volume of the debris flow (once initiated) using a slope-area landscape analysis described in Nyman *et al.* (2015), which enables magnitudes to be estimated as a pre-processed layer. The model consists of three sets of inputs, Figure 1.

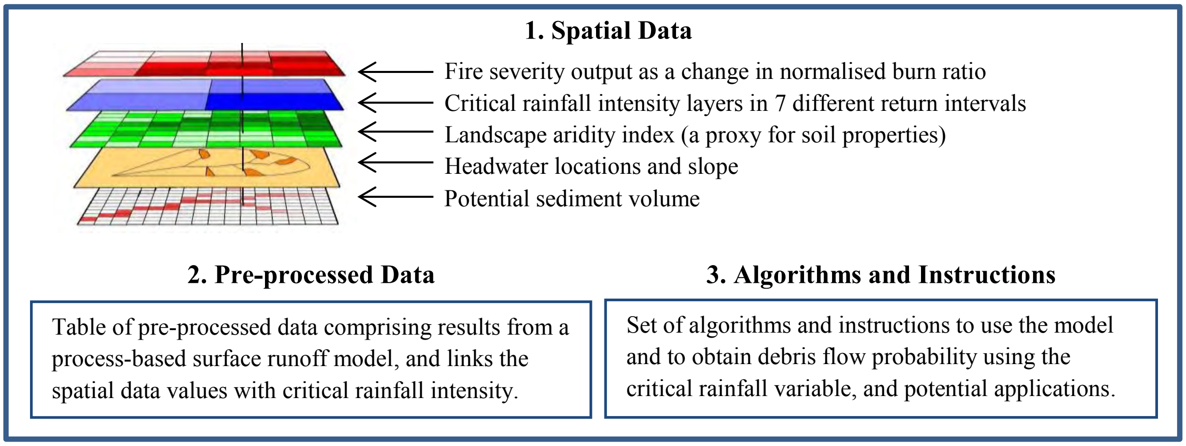

Figure 1. Model inputs for calculating the probability and magnitude of a debris flow event after a fire.

Measuring impacts on water yield

The water yield impacts of fire are associated with the way fire alters the vegetation, which in turn alters the partitioning of rainfall into evapotranspiration and streamflow. Early water yield models are intended for large spatial scales and long temporal scales. They focus on evapotranspiration (ET) and rainfall while neglecting factors such as vegetation, soil properties, and other local climate properties (Budyko 1974). Subsequent research (Zhang *et al.* 2004, Choudury 1999) has incorporated additional parameters which have shown to improve predictions at smaller spatial and temporal scales. These studies suggest that the change in the value of an additional catchment parameter (ω) is largely related to differences in plant available water capacity, which in turn is strongly related to the rooting depth of plants. Locations (and times) where the vegetation is able to exploit deeper/greater soil waters stores will result in a higher value of ω. This influences Budyko model so that at the same point for a given climate, the ω value will shift the model towards a higher ET to rainfall ratio value. Conversely locations where ET losses are due solely to soil evaporation, lower water soil availability results in a lower ω value which will shift the system towards a lower ET to rainfall ratio value. Here we use newly developed relationships between ω, fire severity and mortality, sapwood area and leaf area to estimate the long term mean effects of fire on mean annual water yield. The model consists of two sets of inputs, Figure 2.

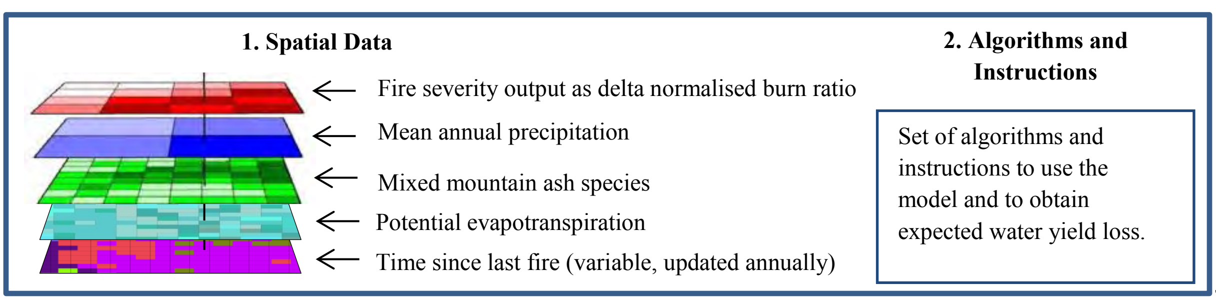

Figure 2. Model inputs for calculating the expected loss of water yield

Incorporating water values in strategic fire management

Fire and emergency management agencies have focused significantly on bushfire risk reduction to human life, property and major infrastructure assets. Efforts are often centred on fuel reduction by planned burning to prevent fire spread into towns. UoM's catchment hydrology research has expanded the ability of predictive tools to estimate the probability and volume of the water supply impact from bushfires and planned burns. This research has been utilised by East Central (DELWP, Victoria) to incorporate water values into strategic fire planning. East Central uses a cyclical approach to analysing bushfire risk to water assets (Figure 3 below). With the assistance of UoM, we identified areas within water supply catchments that, if burnt, are at risk of a debris flow event or may result in water yield loss over time. These assets have been mapped spatially using ArcMap software for integration with bushfire modelling tools.

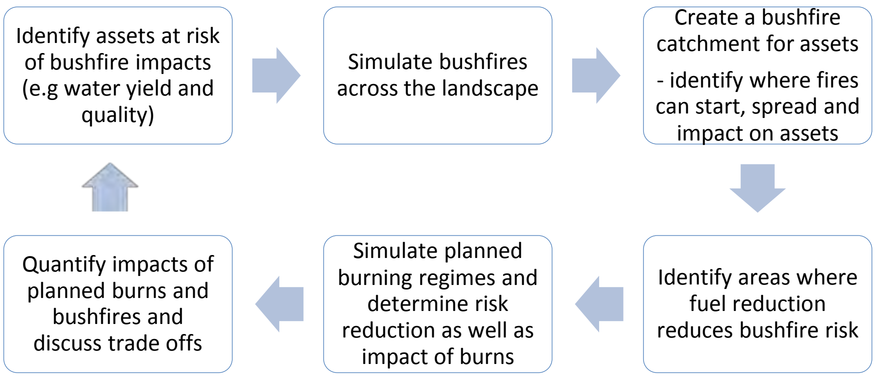

Figure 3. East Central bushfire risk landscape process of determining bushfire risk and risk mitigation effects for an asset.

Using the bushfire simulation tool Phoenix RapidFire, we established where fires might ignite, spread and impact water assets under prescribed weather conditions. This was done by simulating a bushfire every 1km across the East Central area (Figure 4). Ignition points that simulate bushfires which impact water assets can be identified and mapped into bushfire catchments (Figure 5).

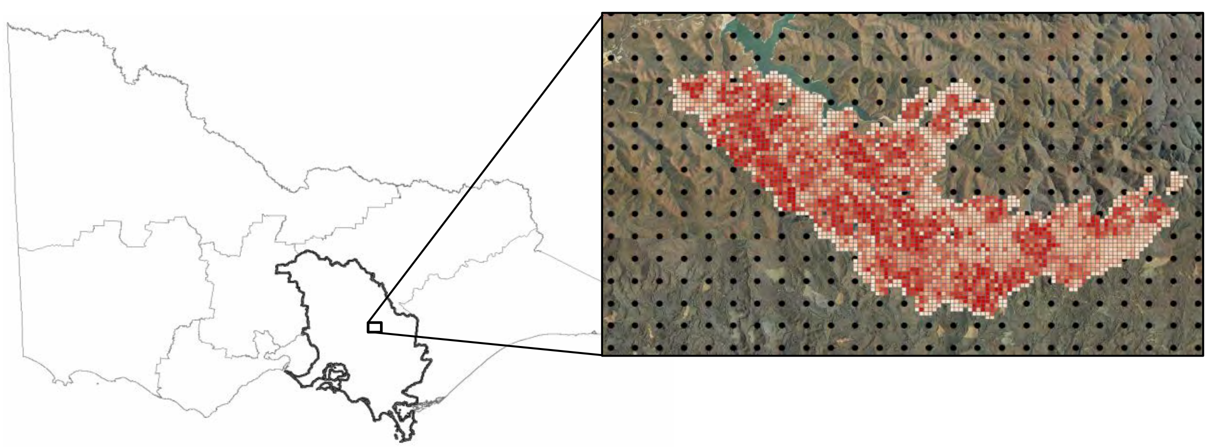

Figure 4. A single fire simulated using Phoenix RapidFire from the 1km ignition grid (shown as black dots), within the East Central bushfire risk landscape outlined in bold. Each ignition point is the starting location for an individual fire simulation. Over the entire East Central footprint, 40 262 fires are simulated using the 1km grid.

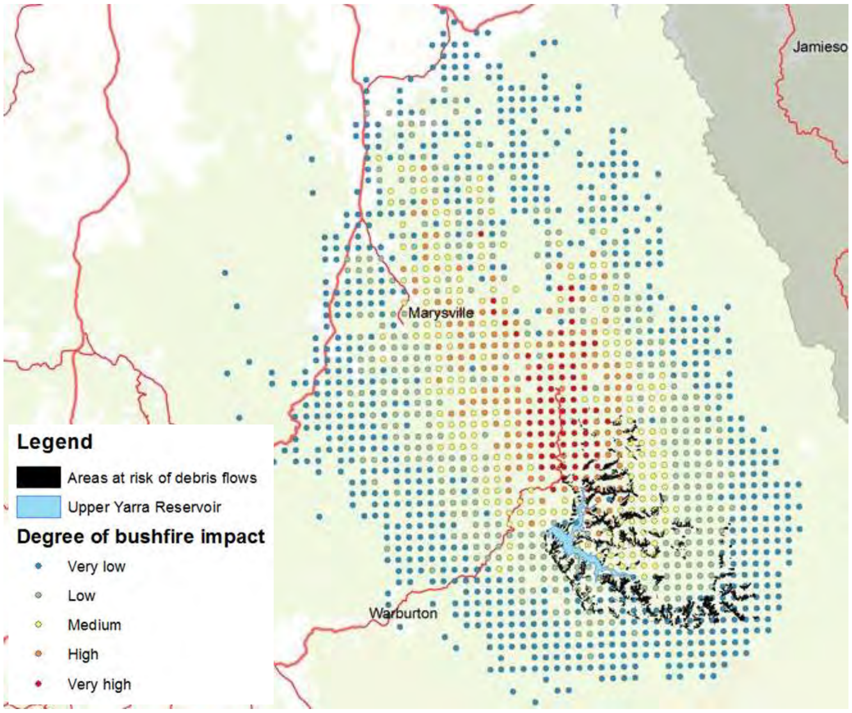

Figure 5. A bushfire catchment derived from Phoenix RapidFire analysis. Each dot represents an ignition point from the 1km ignition grid. Ignitions indicate that if a bushfire were to start at that location under specific weather conditions, it will impact on spatially defined water assets (areas at risk of debris flows in the Upper Yarra reservoir in black). Ignition points are coloured according to their level of impact, red dots indicate that a fire starting at that location will have a much greater impact than a fire starting at a blue ignition point.

Using bushfire catchments and UoM's new water yield and debris flow models, we can identify which bushfires could have the largest impacts (e.g greatest reduction in water yield). This knowledge assists in identifying where to conduct fuel reduction such as planned burns to reduce the impact of bushfires. Different spatial and temporal arrangements of planned burns can then be modelled using Phoenix RapidFire and their contribution to reducing risk to water values can be quantifiably measured.

This process enables land managers to quantify the probability and scale of potential impacts of bushfires on water values, the impacts of proposed planned burns themselves and then finally the reduced impact of the bushfire if the planned burn was conducted. Trade off discussions can occur with agencies such as Melbourne Water by providing information such as the cost of planned burns verses bushfire remediation procedures such as increased filtration capacity in treatment plants to improve water quality. This information can be used in conjunction with practical experience of fire managers to make informed fire management decisions.

Discussion

Information from the application of this work is being used to optimise planning and conduct bushfire mitigation strategies, such as fuel reduction burning, to minimise impacts on water yield and quality in Victorian catchments. It can also be used to prioritise bushfire emergency response in and around catchments.

Future developments to these methods will incorporate the likelihood of a bushfire event occurring. Also, areas of investigation for MW will include cost benefit analysis of preventative and recovery works using outputs from the modelling to compare effectiveness versus dollar cost of treatments. The results of these comparisons should also help with the optimisation of outcomes sought amongst the range of values to be preserved in the water supply catchments.

Using these bushfire and hydrological modelling methods, land managers can now model a variety of scenarios to identify critical points in the landscape including bushfire ignitions and their impact on water assets. Strategies can be optimised to mitigate these modelled outcomes under different weather and fire history scenarios. Increased information from these modelling techniques will help both public and private land holders to make more informed decisions and trade-offs.

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References

Journal Articles
Budyko, MI 1974. Climate and life. Academic Press, New York.
Choudhury, BJ 1999. Evaluation of an empirical equation for annual evaporation using field observations and results from a biophysical model. *Journal of Hydrology*, 216(1-2): 99-110.

Nyman, P, Smith, HG, Sherwin, CB, Langhans, C, Lane, PNJ, Sheridan, GJ 2015. Predicting sediment delivery from debris flows after wildfire. Geomorphology, 250: 173-186.
Smith, R. E., D. C. Goodrich, D. A. Woolhiser, and C. L. Unkrich (1995), Kineros - A Kinematic Runoff and Erosion Model, in Computer models of watershed hydrology, edited by N. P. Singh, pp. 697-732, *Water Resource Publications*, Highlands Ranch, CO.

Tolhurst, KG, Shields, BJ & Chong, DM 2008, 'Phoenix: development and application of a bushfire risk management tool', *The Australian Journal of Emergency Management*, vol. 23, no. 4, pp. 47-54.

Zhang, L, Hickel, K, Dawes, WR, Chiew, FHS, Western, AW, Briggs, PR 2004. A rational function approach for estimating mean annual evapotranspiration. *Water Resources Research*, 40(2).

Reports
Langhans, C, Nyman, P, Lane, P, Benyon, R and Sheridan, G 2016, 'HydroFire Version 1: A model for estimating the impact of forest fire on catchment water yield, quality and debris flow risk', the University of Melbourne, Melbourne, Australia

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Fire reconstructions in Mallee fuel types in north-western Victoria

Nicholas Gellie[*1], Andy Koren[2], Glenn Rudolph[3], Darcy Prior[4], Nathan Christian[2], & Ashley Christian[2]

[1]Ecofuego, 83 Highton Lane, Mansfield, Victoria, 3772, Australia, nic@ecofuego.com.au
[2]Regional Services, DELWP, PO Box 905, Mildura, Victoria, 3502
[3]Regional Services, DELWP, Private Bag 260, Horsham, Victoria, 3402
[4]Strategy and Innovation, DELWP, Private Bag 260, Horsham, Victoria, 3402

Introduction

Fire reconstruction studies aid the evaluation of quantitative fire prediction models (Rothermel, 1991), in post-fire evaluation of fire strategies and suppression performance (Simard *et al.*, 1983), in creating decision support systems and training (Alexander and Thomas, 2003), and in assessing the effectiveness of prescribed burns in mitigating bushfire behaviour (Gellie and Mattingley, 2014). From 2002 to 2014 the Department of Land, Water, and Planning (DELWP) had a succession of major fire seasons in the western and north-western Mallee areas of Victoria during which there were small to very large bushfires with recognisable crown streets (Haines, 1982). Crown streets are elliptical shaped lines of lower fire severity showing up in crown fire spread in coniferous forests and Mallee low open woodlands. Horizontal roll vortices, also known as horizontal convective rolls or cloud streets, are long rolls of counter-rotating air that are oriented approximately parallel to the ground in the atmospheric boundary layer. These are implicated although not scientifically proven to create crown streets in Mallee bushfires.

Only the Big Desert bushfire in December 2002 had been studied at the level of daily fire progression (Wouters, 2003). None had been reconstructed at a high resolution of tens of minutes to a couple of hours with spatial accuracy approaching 20–50 m. Eight major bushfires in the Mallee were identified for fire reconstruction in addition to the four bushfires that previously had been reconstructed as part of a study of the effectiveness of prescribed burning on mitigating the severity and extent of bushfires. These were located in the DELWP Loddon– Mallee region of Victoria. Five of the case studies came from the Big Desert, Wyperfeld, and Murray Sunset National Parks: the 2002 Big Desert, the 2008 Hattah–Wymlet, and the 2014 Bronzewing, Lake Albacutya, and Danyo bushfires. The remaining three case studies were taken from the Little Desert National Park: the 2007 Jungkum Track, and the 2009 and 2013 East–West Track fires.

The study set out to do the following:

- To complete fire reconstructions to the highest possible standard based on crown streets and supporting fire environment information;
- To test whether fire reconstructions could be based on crown streets and the available weather data.

Materials and Methods

This study used a Geographic Information System (GIS)-based interpretative approach in reconstructing fire spread and behaviour of eight bushfire case studies Gellie *et al.* (2010).

Specifically, GIS data were assembled in Quantum GIS® supporting visual data such as remote sensing imagery, photographs before, during, and after the bushfire event, together with documentation and observations provided by DELWP staff involved in the planning and operations of each bushfire. In addition, local 0.5-h weather data were used to determine timing of wind shifts either oscillating or persistent at the nearest weather station.

Materials (data)

Fire reconstruction studies require fire environment data that encompass terrain, fire climate and weather, vegetation and fuels, as well as real-time fire intelligence data. A summary list of this type of data sought for each case study was as follows:

(1) *Bushfire details*: date/time of start and finish of ignition, fire history in the last 10 years, and final fire boundary;
(2) *Pre- and post- fire digital aerial photography*; encompassing the fire and recent bushfires and planned burns surrounding the bushfire;
(3) *Bushfire severity maps*: accurate maps of fire severity classes based on comparison between pre- and post-fire imagery (NDVI based on RapidEye remote imagery before and after the bushfire);
(4) *fuel type information*: vegetation maps, fuel type descriptions and photographs; and any fuel loading, coverage of fine fuel elements data published in the literature or collected as part of the planning for a planned burn data on fuel;
(5) *Seasonal fire climate and weather*: weather data in the lead up to, during, and after the fire from the nearest representative Bureau of Meteorology automatic weather station (AWS) or portable automatic weather station (PAWS)). The data includes daily maximum temperature and rainfall for the last 30 years to calculate Mount Soil Dryness Index (MSDI) (Mount, 1972, Mount, 1981), 0.5-h or1-h temperature, dew point, relative humidity, wind direction, and average 10-m and gust wind speed to calculate dead fuel moisture content (DFMC) and Forest Fire Danger Index (FFDI); and
(6) *Details about the bushfire runs*: when each run started, times and position of fire fronts based on fire linescans, aerial and ground photos or aerial observations during the fire run, and from crown streets observed on aerial oblique photos taken after the fire or from bushfire severity maps.

Method

Where crown streets were identifiable on post-fire digital aerial photography or remotely sensed imagery, the following procedure was used. First, the final fire boundary was overlaid on the background photographic image in the GIS and adjustments to the boundary were made relative to the fire scar (Figure 1(a)). The ignition point was then put on the map from details annotated on a fire situation report or a fire ignition database. Fire isochrones were then drawn over the significant crown streets apparent on the image fire scar (Figure 1 (b)). Then each fire isochrone was attributed with a date and time, as well as spatial and temporal confidence, from available field intelligence data or from wind shifts based on wind direction and wind speed at the local AWS.

In addition to mapping fire isochrones from crown streets, fire isochrones were mapped from other sources of data such as fire linescans, or Sentinel hotspot data from MODIS satellite images, or oblique aerial photographs taken by aerial observers.

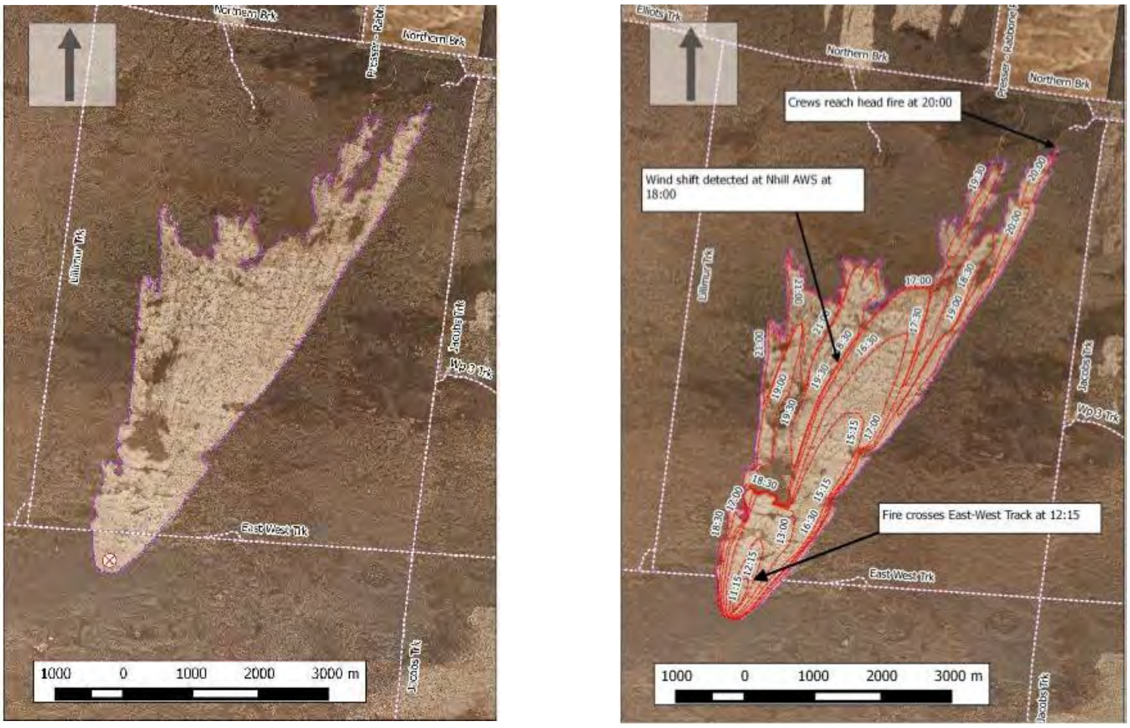

Figure 1: (a) Step 1 - Fire boundary and fire ignition drawn on map from DEPI's final extent digital maps and adjusted to fire scar (b) fire isochrones drawn on top of recognisable crown streets seen in (a). Example used is the 2009 East-West Track fire.

Results and discussion

Fire reconstruction studies require fire environment data that encompass terrain, fire climate and weather, vegetation and fuels, as well as real-time fire intelligence data. However, not all of these datasets are necessarily available for each fire reconstruction case study.

Digital aerial photography was not available for the earlier bushfires: the 2002 Big Desert; the 2007 Jungkum Track; and the 2008 Hattah–Wymlet. From 2009 onwards there was both pre-and post-fire imagery for the rest of the Mallee bushfires. Digital map and fire weather data was available for all fires. However, frequent fire linescans and field fire intelligence were not available for most fires.

The standards of fire reconstruction and issues associated the method for each fire reconstruction and fire simulations are presented in Table 1.

Table 1 Summary table of Mallee bushfires, their standard of reconstruction and the key issues with fire reconstruction

Case study & year	Fuel Types	Terrain	Area burnt	Standard of reconstruction	Key issues with fire reconstruction
2002 Big Desert	Spinifex and chenopod Mallee	Undulating systems	179,000	Moderate to moderate-high	There was no field fire intelligence gathered for this Mallee bushfire–fire linescans were taken mostly at night. Crown streets were not always evident on imagery. Wind shifts on the fireground did not match well at either Nhill or Walpeup AWSs.
2007 Jungkum Track	Arid heath Mallee	Flat dune systems	6,440	Moderate-high	Excellent oblique aerial photography was available for this fire. Crown streets not apparent on imagery once fire's convective activity was increased by back burning. Wind shifts on the fireground did not always match those at Nhill AWS
2008 Hattah–Wymlet	Arid heath Mallee	Undulating dune systems	9.071	Very high	Well defined crown fire streets through Spinifex Mallee, less so in Chenopod Mallee. Wind shift data at Walpeup AWS matched well with those on the fire ground.
2009 East–West Track	Arid heath Mallee	Flat dune systems	1,066	Very high	Crown streets were well-defined on post-fire aerial photography. Field fire intelligence and AWS data supported attribution of times of fire isochrones.
2013 East–West Track	Arid heath Mallee	Flat dune systems	402	Moderate-high	Crown streets were moderately well-defined on oblique aerial photography taken after the fire. Field intelligence pre-and post-fire provided reliable time estimates for isochrones.
2014 Bronzewing	Spinifex and chenopod Mallee	Undulating dune systems	14,029	Moderate	Crown streets were not easily discernible on post-fire RapidEye imagery because of convective fire behaviour. Erratic wind shifts on fire not detected at Walpeup AWS. Field fire intelligence data were sporadic. It was a complex fire to reconstruct.
2014 Danyo	Arid heath and Chenopod Mallee	Flat dune systems	4,669	High	Crown fire streets were readily discernible on post-fire RapidEye imagery. Walpeup AWS wind shift data supported attribution of times of fire isochrones, even though 60–65 km away.
2014 Lake Albacutya (including Paradise FR)	Heath and Broombrush Mallee, & Arid Heathland	Flat dune systems	60,971	Moderate	Crown streets well-defined on post-fire RapidEye imagery and on fire linescans taken late on 17 Jan 2014.Times for fire isochrones were accurate on 17 Jan but not soon 14, 15, and 16 January because of erratic shifts on the fireground relative to Nhill AWS.

Overall, the fire reconstruction of the 2002 Big Desert fire was rated as a moderate to moderate-high, having only the start and finish times of most fire runs from the Wouters (2003) report information, and sometimes inconsistent crown street and wind shift data. Fire linescans were limited to the late eevening and early morning. For fire isochrones based on the fire linescans, the fire spread reconstruction was done at a very high standard where they could be mapped to within ±25–50 m and their times could be determined to within ±2–5 minutes. Otherwise, fire isochrones done at a moderate standard, because wind shifts on the fireground were not consistent with those detected at Walpeup weather station 60–100 km away from the bushfire.

The 2007 Jungkum Track fire was a moderately difficult fire to reconstruct, mainly because it was difficult to correlate the time of change of wind shifts from the Nhill AWS data with the creation of the crown streets on the fireground. There were also relatively few crown streets in the arid heath Mallee in the Little Desert. Some good fire intelligence, such as oblique aerial photographs taken during fire operations. The times of most of the fire isochrones were attributed from wind shifts from Nhill AWS ~26–30 km away. The fire reconstruction was done to a moderate–high standard.

The 2008 Hattah–Wymlet bushfire was reconstructed to a moderately high standard where most of the fire isochrones could be mapped to within ±20–50 m on most of them and their times could be determined within ±10–15 minutes. The bushfire burnt through mainly Spinifex Mallee on flat to undulating sand ridges in the eastern part of Murray-Sunset National Park. There were readily apparent crown streets on the post-fire aerial photography taken one year after the fire. Time attribution for the fire isochrones was relative accurate because the wind shifts on the fireground lined up well with those at Walpeup weather station, as well as good field fire intelligence.

The 2009 East–West Track fire was a simple straightforward fire to reconstruct. Like the 2008 Hattah–Wymlet fire, this fire had good crown streets and field operational intelligence with which to create fire isochrones. The reconstruction for this bushfire was completed to a high standard where the fire isochrones could be mapped to within ±25–50 m on most of them and their times could be determined within ±5–10 minutes.

The 2013 East–West Track fire was a straightforward fire to reconstruct because there were distinct crown streets captured on oblique aerial photographs and start and finish of the major runs were well documented by local DEPI staff. Wind shifts were also in phase with the Nhill AWS 30 km away. The fire reconstruction was done to a moderately high standard where most of the fire isochrones could be mapped to within ±51–100 m and their times could be determined within ±10–15 minutes.

The 2014 Danyo bushfire fire proved to be a straightforward fire to reconstruct its fire spread. The fire burnt through mainly Spinifex Mallee fuels. The crown streets were very discernible one year after the fire using the Normalized Difference Vegetation Index (NDVI) derived from the RapidEye imagery. Wind shifts were overall consistent with those detected speed and direction recorded at the Walpeup weather station. The fire spread reconstruction was done to a moderately high standard where the fire isochrones could be mapped to within ±51–100 m and their times could be determined within ±6–10 minutes.

The 2014 Bronzewing fire proved to be a complex fire to reconstruct its fire spread. Because of the long unburnt Spinifex and Chenopod Mallee, fire intensity was very high on 16 and 17 November, resulting in few crown streets for fire isochrone delineation. Start and finish times for fire runs were available from field fire intelligence. Marking up the times of the fire isochrones also was quite difficult with northerly winds because the wind shifts on the fireground did not correspond to those at the Walpeup AWS.

The 2014 Lake Albacutya was a very complex fire to reconstruct particularly from the afternoon of 16 January until the evening of 17 January. The fire spread reconstruction was done to a moderate standard because of complex wind behaviour patterns on the fire ground. Much of the time attribution of the fire isochrones was done using the major wind shifts that occurred during the fire. Detailed fire situation report maps would have greatly enhanced and speeded up the fire reconstruction of the Lake Albacutya Complex fire.

Conclusions

The most accurate fire reconstructions were completed when there was high resolution aerial photography that showed the crown streets seen on post-fire digital imagery, vegetation and fire history, digital data, a weather station close to the fire, and frequent fire observations and photographs taken during fire operations on the fire. In addition, two major factors, the presence of crowns streets on the post-fire imagery and the wind shifts on the fire ground being in phase with those recorded at the nearest weather station.

Crown streets are not always created during periods of Mallee bushfires. Preliminary field evidence suggests that intense convective bushfire behaviour associated with long lines of fire most likely cause their absence.

References

Alexander, M. E. & Thomas, D. A. 2003. Wildland fire behaviour case studies and analysis: value, approaches, and practical uses. *Fire Management Today,* 63**,** 4-8.

Gellie, N. J. H., Gibos, K. E., Mattingley, G., Wells, T., & Salkin, O. 2010. Reconstructing the spread and behaviour of the February 2009 Victorian fires. *3rd Fire Behaviour and Fuels Conference.* Spokane, Washington: International Association of Wildland Fire, Birmingham, Alabama.

Gellie, N. J. H. & Mattingley, G. Effectiveness of recent prescribed burning in reducing fire severity of the Black Saturday fires in Victoria. *In:* FOX, R., ed. 4th Fire Behaviour and Fuels Conference, 2014 February 18 – 22, 2013, Raleigh, North Carolina, USA and July 1-4, 2013, St. Petersburg, Russia.
Published by the International Association of Wildland Fire, Missoula, Montana, USA.

Haines, D. A. 1982. Horizontal Roll Vortices and Crown Fires. *Journal of Applied Meteorology,* 21**,** 751763.

Mount, A. B. 1972. The derivation and testing of a soil dryness index using run-off data. *Bulletin No. 4.* Forestry Commission of Tasmania.

Mount, A. B. Which drought index? Proceedings of the Third Australian Fire Weather Conference, May 18-20, 1981 Hobart, Tasmania. Commonwealth of Australia Bureau of Meteorology, 128-132.

Rothermel, R. C. 1991. Predicting behaviour and size of crown fires in the Northern Rocky Mountains. *Research Paper INT-438.* Ogden, Utah: USDA Department of Agriculture, Intermountain Research Station.

Simard, A. J., Haines, D. A., Blank, R. W. & Frost, J. S. 1983. The Mack Lake Fire. *General Technical Report NC-83.* St. Paul, Minnesota: North Central Forest Experiment Station, Forest Service-U.S. Department of Agriculture.

Wouters, M. A. 2003. 2002/03 Big Desert Fire - Fire Suppression and Biodiversity Impacts. Adelaide, South Australia: Department of Environment and Heritage, Adelaide, South Australia.

HASTINGS BUSHFIRE CASE STUDY

Boura J[*] *, Tibbits A *, Hansby M *, Taylor D[+], Tetteroo J[+], McKenzie K[+] and Thorning S[+].

* Terramatrix Pty Ltd, Collingwood, Victoria, Australia
[+] Mornington Peninsula Shire Council, Rosebud, Victoria, Australia

1 Introduction

Fire management of peri-urban bushland reserves poses particular issues for land managers, including quantifying risk from relatively small or developing fires, exposure of large numbers of buildings immediately adjacent to bushland fuels, a suburban population with limited understanding of their bushfire risk, and the need to manage small reserves for multiple objectives including conservation and bushfire safety. The findings of the case study has informed the management of the reserve, including increased fire management zones.

Warringine Park (Coastal Section) is a reserve on the western shore of Western Port Bay at Hastings, Victoria (Australia), managed by Mornington Peninsula Shire. On the 3rd January 2015 a bushfire burnt through the reserve, impacting upon private property adjacent to the reserve boundary.

Mornington Peninsula Shire and CFA commissioned Terramatrix to analyse:

- The fire behaviour in the reserve;
- The effectiveness of fuel management zones in the reserve;
- The role of land use planning and building controls; and
- The community's level of preparedness and their experience of the fire.

A comprehensive case study report was produced which can be accessed at http://www.mornpen.vic.gov.au/Services_For_You/Fire_Emergency_Management/Fire_Management_Plans

2 Methodology overview

2.1 Fieldwork

Mornington Peninsula Shire and Terramatrix staff conducted a preliminary inspection of the fire site on 7th January 2015 to collect data that were likely to rapidly degrade due to rainfall or clean up, and to inform the scope of the case study. The inspection entailed:

- Inspecting the assumed point of origin;
- Walking the northern and western perimeters of the fire;
- Identifying properties that suffered damage, and photographing that damage;
- Making an initial appraisal of fire behaviour and impact; and
- Planning the more detailed fieldwork.

Terramatrix conducted additional fieldwork on 18th February 2015. This work entailed:

[*] Jon Boura, Managing Director, Terramatrix. PO Box 1391 Collingwood, Australia 3066. info@terramatrix.com.au www.terramatrix.com.au

- Inspecting the spot fires in the north of the reserve and on the rail reserve;
- Assessing fuel hazard and load in the Woodland and Swamp Scrub;
- Ground truthing fire severity mapping derived by Terramatrix from aerial photograph interpretation;
- Establishing the approximate location of the eastern flank at the time of the westerly wind change (using leaf freeze indicators);
- Measuring fire management zone width and setback of dwellings from the reserve boundary; and
- Correlating fire severity mapping with the location of damaged properties.

2.2 Eyewitness accounts

To inform the fire reconstruction, eyewitnesses, both residents and emergency service personnel, were interviewed about their experiences on the day of the fire. Interviews were by face-to-face meeting and/or telephone. Copies of photographs and video footage were obtained if possible.

To understand the communities level of preparedness and experience of the fire, face-to-face interviews were conducted with householders who live or own a property directly adjacent to Warringine Park (Coastal Section). A total of 24 interviews were conducted, 22 were face-to-face in the house of the interviewees, the other two were conducted over the phone. A set of interview questions guided the conversation and ensured broad consistency across the interviews.

3 The stud y site

Warringine Park (Coastal Section) is a 146ha RAMSAR listed bushland reserve on the western shore of Western Port Bay at Hastings, managed by Mornington Peninsula Shire Council. The reserve is located on the eastern coastal flatlands of the Morning Peninsula, with the vast majority of the reserve having very little topographical relief.

Three broad fuel types were present within the fire area:

- Eucalypt woodland (Grassy Woodland and Plains Grassy Woodland) in the north of the reserve, dominated by Eucalyptus viminalis spp. pryoriana , E. radiata and E. ovata ;
- Tall scrub (Swamp Scrub) dominated by Melaleuca ericafolia and to a lesser extent Leptospermum lanigerum in the south of the reserve; and
- A grassy area in the west of the reserve dominated by exotic and pasture grass species.

The bushfire burnt through approximately 50% of the reserve. The majority (51.2%) of the area burnt was Swamp Scrub that comprised nearly a quarter of the reserve. Other EVCs that burnt included Plains Grassy Woodland (11.8% of burn area), Grassy Woodland (13.2%), and exotic pasture grass (18.8%). Just over half the area of the reserve was Coastal Saltmarsh or Mangrove Shrubland of which very little was burnt during the fire.

Overall fuel hazard in the woodland was Extreme, comprising Very High bark hazard, Very High elevated fuel hazard, High near-surface and Very High surface fuel hazard, providing an overall fine fuel load of 21-34t/ha. The Swamp Scrub was 3-4m in height and an assessment of overall fuel hazard indicated a fine fuel load of 14-23t/ha. For the purpose of determining defendable space requirements of adjacent dwellings the AS 3959-2009 default fuel load for Scrub of 25t/ha was assigned.

4 Findings

4.1 Fire behaviour

The night of 2nd-3rd January was warm and dry, with the temperature in the high 20s to low 30s and relative humidity rarely above 30% from 3:00am onwards. Extreme bushfire weather had been forecast for the 3rd and conditions at 3.30pm (about the time the fire became established in the reserve) were a temperature of 38°C, relative humidity of 16% and a north-northwesterly wind of 30-35km/h, and the drought factor for HMAS Cerberus was 6.9. This resulted in a FFDI of 39 and a Very High fire danger rating.

The distribution of FFDI at HMAS Cerberus AWS showed that weather conditions comparable to those experienced on the day could be expected nearly every fire season. The 1 in 50 year and 1 in 100 year FFDI for HMAS Cerberus were 111 and 125 respectively.

The fire started at approximately 2.10pm at the rear of properties between Frankston-Flinders Road and the railway line, north of Reid Parade and burnt into a large windrow of unprocessed eucalypt logs. There were multiple spots thrown downwind from this pile fire. A substantial spot fire developed in the northwest corner of the reserve soon after 3.30pm. This fire spread under the influence of a 30km/h northerly wind. There was significant spotting of several hundred metres within the reserve, and flame heights of around 8-9m were recorded in the Swamp Scrub.

At around 5.30pm a strong westerly wind change reached the area and for a short period winds increased to nearly 60km/h, driving the eastern flank of the fire towards private property on James Hird Drive and Warranqite Crescent. The fire developed quickly after the wind change, and within 30m from where the fire was at the wind change the new head fire was burning canopy of the Swamp Scrub. Maximum recorded flame heights were 12-15m. The head fire was approximately 300m wide as it burnt towards the residential area, but was narrowed to approximately 150m, as it impacted the rear of houses, by a band Coastal Saltmarsh and Mangrove Shrubland associated with the Warringine Creek that was too moist to burn. In this period the fire impacted the residential area adjacent to the northern boundary of the reserve, damaging some homes and destroying fences and sheds.

4.2 Comparison with modelled fire behaviour

A prediction of fire behaviour on the day of the fire was conducted using the most applicable models and the stream of weather data from the HMAS Cerberus AWS.

It was initially thought that an accurate re-creation of the progress of the fire within Warringine Park (Coastal Section) would be possible, as it initiated from one or more point ignitions in close proximity to each other, spread under a relatively constant wind speed and direction, and the timing and strength of the wind change were recorded in the HMAS Cerberus AWS data. However, the inspection of the fire ground and completion of the fire severity mapping revealed that fire development was heavily influenced by multiple spot fires, which coalesced before or with the westerly / southwesterly wind change. The timing of these spot fires could not be established from eyewitness accounts, photographs or CFA logs.

Without accurately knowing the location and timing of the spot fires, a reliable detailed re-creation of the progression of the fire was virtually impossible. A simplified re-creation based on the 15:38 hours timing of the spot fire in the northwest of the reserve was possible, but this did not account for the multiple fire runs observed.

4.3 Fuel management zones

Mornington Peninsula Shire had undertaken a range of fire management works within the reserve, including an intensively-managed Fuel Management Zone 1 (FMZ1) along the northern and southern boundaries

The northern FMZ1 provided direct protection to adjacent dwellings from radiant heat and flame ignition. Although a number of dwellings were ignited, this was from ember attack or from combustible material burning within the private property such as garden vegetation, planter boxes and decking. The FMZ was considered to have achieved the Shire's objective of preventing radiant heat and flame ignition of houses from a fire in the reserve. The FMZs were less effective in protecting perimeter fences and outbuildings, as some residents expected them to, and would need to be substantially larger if this was to be their purpose in the future. Ongoing discussion with neighbouring residents may lead to a better shared understanding of fire management in and around bushland reserves.

The likely adequacy of the existing FMZs was also assessed against the more severe weather conditions (FFDI 100) assumed by AS 3959-2009 Construction of buildings in bushfire prone areas . This was done using the default AS 3959-2009 assumptions about fire development, and also taking into account the constraints on fire development imposed by the physical characteristics of Warringine Park (Coastal Section). The Warringine bushfire was a reasonably good match to the AS 3959-2009 'test fire' and assumptions for Scrub (i.e. 3m in height and 25t/ha fuel load). Weather on the day was not dissimilar to AS 3959-2009 assumptions, particularly in wind speed, which is key to fire behaviour in Scrub. AS 3959-2009 assumes a wind speed of 45km/h, whereas the north-south run of the Hastings fire was under approximately 35km/h winds, which increased to 55km/h for a short period with the westerly change.

Both modelling exercises indicated the need for wider FMZs, especially where dwellings have been constructed close to the reserve boundary. It was recommended that Mornington Peninsula Shire consider managing the regeneration of vegetation within the reserve so as to provide at least some of the additional defendable space suggested. The feedback received from the residents interviewed suggested that wider FMZs were likely to be supported by the majority. The implementation of FMZs adjacent to the Warringine Creek will require careful planning to minimise environmental impact.

The question of what fire weather conditions to use in planning FMZs is fundamental to determining what level of work is required and under what conditions the works are likely to be effective.

4.4 Planning and building controls for bushfire

At the western end of the residential area James Hird Drive, a perimeter road around a small subdivision, provided additional defendable space between the FMZ and the dwellings; and the level of impact on private property was correspondingly less

Perimeter roads are recommended for new subdivisions in bushfire prone areas and can provide valuable defendable space. However, these roads can be exposed to dangerous levels of radiant heat during the passage of the fire front, which may hinder asset protection by the CFA or late evacuation by residents.

The homes adjacent to the eastern half of the reserve were sited very close to the reserve boundary, meaning little defendable space could be provided on the private land and the homes depended almost entirely on the reserve FMZ provided by Mornington Peninsula Shire.

Australian Standard 3959 'Construction of Buildings in Bushfire Prone Areas', specifies construction standards to reduce the likelihood of ignition by embers or radiant heat, such as preventing gaps through which burning material can enter the building and using fire resistant building materials. At least six homes were constructed to this standard, and five of these were undamaged. The other, which experienced the greatest damage overall, had been constructed to an early version of AS 3959. It should also be noted that the presence of flammable garden vegetation and combustible objects close to the home were ignited by ember attack and may have reduced the effectiveness of the AS 3959 construction standard.

About 30 houses had timber fences that were damaged or destroyed in the fire. Timber fences that ignited during the bushfire contributed to fire spread into the residential area via side fences and garden beds. Non-combustible fencing would have provided a better radiant heat shield for the houses, and there is an opportunity to consider how the Planning Scheme can encourage non-combustible fencing in bushfire prone areas.

There were also numerous examples of polyethylene water tanks and associated piping and pumps being damaged or destroyed by heat from the fire. Although in this instance there was no evidence found of residents or the fire services having relied on domestic supplies for fire fighting or asset protection, the resilience of the water tank to fire impacts is an important consideration if it is to be used as a water source.

4.5 Community preparedness and experience on the day

Residents' perceptions of bushfire risk varied considerably, with about half thinking their homes could be threatened by bushfire due to the presence of the reserve. The other half did not consider bushfire to be a risk, citing as reasons the fact they lived in suburbia; the FMZ in the reserve was adequate; or that a fire would burn away from the houses under a northerly wind.

Less than half the residents had received or sought information about preparing for bushfire, but more than half felt they were well prepared for a bushfire. More than half had planned to leave their properties once they were aware of a fire in their area, although none intended to leave proactively due to elevated fire danger, such as a forecast Code Red rating.

All residents interviewed who were present on the day of the fire left their properties, with most leaving around the time of fire impact and retreating a short distance into the urban area. None left the area early before the fire started in response to the forecast extreme fire weather. There is an opportunity to review the recommended actions for people living on the urban edge who can readily retreat a short distance into an urban area, and to tailor warning messages to this situation.

The Warringine fire highlighted the difficulty of providing "early" warning in short, sharp interface fires. About half the residents reported receiving an official warning of the fire, either electronically (albeit most reported receiving the warning after the fire impacted) or directly from emergency service personnel who door knocked the area. Many of those who stayed in the local area reported that they did not know where they should have gone or how to access support services. About half of the residents congregated in the Hastings area and the remainder went further afield to family or friends. There was evidence of congestion of the local road network, which was not designed to facilitate the movement of large numbers of people in a short time frame. The design and infrastructure of new urban fringe areas should consider the likely evacuation, whether spontaneous or organised, of large peri-urban populations.

Most respondents praised the performance of emergency service personnel, particularly the CFA, but were seemingly unaware of the role the Shire played in the fire operations. Residents were generally of the opinion that the occurrence of the bushfire and the level of damage done were unacceptable.

5 Conclusion

A solid understanding of the broad progress and behaviour of the bushfire was obtained from physical inspection and API of the burnt area, operational logs, eyewitness accounts, photographs and video footage. The lack of detailed records of the location of the fire front and/or spot fires at particular times made it impossible, however, to make a detailed comparison between the actual and predicted fire behaviour. In general, the predictions and observations of the actual fire behaviour in terms of spotting, flame height and overall rate of spread were reasonably well matched.

The interviews with residents provided a picture of their perception of the bushfire risk, their level of preparedness and their experience on the day. Generally, the potential for a bushfire and for that fire to impact on houses, was underestimated. Most residents interviewed did not have a fire plan. All those that did have a fire plan stated they intended to "evacuate", but in general the plans lacked detail of when they would leave and where they would go. The urban setting and the limited potential for a large, uncontrollable bushfire, meant the standard CFA messages for residents' planning and preparation may not have been directly applicable to this area. Consideration should be given to how messages can be better tailored to suit this type of environment.

Local governments, and other land managers, invest significantly in bushfire management. Reviewing fires of different sizes, and burning under the influence of varying vegetation, topography and weather, allows land managers to target research that directly informs their management decisions by evaluating the effectiveness of their fire management programs in the context of their bushland reserves. The Warringine Park (Coastal Section) case study documented how reserve management, land use planning, building controls and community preparedness, combined with fire service response, contributed to the outcome of the bushfire on January 3 2015. Whilst there was damage to a small number of dwellings, and more widespread loss of fences and outbuildings, the case study identified that many programs were effective in reducing the consequences of the fire. A number of opportunities to improve programs were also identified.

How fire propagates from the dead surface fuel to the first branch in ornamental vegetation of WUI

Ganteaume A.*, Bertin A., Audouard M., Guerra F., Lopez J.M., Morge D., Travaglini C.

IRSTEA, Aix-en-Provence, France

anne.ganteaume@irstea.fr

1. INTRODUCTION

South-Eastern France is characterized by Mediterranean climate conditions with hot, dry and often windy summers as well by an increasing wildland-urban interface (WUI) that presents high fire occurrence (Ganteaume and Long-Fournel 2015a). These characteristics entail to this area a high fire risk. In WUI, the ornamental vegetation can be an efficient vector of fire propagation from the wildland to housing. Studies have been carried out to identify native species with low flammability to be used in WUI (Monroe *et al.* 2003) and have provided up-to-date reviews of vegetation flammability ratings in Europe and in USA but without using a standard method to test and rank the flammability of plants (Dimitrakopoulos 2001 ; Etlinger and Beall 2004). Previous works showed that the main ornamental species used in the WUI of SE France differed in their flammability (Ganteaume et al. 2013a, b); and that, for some species, this flammability varied according to the type of fuel, e.g. litter or live leaf (Ganteaume et al. 2015b). In WUI, homeowners are often advised to minimize or eliminate the use of highly flammable vegetation when landscaping their homes. Lists containing species that are appropriate for use in fire-wise landscaping are often requested. Indeed, reducing the vegetation fire hazard can be accomplished through the arrangement, maintenance and selection of species. However, none of these works detailed the impact of this maintenance on the fire propagation.

The aim of this work was to assess the fire propagation from the dead surface fuel to the first branch of a plant in several species planted in ornamental hedges. We also wanted to find out if there was an impact of species and of the litter clean up underneath the hedges on this fire propagation. This would be a further step toward the assessment of the whole plant flammability and would help to improve fire prevention in WUI.

2. MATERIAL AND METHODS

2.1. Study area

SE France is composed of 15 administrative districts called départements and the study area is located in the département Bouches du Rhône (Northwestern coordinates: 43.655°N, 5.495°E; Southeastern coordinates: 43.832°N, 5.672°E; total area: 508 700 ha), which is one of the most affected by wildfires (more than 10% of the total occurrence and of the total burned area in the study area according to the regional forest fire database Prométhée), especially in the wildland-urban interface (WUI represents 15% of the study area and concentrates 43% of the total fire ignitions).

* IRSTEA, RECOVER- EMAX, 3275 route de Cézanne- CS 40061 - 13183 Aix-en-Provence cedex 5- France
anne.ganteaume@irstea.fr

2.2 Species studied and samples collection

The four ornamental species chosen for the flammability experiments were among the most frequent in the study area and their flammability at the particle level (live leaf and litter) was already assessed in previous works (Ganteaume et al. 2013a, b; Ganteaume et al. 2015b): two species whose flammability was higher in live leaves than in litter (*Prunus laurocerasus, Pyracantha coccinea*) and two species whose flammability was higher in litter (*Elaeagnus ebbingei, Ligustrum japonicum*).

Each species was characterized by different physical parameters that were recorded in the field, such as litter depth (from 3.8 to 6 cm), number of leaves per branch (from 8 to 46 leaves), leaf mass, surface area, surface to volume ratio and thickness, first branch height (from 2.5 to 16 cm) and angle between trunk and branch (from 60° to 110°). Other parameters were measured in the laboratory just before burning such as leaf moisture content (95 to 166%), branch and litter load and litter bulk-density. Calibrated live branches of 20 cm long and undisturbed litter samples, deep enough to sustain a flame front, were collected in the hedges during the summer season. The litter samples were oven-dried 48h at 60°C before the flammability experiments in order to have the litter burning as steadily as possible.

2.3 Flammability experiments

The flammability experiments were carried out just after the sample collection in order to avoid a variation of live fuel moisture content. The fire propagation from the litter to the first branch was assessed in laboratory conditions using a fire bench on which the samples were placed, respecting the species characteristics previously measured. Three thermocouples were used to record the variation of temperature during the burns, a ruler helped to record the flame height, and a scale recorded the mass loss during the burns (Fig. 1a). In order to have a linear flame front, we used a line ignition to ignite the litter samples. The flammability variables that characterized (i) ignitability - branch vertical and horizontal ignition frequency (V_IF and H_IF), branch time-to-ignition (TTI), ignition temperature (IgnT) -, (ii) sustainability -branch flaming duration (FD) -, (iii) combustibility - rate of branch combustion (RBrC), maximum temperature (MaxT), sum of temperatures (SumT), flame height (FH), rate of litter combustion (RLitC), heat released under the branch[1] (E_15) and total heat released[1] (E_tot) - and (iv) consumability - percentage of branch burned (%BurBr) -, were recorded during the burns or calculated afterwards for each species.

Beside the impact of species on fire propagation, two modalities of litter management were tested: a modality "Whole litter", that aimed at testing the fire propagation when the litter was not cleaned up from underneath the plant, and a modality "Half litter", that aimed at testing this fire propagation when the litter was removed from underneath the plant (Fig. 1b). In the latter, the purpose of the remaining litter was to allow the generation of a flame front.

2.4 Data analysis

ANOVAs were used to test the impact of species on the different flammability variables that characterized the flame propagation and comparisons of medians were used to highlight the

[1] calculated according to Byram's fire intensity equation : I=HwR (H : fuel heat of combustion, w : weight of fuel consumed per unit area, R: rate of spread)

impact of the litter modality on these variables. Logistic and multiple linear regressions were used to model the relationships between the explicative variables (ignition temperature, maximum temperature, sum of temperatures, rate of litter combustion, heat released under the branch, and total heat released) and the dependent flammability variables (both ignition frequencies, time-to-ignition, flaming duration, rate of branch combustion, and percentage of branch burned). Taking into account these dependent variables, hierarchical cluster analysis allowed the ranking of species according to their flammability (for the modality "Whole litter", only). Principal Component Analysis was used to describe the links between flammability variables and species physical characteristics.

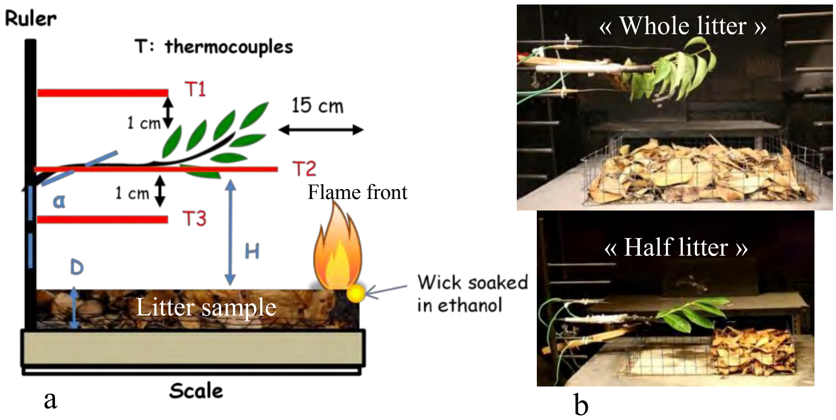

Figure 1: Experimental design for the flammability experiments (a) and the two modalities of litter tested (b). D: litter depth, H: branch height, α: angle branch-trunk.

3. RESULTS

3.1 Impact of the litter modality

Regardless of species, for the modality "Whole litter", the flames propagated well vertically from the litter to the branch (100%) and horizontally throughout the branch (91%), consuming the branch, completely or almost completely (>70%) as enough heat was released to sustain the flame propagation. In contrast, for the modality "Half litter", the vertical flame propagation was highly reduced (57%), burning only the tip of the leaves, and no horizontal propagation occurred throughout the branch, with no or little branch consumption (<14%) as not enough heat was released. For this modality, we were not able to record the horizontal ignition frequency, and thus, neither branch flaming duration, rate of branch combustion or percentage of burned branch. Due to the difficulty to assess the beginning of the flaming combustion (time-to-ignition), data recorded for time-to-ignition and ignition temperature is not accurate.

Comparing the flammability in both modalities, we found that the variables recorded for the modality "Whole litter" were significantly higher than those recorded for the modality "Half litter" except for time-to-ignition and rate of litter combustion that did not differ significantly from one type to the other (Tab.1).

For the modality "Whole litter", we wanted to know whether and how the flammability variables were related, taking into account MaxT, SumT IgnT, E_15, E_tot and RLitC as explicative variables of the dependent variables H_IF, V_IF, TTI, FD, RBrC and %BurBr. The following equations were obtained using logistic and multiple linear regressions:

$$H\_IF = e^{(-8.143 + 0.01846\ MaxT)}/(1 + e^{(-8.143 + 0.01846\ MaxT)})\ (R^2_{adj} = 43\%,\ p < 0.0001)$$

$$TTI = 22.8682 + 0.016\ IgnT - 0.5053\ E\_15\ (R^2_{adj} = 16\%,\ F = 10.99,\ p < 0.0001)$$

$FD = 124.686 – 87.1582RLitC - 0.03839IgnT + 0.00144SumT$ (R^2_{adj}=73%, F=103.27, p<0.0001)

$RBrC = 0.092278 – 0.006915E\_15 - 0.0001778MaxT + 0.266248 RLitC$ (R^2_{adj}=77%, F=120.51, p < 0.0001)

$\%BurBr = 17.6954 + 0.0661MaxT + 0.35682 E\_tot$ (R^2_{adj}= 39%, F = 37.5, p < 0.0001)

Max temperature was the only significant explicative variable of horizontal ignition frequency. For FD and RBrC, the significant explicative variables explain more than 70% of the variability and RLitC was the most significant of these variables (negative effect on FD but positive on RBrC). The other relationships were moderate or weak (for TTI) with R_{adj}^2<50%.

Given the lack of accuracy of the data recorded in the modality "Half Litter", we did not run the multiple linear regressions for this modality (TTI being the only significant dependent variable).

Table 1: Comparison of the flammability variables (V_IF: vertical ignition frequency, H_IF: horizontal ignition frequency, TTI: time-to-ignition, FD: flaming duration, RBrC: rate of branch combustion, %BurBr: percentage of burned branch) recorded during the flammability experiments for both litter modalities (***: highly significant, NS: non significant, ND: data not recorded, in italic: not accurate).

Flammability variables Litter type	**V_IF (%)**	**H_IF (%)**	**TTI (s)**	**FD (s)**	**RBrC ($g\ s^{-1}$)**	**%BurBr (%)**	**MaxT (°C)**	**sumT (°C)**	**IgnT (°C)**	**RLitC ($g\ s^{-1}$)**
Whole litter	100	91	20.8 (11)	83.2 (42.7)	0.13 (0.09)	72.5 (14.8)	655.9 (101.3)	36,927 (8643.2)	250.6 (29.3)	0.93 (0.3)
Half litter	57	ND	*27.9* (19.9)	ND	ND	ND	344.9 (192.4)	17,489 (8472.5)	*198.8* (53)	1.37 (0.8)
Comparison of medians	***	-	NS	-	-	-	***	***	***	NS

3.2 Impact of species

For the modality "Whole litter", the impact of species on the flammability variables was highly significant (p<0.0001) or very significant (TTI: p=0.004) except for V_IF (p=0.12). *Elaeagnus ebbingei* presented the shortest time-to-ignition, the highest maximum temperature and heat released before ignition, as well as the highest %BurBr and RLitC along with *Prunus laurocerasus*. This latter species and *Ligustrum japonicum* showed the highest rate of branch combustion and *Pyracantha coccinea* displayed the lowest horizontal ignition frequency, the longest branch flaming duration and the lowest ignition temperature. For the modality "Half litter", the variables V_IF and TTI were significantly affected by species contrary to IgnT. *Ligustrum japonicum* presented the lowest ignition frequency which may be due to the height of the first branch which was the highest and to the little heat released in this modality.

For the modality “Whole litter”, using Hierarchical Cluster Analysis that took into account the dependent flammability variables, the four ornamental species were ranked according to their flammability from the species the most flammable (*Elaeagnus*) to the lowest flammable (*Pyracantha*); *Prunus* and *Ligustrum* belonging to a group with moderate flammability (Fig. 2).

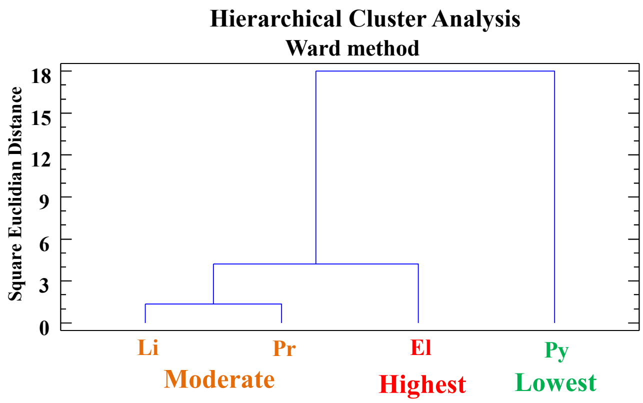

Figure 2: Ranking of species according to their flammability (*Li: Ligustrum japonicum Pr: Prunus laurocerasus, El: Elaeagnus ebbingei, Py: Pyracantha coccinea*)

To emphasize the impact of species on the flame propagation, taking into account their specific physical characteristics, and to bring out strong patterns between these variables, we used Principal Correspondence Analysis (Fig. 3). For both litter modalities, the first three components accounted for at least 79% of inertia with 55% and 64% (for the modalities “Whole litter” and “Half litter” respectively) on the first component. This component contrasted the four species, from *Pyracantha* (negative part of the axis), which was characterized by high number of leaves and leaf surface to volume ratio, to *Prunus* (positive part of the axis), which was characterized by high leaf mass, thickness, surface area and moisture content, as well as by high angle branch-trunk. The flammability variables were contrasted on the second (flaming duration, percentage of burned branch and rate of branch combustion) and the third component (time-to-ignition and horizontal ignition frequency). It is worth noting that, most physical characteristics, including FMC, were weakly linked to the flammability variables. Usually FMC is one of the most significant parameters of the flammability of live fuel (Chuvieco et al. 2004) but this parameter is not always a relevant factor in the modelling of fire behavior (Alexander and Cruz 2012).

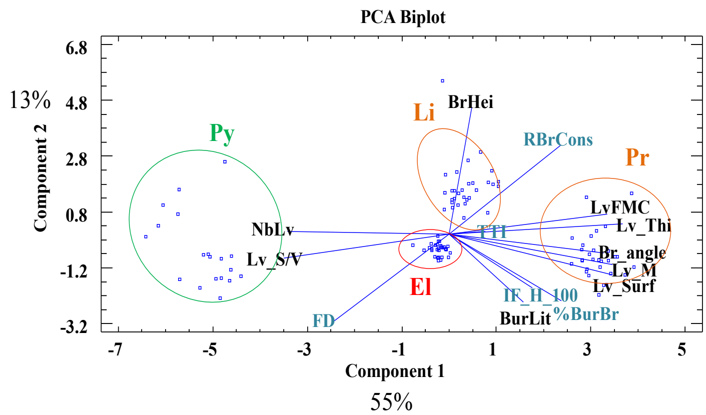

Figure 3: Links between the physical characteristics (Nb_Lv: number of leaves, Lv_S/ V: leaf surface to volume ratio, BrHei: first branch height, BurLit: burned litter, Lv_FMC: leaf moisture content, Lv_Thi: leaf thickness, Lv_M: leaf mass, Lv_Surf: leaf surface area, Br_angle: angle branch-trunk) of the four ornamental species (Py: *Pyracantha coccinea*, Li: *Ligustrum*

japonicum, El: *Elaeagnus ebbingei*, Pr: *Prunus laurocerasus*) and their flammability variables (IF_H: horizontal ignition frequency, TTI: time-to-ignition, FD: flaming duration, RBrC: rate of branch combustion, %BurBr: percentage of burned branch) for the modality "Whole litter".

4. CONCLUSIONS

This work confirmed that, in laboratory conditions, removing the litter from underneath the branch is an efficient mean for mitigating the fire risk; the vertical flame propagation was strongly decreased and the horizontal propagation was not possible due to the insufficient heat released. Moreover, choosing the ornamental species the least fit for flame propagation from the dead surface fuel to the first branch will also improve fire prevention in WUI.

5. REFERENCES

Alexander ME, Cruz MG (2013) Assessing the effect of foliar moisture on the spread rate of crown fires. *Int. J. Wildland Fire* 22(4):415-427

Chuvieco E, Aguado I, Dimitrakopoulos A (2004) Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment. *Canadian Journal of Forest Research* 34, 2284–2293.

Dimitrakopoulos AP (2001) A statistical classification of Mediterranean species based on their flammability components. *International Journal of Wildland Fire* 10, 113-118.

Etlinger MG, Beall FC (2004) Development of a laboratory protocol for fire performance of landscape plants. *International Journal of Wildland Fire* 13, 479–488. doi:10.1071/WF04039

Ganteaume A, Long-Fournel M (2015a) Driving factors in fire density can spatially vary at the local scale in south-eastern France. *International Journal of Wildland Fire* 24, 650-664.

Ganteaume A, Lopez JM, Guerra F, Esteve R, Jappiot M (2015b) Can ranking the flammability of ornamental species be used for the fire risk assessment in WUI ? *6th International Fire Ecology and Management Congress San Antonio, USA, Nov. 16-20, 2015.*

Ganteaume A, Jappiot M, Lampin-Maillet C (2013a) Assessing the flammability of surface fuels beneath ornamental vegetation in wildland–urban interfaces, in Provence (south-eastern France). *International Journal of Wildland Fire* 22 (3), 333-342.

Ganteaume A, Jappiot M, Lampin C, Guijarro M, Hernando C (2013b) Flammability of Some Ornamental Species in Wildland–Urban Interfaces in Southeastern France: Laboratory Assessment at Particle Level *Environmental Management* 52 (2), 467-480.

Monroe MC, Long AJ, Marynowski S (2003) Wildland fire in the Southeast: Negotiating guidelines for defensible space. *Journal of Forestry* 101, 14–19.

Improving Estimates of Fuel Consumption and Fire-Related Carbon Emissions in Siberia with Ecosystem Specific Field Data

Elena A. Kukavskaya[1]*, Susan G. Conard[2], Ludmila V. Buryak[3], Galina A. Ivanova[1], Olga P. Kalenskaya[3], Sergey V. Zhila[1], Denis S. Zarubin[3]
[1]V.N. Sukachev Institute of Forest, Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk, Russian Federation, kukavskaya@ksc.krasn.ru
[2]Emeritus Scientist, US Forest Service, Rocky Mountain Research Station, Missoula, Montana, USA; George Mason University, Fairfax, VA, USA, sgconard@aol.com
[3]Siberian State Technological University, Krasnoyarsk, Russian Federation

Introduction

Boreal forests play an important role in the global carbon cycle, as they contain the largest amount of terrestrial ecosystem carbon (Goodale *et al.* 2002). Russia supports about 2/3 of the 1.2 billion ha of global boreal forest (FIRESCAN 1994). Wildfires are an important source of carbon emissions to the atmosphere, with fire disturbances causing significant impacts on the carbon budget (Harden *et al.* 2000). During some years with high fire hazard, regional fire-related emissions can reach the level of fossil fuel emissions (Isaev and Korovin 1999). To quantify emissions and to estimate effects of fires on the atmosphere, the approach of Seiler and Crutzen (1980) is widely used. In this approach, emissions are calculated based on data on area burned, fuel loads (FL), and fuel consumption (FC). To determine species-specific emissions (CO_2, CH_4, etc.) emissions factors are used (e.g., Akagi *et al.* 2011). A number of freely available satellite-derived products on burned areas and land cover types could be used to estimate fire-related emissions. While various fire and vegetation products result in large uncertainties of wildfire emissions (Kukavskaya *et al.* 2013b), they are improving over the time. However, the lack of data on fuel loading and fuel consumption remains one of the largest problems for accurate calculation of wildfire emissions (van Leeuwen *et al.* 2014), especially across the extensive Russian territory (Kukavskaya *et al.* 2013b).

Currently, several million hectares burn annually in Russia, most of which is in Siberia and the Far East (Vivchar 2011). Wildfire emission estimates for Russia vary from 5 to more than 500 Mt per year (Kukavskaya *et al.* 2013b). There is a large interannual variability depending on differing regional patterns of fire danger in specific years. Different methodologies and datasets used also result in a wide range of published estimates for Russia (Kukavskaya *et al.* 2013b). Global databases used to estimate fire emissions contain fuel loads and consumption data mainly for the boreal forests of Northern America with only a few values specific to Russian ecosystems (e.g., van Leeuwen *et al.* 2014). In the IPCC Guidelines for National Greenhouse Gas Inventories (2006) mean fuel consumption values for the boreal forests were calculated based solely on data from North America. However, fire regimes in North America and Eurasia differ significantly. Fires in the Northern America are characterized by larger fire radiative power, higher rate of spread and severity, and greater tree mortality (Rogers *et al.* 2015), leading to substantial differences in fire emissions parameters between the two regions.

Accurate fuel consumption estimates can be obtained from fire experiments with pre- and post-fire biomass measurements (e.g., McRae *et al.* 2006) or by comparing post-fire fuels to the amount of live and dead fuels in similar pre-burn forest types (e.g., deGroot *et al.* 2009). Data on fuel consumption in Russian forests are scarce in comparison to the size of the continent and the amount and diversity of wildland fuels. Amosov (1964) determined depths of burn ranging from 0.3 to 50.0 cm in the course of 0.015-0.03 hectare fire experiments. Furyaev (1996) estimated ground fuel combustion completeness of 77 to 97% of pre-fire loading (fuel consumption – 2.66 to 16.26 tC/ha) in feather moss/*Vaccinium vitis-idaea* Scots pine forest. Fuel consumption measured during high intensity surface and crown fire in Scots pine forest averaged 34.4 t/ha (FIRESCAN 1994). However, all these experiments on modeling fire behavior covered just a few forest types (primarily pine stands). There are still numerous ecosystem types in Siberia with insufficient data on fuel loading and consumption. In addition, disturbance (e.g., logging, insects) increases fire hazard and can result in higher fuel consumption. For example, logged areas often have extremely high fuel loads due to logging debris and typically experience higher fire severity and fuel consumption (Kukavskaya *et al.* 2013a).

The aims of this paper are to compile field-measurement data on fuel loads and fuel consumption in Siberia and to determine the relations with ecosystem types, weather conditions, and anthropogenic disturbances. Field-measurement data were compiled based on available data from the literature as well as published and unpublished results of our own research.

Materials and Methods

We have compiled available published data and carried out field measurements to determine FL and FC in Siberia with respect to vegetation types, weather conditions/fire severity, and previous disturbances. As surface fires dominate in Siberia (Korovin 1996) we mainly estimated surface and ground fuel consumption. From 2000 to 2007 we conducted a number of experimental surface fires of varying severity in the light-coniferous forests of Central Siberia to obtain quantitative and qualitative data on fire behavior and carbon emissions due to fires of known behavior. The prescribed burns were conducted on 1 to 4 ha plots located in Scots pine (*Pinus sylvestris*) and mixed larch (*Larix sibirica*) forests in central and southern taiga of Central Siberia. These are the most frequently burned forest types in Russia (Korovin 1996). To coordinate data collection and distribute sampling across the study plots, a sampling grid was established on each plot. Detailed information on experimental fires and their design is presented in McRae *et al.* (2006).

In addition to prescribed burns, we have examined ecosystem types that are characterized by high fire activity and widely spread in the region for which data on fuel consumption are underrepresented or absent in the literature. We investigated various ecosystem zones of Siberia that are characterized by different climatic conditions that impact forest characteristics, fuel structure and fuel loads as well as fire behavior: central and southern taiga, forest-steppe, steppe, and mountain forests. Study sites were located in areas of the Russian Federation characterized by high fire activity: Krasnoyarsk region, Republic of Khakassia, Republic of Buryatia, Tuva Republic, and Zabaikal region. From 2009 to 2013 we examined a number of burned logged areas (Kukavskaya *et al.* 2013a) and forest plantations to assess the potential impact of forest practices on fire emissions. In 2013-2015 burned areas in dark-coniferous and deciduous forests were examined to determine fuel consumption and carbon emissions. In addition, we investigated wildfire effects in evergreen coniferous shrubs, steppe, grassland, and peat ecosystems (Figure 1).

Wildfire sites were examined in the year of fire to get the most accurate estimate of fuel consumption. Fuel consumption was determined by comparing fuel loads on burned sites to the amount of live and dead fuels on similar unburned sites. The burned and unburned sites were located in immediate proximity or within 1 km of each other in the same growing conditions, and selected stands had comparable species composition and stand characteristics before disturbance.

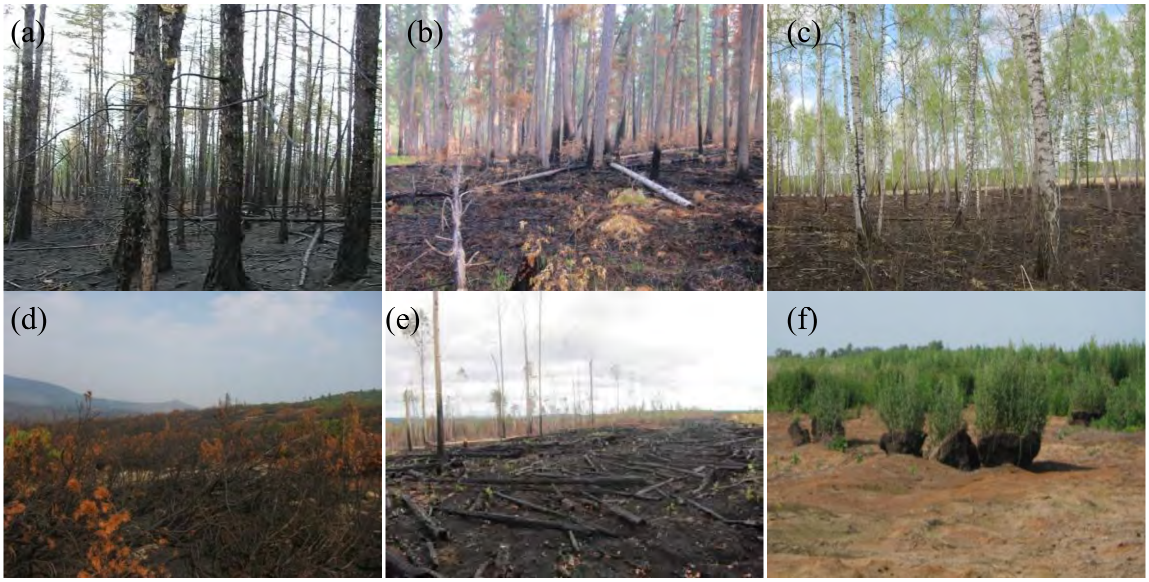

Figure 1: Burned ecosystem types of Siberia: (a) larch forest in the southern taiga (b) dark-coniferous forest in the central taiga; (c) deciduous forest in the forest-steppe zone; (d) evergreen shrubs in the mountains; (e) clear-cut light-coniferous forest; (e) drained peat lands.

We sampled dead surface fuels (dead and down woody debris above the litter layer) with the line intersect method developed by Van Wagner (1968) as adapted by McRae *et al.* (2006). To quantify living surface vegetation and ground fuel loads, we sampled ten to fifteen 20x25-cm quadrats uniformly laid out across the plot. First, living surface vegetation within the frame was harvested to estimate fuel loads of grasses and small shrubs (e.g. *Vaccinium vitis-idaea, Ledum palustre, Calamagrostis arundinacea*). To determine ground fuel loads of litter (foliage, bark, cones, cured grasses and easily recognisable plant parts), mosses, lichens and duff layers, each sample was removed from the forest floor by cutting through the layers with a knife along the inside edge of the sampling frame. All samples were taken to the laboratory to determine oven-dry weights. To estimate carbon emissions, carbon content in combusted materials was assumed to be 0.5 of the absolutely dry mass (Alexeyev and Birdsey 1998).

Results and Discussion

On the sites burned by wildfires, estimated fire emissions in the light-coniferous forests of southern taiga in Central Siberia varied from 1.3. to 13.0 t ha^{-1} with the majority of burned material (up to 85% of the total fuel consumption) being moss, lichen and duff. These data correlate well with values obtained in the course of the experimental fires in the central and southern taiga where carbon emissions varied from 1.5 to 15.9 t ha^{-1} with the lowest values due to fires of low severity and the highest due to fires of high severity (McRae *et al.* 2006, Kukavskaya and Ivanova 2006, Ivanova *et al.* 2011). On clear-cut logged sites in the light-coniferous forests of southern Siberia, carbon emissions reached 41 t ha^{-1}, which was 150 to 500% of those in the unlogged sites (Figure 2). The majority of burned material (50 to 80%) was down woody debris.

In dark-coniferous forests with a dominance of *Pinus sibirica* and occurrence of *Picea obovata*, *Abies sibirica*, and *Larix sibirica*, carbon emissions reached 29.0 t ha^{-1} (Figure 2). Higher fire emissions in the dark-coniferous forests compared to those in the light-coniferous stands is attributed to the larger prefire fuel loads, longer fire return interval, and the dominance of slowly-moving fires with greater depths of burn. The contribution of the down woody debris to the total fuel consumption was 14 to 49%, living ground cover - 6 to 29%. Good correlation (r = 0.90) was found for the prefire down woody debris loads and their consumption with correlation for ground fuels (litter, moss, duff) and their consumption being 0.45. This can be attributed to the varying fuel moisture of mosaic vegetation across the study sites.

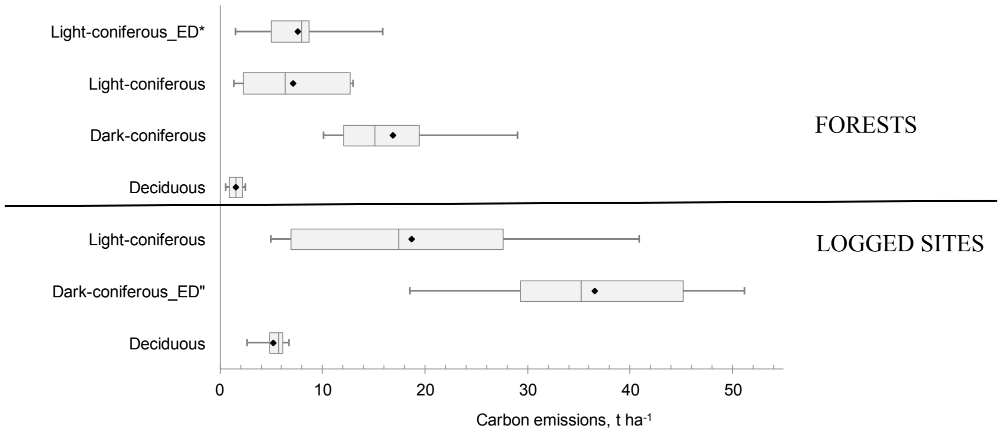

Figure 2: Comparison of inter-site range of estimated carbon emissions from fire in the forests and logged sites of Central Siberia. The box extends from the 25th to 75th percentiles. The whiskers represent the highest and lowest values in the data. The line in the box is the median and the dot is the mean. Note: * - experimental data from McRae *et al.* 2006, Kukavskaya and Ivanova 2006, Ivanova *et al.* 2011; ″ - experimental data from Valendik *et al.* 2011.

According to data from the literature fuel consumption on logged sites in the dark-coniferous forests of Central Siberia varied from 44.0 to 102.4 t ha^{-1} (Valendik *et al.* 2011), thus carbon emissions ranged from 22.0 to 51.2 t ha^{-1}. In mountain evergreen coniferous shrubs stands of *Pinus pumila* we found that burning of crowns dominated the total fuel consumption with surface and ground fuels accounting for up to 30%.

Carbon emissions in deciduous (*Betula pendula*, *Populus tremula*) forests ranged from 0.5 to 2.5 t ha^{-1}. The lower fuel consumption in deciduous forests compared to coniferous stands can be attributed to the smaller amount of accumulated surface fuels as well as the dominance of fast-moving spring surface fires. At logged sites in the deciduous stands carbon emissions increased up to 6.7 t ha^{-1} with down woody debris proportion increased from 3 to 20% of the total fuel consumption. It is 150 – 400% more than on the unlogged sites.

Estimated carbon emissions on the drained peats were 650 to 950 t ha^{-1} depending on the depth of burn.

On repeatedly burned sites in southern Siberia, fires released from 3-50% as much carbon as was emitted from fires in undisturbed forests due to fuel consumption in the previous disturbance. While one would expect fuels to increase once trees begin to fall on the ground, this usually does not happen for several years after a fire. Furthermore in the most burned regions of southern Siberia dead and damaged trees on accessible sites are often harvested within a few years after fire. Clearly, any estimates of emissions from combustion of forest fuels in regions with frequent repeat disturbances will be inaccurate unless they take the effects of previous disturbances into account.

To examine the effects of different land cover types and weather conditions, we calculated carbon emissions in the National Park "Shushensky Bor" under two projected scenarios: low- to moderate- and high- severity burning (Figure 3). Twenty-seven vegetation types with different fuel loads were distinguished and sampled in the area. We estimated that in case of spreading of surface low- to moderate- severity fires carbon emissions on the territory of the Perovskoe forestry of the National Park would be as much as 70.6 x10^3 t, while high-severity surface fires lead to 142.3 x10^3 t of carbon emitted to the atmosphere. The highest contribution to the total emissions under a scenario of high fire danger is from the peat lands which occupy 18% of the area and are easily burnable under severe droughts. The maps developed might be used to forecast fire effects in the National Park under different weather conditions and levels of fire hazard.

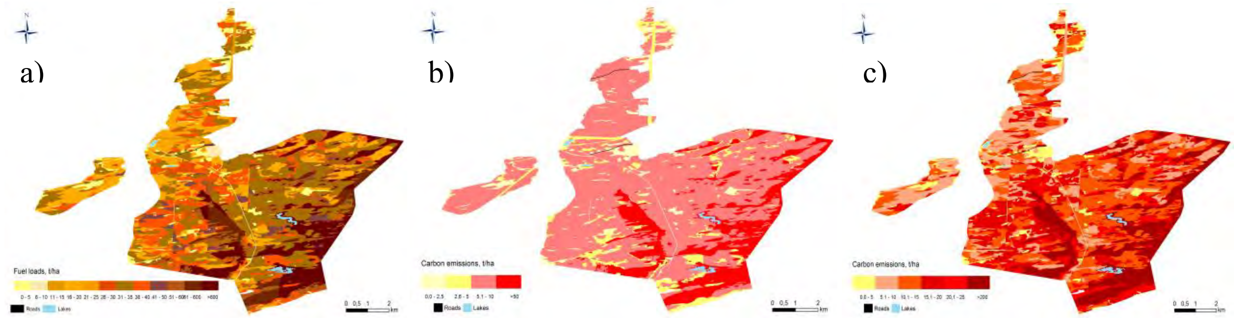

Figure 3. Surface and ground fuel loads (a) and projected carbon emissions due to fires of low to moderate (b) and high (c) severities in the National Park «Sushensky Bor» (Perovskoe forestry), southern Siberia

Conclusions

We found large variations of fuel consumption and fire emission rates among different vegetation types depending on growing conditions, fire behavior characteristics and anthropogenic factors. Changes in the climate system result in an increase in fire frequency, area burned, the number of extreme fires, fire season length, fire season severity, and the number of ignitions from lightning. This leads to an increase of fire-related emissions of carbon to the atmosphere. The type of field measurement database we have compiled is necessary for improving the accuracy of existing biomass burning models and for use by air quality agencies in developing regional strategies to mitigate negative smoke impacts on human health and environment.

Some additional research is required to examine fuel consumption in the other ecosystem types (for example, tundra and northern taiga larch forests) for which specific data are not yet available, mainly due to their remote locations and long fire return intervals.

Acknowledgements

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References

Akagi SK, Yokelson RJ, Wiedinmyer C, Alvarado MJ, Reid JS, Karl T, Crounse JD, Wennberg PO (2011) Emission factors for open and domestic biomass burning for use in atmospheric model. *Atmos. Chem. Phys.* **11**, 4039-4072.

Alexeyev VA, Birdsey RA (1998) Carbon storage in forests and peatlands of Russia (U.S.D.A. Forest Service Northeastern Research Station: Radnor). Initially published in Russian in 1994.

Amosov GA (1964) Some patterns of surface forest fires development. In 'Beginnings of forest fires'. pp. 152-183. (Nauka: Moscow) (in Russian)

de Groot WJ, Pritchard JM, Lynham TJ (2009) Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. *Canadian Journal of Forest Research* **39**(2), 367-382.

FIRESCAN Science Team (1994) Fire in Boreal Ecosystems of Eurasia: First Results of the Bor Forest Island Fire Experiment, Fire Research Campaign Asia-North (FIRESCAN). *World Resource Review* **6**, 499-523.
Furyaev VV (1996) Role of fire in forest development (Novosibirsk: Science) (In Russian)
Goodale CL, Apps MJ, Birdsey RA, Field CB, Heath LS, Houghton RA, Jenkins JC, Kohlmaier GH, Kurz W, Liu SR, Nabuurs GJ, Nilsson S, Shvidenko AZ (2002) Forest carbon sinks in the northern hemisphere. *Ecological Applications* **12**, 891–899.
Harden JW, Trumbore SE, Stocks BJ, Hirsch A, Gower T, O'Neill KP, Kasischke ES (2000). The role of fire in the boreal carbon budget. *Global Change Biology* **6**, 174-184.
Isaev AS, Korovin GN (1999) Carbon in the forests of Northern Eurasia. Carbon cycling at the territory of Russia. 63-95 (in Russian)
Ivanova GA, Conard SG, Kukavskaya EA, McRae DJ (2011) Fire impact on carbon storage in light conifer forests of the Lower Angara region, Siberia. *Environmental Research Letters* **6**, 045203.
Korovin GN (1996) Analysis of the distribution of forest fires in Russia. In 'Fire in Ecosystems of Boreal Eurasia' (Ed JG Goldammer, VV Furyaev) pp. 112–128. (Kluwer: Dordrecht)
Kukavskaya EA, Buryak LV, Ivanova GA, Conard SG, Kalenskaya OP, Zhila SV, McRae DJ (2013a) Influence of logging on the effects of wildfire in Siberia. *Environmental Research Letters* **8**, 045034. doi:10.1088/1748-9326/8/4/045034.
Kukavskaya EA, Soja AJ, Petkov AP, Ponomarev EI, Ivanova GA, Conard SG (2013b) Fire emissions estimates in Siberia: Evaluation of uncertainties in area burned, land cover, and fuel consumption. *Canadian journal of forest research* **43**(5), 493-506. doi: 10.1139/cjfr-2012-0367.
Kukavskaya EA, Ivanova GA (2006) Fire influence on Scots pine stand biomass in central Siberia. *Herald of Krasnoyarsk Agricultural University* **12**, 156-162 (in Russian)
McRae DJ, Conard SG, Ivanova GA, Sukhinin AI, Baker SP, Samsonov YN, Blake TW, Ivanov VA, Churkina TV, Hao WM, Koutzenogij KP, Kovaleva N (2006) Variability of fire behavior, fire effects and emissions in Scotch pine forests of central Siberia. *Mitigation and adaptation strategies for global change* **11**, 45-74.
Rogers BM, Soja AJ, Goulden ML, Randerson JT (2015) Influence of tree species on continental differences in boreal fires and climate feedbacks. *Nature Geoscience*. DOI: 10.1038/NGEO2352.
Seiler W, Crutzen PJ (19800 Estimates of gross and net fluxes of carbon between the biosphere and atmosphere from biomass burning. *Clim. Change* **2**, 207-247.
The 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.
Valendik EN, Verkhovets SV, Kisilyachov EK, Ivanova GA, Bryukhanov AV, Kosov IV, Goldammer IG (2011) 'Technology of prescribed burning in forests of Siberia.' (SFU Press: Krasnoyarsk) (in Russian)
van Leeuwen TT, van der Werf GR, Hoffmann AA, Detmers RG, Rücker G, French NHF, Archibald S, Carvalho Jr JA, Cook GD, de Groot WJ, Hely C, Kasischke ES, Kloster S, McCarty JL, Pettinari ML, Savadogo P, Alvarado EC, Boschetti L, Manuri S, Meyer CP, Siegert F, Trollope LA, Trollope WSW (2014) Biomass burning fuel consumption rates: a field measurement database. *Biogeosciences* **11**, 7305-7329.
Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* **1**, 20-26.
Vivchar A (2011) Wildfires in Russia in 2000-2008: Estimates of burnt areas using the satellite MODIS MCD45 data. *Remote Sensing Letters* **2**(1), 81-90.

Indigenous Fire Knowledge and Best Practice Science in the Gulf of Carpentaria

Terrence Taylor*
Senior Head Ranger of the Gangalidda & Garawa Rangers,
Carpentaria Land Council Aboriginal Corporation, Burketown, QLD, Australia,
ttaylor@clcac.com.au

Introduction

Throughout Australia there is growing interest from governments, land managers, Indigenous groups and academics alike in utilising Indigenous fire knowledge for various environmental, social, cultural and economic outcomes. The Carpentaria Land Council Aboriginal Corporation's (CLCAC) landscape-scale fire management project provides a valuable case study in this field. Through this presentation, Taylor discusses the objectives, methodology and collaborations involved in this project, as well as its foundations in long-standing Indigenous fire management traditions. This project demonstrates a fundamentally interdisciplinary approach to fire management as 'new solutions' are generated by looking back to traditional cultural practices, harnessing local experience and uniting these with contemporary science.

Materials and methods

CLCAC's fire management project operates on a regional scale and covers 68,000 square kilometers in the lower Gulf of Carpentaria, Queensland and into the Northern Territory. Fire management is undertaken with the key goals of controlling wildfire, enhancing biodiversity and managing Weeds of National Significance (WoNS). Beyond this, the project facilitates more long-term wide-reaching outcomes in providing an opportunity for training, capacity building and knowledge sharing between Indigenous rangers and other landholders in the Gulf.

This project highlights CLCAC's approach to fire management, which marries the rich Indigenous fire knowledge that exists in the Gulf with western science. Burns are planned using scientific data from sources such as the Bureau of Meteorology (BoM) and North Australian Fire Information (NAFI), in conjunction with understandings of when, how and why Indigenous people have traditionally burned this country. Fire planning also takes into consideration the requirements of local landholders. CLCAC rangers carry out fire regimes focused on early season cool mosaic burns and strategic late season storm burns. The early season firework is conducted using a raindance incendiary machine to reconstitute patch-work burning patterns used traditionally to reduce fuel loads to assist in wildfire mitigation, whilst storm burning practices utilise a gel torch to target specific weeds such as Rubber Vine. These activities form part of CLCAC's holistic and seasonal approach to land management (as reflected in Illustration 1).

* Corresponding author: Terrence Taylor. PO Box 6662, Cairns, QLD, 4870, Australia. info@clcac.com.au. www.clcac.com.au.

Illustration 1: CLCAC Seasonal Calendar

Community partnerships and stakeholder engagement

The success of this project in large hinges on establishing and maintaining effective collaborative relationships with stakeholders throughout the region. CLCAC engages a wide range of parties including Traditional Owners, rural fire service, pastoralists, all levels of government, mining companies and national parks. As such, project staff negotiate diverse and contrasting perceptions of fire and its role in land management. Through this project, CLCAC staff have endeavored to find common ground with other stakeholders and have successfully built effective collaborations where relations may have been disconnected or antagonistic in the past. For example, pre-season planning meetings that involve all stakeholders have proved invaluable in this regard.

Another important part of the stakeholder engagement process has been the development and publication of CLCAC's *Gulf Savannah Fire Management Guidelines.*[1] This document captures local understandings and experiences as gained through interviews with various stakeholders and

[1] CLCAC's *Gulf Savannah Fire Management Guidelines* are available for download at: http://www.clcac.com.au/home

defines a range of fire landscapes accordingly. Management recommendations for each fire landscape are backed up with scientific detail and presented in an easy to read 'dashboard' format. These guidelines provide a resource for all land managers in the Gulf and promote common understandings of appropriate fire management in this context.

Results

All on ground works are recorded using I-tracker with specialised sequences. This allows staff to accurately analyse and map data, critically review their performance, and all importantly, gain public support and demonstrate a return on investment. Results of fire activities are measured through a series of annual monitoring processes including pre- and post-fire monitoring plots, weed density measurements, photo points and yearly fauna and flora surveys. While this project is still in progress, the initial results have been very encouraging. For example, NAFI data demonstrates that since this project commenced in 2013 there has been an average reduction in the percentage of total area burnt and a shift towards fires concentrated in the early dry season (Figure 1).

Discussion

Australia's long history of fire management

The Australian continent has been shaped by a long history of Indigenous fire management. Rhys Jones (1969) first coined the term *fire-stick farming* to refer to the ways Indigenous people have systematically applied fire to the landscape and created change in the distribution and abundance of particular species.[2] In Australia's pre-European history, fire served myriad functions from signaling, hunting, influencing patterns of vegetation and assisting travel (Flood 2004). In her review of this literature, Flood states that 'regular, light burning was the pattern all over Australia at the time of European contact' (p. 251). Extending on this work, Gammage (2011) frames Australia as the 'biggest estate on earth'. Gammage describes the ways Indigenous people skillfully and productively undertook land management prior to the arrival of Europeans, drawing particularly on observations made by European explorers and settlers. Gammage considers fire to be pivotal in this management as it was used universally across the continent in accordance with local contexts and customary law. Such an analysis is relevant in the Gulf as historical materials suggest that Europeans may have arrived to a landscape that had been significantly altered by Indigenous fire management.

In *Discoveries in Australia,* John Lort Stokes documents his experiences travelling in the Gulf of Carpentaria during 1837 – 43 aboard the H M Brig Beagle (the same ship which had previously carried Darwin on his voyage). On his initial approach to the Gulf, Stokes remarked that 'it appeared to be thickly inhabited' according to the observation of 'numerous fires' (1846: n.p.). Stokes' account of the Gulf region is punctuated with observations of Indigenous people using fire. For example, he records that 'during our absence a few natives had made their appearance

[2] The *fire-stick farming* thesis has been subject to much debate and critique. For example, Hiscock (2008) raises concerns regarding the use of contemporary Indigenous fire practices to interpret otherwise ambiguous archaeological records.

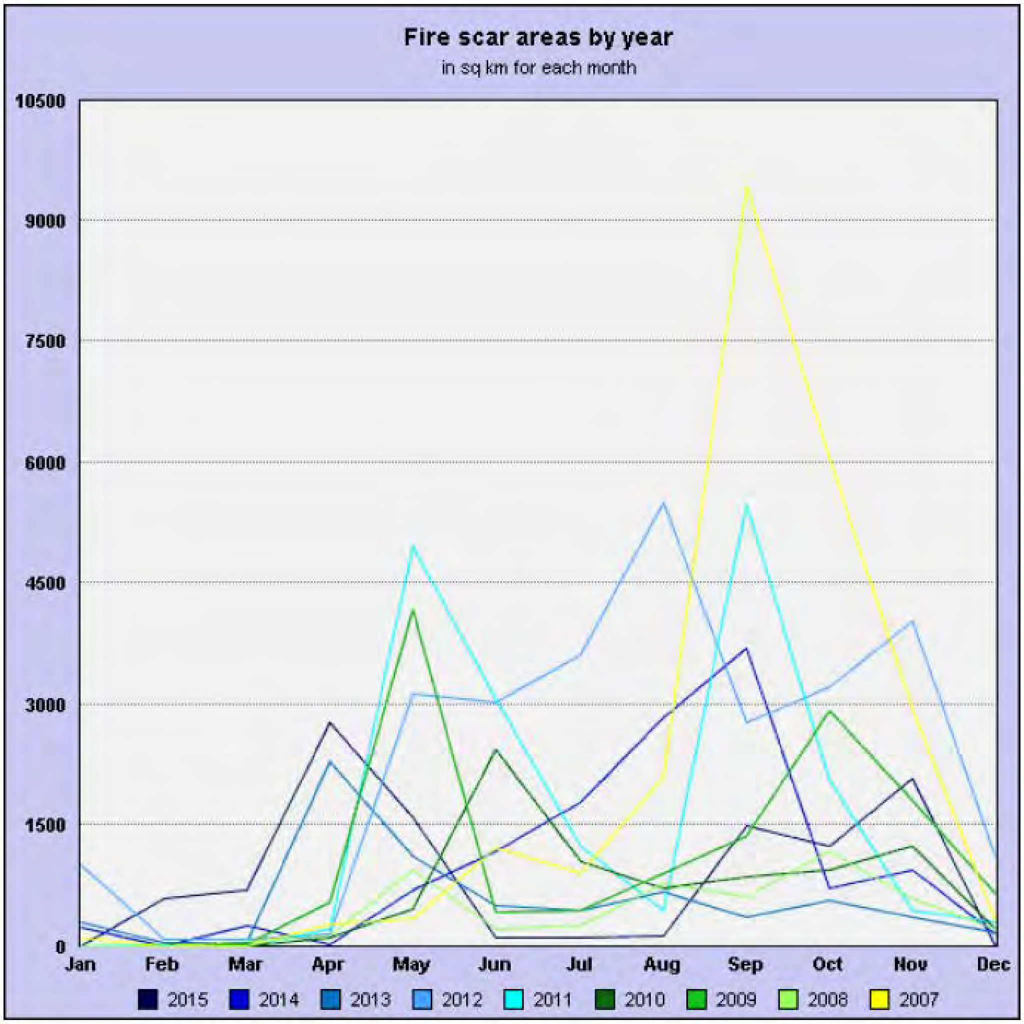

Figure 1: Fire scar areas by year in the project area (Source: http://www.infonet.org.au)

on the beach, attending some fire, it seemed, on a hunting excursion' (n.p.). Stokes paints a picture of the Gulf as an encouraging landscape shaped by fire:

> 'In the present case, with the exception of a clump of trees to the southward, there was nothing to break the vast level that stretched before us, its rim sharply defined against the morning sky. Here and there a charred stump, the relic of some conflagration, reared its blackened face, serving to keep us in the direction we had taken at starting, which was over a rich alluvial soil, that seemed to hold out a promise of a future brilliant destiny to this part of the continent'(n.p.).

In fact, Stokes's party was so impressed with the viability of this landscape that they named a section of country near the Albert River the 'Plains of Promise'. This early account not only verifies a long history of fire management in the Gulf, it may also indicate that fire stick farming activities may be responsible for creating the landscape that held such virtue and promise for

Stokes. Just as fire was a powerful force in shaping the Australian landscape prior to European settlement, it continues to have an important presence in the Gulf today.

Contemporary Indigenous fire management

Traditional fire practices continue to be a fundamental part of life in the Gulf of Carpentaria. These practices are deeply embedded in the cultural customs and are centrally adopted in CLCAC's approach to environmental management. Proper fire management ensures the availability of important bush foods for communities, like thoongathu (wild grapes), wulunku (white current), junggula (bush cucumber), jardabu (emus) and bulginda (wallaby). In the Gulf, fuel loads have always been managed in complex ways. For example, traditional burning practices are designed to ensure that sufficient grass is available as a resource in constructing shelters (Illustration 2 and 3).

Illustration 2: Traditional shelter under construction

Illustration 3: Finished construction using native grass to insulate

Since settlement, the European use of fire in the Gulf has undergone some changes. For instance, fire has been employed by some pastoralists as a mechanism to create green pick and muster livestock. There is still an important cultural difference that remains, however, in relation to attitudes about fire – while Aboriginal people use fire as a tool for conserving and increasing the productivity of the natural environment, Europeans view fire as a threat. In order to keep fire management strong, Indigenous people in the Gulf pass on their knowledge and practices to younger generations through ceremonies and law. Anthropologists have documented the existence of on-going fire management in this region for purposes such as creating new hunting grounds (Bradley 2010) and honouring ancestral obligations (Martin 2013).

The use of Indigenous fire strategies in conjunction with western scientific knowledge is gaining traction across Australia. Partnerships between Traditional Owners and scientists offer new and effective pathways for fire management, particularly in Australia's north (Russel-Smith *et al.* 2009). Peak bodies in the field of fire management are increasingly recognising the value of Indigenous expertise. For example, at the 2015 Australasian Natural Hazards Management Conference, the Bushfires and Natural Hazards CRC hosted a panel discussion to raise 'awareness of traditional, local and Indigenous knowledge and practices that complement the current science and research' (Jones 2016: n.p.).

Not only does Indigenous fire knowledge offer insights for science and practical tools for management, the increasing public valuation of this knowledge supports Indigenous people to take the lead in managing their lands. As Kerins (2012: 32) suggests in a case study from the Northern Territory, the use of Indigenous ecological knowledge in 'planning meetings (along with scientific knowledge) was crucially important in recalibrating the power relationship between Indigenous people and government agencies'.

As greater access to traditional lands is gained through native titles processes, and governments show a willingness to invest in Indigenous land managers, increased opportunities exist for Indigenous people to carry out fire management.[3] The fundamental importance of this is demonstrated by the success of CLCAC's Indigenous Fire Project. In a time when Australia is facing significant environmental challenges posed by future development, climate change and biodiversity loss, much stands to be gained by utilising Indigenous fire knowledge and practices alongside western science.

References

Australian Institute of Aboriginal and Torres Strait Islander Studies (2014) 'Emerging Issues in Land and Sea Management.' Report from National Native Title Conference, 4 June. (Coffs Harbour, NSW)

Bradley J with Yanyuwa families (2010) 'Singing saltwater country: journey to the songlines of Carpentaria.' (Allen & Unwin: Crows Nest)

Flood J (2004) 'Archaeology of the dreamtime: the story of prehistoric Australia and its people.' (Gecko Books: Marleston)

Gammage B (2011) 'The biggest estate on earth: how Aborigines made Australia.' (Allen & Unwin: Sydney)

Hiscock P (2008) 'Archaeology of ancient Australia.' (Routledge: London)

Jones F (2016) Knowledge for life. *Bushfire and Natural Hazards CRC*, viewed 27 March 2016, <http://www.bnhcrc.com.au/news/2016/knowledge-life>

Jones R (1969) Fire-stick farming. *Australian Natural History* **16:7**, 224-228.

Kerins S (2012) Caring for country to working on country. In 'People on country: vital landscapes, Indigenous futures.' (Eds J Altman, S Kerins) pp. 26-44. (The Federation Press: Leichhardt)

Marin RJ (2013) Sometime a fire: re-imagining elemental conflict in northern Australia's Gulf country. *Australian Humanities Review* **55**, 67-91.

Russell-Smith J, Whitehead PJ, Cooke P (2009) 'Culture, ecology and economy of fire management in northern Australian savannas: rekindling the wurruk tradition.' (CSIRO Publishing: Collingwood)

Stokes JL (1846) 'Discoveries in Australia' Vol. 2. (Boone: London)

[3] Indigenous ranger groups are subject to a dynamic and competitive funding environment and this often affects the long-term viability of projects such as the one discussed here. At a recent conference concerns were expressed across this field regarding the over dependence on often unreliable government funding to carry out such important work (Australian Institute of Aboriginal and Torres Strait Islander Studies 2014).

Investigation of Firebrands Generation in a Pine Forest

Alexander Filkov[1,2*], Sergey Prohanov[1], Eric Mueller[3], Denis Kasymov[1], Pavel Martynov[1], Mohamad El Houssami[3], Jan Thomas[3], Nicholas Skowronski[4], Bret Butler[5], Michael Gallagher[4], Kenneth Clark[4], William Mell[6], Robert Kremens[7], Rory Hadden[3], Albert Simeoni[8]

[1] University of Melbourne, Creswick, VIC, Australia, alexander.filkov@unimelb.edu.au
[2] Tomsk State University, Tomsk, Russia, aifilkov@gmail.com
[3] University of Edinburgh, Edinburgh, UK, r.hadden@ed.ac.uk
[4] USDA Forest Service, Morgantown, WV and New Lisbon, NJ, USA, nskowronski@fs.fed.us
[5] USDA Forest Service, Missoula, MT, USA, bwbutler@fs.fed.us
[6] USDA Forest Service, Seattle, WA, USA, ruddymell@gmail.com
[7] Rochester Institute of Technology, Rochester, NY, USA, kremens@cis.rit.edu
[8] Exponent, Natick, MA, USA, asimeoni@exponent.com

Introduction

Spot fires are generally recognized as being an important and complex problem in the context of the prediction of forest fire propagation. They can be a threat for fire fighters and other persons which have to deal with forest fires.

The ignition of structures in a Wildland-Urban Interface (WUI) community is caused by the exposure of heat fluxes from flame or firebrands generated by a wildfire. Firebrands are generated due to combustion of trees and buildings during fires in such territories. The flow of firebrands generated in WUI fires may ignite vegetation and mulch located near houses and buildings (Cohen, 1991). Understanding the ignition mechanisms of fuel beds and structures, due to firebrand exposure, is important for the development of a new generation of mathematical models of for predicting and preventing the propagation of fires in populated areas (Pagni, 1993).

Ignition of fuels due to firebrand exposure has been insufficiently investigated, but a limited number of laboratory studies are available in the literature (Babrauskas, 2003). Beyond that the size distribution of firebrands produced during the combustion of vegetation and structures is relatively unknown in field conditions (Houssami et al., 2015). Therefore, a study on the characterization of firebrand production was carried out, using experimental fires conducted as prescribed fires in the New Jersey Pine Barrens, USA in March of 2013, 2014 and 2015.

Methods

Plots and equipment description

The experiment was conducted in the Pinelands National Reserve in southern New Jersey (USA). It included a series of full-scale experiments in 2013 (EX1), 2014 (EX2) and 2015 (EX3), respectively. The area of the experimental sites was varied from 4.3 (EX2) to 6.7 (EX1 and EX3) ha (Fig. 1).

* School of Ecosystem and Forest Sciences, Faculty of Science, The University of Melbourne, 4 Water St, Creswick, Victoria, 3363, Australia, Email: alexander.filkov@unimelb.edu.au

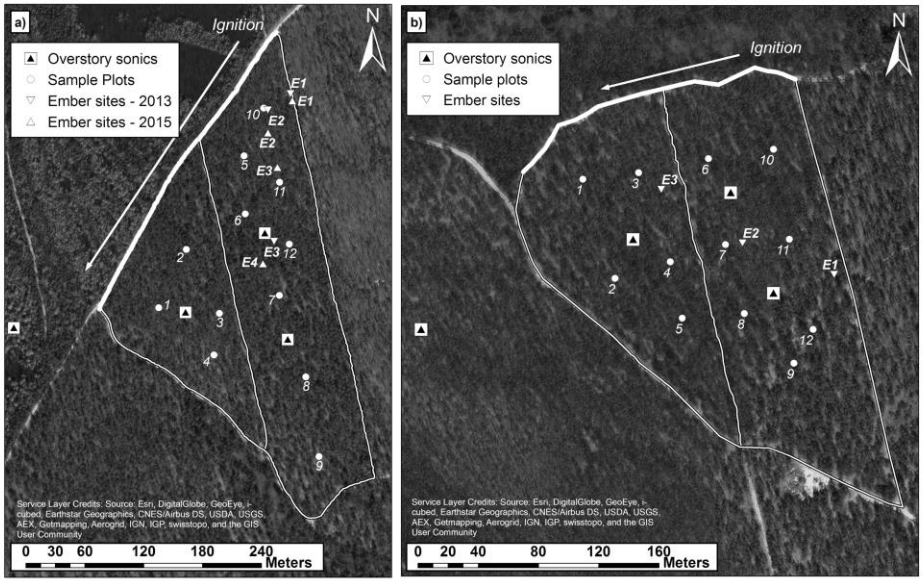

Figure 1. Location of 4 overstory towers, 12 plots for collection of fuels and 3 plots for collection of firebrands for EX1, EX3 (a) and EX2 (b)

It should be noted that EX3 was conducted again at the same site as EX1. The forest type for the both blocks was pitch-pine scrub-oak, dominated in the canopy by pitch pine, with intermittent clusters of post-oak and white oak in the sub-canopy. The understory contained a shrub layer of huckleberry, blueberry, and scrub oaks. In all cases, the burns were carried out in early March, before the initiation of 'green-up', or the growth of new vegetation in the spring. Both fires were ignited in a line, by drip torch, along the northern-most road (~330 m and ~207 m long, respectively). The lines were continuously drawn out from east to west.

Four 12.5 m tall overstory towers and twelve understory towers were set on the experimental sites (Fig. 1). One overstory tower was located outside of each block, to the west, in order to monitor the ambient conditions throughout the course of the fire. The sensors, installed in the overstory towers, included 3D sonic anemometers (RM 80001V, R. M. Young Co.) which provided measurements of wind velocity, turbulence, and air temperature.

Before each experiment, destructive sampling of the forest floor and shrub layer was carried out in 1 m^2 clip plots (Clark et al., 2015). Three clip plots were selected within each of 12 larger 20 m x 20 m sites, centered at the locations indicated in figure 1 (around of each of 12 understory towers). This destructive sampling technique was repeated after the fire (using an additional three clip plots per site), and consumption was estimated by comparing the measurements.

A time history of the fire progression was recorded from an aircraft using Rochester Institute of Technology's Wildfire Airborne Sensor Program (WASP) (McKeown et al., 2011; Houssami et al., 2015). The WASP provided time-stamped, othomosaiced, and georeferenced long-wave infrared (8.0-9.2 µm) and visible (0.4-0.9 µm) spectral band images, at a resolution of 640x512. In addition, a number of digital and analog cameras were placed within the sites.

The thermal imagers FLIR A325 and Mikron 7600PRO were used for the diagnostics of firebrands and their characteristics on the Plot 1 EX2 and EX3. FLIR A325 operated in the range of 7.5 - 13 microns and Mikron 7600PRO operated in the range of 8-14 microns. Both thermal imagers recorded a video with a frequency of 30 Hz. To record the particles in the air flow, the screen was installed in front of the thermal imagers. The screen was a 2.5 x 1.5 m gypsum wall board installed perpendicular to the underlying surface and coated with black heat-resistant paint. More details related to experimental methods can be found in (Houssami et al., 2015).

Firebrand collection
We used the same methodology for firebrand collection as in (Houssami et al., 2015). Plot 1 was placed near the track, delimiting the experimental parcel (Fig. 1), Plot 2 and Plot 3 were placed near understory towers. In EX1, only Plot 2 pans were covered by a thin plastic film. In EX2, all pans were covered by plastic film. Laboratory experiments showed that holes burnt in the film allowed the location and approximate size of particles to be determined. However, analysis of video from EX2 showed that some small and light firebrands can bounce and blow from film. Therefore, in EX3 each plot had pans with and without film.

The collected firebrands were dried at 80°C in an oven until reaching a constant weight, then weighed on a laboratory balance with a precision of 0.1 mg, taking into account only particles with a mass greater than 5 mg. Particle dimensions (length, width, and thickness) were measured in EX1 using an electronic caliper ($\pm 10^{-5}$ m). In EX2 and EX3 another technique was used to measure particle dimensions. For these particles, the area was determined using MATLAB code that calculated the total area of the particle from individual photographs. The software has a precision of 4.84×10^{-5} m^2. Particles smaller than 5×10^{-3} m were discarded.

IR Data Processing
To analyze the recorded thermograms, the following method was developed. The data from «SEQ» format (file from the FLIR A325 thermal imager) were exported to the MATLAB format by using the FLIR ThermaCAM Researcher software. As a result, a set of files was received to provide the number of the test frames, the recording time up to the millisecond, and a matrix containing the temperature at each point of space.

The IR video processing task was to search for the location of flying particles, determine the temperatures and sizes and calculate the number of the particles which dropped on the surface under study. Therefore, a particle detector was developed to determine the location of specific particles. After detection of all particles in the frame the particle tracker was used. The software creates a video file that contains all the detection areas marked, the identification numbers of the particles, the frame number, and minimum and maximum temperatures in the frame. More detailed information is recorded in a xml-file.

Results and Discussion

Collection Analysis
It should be noted that the combustion intensity varies, depending on the year of the experiment conducted, as well as the location of the experimental plot within a site. In the 2015 EX3 experiment, the loading of fine surface fuels (needles + 1hr wood + 1hr shrub stems) was reduced as a result of the 2013 EX1 fire (whole block average in 2015 was 0.83 kg/m^2 compared to 1.37 and 1.68 kg/m^2 for EX1 and EX2, respectively), with a lower proportion in the shrub layer compared to previous years. The resulting consumption was lower as well (block average of 0.45 kg/m^2), with 54% (67% and 72% for EX1 and EX2, respectively) of the average load being consumed. Combined with drastically lower spread rates, the fire intensity in 2015 was not

sufficient to generate measurable quantities of embers. More details related to analysis of the fire behavior can be found in (Houssami et al., 2015).

Table 1 shows the amount of the particles collected on the plots, depending on their type.

Table 1
Quantity and percentage of collected firebrands (>5 mg and >5 x10^{-3} m) in each plot and its corresponding density

Firebrands	EX1			EX2		
	Plot 1	Plot 2	Plot 3	Plot 1	Plot 2	Plot 3
Total amount	83	61	333	17	1343	54
Branches (%)	15	30	11	70	31	28
Bark (%)	85	70	89	30	69	72
Density (pcs./m^2)	60	44	238	12	960	39

It stands to mention that most particles were bark slices and the rest were pine and shrub branches. An exception is Plot 1 for EX2. The mass and area distribution for each particle for all plots is shown in figure 2.

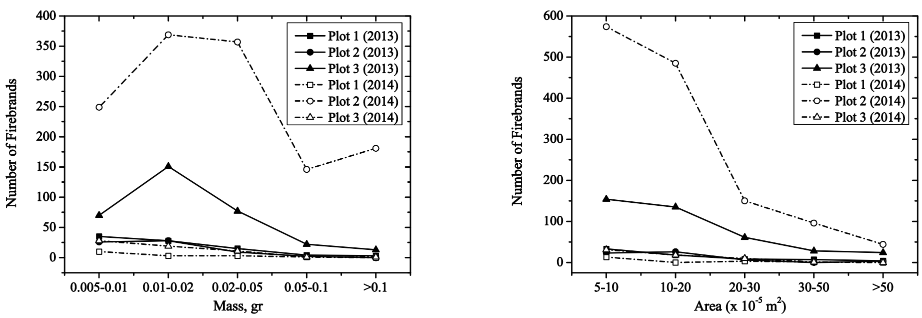

Figure 2. Firebrands distribution for different mass ranges and area

A substantially higher number of particles were collected in Plot 2 from EX2. This can be attributed to the fact that this plot was on the downwind edge of an area with more intense fire behavior, which included passive crowning (compared with the predominantly surface fire behavior observed elsewhere). Additionally, video footage revealed that the passage of this intense fire melted the plastic film, allowing the deposition of more particles.

The majority of firebrands weighed between 5 and 20 mg, and the maximum number of the particles was observed for the range of 10-20 mg. A size analysis of firebrands shows that the majority (42%-76%) were particles with a cross section area of (5-10) x 10^{-5} m^2. Cross sectional areas are estimated in EX1 by considering bark pieces as rectangles and branches as cylinders. About 80% of all particles had a cross sectional area in the range of (0-20) x10^{-5} m^2. These findings are in agreement with the case study findings of the Angora fire (Manzello and Foote, 2014) where more than 85% of holes that firebrands had made on trampolines were measured at less than 50 x 10^{-5} m^2.

IR Video Analysis
Due to the calibration that was chosen for the IR cameras, the maximum temperature was limited to 147 °C. This did not allow us to measure temperatures for all firebrands but it was the best way to detect most firebrands and their trajectories. Nevertheless, it was found that most of them are "cold", between 60 and 100 °C. Only 117 firebrands had a temperature above 147 °C.

Different characteristics of the particles moving in the flow were obtained after processing the video data from the thermal imagers. Figure 3 shows the number of the particles versus the distance to the fire front.

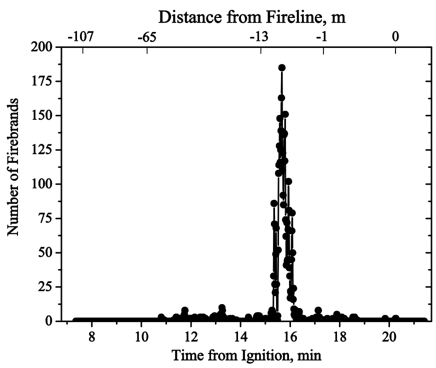

Figure 3. Amount of particles versus the distance to the fire front

Spread rates were obtained from fire isochrones created using the long-wave aerial IR imagery (Houssami et al., 2015). The isochrones were drawn by mapping the gradient of pixel intensity for each image and manually tracing a curve along the highest gradient. These were compared visually against the visible spectrum aerial imagery, and it was determined that this method was sufficiently accurate for determining the location of the leading edge of the fire front. By measuring the distances between fire isochrones in ArcGIS, it was possible to estimate spread rates. Knowing the position of IR cameras, fire front spread rate and time, we can calculate the distance from the fire front to IR cameras. The distance was calculated between nearest point of fire front line and IR cameras position.

Processing of infrared video (Fig. 3) showed that starting from a distance of 13 m from fire front, an increasing number of firebrands were observed in a controlled volume, increasing from only a few to 180 per second. At the same time, it is seen that the number of the particles is practically equal to zero at a distance of several meters before the fire front. This fact can be explained by the pre-burn removal of fuels on the plot to protect the equipment. Figure 4 shows the effect of wind speed on the velocity of the flying particles.

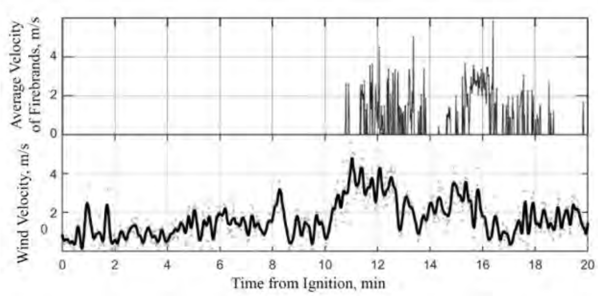

Figure 4. Wind characteristics and average velocity of firebrands versus time

Figure 4 clearly shows that the velocity of the particles depends on the wind speed. Between 10 and 20 minutes, the distribution of the maximum velocities has similar trends and magnitudes. We can assume that at low intensity surface fire the firebrands velocity follow by the ambient wind speed.

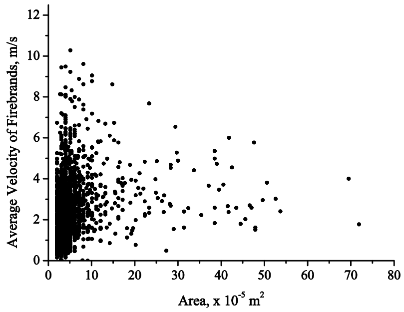

Figure 5. Average velocity of the firebrands versus the surface area

It can be seen from figure 5 that the increase in surface area of the particles leads to the decrease in average velocity. The maximum velocities are observed for the smallest particles. The velocities of the largest particles do not exceed 6 m/s. It is also seen that the particle velocity varies in the range of 0.1-10.5 m/s and the average velocity is 2.5 m/s. Analysis of the surface area of the particles has also shown that majority of the particles is in the range of 0-10 x 10^{-5} m^2, which is 89% of the total number of the particles. This number is in good agreement with the observed data (76%, Fig. 2). In addition, the number of the particles is similar to that on the curves in figure 2 and decreases with increasing the surface area.

Acknowledgements

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References

Babrauskas V (2003) 'Ignition Handbook'. (Fire Science Publishers: Issaquah)

Clark K, Skowronski NS, Gallagher MR (2015) Fire management and carbon sequestration in Pine Barren Forests. *Journal of Sustainable Forestry* **34**, 125-146.

Cohen JP (1991) 'A Site-Specific Approach for Assessing the Fire Risk to Structures at the Wildland-Urban Interface'. U.S. Department of Agriculture, Forest Service, Report SE GTR-69. (Ashville, NC)

Houssami M, Mueller E, Filkov A, Thomas JC, Skowronski NS, Gallagher MR, Clark K, Kremens R, Simeoni A (2015) Experimental Procedures Characterising Firebrand Generation in Wildland Fires. *Fire Technology*, 1-21.

Manzello SL, Foote EID (2014) Characterizing Firebrand Exposure from Wildland–Urban Interface (WUI) Fires: Results from the 2007 Angora Fire. *Fire Technology* **50**, 105-124.

McKeown D, Faulring J, Krzaczek R, Cavilia S, Aardt J (2011) Demonstration of delivery of orthoimagery in real time for local emergency response. SPIE Conf. on Conf. Algorithms Technol. Multispectral, Hyperspectral, Ultraspectral Imag. XVII, Orlando, FL, USA, 25.-28.

Pagni PJ (1993) Causes of the 20 October 1991 Oakland-Hills conflagration. *Fire Safety Journal* **21**, 331-340.

Knowing Fire: Understanding and Managing the Tacit Knowledge of Fire Held by Agency Staff Members

Anthony English, District Manager Western Basalt, Parks Victoria. 14 Mineral Water Drive, Daylesford, Victoria. Australia, 3460 Email: tony.english@parks.vic.gov.au

Introduction

In 2015 The Victorian Government released a document titled "Safer Together: A new approach to reducing the risk of bushfire in Victoria" (State of Victoria, 2015). Drawn from the hard won lessons of the last few fire seasons this report emphasises that government and the community will take a new and collaborative approach to identifying and managing fire risk in the landscape. The concept of knowledge is a critical element of the document. It emphasises that utilising scientific research and modelling, as well as local community understanding of landscape will drive this change.

It is timely then to analyse more closely what constitutes fire knowledge. This paper focuses on one element which like community based knowledge has tended to be overlooked; the tacit knowledge held by staff of land and fire agencies in Victoria. It explores the extent to which staff member's tacit fire knowledge is valued, critiqued and utilized by these agencies. It is argued that while the role of tacit knowledge in shaping fire practice is substantial, its scope and influence is poorly understood. To achieve the transformation outlined in "Safer Together", agencies will need to better understand its role and explore how tacit knowledge held by staff and the community can contribute to important organizational, social and environmental objectives.

Fire knowledge is attained by staff in a range of ways. Training and related activities focusing on the transfer of formal or explicit knowledge are important components of knowledge development. Much, if not most knowledge development however is the result of practical involvement in fire management and can be classed as tacit knowledge.

Tacit knowledge is knowledge that is not easily written down and derives from observing and doing. It is drawn from a person's subjective insights and intuitions, is context specific, not easily visible or expressible, is difficult to formalize or transfer and is a key driver of personal decision making (Kakabadse, et.al. 2001, Linde, 2001 and Stenmark 2001). It is argued here that tacit knowledge, and its use, is one of the primary determinants of how staff members apply fire management on the ground. People use their tacit knowledge to not only respond to situations in the field, but to also interpret and then apply formal training and agency procedures and policies.

The tacit knowledge referred to here exists at a variety of scales. It can include personal understanding of fire behaviour in specific landscapes, or awareness of how lighting patterns can be used to achieve planned burn objectives. Such knowledge, despite its elusiveness, is critical to the development of fire practice as it reflects the development of insight gained from years of observation, trial and error.

Why Draw out and Recognise Tacit Fire Management Knowledge?

There are at least six primary reasons why fire agencies need to better recognize and draw out the tacit fire knowledge of their staff:

(1) Tacit knowledge is a primary determinant of staff behaviour, decision making and performance. An employer can only manage and understand the skill base of their employees and gain insight to their work practices and culture if they appreciate the scope and form of their tacit knowledge and its influence on their decisions.

(2) Tacit knowledge is valuable and pivotal to driving organisational performance. It forms part of what Cabrera and Cabrera (2005) refer to as the “human capital” of organizations. In a fire agency it represents knowledge that can drive and generate efficiencies, overcome problems and provide insight for more formal research and strategy. It contributes to what Roux et.al. (2006) refer to as the co-production of knowledge across the science-operational divide.

(4) Despite its value and influence, it can be fragile and easily lost. When an experienced staff member leaves they can take with them knowledge and insights that cannot be replicated or easily captured in explicit forms like manuals and procedures.

(5) Tacit knowledge has local and cultural dimensions that can have a resonance with the community. Unlike explicit or formal knowledge, tacit knowledge and associated ways of working may reflect awareness of the needs, values and views of the local communities which agencies serve. Staff may use their tacit knowledge, which includes their social awareness, as a context to carry out their work in ways that engender community support and partnership.

(6) An organisation that recognises internal tacit knowledge will be better able to recognise the knowledge that exists in the community as it will be open to learning and engagement in its truest form.

Most importantly, recognition of staff tacit knowledge is an essential pre-cursor to the development of innovative organisations. Roux et.al (2006) has demonstrated that recognition is essential to the “co-development” of knowledge across the science management divide. They argue that innovation in land management practice is constrained in agencies by the presence of separate “operational” and “research” cultures that struggle to communicate and share knowledge. Valuing and drawing out the tacit knowledge of operational staff is shown to be a critical factor in breaking this barrier down.

In Victoria, this divide is real, and perhaps best illustrated by the challenge of integrating fire ecology practice into operational fire management. The initial interviews I have conducted with staff have revealed that they can possess significant knowledge about the relationship between fire and ecological condition. Despite this, they are rarely asked to reveal or discuss this knowledge and have little direct exposure to structured fire ecology research programs.

Understanding the Tacit Dimension in Fire Management

As Stenmark (2001) notes, tacit knowledge can be elusive. We are ourselves not necessarily aware of the tacit knowledge that we possess, can have little personal reason to share it, and may perceive sharing it as reducing our own competitive advantage. Its elusiveness can hide that fact that tacit knowledge is highly valuable and a critical driver of personal behaviour, attitudes and performance.

Sitting behind tacit knowledge is the formal or explicit knowledge that is relayed to staff in training courses, manuals and procedures. Referred to by researchers such as Polanyi (1966) as context-free theory, this formal knowledge is then applied, utilized and reshaped in its application, to suit specific circumstances and objectives on the ground. It is here that tacit knowledge shows its influence as staff members rely on the observed behaviour of their peers, their own personal experience, and their interpretation of procedures to direct their actions and decisions.

Blair et.al. (2010a and 2010b) have argued that land and fire agencies in Victoria have tended to see knowledge as an object to be imparted, rather than as a process that is embedded in social systems and personal experiences. This has meant that formal rather than tacit knowledge has been a focus of knowledge development and exchange systems in these agencies. They argue that this view of knowledge has restricted agency capacity to recognise and respect community based fire knowledge.

Two methods were used here to conduct a preliminary assessment of the scope and influence of staff member tacit knowledge on fire practice in Victoria. The first involved a personal review of how my own fire knowledge has developed, and is developing. This approach reflects the observed value of reflection as a learning tool (Kakabadse 2001). The second involved the conduct of a small number of interviews with staff that focused on their own knowledge development journey, and on specific elements of their tacit knowledge. This approach relied on the efficacy of learning history approaches to organizational knowledge gathering and exchange (Linde 2001, Department of Defence 2010, Parent and Beliveau 2007 and Elliot et.al. 2009).

Personal Reflection

My own experience in fire management sheds light on the way that tacit fire knowledge is developed and used, and I argue is typical of the experience of agency staff. I have become familiar over time as I plan and conduct subsequent planned burns with how different vegetation and fuel types in Central Victoria respond to varied lighting patterns. This knowledge and perspective has been shaped by my conversations with others (social), developed within a specific set of landscapes and activities (context), shaped by training, observation and doing (process), and by sight, sound and smell (modes of being). My personal experience of knowledge development therefore accords with the definition of knowledge applied by Blair et.al (2010a). It reveals that formal training in planned burning forms only one element in my knowledge development and in turn only one influence on how I actually conduct activities on the ground. I continue to use my direct experience to place the formal or explicit knowledge gained at training, into a context.

Observation of work place practices and the deployment of knowledge at planned burns and wildfires also reveal the critical role played by tacit knowledge in shaping fire practice. I have observed that individual teams believe that they have locally derived techniques for applying fire to the landscape that reflect their particular knowledge of landscape and fire behaviour. When discussing tactics and techniques it is common for staff to refer back to previous planned burns to illustrate the insight they have gained over time. This reflection is used to help justify or explain the way that they carry out their work. It is also not unusual to hear staff referring to crews sent to work in their area from other locations as requiring specific direction to ensure that they burn in a way that matches local conditions and by extension, associated norms and expectations. Published research has revealed similar insights to the role played by past experience and hence tacit knowledge, in shaping staff decisions and actions. A good example is cited in Elliot et.al. (2009) who report that staff experience of near misses and accidents is a major influence on their future planning and decision making.

Interviews with Staff

The small number of interviews I conducted with experienced staff also revealed information about how tacit fire knowledge is both developed and applied. These interviews explored specific elements of a person's tacit knowledge. Staff members were asked to reflect on how their understanding of the influence of variables such as season, vegetation types, crew behaviour and terrain on planned burning outcomes had developed across their career. This revealed the complex inter play that exists between explicit and tacit knowledge and reinforced the hidden but critical role played by the latter in shaping both decisions and outcomes.

Using the outcomes of these interviews and personal reflection, Table 1 seeks to identify some of the key factors that may be critical in shaping staff tacit fire knowledge in a fire agency. Their relevance and influence needs to be tested through structured inquiry.

Table 1: Potential Factors Shaping the Development and Use of Staff Tacit Fire Knowledge

Factor	**Knowledge Impact**
New legislation, policy and operating procedures	Generates changed procedures and practices that over time become embedded in staff behaviour and norms. As an example, comparison of work place safety practices over the last twenty years would reveal that significant change has occurred in staff behaviours and expectations associated with safe working procedures
Community based debates and expectations, for example about the value and conduct of prescribed burning	Staff members are embedded in social systems so they absorb debates and points of view being expressed in the community. This and their personal values will shape their attitude toward fire practice over time
New technology and equipment	Staff members learn how to do tasks differently and more effectively. This can accelerate staff capacity and innovation and generate flow on changes in fire practice
Personal experience over time such as exposure to different seasonal conditions and landscapes	Growth of staff awareness of factors that shape decision making and its outcomes such as the relationship between fuel types, topography, fire behaviour and operational tactics
Team dynamics	Staff may have access to significant levels of tacit knowledge within their teams. This knowledge helps form workplace norms or peer generated views about tactics, standards and procedures. See for example Hayes et.al., (2013)
Change in a staff member's personal fire role such as from a fire fighter to a planner or incident controller	Staff will re-evaluate their knowledge as they move into different roles and become exposed to different expectations, perspectives, information and systems

Current Approaches in Victoria

We can use this research context to assess how current approaches to knowledge management in fire agencies in Victoria may support or constrain the recognition and transfer of tacit knowledge.

Positive Dimensions

Positive dimensions of tacit knowledge review and exchange in Victoria include:

(1) The ongoing informal conversations, mentoring and debates about fire practice that occur at the local team level. These may constitute small or local "communities of practice."

(2) The presence of extensive and high quality formal training that has the effect of increasing the confidence and self-efficacy of staff and providing them with a context as individuals in which to develop and review their tacit knowledge. Publications used in fire training have at times sought to combine operational and research based knowledge (Tolhurst and Cheney, 1999).

(3) A strong sense of team and shared identity which allows some elements of social capital theory (Cabrera and Cabrera 2005) to thrive

In addition, the use of systems of competencies for fire roles is also bound up with the management and recognition of knowledge. Operationally, there are also numerous knowledge gathering or exchange processes in place that are routinely used in fire management settings. Common tools are debriefs, or After Action Reviews (AARs) which occur after individual events such as a prescribed burn or at a larger scale after a full fire season. AARs can identify important improvements in practice that can then be implemented by teams on the ground. The improvements identified are often derived from the expression of, or referencing to, staff tacit knowledge.

Negative Dimensions

These positive elements are combated by a number of factors including:

(1) A tendency, as noted previously, for agencies to view knowledge as an object to be imparted, rather than being a process (Blair et.al 2010). This generates a consequent lack of recognition of tacit knowledge and an inability to understand how staff knowledge is deployed in context.

(2) An emphasis on hierarchical structures that support command and control and which run counter to the importance of egalitarian work place cultures (Kakabadse et.al, 2001) and psychological safety (Edmondson and Lei, 2014) in supporting knowledge exchange within organisations. This specific challenge has been noted as affecting emergency services organisations in Australia (Owen, et.al., 2015)

(3) A related fragmentation of operational and research knowledge sets and a retention of the operational-science divide (Roux et.al, 2006) that mitigates against the co-production of knowledge.

(4) A strong reliance on formal knowledge management techniques such as AARs and debriefs that again, reflect a preference for hierarchical structures.

Changing the Approach

Four changes are outlined here that reflect the need to develop new approaches to knowledge exchange and development. It is argued that land and fire agencies should:

(1) Establish new work place systems such as “Communities of Practice” (CPs), cross-functional teams and performance management norms which create a more egalitarian work place culture and support the interaction between researchers, community and staff members.

(2) Adopt new forms of operational analysis that explore how staff use and develop their knowledge in context. Oral history and learning history approaches (Parent and Beliveau 2007) to knowledge gathering and review should form core elements of this approach. This may involve but not be limited to, pre-event review of the operational and policy context that

staff rely on when planning an activity. This could be followed by observation of staff behaviour and decision making at actual events, and then by post event interviews and comparative analysis that explores how tacit and explicit knowledge have variably influenced staff decision making and action.

(3) In line with this, agencies should fundamentally rethink the design of existing knowledge exchange processes such as AARs to better support explicit recognition and evaluation of staff tacit knowledge and connect these more formal processes back to ongoing conversations occurring within CPs and other egalitarian forums. AARs could adhere more closely to the CP model and revolve more around constructive debate than old style military review. The Students of Fire model, (Stebbing and Strickland, 2014) is an example of a CP that is already active and could be adapted to suit agency needs.

(4) Tap into the revolution that is occurring in the design and conduct of serious accident investigation by United States land and fire agencies. Exemplified by Pupulidy (2009), this work recognises that decision making in dynamic situations like wildfires is shaped by tacit knowledge. In this setting, investigations focus not on finding errors and ascribing blame to individuals. Instead, they seek to understand the context in which decisions were made and the conditions which prompted them to be formulated. This approach is a shift away from simple casual analysis to one that replaces use of hindsight with recognition of how knowledge is deployed by staff in certain circumstances. Pupulidy's review of the Panther Fire Fatality Incident is a pivotal illustration of both the presence of tacit knowledge in a work place, and its influence on decision making. It also highlights how tacit knowledge can be adapted and used to drive improvement. This approach can be broadened beyond accident investigation to looking at how tacit knowledge is deployed in standard operational settings.

If designed well, adopting these five changes could form a self sustaining loop of knowledge development and exchange.

References

Blair, S., Campbell, C, Wilson, A, and Campbell, M (2010a) Understanding, developing and sharing knowledge about fire in Victoria, Australia. Fire and Adaptive Management, Report Number 77. Published by the Department of Sustainability and Environment, Melbourne

Blair, S., Campbell, C and Campbell, M (2010b) A Case Study of a Strategic Conversation about Fire in Victoria, Australia. Fire and Adaptive Management Report Number 79. Published by the Department of Sustainability and Environment, Melbourne.

Cabrera, F., and Cabrera, A (2005) Fostering knowledge sharing through people management practices. International Journal of Human Resource Management 16(5), pp.720-735

Campbell, C., Blair, S and Wilson, A.G. (2010) Adaptive Management of Fire. The Role of a Learning Network. Fire and Adaptive Management Report Number 76. Published by the Department of Sustainability and Environment, Melbourne.

Department of Defence (2010) Defence Instructions (Army). The Army Oral History Program, Admin 34-3. Published by the Department of Defence, Canberra.

Edmondson A. And Lei, Z. (2014) Psychological Safety: The History, Renaissance, and Future of an Interpersonal Construct. Annual Review of Organisational Behaviour (1), pp.23-43.

Elliot, G., Omodei, M., and Johnson, C (2009) How Human Factors Drive Decisions at Fire Ground Level. Fire Note 44. Published by the Bushfire Co-Operative Research Centre and AFAC, Melbourne

Hayes, P., Omodei, M., and Cumming, G (2013) The Influence of Familiarity on Teamwork and Decision Making. Fire Note 106. Published by the Bushfire Co-Operative Research Centre and AFAC, Melbourne

Kakabadse, N.K., Kouzmin, A., and Kakabadse, A (2001) From Tacit Knowledge to Knowledge Management: Leveraging Invisible Assets. Journal of Knowledge and Process Management 8(3), pp.137-154

Linde, C (2001) Narrative and Social Knowledge. Journal of Knowledge Management 5(2), pp.160-171

Owen, C., Scott, C., Adams, R. and Parsons, D (2015) Leadership in Crisis: developing beyond command and control. Australian Journal of Environmental Management 30(3)

Parent, R., and Beliveau, J (2007) Organisational Knowledge Transfer: Turning Research into Action through a Learning History. The Electronic Journal of Knowledge Management Volume 5, Issue 1, pp.73-80, available online at www.elkm.com

Polanyi, M (1966) The Tacit Dimension. Routledge and Kegan Paul, London

Pupulidy, I. (2009) Operationalization of a Systematic and Human Performance Analysis for Serious Accident Investigation- US Forest Service Panther Fire Fatality Investigation. Doctor of Philosphy thesis, Lund University, Sweden.

Roux, D.J., Rogers, K.H., Biggs, H.C., Ashton, P.J and Sergeant, A (2006) Bridging the Science-Management Divide: Moving from Unidirectional Knowledge Transfer to Knowledge Interfacing and Sharing. Ecology and Society 11(1):4 [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art4/

State of Victoria, (2015) Safer Together: A new approach to reducing the risk of bushfire in Victoria.

Stebbing, R and Strickland, S (2014) Students of Fire: Learning and sharing our lessons- globally. Wildfire Journal. Published by the International Association of Wildland Fire.

Stenmark, D (2001) Leveraging Tacit Organisational Knowledge. Journal of Management Information Systems 17(3), pp.9-24

Tolhurst, K and Cheney, N (1999) Synopsis of the Knowledge Used in Prescribed Burning in Victoria. Published by the Department of Natural Resources and Environment, Melbourne.

Large-eddy simulations of pyro-convection and its sensitivity to moisture

William Thurston*[1,2], Kevin J. Tory[1,2], Robert J. B. Fawcett[1] and Jeffrey D. Kepert[1,2]
[1] Bureau of Meteorology, Docklands, Victoria 3008, Australia
[2] Bushfire and Natural Hazards CRC, East Melbourne, Victoria 3002, Australia

Introduction

Intense heating of air in the vicinity of a bushfire leads to deep ascent. If this ascent is deep enough to lift air above the lifting condensation level, cumulus or cumulonimbus clouds form in a process known as moist pyro-convection. There is abundant anecdotal evidence to suggest that pyro-convective clouds may have a significant impact on fire behaviour by (i) amplifying burn and spread rates (Fromm et al., 2012); (ii) enhancing spotting through plume intensification (Koo et al., 2010; Thurston et al., 2015); and (iii) igniting new fires via pyrocumulonimbus lightning, noting that pyrocumulonimbus lightning conditions favour hotter and longer-lived lightning strikes (Rudlosky and Fuelberg, 2011). Pyro-convective clouds are also responsible for the transport of smoke and other aerosols into the stratosphere, resulting in hemisphere-scale smoke transport and substantial climate impacts (Fromm et al., 2010). Therefore a knowledge of the processes that lead to the generation of moist pyro-convection is important for understanding and predicting fire behaviour, as well as the potential climatic influences of large fires. In this study we use large-eddy simulations to investigate the potential for the generation of moist pyro-convection by bushfire plumes. Firstly we perform simulations over a range of fire intensities and environmental moisture levels. Secondly we repeat a subset of these simulations with differing amounts of moisture released by the fire in order to assess the relative roles of environmental moisture and fire-derived moisture in the formation of pyro-convective clouds.

Methodology

Idealised simulations of bushfire plumes are performed using a cloud-resolving model, the UK Met Office Large-Eddy Model (LEM), described by Gray et al. (2001). The model configuration used here for simulating bushfire plumes with the LEM is described in Thurston et al. (2013), with some modifications as follows. The main change made is the inclusion of moist processes within the model, necessary for the simulation of pyro-convection. The model includes a three-phase microphysics scheme, which calculates the phase changes between the vapour, liquid and frozen water species. The domain top is also raised to 12.7 km to allow the vertical growth of pyrocumulus, which may have been restricted in our previous cloud-free simulations.

The model is initialised with a potential temperature profile consisting of a 4.0 km deep well-mixed layer, of a constant value of 310 K, and a stably stratified troposphere with a gradient of 3.0 K km^{-1} above the mixed layer. The initial water vapour mixing ratio profile is specified as a constant value throughout the 4.0 km deep well-mixed layer, and is then reduced above the mixed-layer top at a rate such that the relative humidity remains constant throughout the troposphere. This temperature and moisture profile characterises high fire danger conditions. The boundary layer is deep and well mixed, ensuring potential temperature and water vapour mixing ratio are constant, and the relative humidity increases with height. The model is initialised with no background wind, allowing us to concentrate on the effects of the thermodynamics on pyro-convective cloud formation.

A range of simulations is performed here, in order firstly to explore the sensitivity of the formation of pyro-convection to the background moisture and fire intensity. Five sets of initial conditions for the simulation of bushfire plumes are created by initialising the model as described above, with five different values for the (constant) boundary-layer water vapour mixing ratio, q_v, of 2.0, 2.5, 3.0, 3.5 and 4.0 g kg^{-1}. Bushfire plumes are then generated by imposing a localised intense heat flux at the model surface over a circular area of radius 250 m, centred at (x, y) = (0.0, 0.0) km. Four different fire intensities, Q, of 5, 10, 20 and 30 kW m^{-2} are simulated and in each case the heat flux is linearly ramped up from zero to its peak value over five minutes, then held constant for one hour, before being linearly ramped down back to zero over five minutes. The combination of five background moisture profiles and four bushfire intensities gives us twenty different simulations in total. In these simulations there is no representation of the moisture flux from the fire, either from moisture within the fuels or from the combustion process itself. We then repeat all five Q = 30 kW m^{-2} fire intensity simulations twice, once with a latent heat flux of $L.E.$ = 2.1 kW m^{-2} and once with a latent heat flux of $L.E.$ = 11.4 kW m^{-2}. These values are designed to represent the range of realistic ratios of heat to moisture fluxes from bushfires, based on the calculations of Luderer et al (2009).

Results

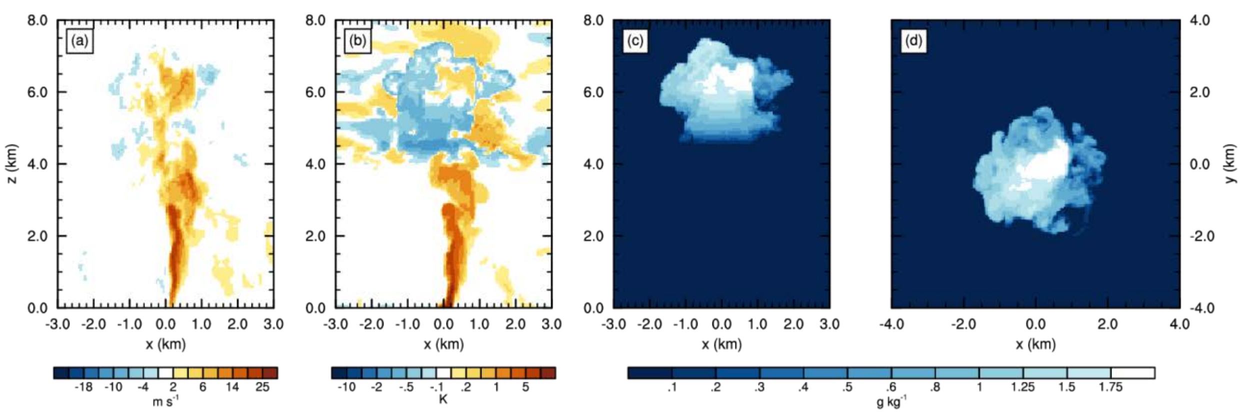


Figure 1: Vertical cross-sections of the instantaneous (a) plume vertical velocity, m s^{-1}, and (b) plume potential temperature perturbation, K, both in the y = 0 plane. Instantaneous liquid water mixing ratio, g kg^{-1}, maximum values in the (c) y− and (d) z−directions. All plots are shown at 22 minutes after the fire has reached full intensity and are for the Q = 30 kW m^{-2} fire intensity and q_v = 4.0 g kg^{-1} boundary-layer water vapour mixing ratio case.

Figure 1 shows a snapshot from the Q = 30 kW m^{-2} fire intensity and q_v = 4.0 g kg^{-1} boundary-layer water vapour mixing ratio simulation, 22 minutes after the fire has reached maximum intensity. The bushfire plume has a strong updraft throughout most of the extent of the boundary layer, with a maximum vertical velocity in excess of 25 m s^{-1}. The plume decelerates as it penetrates into the stably stratified troposphere, but the ascent is deep enough to trigger the formation of a pyrocumulus cloud. The cloud base is located at 4.5 km above ground level (AGL) and the cloud extends to an altitude of 7.5 km AGL. Although the bushfire updraft core is relatively slender within the boundary layer, the horizontal extent of the pyrocumulus cloud is much greater, having a diameter in excess of 3 km. Extensive condensation within the cloud, notable in the liquid water mixing ratio field around $(x,z) = (0.5,6.5)$ km, leads to the release of latent heat which is evident in the potential temperature perturbation field at the same location. There is a co-located updraft greater than 10 m s^{-1} within the pyrocumulus cloud, which is separated from the main plume updraft within the boundary layer. This resurgence of the updraft is due to latent heat release increasing the local plume buoyancy.

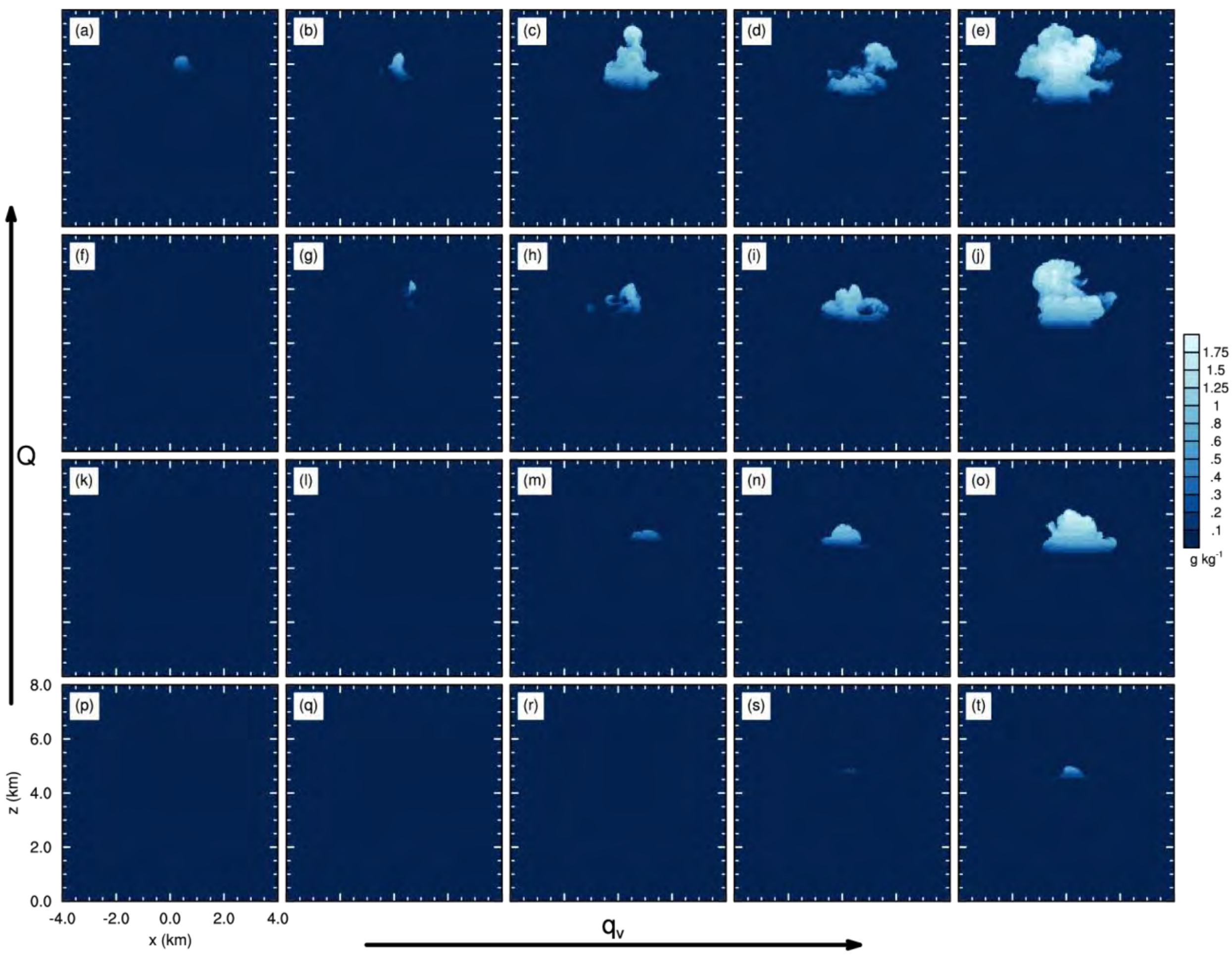


Figure 2: Vertical cross-sections of the maximum instantaneous liquid water mixing ratio in the y–direction, g kg^{-1}, at 22 minutes after the fires have reached full intensity. Panels show all twenty combinations of fire intensity, Q = (5,10,20,30) kW m^{-2}, arranged vertically and boundary-layer water vapour mixing ratio, q_v = (2.0, 2.5, 3.0, 3.5, 4.0) g kg^{-1}, arranged horizontally. Fire intensity increases from the bottom row of panels to the top row of panels and boundary-layer water vapour mixing ratio increases from the left-hand column of panels to the right-hand column of panels, as indicated by the arrows.

Figure 2 shows a snapshot of the liquid water mixing ratio vertical cross-sections for all twenty combinations of Q and q_v, at 22 minutes after the fires have reached full intensity. The potential formation of a pyrocumulus cloud and the properties of that cloud are dependent on both the intensity of the fire and the environmental moisture. Pyrocumulus is more likely to form if the environment is moist and the fire intensity is high. The size of a pyrocumulus and its cloud top height both increase with environmental moisture and fire intensity. In the driest environment, with a boundary-layer water vapour mixing ratio of 2.0 g kg^{-1}, pyrocumulus only forms for the most intense fire and the cloud that does form is very small. As the environmental moisture increases, pyrocumulus forms for weaker and weaker fire intensity, and by the time the boundary-layer water vapour mixing ratio reaches the maximum value of 4.0 g kg^{-1}, pyrocumulus forms for all values of fire intensity. For a fixed fire intensity, increasing the boundary-layer water vapour mixing ratio lowers the cloud-base height, from 5.7 km AGL for the driest to 4.5 km AGL for the moistest. Conversely for a fixed boundary-layer water vapour mixing ratio, increasing the fire intensity does not substantially affect cloud-base height.

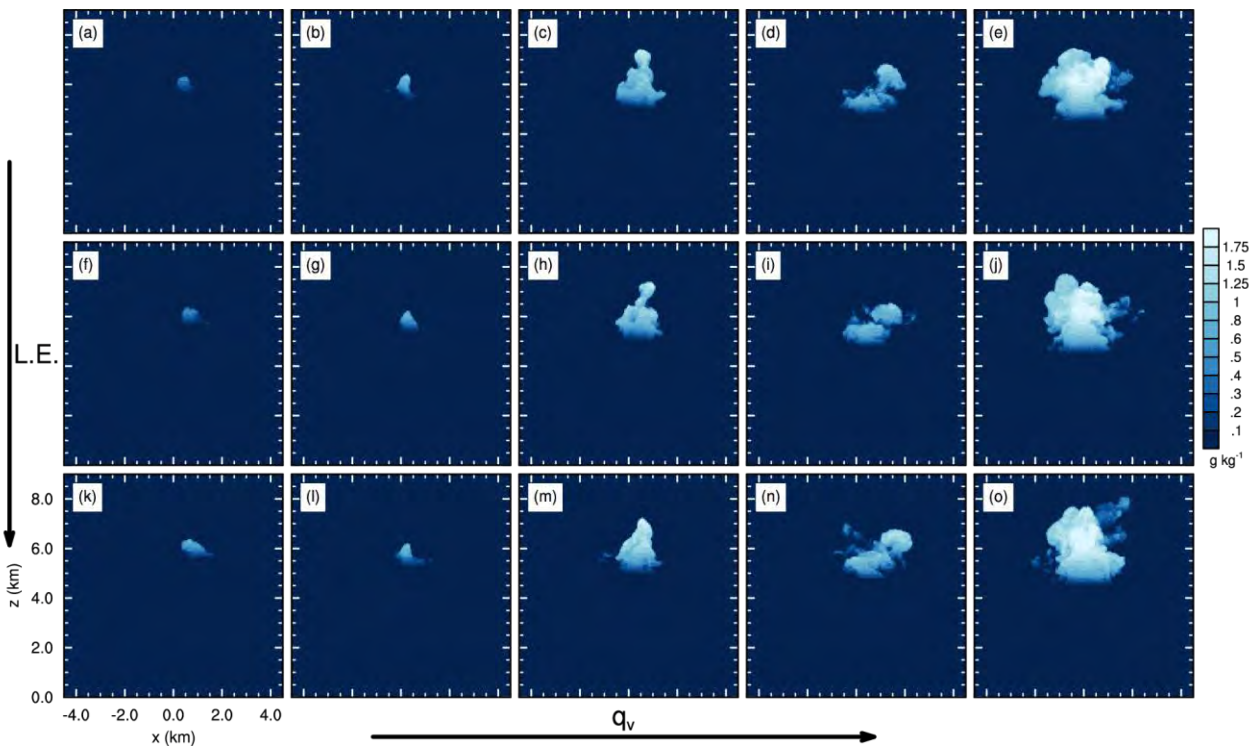


Figure 3: Vertical cross-sections of the maximum instantaneous liquid water mixing ratio in the *y*−direction, g kg^{-1}, at 22 minutes after the fires have reached full intensity. Panels show all fifteen combinations of fire latent heat flux, *L.E.* = (0.0,2.1,11.4) kW m^{-2}, arranged vertically and boundary-layer water vapour mixing ratio, q_v = (2.0, 2.5, 3.0, 3.5, 4.0) g kg^{-1}, arranged horizontally. Fire latent heat flux increases from the top row of panels to the bottom row of panels and boundary-layer water vapour mixing ratio increases from the left-hand column of panels to the right-hand column of panels, as indicated by the arrows. All simulations are performed with a fire intensity *Q* = 30 kW m^{-2}.

Snapshots of the liquid water mixing ratio vertical cross-sections for all five Q = 30 kW m^{-2} fire intensity simulations, with latent heat flux *L.E.* of (0,2.1,11.4) kW m^{-2} at 22 minutes after the fires have reached full intensity are shown in Figure 3. The effect of adding a latent heat flux to the fire is very small, slightly increasing cloud amount and cloud top height, for all of the boundary-layer water vapour mixing ratios shown.

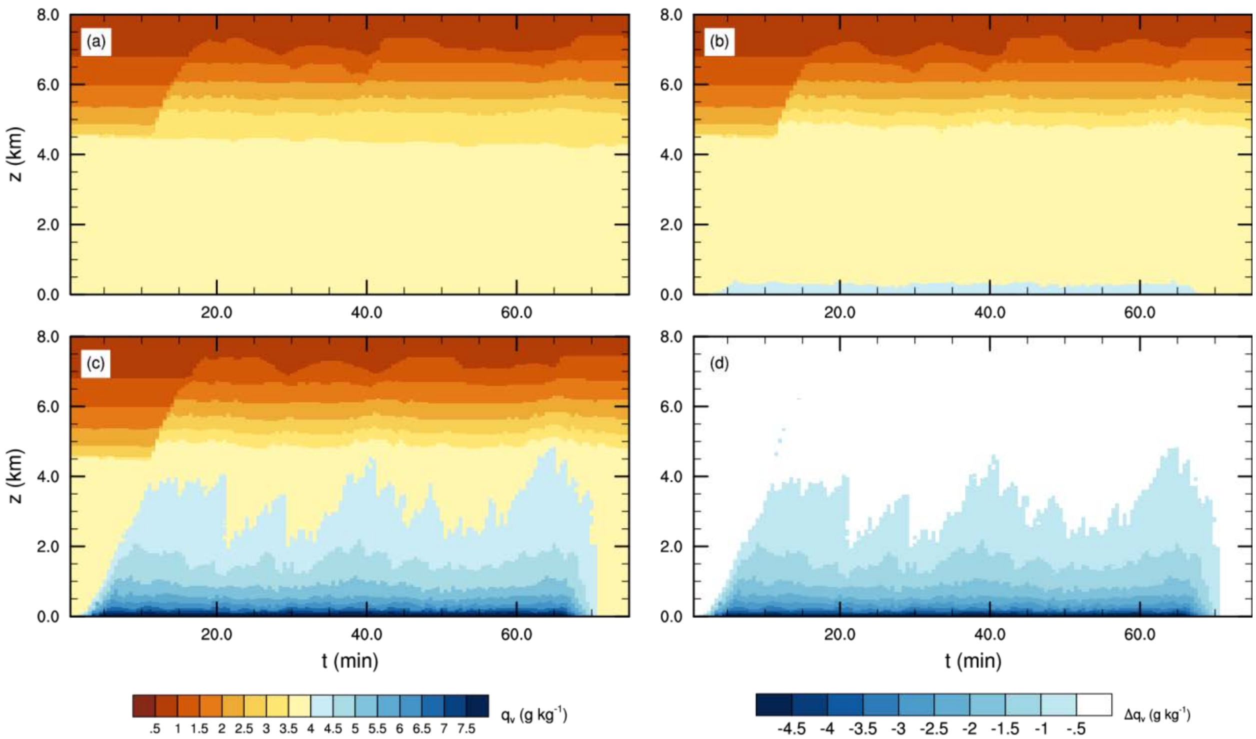


Figure 4: Time-height diagrams of the maximum instantaneous water vapour mixing ratio, g kg^{-1}, for simulations with fire latent heat fluxes, *L.E*, of (a) 0.0 kW m^{-2}, (b) 2.1 kW m^{-2} and (c) 11.4 kW m^{-2}. Panel (d) shows the difference between (a) and (c). All simulations shown are for the *Q* = 30 kW m^{-2} fire intensity and q_v = 3.5 g kg^{-1} boundary-layer water vapour mixing ratio case.

To investigate why the addition of a moisture source, in the form of a latent heat flux, to the fire has only a small effect on pyrocumulus formation, we construct time-height diagrams of the maximum water vapour mixing ratio at each model level (Figure 4). In the zero latent heat flux case the boundary-layer water vapour mixing ratio is constant throughout the simulation and the lifting of the boundary layer air by the plume into the relatively dry free troposphere is evident after about 10 minutes. In the *L.E.* = 2.1 kW m^{-2} case, the water vapour mixing ratio is greater near the surface, above which the moisture becomes more diffused with height and is similar to the zero latent heat flux case. Even in the *L.E.* = 11.4 kW m^{-2} case, the moisture released by the fire is only just reaching the top of the boundary layer, where it is then able to have a minimal effect on pyrocumulus formation. The amount of moisture that gets transported upwards in the *L.E.* = 11.4 kW m^{-2} case is made clear by the difference plot of time-height water vapour mixing ratio in Figure 4 (d).

Summary

We have performed large-eddy simulations of bushfire plumes in background atmospheric conditions representative of high fire-danger days. Firstly the potential for the formation of pyro-convection has been investigated by varying the fire intensity and environmental moisture. Then the relative importance of environmental and fire-derived moisture has been assessed by repeating a set of fixed-intensity runs twice, with latent heat fluxes representative of dry and moist fuels respectively. Intense fires in moist atmospheres formed larger pyrocumulus than weak fires in dry atmospheres, which in some cases formed no pyrocumulus at all. Increasing the environmental moisture reduced the cloud-base height, whereas increasing the fire intensity had no discernible effect on cloud-base height. Adding latent heat flux to the fire, to simulate the release of moisture within the fuel and by the chemistry of combustion, only has a small effect on pyrocumulus formation. This is because even for high rates of moisture release, this moisture becomes diluted as is transported by the plume to the top of the boundary layer.

References

Fromm M, Lindsey DT, Servranckx R, Yue G, Trickl T, Sica R, Doucet P, Godin-Beekmann S (2010) The untold story of pyrocumulonimbus. *Bulletin of the American Meteorological Society* **91,** 1193–1209.

Fromm MD, McRae RHD, Sharples JJ, Kablick III GP (2012) Pyrocumulonimbus pair in Wollemi and Blue Mountains National Parks, 22 November 2006. *Australian Meteorological and Oceanographic Journal* **62,** 117–126.

Gray MEB, Petch J, Derbyshire SH, Brown AR, Lock AP, Swann HA, Brown PRA (2001) Version 2.3 of the Met Office large eddy model: Part II. Scientific documentation. Turbulence and Diffusion Note 276, UK Met Office, 49 pp., Exeter, United Kingdom.

Koo E, Pagni PJ, Weise DR, Woycheese JP (2010) Firebrands and spotting ignition in large-scale fires. *International Journal of Wildland Fire* **19,** 818–843.

Luderer G, Trentmann J, Andreae MO (2009) A new look at the role of fire-released moisture on the dynamics of atmospheric pyro-convection*.* *International Journal of Wildland Fire* **18,** 554–562.

Rudlosky SD, Fuelberg HE (2011) Seasonal, regional, and storm-scale variability of cloud-to-ground lightning characteristics in Florida. *Monthly Weather Review* **139,** 1826–1843.

Thurston W, Tory KJ, Fawcett RJB, Kepert JD (2013) Large-eddy simulations of bushfire plumes in the turbulent atmospheric boundary layer. *MODSIM2013, 20th International Congress on Modelling and Simulation,* J. Piantadosi, R. S. Anderssen, and J. Boland, Eds., Modelling and Simulation Society of Australia and New Zealand, 284–289. ISBN: 978-0-9872143-3-1.

Thurston W, Tory KJ, Fawcett RJB, Kepert JD (2015) Large-eddy simulations of pyro-convection and its sensitivity to environmental conditions. *Research proceedings from the Bushfire and Natural Hazards CRC & AFAC 2015 Conference*, M. Rumsewicz (ed.), Bushfire and Natural Hazards CRC, 148-160, ISBN: 978-0-9941696-5-5.

Lessons from the operational application of Himawari-8 products

Rick McRae
ACT Emergency Services Agency, Canberra, Australia, rick.mcrae@act.gov.au

Introduction

For decades, Australia has used imagery from Japanese geostationary satellites as its primary source of weather imagery. The latest in this family - Himawari 8 (H8) - was commissioned late last year, and has been operational for the austral summer just finished. With its use of the latest generation of hardware, there were expectations of significant benefits arising from it. A workshop at the 2015 AFAC Conference provided an overview of the potential of H8 and of what users expected from it. This paper presents some of the findings from the operational use of the imagery, and some key lessons learnt.

Table 1: Comparison with previous satellite

Parameter	MTSAT-2 (HIMAWARI-7)	HIMAWARI-8
Repeat time	1 hour	10 minutes
Channels	5: 1 visible 2 thermal IR 1 water vapour 1 near IR	16: 3 visible 6 thermal (long-wave) IR 3 water vapour 3 near IR
Ground resolution (nominal)	1km visible 4 km IR	05 – 1 km visible & near IR1 2km IR

The changes in Table 1 promised operational benefits that were both improvements on previous capabilities and new capabilities. This paper presents the results of my work as a risk analyst, fire behaviour analyst and research scientist working closely with incident managers.

As we approached the summer a range of plans were being implemented to:

- Provide rapid access to basic imagery
- Provide value-added access to imagery, such as animations.
- Provide value-added products derived from imagery, including (a) hotspots and (b) EUMETSAT-standard RGB composite products.
- Archives to aid post analyses and scientific studies.

A number of on-line sources of imagery were utilized.

- The Meteorological Satellite Center of Japan Meteorological Agency provides key imagery and all standard RGB composite products as static JPEG images, including a wide range of regional subsets. This site has the lowest latency but reduced resolution.
- The Bureau of Meteorology has kept using MTSAT2 for standard products but built a special H8 viewer. The supply of MTSAT2 images has stopped.
- The Space Science Engineering Centre at the University of Wisconsin/Madison included H8 imagery in its versatile RealEarth system, using WMS technology.

- The Regional and Mesoscale Meteorology Branch at Colorado State University posts a series of H8 products, providing static subset JPEG images.

Can we detect fires?
It was found that fires above threshold intensities and extents (i.e. radiative power) could be reliably detected if the sky is clear (Fig 1A). The ability to do so drops as cloud cover increases. Detection can be done with visible imagery (seeing the fire and its smoke), with near infrared (seeing the radiated glow of the fire) and the 3.9μ infrared channel (seeing the heat emitted by the fire and its surrounds).
The latter was also found to work well at night. While the VIIRS satellite provides useful high-resolution nighttime visible images of fires, it provides only one pass per night. H8 provides a near-real time dynamic view of fires through the night.
Fire detection is aided by the animation of the 10 minute imagery.

Can we monitor fires?
With H8's improved resolution and better orbital stability, it is possible to monitor fire dynamics in near-real time. This requires a fire of sufficient intensity to affect multiple pixels and a clear sky. While most fires will not rapidly move between 1km-scale pixels, some do. Fires near Esperance, WA, on 17 November 2015 moved nearly 100km in an afternoon (Fig 1B). A number of archival animations of these fires were produced.

Can we track smoke plumes?
A number of aspects of smoke plumes can be assessed using H8 imagery. Visible bands allow the extent of a plume to be determined (Fig 1C). The plume injection height may be determined from the cloud top temperature. Wind shear can be assessed in some cases through animation of plume movement. Cloud colour can confirm a pyrogenic origin. The interaction of plumes with fronts, convergences and gravity waves can be detected.

Can we detect pyroCb events?
The major pyro-convective event that has been tracked using H8 was the Waroona Fire in Western Australia on 6 Jan 2016 (Fig 1D). This fire pulsed to form pyroCbs on three occasions. H8 data were used by researchers to (i) verify pyroCb formation, (ii) assess the height of the cloudtop and (iii) track the advection of smoke. This allowed far better discrimination of critical features than did previous satellites.

Can we track other important weather phenomena?
H8 imagery, like that from other satellites, has value for tracking a number of critical weather events. While H8 does not provide the best imagery in most cases, it does provide the best mix of imagery and repeat time for emergency uses.

Severe thunderstorms show the low temperatures of their anvils and overshooting tops (Fig 1C). H8 imagery can be combined with radar and lightning data in a GIS environment, using WMS feeds. Such overlays require all feeds to have balanced repeat times and latencies. Animated imagery of tropical cyclones (typhoons) has been well studied north of the Equator.

Other weather features of importance to emergency services can be tracked. Knowing the urban heat island intensity (Fig 1F) is important for field crew health and safety and for public safety. Fog (Fig 1G) can affect public safety, smoke dispersal and fireground aviation.

Is the balance between resolution and repeat time useful?
Discussions with operational staff show that H8 is broadly considered a significant improvement on past systems. There is a desire for better resolution, as this would allow smaller fires to be detected. The majority of image display systems do not provide full resolution, and some users have expressed concern about that. For general public users, the consideration of internet bandwidth might justify reduced resolution, but for technical users this is not an issue. Most users express no need for repeat times below ten minutes. The key area for improvement would be the latency in post-processing. Some systems provide a 10 minute latency, but for the majority this sits at around 45 minutes at present. With time, this should decrease as systems are improved.

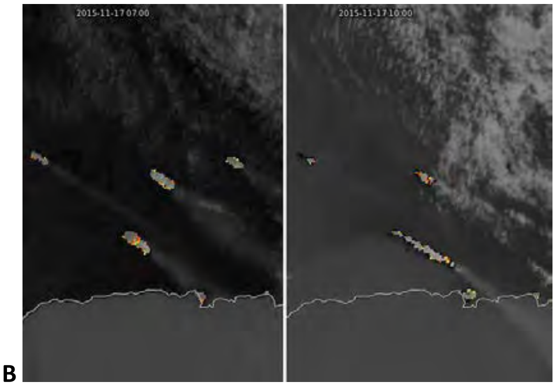
What are potential errors to watch out for?
The primary error for users of H8 imagery is not checking the date-time stamp of the imagery. Not all providers offer a high guarantee of service, and unannounced changes in latency can cause errors, which can be serious in a suppression context.

Most operations staff are familiar with interpreting visual and thermal infrared imagery. In these cases there has been a monotonic colorbar ranging from white to black. The use of real colour RGB products with channel scaling may cause confusion until familiarity is acquired. RGB composites require training and familiarity, and this has commenced. Imagery such the standard 3.9µ products have a colorbar with a colours applied for temperatures above a threshold. Most fires show up through their colour pattern, but many users would fail to pick up a low intensity fire that shows only as grey-scale changes, all near black. There is a common perception that colour means fire. When hot ground saturates that color bar, a high level of technical skill is required to detect fires.

The satellite is well off-zenith in Australia and this can cause interpretation problems. The anvil of a pyroCb is projected onto the ground well to the south of its true plan position. Detected surface heat signatures will thus appear on the north side in the imagery. This can be misinterpreted as a northerly upper level steering wind or that southerly fire flanks are less intense.

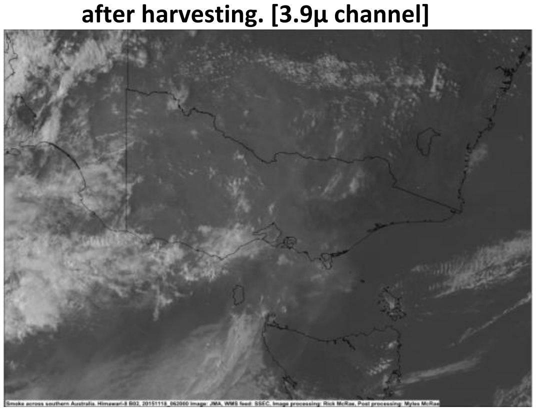
A

Wheat stubble burns, NSW & Vic, 22 Apr 2016. These burns are typically lit in the late afternoon after harvesting. [3.9μ channel]



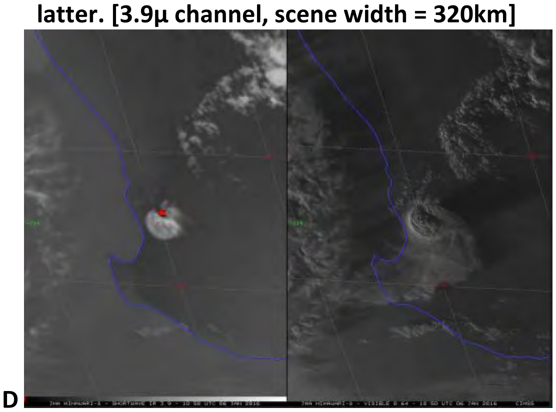
B

Evolution of fires between 07UTC and 10UTC, 17 Nov 2015, Esperance, WA. Note cloud blocking in the latter. [3.9μ channel, scene width = 320km]



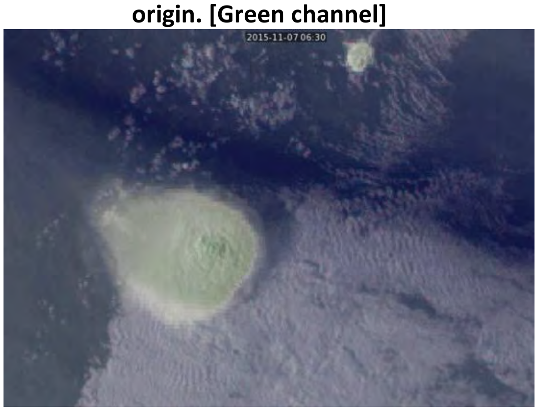
C

Smoke from Western Australia passing over Victoria, 18 Nov 2015. If widespread smoke is seen in an area, it is useful to be able to calculate its origin. [Green channel]



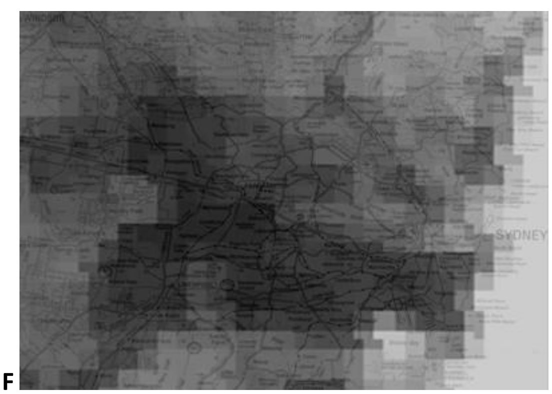
D

PyroCb event, Waroona Fire, WA, 6 Jan 2016. [Left: 3.9μ channel, right: Red channel. Imagery: Scott Bachmeier, CIMSS]



E

A dry slot and an associated thunderstorm over Newcastle, NSW, 7 Nov 2015. Both were tracking to the north. This unusual storm was involved in an aircraft crash. [A mix of RGB composite and low-level water vapour channel]

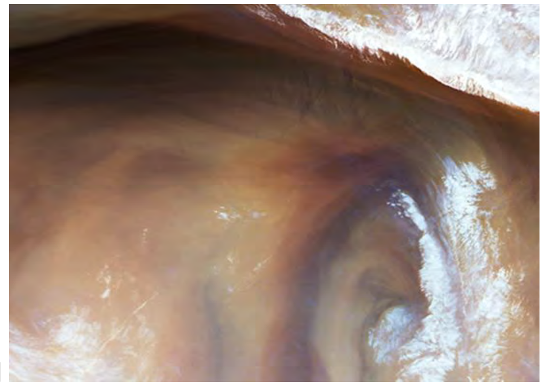


F

Urban heat map of Sydney, NSW, 10 Nov 2015. Urban heat in general is an area where much is yet to be learnt both for community risks and for emergency crew safety. [3.9μ channel]

G

Widespread valley fog in SE Australia. 08:00 am, 29 Jun 2015. [preliminary RGB composite]



H

RGB composite image using three water vapour channels. [Red: low level, Blue: high level]

Figure 1. Imagery examples.

What else needs to be done?

As mentioned above, the latency of on-line systems needs to be improved as much as possible. The reliability of feeds also needs to be improved, as emergency services are likely to become increasingly reliant on H8 data for developing situation assessments.

In terms of basic imagery, user needs - with respect to projection and application of colorbars - need to be reviewed. In terms of value-added imagery, there are a number of issues. The EUMETSAT composites are currently provided at a resolution that is too coarse to aid in wildfire management, and are JPEG images containing compression fringes.

I would make a personal request for an RGB composite product from the three H8 water vapour channels (Fig 1H). Draft products circulated for comment have been well received. They allow a visualization of the three-dimensional dynamics of the atmosphere, including detection of dry slots, gravity waves and undular bores.

While LandGate has successfully implemented a hotspot system using H8 data, and Geoscience Australia is implementing another system, the users need to explore what can be done with the hotspot data. Key users are assessing whether the hotspot algorithms are working optimally.

McRae and Featherston (2015) did a continent-scale seasonality review using MODIS data.H8 data does not automatically augment that dataset. The main issues are the different resolution and the shorter repeat time yielding a far denser depiction for many fires. Making this backwards compatible with MODIS archives will require significant effort.

Research topics arising from H8:

The improved discrimination of elements of the environment achieved through the use of H8 imagery has opened up some research questions. Some indicative examples are given below.

In grasslands on a hot day with clear skies, the difference between the ground temperature, as shown in the 3.9μ channel, and the air temperature (either measured or modeled) is a direct function of curing. This suggests that evapotranspiration is modifying the ground temperature. This in turn offers insights into both urban heat island effects and climate change modeling.

The Waroona Fire appeared to be affected at one point by an undular bore (Fig 2A), which was detected moving across the region in H8 imagery. These have been associated with past pyroCb events in Australia (Fawcett *et al.*, 2013) and Asia. With the improved resolution of H8 we should be able to gain an improved understanding of these events. H8 imagery is showing "Glory Clouds" (Fig 2B) to be relatively common in situations like cold fronts passing the southern and eastern coasts, and in systems moving across the Timor Sea. These are related to bores, and understanding both may lead to better understanding of the stability environment of blow-up fires.

Smoke from the Esperance fires (Fig. 1B) became entrained in offshore gravity waves and advected laterally over large distances (Fig 2C). This contributed to the situation in Fig. 1C. Current smoke models will struggle with this process.

Conclusion:
For the first time we can observe the dynamics of the entire Australian pyro-environment. We clearly have a lot to learn. Many things now considered unusual may soon be considered normal.

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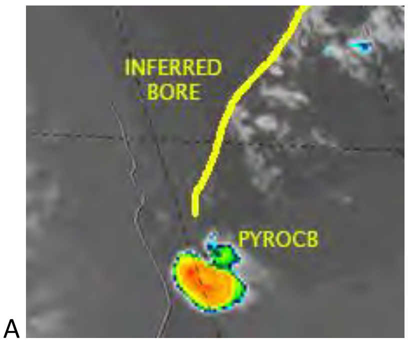
Scott Bachmeier (University of Wisconsin – Madison) and Dan Lindsey (NOAA) provided access to value-added material. Stuart Matthews (NSWRFS) and Richard Woods (ACTRFS) provided operational feedback. Ron Craig (Landgate) David Hudson (Geoscience Australia) and Denis Margetic (Bureau of Meteorology) provided input to the H8 workshop prior to the fire season.

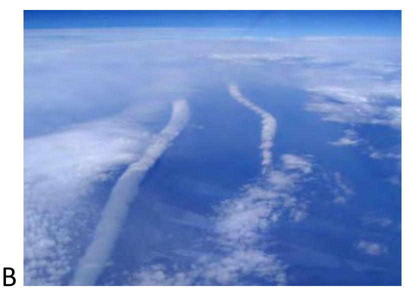
References
Fawcett, RJB, Wain, A, Thurston, W, Kepert, JD Tory, KJ (2013) A comparison of the fire weather characteristics of the Melbourne dust storm (1983) and Black Saturday (2009): a high-resolution ACCESS case study. *Proceedings, 20th International Congress on Modelling and Simulation, Adelaide, Australia*.

McRae, R, Featherston, G. (2015) Assessing mitigation of the risk from extreme wildfires using MODIS hotspot data. *Proceedings, 19th International Congress on Modelling and Simulation, Gold Coast, Australia.*



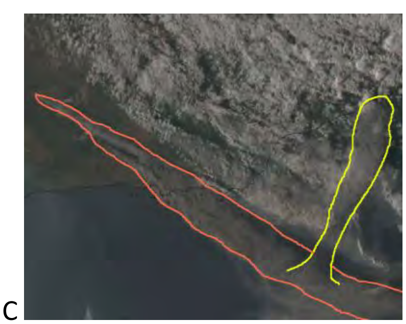
A

Possible undular bore impact on Waroona Fire, WA, 6 Jan 2016 11:00UTC.



B

Glory clouds near Esperance (Photo: Rod Dickson, Virgin Airlines)



C

Laterally advected smoke (yellow outline) from main plume (orange outline), Esperance fires.

Figure 2.

Leveraging smart phone technology for assessing fuel hazard in fire prone landscapes

Luke Wallace*[1,2], Bryan Hally[1,2], Karin Reinke[1,2], Simon Jones[1,2], and Samuel Hillman[3]
[1]School of Sciences, Mathematical and Geospatial Sciences, RMIT University, Melbourne, Australia, Luke.Wallace2@rmit.edu.au
[2]Bushfire and Natural Hazards Cooperative Research Centre, Melbourne, Australia
[3]Department of Environment, Land, Water & Planning, Colac, Victoria 3250

1 Background

Evaluating fire hazard in the landscape requires localised information describing the properties of the vegetation.The collection of this information typically involves attribution of fire fuel properties at plot scales, including vertical and horizontal structure, fate (dead or alive), the degree of curing and moisture content, based on ocular estimates. Although these estimates follow guidelines, such as presented in Hines et al. (2010), the results have been shown to be subjective (see Watson et al. (2012)) and do not provide the quantitative information required for input into advanced fire and risk modeling procedures.

Remote sensing information, captured from airborne and satellite platforms, has been shown to be a viable option for providing landscape-level vegetation description (Mutlu et al., 2008; Kramer et al., 2014; Martin et al., 2015). However, estimates of fuel hazard and fire risk made using remote sensing still require input at the local (or plot) level for calibration and validation purposes. Martin et al. (2015), for example, demonstrated the significant improvements that ground observations made to estimates of grassland curing produced using the MODIS satellite sensor.

Terrestrial remote sensing techniques can provide an alternative (or complementary) source of information to traditional field assessments and large scale remote sensing used to quantify and describe vegetation properties. Terrestrial laser scanning, from both mobile and static platforms, can provide precise information describing the amount and 3D arrangement of fuel (Olsoy et al., 2014; Gupta et al., 2015) otherwise unavailable from visual assessments and large scale remote sensing. Despite these benefits, laser scanning technology remains limited for operational deployment and uptake due to the cost of instrumentation and expertise required to operate scanners in the field.

Computer vision and photogrammetric algorithms, which utilise overlapping imagery, are currently being employed in a wide variety of fields to provide information describing the 3D structure of the surrounding environment. For example, 3D information has been collected to describe the structure of vegetation in both forest (Liang et al., 2014) and agricultural settings (Bendig et al., 2015). Unlike other remote sensing techniques, the collection of this information requires relatively low-cost sensors (such as consumer-grade digital cameras) and lower expertise for data collection in comparison to laser scanning technology.

2 Objectives and organisation

The objective of this paper is to present initial developments of a proposed workflow for collecting fuel hazard information using smartphone technology. The workflow makes use of point clouds generated from imagery collected using smartphone technology to derive structural information for use in fuel hazard assessments.

3 Image based point clouds

Structure from Motion is a technique developed in the early 1990s to recover 3D geometry from a set images (Snavely et al., 2006). To achieve this 3D reconstruction, a feature detection algorithm, such as SIFT or SURF, is used to locate and describe features within every image. Such features could include salient points in the image, corners of objects or lines. The extracted features are then associated to their corresponding instantiations in other images. Knowing the locations of several features in multiple images allows estimates of the 3D camera location and 3D point coordinates in relative image-space to be made based on the principles of photogrammetry (Snavely et al., 2006). The coordinates of camera locations and features are provided in an arbitrary space, which can then be transformed (scaled, rotated and translated) into object (or real-world) coordinates based on a small number of ground control points.

Several software packages (both open-source and commercial) are now available to recover 3D geometry using the SFM approach. As poor geometry image capture can result in ambiguity and resultant errors in the image matching process. These packages require image sets to contain a high degree of overlap that capture full three-dimensional structure of the scene viewed from a wide array of positions.

4 Proposed Fuels3D workflow

Fuels3D is a proposed tool set for the collection of quantifiable information describing current fuel hazard. This set of tools aims to make use of already existing infield technology (i.e. smartphones or other cameras), SfM algorithms and the prevalence of cloud computing. As such, Fuels3D consists of a user (or smartphone) data collection segment and a cloud-based processing segment (Figure 1).

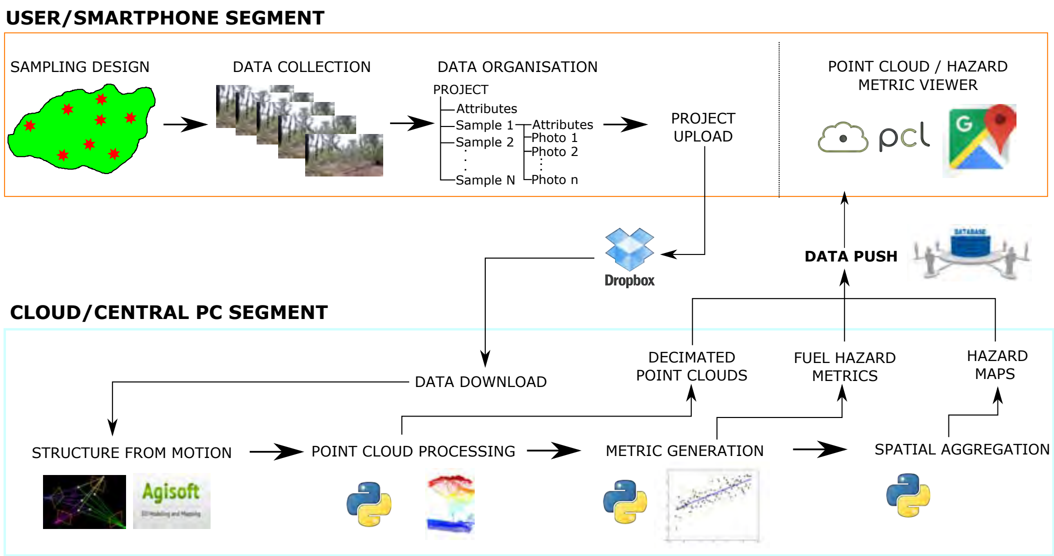


Figure 1: A schematic view of the proposed structure of Fuels3D workflow.

In the workflow, depicted in Figure 1, a project represents a user defined area (e.g. planned burn unit) and acts as a data container for the images and attributes of samples collected.

Once all samples for a project are collected, the data is pushed into the data processing segment which processes the images into point clouds, from which attributes on the fuel hazard can be derived. The results are then pushed back to the user.

5 Initial developments

The project is currently in a pre-alpha stage of development. This stage is designed to enable the collection of samples for the calibration of the information provided by the SFM algorithms. To achieve this a pre-alpha app ”Fuels3D” has been developed and provided to various Australian land management agencies for testing. A workshop was provided to these users to provide an overview of the current app workflow, the preferred image capture method, including a proposed Fuels3D sampling reference quadrat. A summary of the information provided to workshop attendees follows.

5.1 The Fuels3D app

This current version of Fuels3D allows for the creation of projects, the collection of samples and the uploading of data to a cloud based service. Projects are defined according to the Tier 1 fuel growth form and cover classes outlined in the draft Australian Bushfire Fuel Classification (Australasian Fire and Emergency Service Authorities Council, 2015). Samples consist of image sets and additional (optional) attributes. Currently, additional sample attribution has been extended to allow for calibration data (e.g. dry harvested weight per sample) to also be included.

5.2 Image Collection Protocol

A image collection protocol was provided to workshop attendees. This protocol includes instructions on how to capture an image network with strong geometric properties and sufficient overlap to achieve an accurate reconstruction of the fuels 3D structure. Specifications for a reference quadrat that is used to define a sample area, and also to provide scale for the resultant point cloud were also included. The reference quadrat is composed of 10 mm diameter PVC pipe and includes scaling marks placed at 20 cm intervals on four vertical poles. Images are collected to form a dome over the reference quadrat 2. Users are instructed to capture a minimum of 15 photos from a distance of approximately 1 m from the reference frame location at random positions to form the dome. All images should be focused on the center of the sample area.

6 Case study

6.1 Study site and reference data

Samples were harvested at 10 m intervals along a transect in a grassland in Sebastian, Victoria, representative of an open grassland fuel type. Clumpy standing grass, thatch and visible mineral earth were present at most sample locations. Vegetation was destructively sampled from within a 0.25 m^2 sample.

6.2 Image collection and point cloud processing

Data was collected by volunteers from the Victorian Country Fire Association following the field protocol outlined in section 5.2. A Samsung Galaxy Core Prime smartphone with a 5

Figure 2: An simulated example of how images can be collected to provide strong geometry for 3D reconstruction of the scene. The figure also shows an example of a scaling quadrat.

MP back facing camera was used to capture between 49 and 62 images of each sample. In this case, a firefighter's helmet of known dimensions was placed next to the sample location to provide scale. Each set of images took the observer less than 5 minutes to collect. Images were uploaded by the observer to the Fuels3D dropbox.

6.3 Image processing

Downloaded images were processed using Agisoft Photoscan Professional software to produce a 3D representation of the vegetation structure. The high and medium-quality settings were used for image matching and the building of dense point cloud processing stages respectively. Known dimensions of the helmet were manually digitised in six images to provide scale. The resultant dense point cloud was exported to las format for further processing.

Vegetation depth was calculated from the dense cloud based on the estimated depth of fuel in the cells of a 5x5 cm grid. To estimate fuel depth, ground points were extracted and above ground points normalized using a combination of the lasground and lasheight tools of lastools. Vegetation depth was calculated as the 90^{th} percentile of the above ground heights of all points from the normalised point cloud that fell within each grid cell. Vegetation volume was then calculated as the grid cell area multiplied by the vegetation depth. Correlation analysis between volume and field measure vegetation dry weight was then used for validation of the approach.

6.4 Results and discussion

Feedback from the volunteer observers were that they were able to follow the image capture protocol easily and quickly, providing image sets with strong geometric properties for the 3D reconstruction of the surround grassland environment. As a result, the SFM software was able to adequately reconstruct the 3D structure of the grassland environment in all 9 samples (for an example see Figure 3a).

The Sebastian site contained grass fuel loads between 1.15 and 3.79 t/ha . Strong correlation (r2 = 0.83) was found between the harvested dry weight and SFM estimated field observations of samples (Figure 3b). This result highlights the potential of the technique in sparse grassland. Further investigation will be undertaken into more challenging environments with complex fuel layers such as long grasses and shrublands.

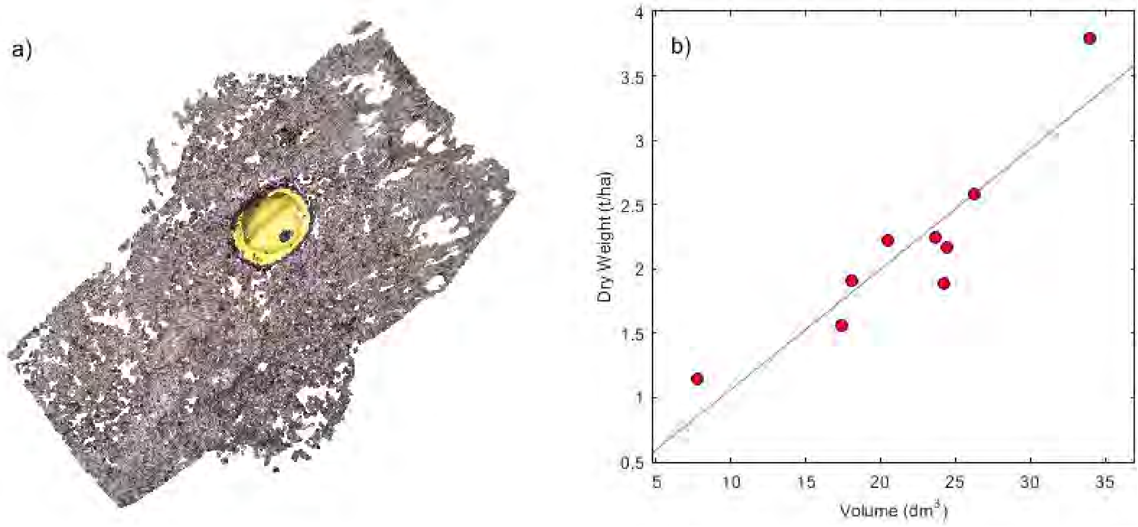


Figure 3: a) an example point cloud derived from the photoset of one sample and b) A scatter plot showing the correlation between dry weight and vegetation volume estimated from the point clouds.

Although, the helmet is not an optimum source of scale, due to poorly defined reference points, its use in this case study demonstrates the flexibility of the proposed technique. Stronger correlation may be achieved when scale is provided by a more easily identified control such as the reference quadrat with pre-measured markers. Ongoing research is being undertaken to determine a source of control that balances functionality (both in field and processing) with accuracy.

Acknowledgments

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References

Australasian Fire and Emergency Service Authorities Council (2015) Bushfire fuel classification. *Tech. rep.*, Department of Computer Science, Michigan State University.

Bendig, J., Yu, K., Aasen, H., Bolten, A., Bennertz, S., Broscheit, J., Gnyp, M. L. and Bareth, G. (2015) Combining uav-based plant height from crop surface models, visible, and near infrared vegetation indices for biomass monitoring in barley. *International Journal of Applied Earth Observation and Geoinformation*, **39**, 79–87.

Gupta, V., Reinke, K. J., Jones, S. D., Wallace, L. and Holden, L. (2015) Assessing metrics for estimating fire induced change in the forest understorey structure using terrestrial laser scanning. *Remote Sensing*, **7**, 8180–8201.

Hines, F., Tolhurst, K. G., Wilson, A. A. and McCarthy, G. J. (2010) *Overall fuel hazard assessment guide*. Fire Management Branch, Department of Natural Resources and Environment.

Kramer, H. A., Collins, B. M., Kelly, M. and Stephens, S. L. (2014) Quantifying ladder fuels: a new approach using lidar. *Forests*, **5**, 1432–1453.

Liang, X., Jaakkola, A., Wang, Y., Hyyppä, J., Honkavaara, E., Liu, J. and Kaartinen, H. (2014) The use of a hand-held camera for individual tree 3d mapping in forest sample plots. *Remote Sensing*, **6**, 6587–6603.

Martin, D., Chen, T., Nichols, D., Bessell, R., Kidnie, S. and Alexander, J. (2015) Integrating ground and satellite-based observations to determine the degree of grassland curing. *International Journal of Wildland Fire*, **24**, 329–339.

Mutlu, M., Popescu, S. C., Stripling, C. and Spencer, T. (2008) Mapping surface fuel models using lidar and multispectral data fusion for fire behavior. *Remote Sensing of Environment*, **112**, 274–285.

Olsoy, P. J., Glenn, N. F., Clark, P. E. and Derryberry, D. R. (2014) Aboveground total and green biomass of dryland shrub derived from terrestrial laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, **88**, 166–173.

Snavely, N., Seitz, S. M. and Szeliski, R. (2006) Photo tourism: exploring photo collections in 3d. In *ACM transactions on graphics (TOG)*, vol. 25, 835–846. ACM.

Watson, P. J., Penman, S. H. and Bradstock, R. A. (2012) A comparison of bushfire fuel hazard assessors and assessment methods in dry sclerophyll forest near sydney, australia. *International Journal of Wildland Fire*, **21**, 755–763.

Long-range spotting by bushfire plumes: The effects of plume dynamics and turbulence on firebrand trajectory

William Thurston*[1,2], Kevin J. Tory[1,2], Robert J. B. Fawcett[1] and Jeffrey D. Kepert[1,2]
[1] Bureau of Meteorology, Docklands, Victoria 3008, Australia
[2] Bushfire and Natural Hazards CRC, East Melbourne, Victoria 3002, Australia

Introduction

Spotting is a hazardous phenomenon that leads to unpredictable fire behaviour and accelerated fire spread. Spot fires occur when embers are launched by bushfire plumes into the background wind, which then carries the embers a significant distance from the fire front. If the embers land in a suitable fuel bed and are still smouldering a spot fire may be ignited. The magnitude of the problem is illustrated by Cruz et al. (2012), who provide evidence of long-range spotting in excess of 30 km during the Black Saturday bushfires of February 2009. Therefore a better understanding of the processes that contribute to long-range spotting is essential for the prediction of fire spread. In this paper we aim to assess the contribution of turbulent plume dynamics to the process of long-range spotting.

Methodology

We use a two-stage modelling approach to calculate the landing positions of potential firebrands launched by bushfire plumes. Firstly, we use the UK Met Office large-eddy model (LEM), described by Gray et al. (2001), to perform numerical simulations of idealised bushfire plumes. A number of plumes are simulated for background winds varying from 5 to 15 m s^{-1}, following Thurston et al. (2013). Secondly, the three-dimensional, time-varying velocity fields produced by the LEM are used to drive a Lagrangian particle-transport model. Potential firebrands are released near the base of the plume and then advected by the LEM velocity field with a constant fall velocity of 6 m s^{-1} subtracted, representative of jarrah and karri bark flakes (Ellis, 2010). In order to assess the contribution of the in-plume turbulence to the firebrand transport, the time-varying particle-transport calculations are then repeated using a steady-state plume velocity, calculated from the one-hour mean plume fields.

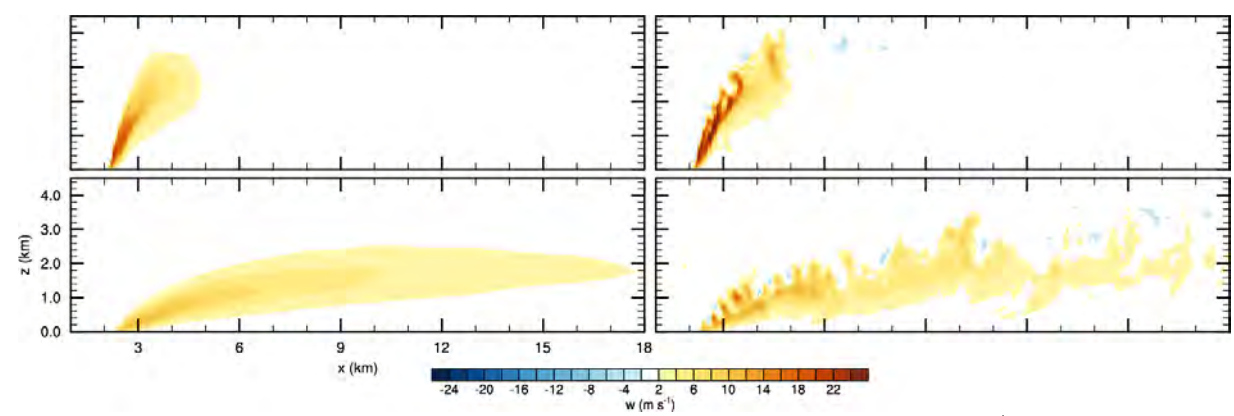

Figure 1: Vertical cross-sections of the mean (left) and instantaneous (right) vertical velocity, m s^{-1}, through the plume centre line, for background wind speeds of 5 (top) and 15 (bottom) m s^{-1}.

Results

Vertical cross sections of the instantaneous and 1-h mean updrafts for plumes in the weakest (5 m s^{-1}) and strongest (15 m s^{-1}) background winds are shown in Figure 1. The instantaneous plumes in strong wind have weaker updrafts, and are more bent over than the plumes in weak wind. The instantaneous strong-wind plume is turbulent over its whole height, whereas its weak-wind counterpart is only fully turbulent above a height of about 2 km. Plan views of the weak-wind plume, not shown here but seen in Thurston et al. (2014), reveal that the plume has two updraft cores that form a counter-rotating vortex pair. The 1-h mean plumes do not exhibit any of the turbulence that is visible in the instantaneous plume updrafts, and as a result the peak updraft is weaker, but more uniform.

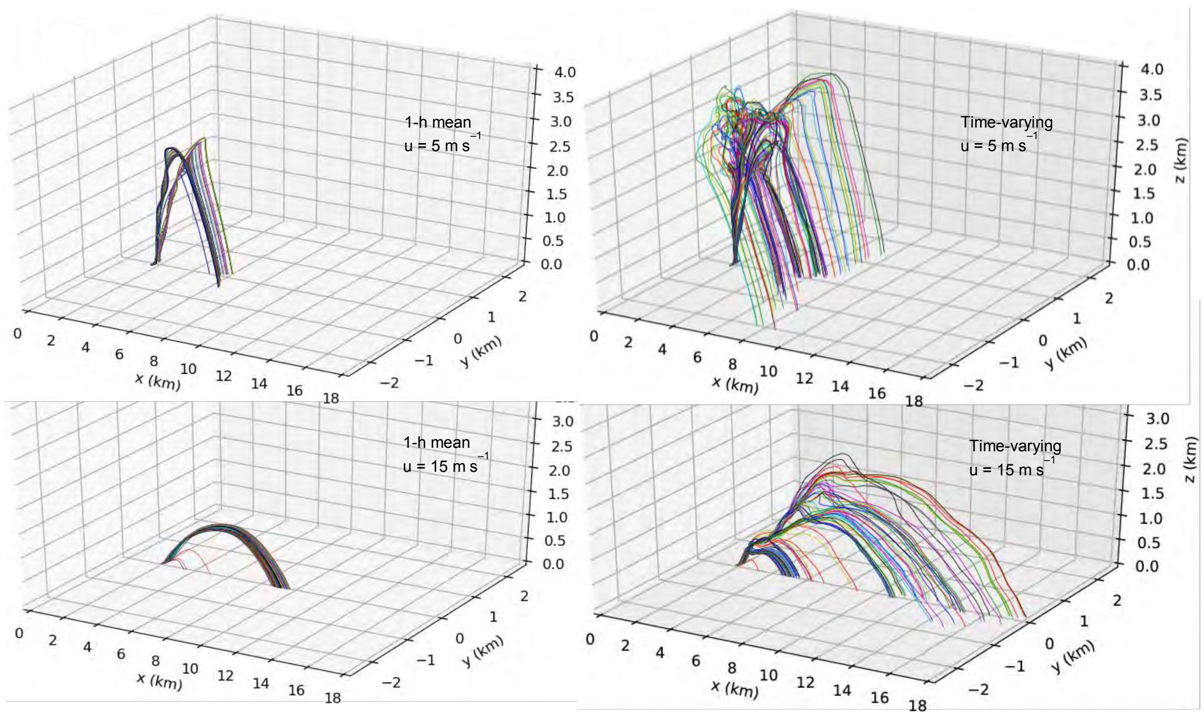

Figure 2: Trajectories of 100 firebrands lofted by the mean (left) and time-varying (right) plumes under background wind speeds of 5 (top) and 15 (bottom) m s^{-1}.

The trajectories of 100 firebrands lofted by each of the plumes in Figure 1 are shown in Figure 2. Firebrands lofted by the time-varying weak-wind plume initially travel up the two branches of the counter-rotating vortex pair, and are then spread out further laterally as they reach the turbulent region of the plume above a height of 2 km. Firebrands lofted by the time-varying strong-wind plume do no exhibit any of this lateral spread, instead landing near the plume centre line. These firebrands appear to be lofted in clumps by the turbulent puffing of the plume, and hence tend to fall out in clusters. The trajectories of firebrands lofted by the 1-hr mean plumes highlight the importance of the in-plume turbulence. In the weak-wind case the firebrands still travel up the two branches of the counter-rotating vortex pair, but there is less lateral dispersion above 2 km. In the strong-wind case the effect of the in-plume turbulence is more pronounced, with most firebrands lofted by the 1-h mean plume now having similar trajectories.

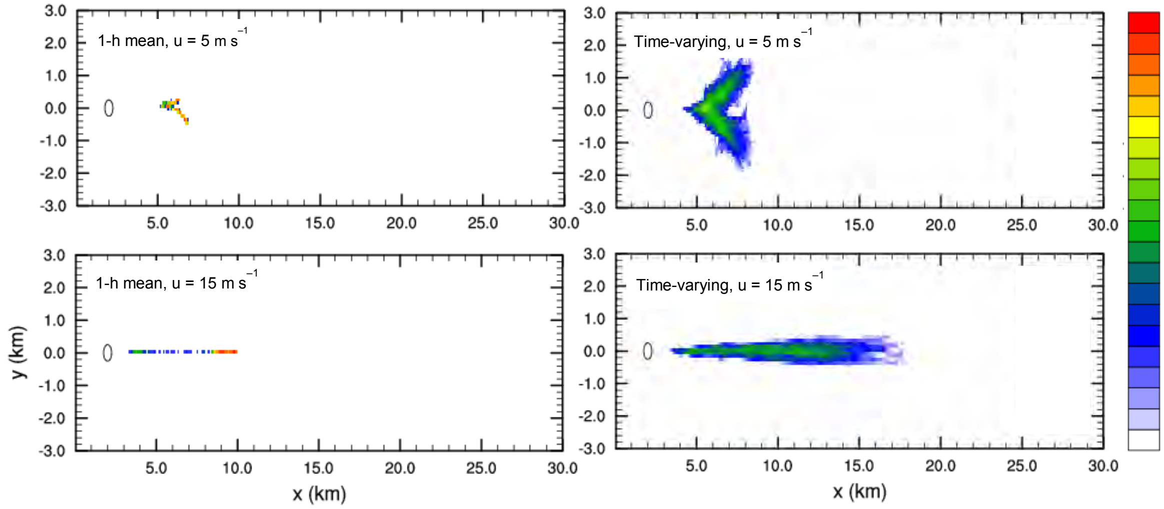

Figure 3: Spatial distributions of firebrand landing position (percent of particles launched per km²) for the mean (left) and time-varying (right) plumes under background wind speeds of 5 (top) and 15 (bottom) m s⁻¹.

Figure 3 shows the two-dimensional landing distributions for 1.5 million firebrands launched by each of the plumes in Figure 1. The counter-rotating vortex pair and upper-level turbulence of the time-varying weak-wind plume lead to the firebrands landing in a V-shaped pattern with considerable lateral spread. The landing positions of firebrands lofted by the 1-h mean plume in weak winds still land in a V-shaped pattern, but there is less lateral spread due to the lack of in-plume turbulence. Firebrands lofted by the time-varying strong-wind plume travel on average about twice as far as their weak-wind plume counterparts, have more longitudinal spread and less lateral spread in their landing distribution. The landing positions of firebrands lofted by the 1-h mean plume in strong winds show much less spread and crucially the maximum spotting distance is reduced by half from about 16.7 km to 8.4 km.

Summary statistics of the landing positions for embers lofted by the 1-h mean and time-varying plumes in all background wind speeds from 5 to 15 m s^{-1} are shown in Figure 4. It is seen that the mean (Figure 4 (a)) and maximum (Figure 4 (b)) spotting distance increase with increasing wind speed, for both the 1-h mean and time-varying plumes. Whilst there is little difference between the mean spotting distances calculated from the 1-h mean and time-varying plumes, the maximum spotting distances calculated from the time-varying plumes are much greater than the maximum spotting distances calculated from the 1-h mean plumes. This indicates that in-plume turbulence has a large effect on the maximum spotting distance, but not on the mean spotting distance. The effect of in-plume turbulence increases with background wind speed, as the plumes are more turbulent under stronger background winds (Figure 1). The spread in spotting distance, given by the standard deviation in longitudinal landing position (Figure 4 (c)), increases with background wind speed. At low wind speeds the in-plume turbulence increases this spread by a factor of about two, which increases to about three at high wind speeds. Conversely, the lateral spread in landing position (Figure 4 (d)) decreases with increasing wind speed and at low wind speeds the in-plume turbulence is responsible for about two-thirds of the lateral spread, increasing to almost all of the lateral spread at high wind speeds.

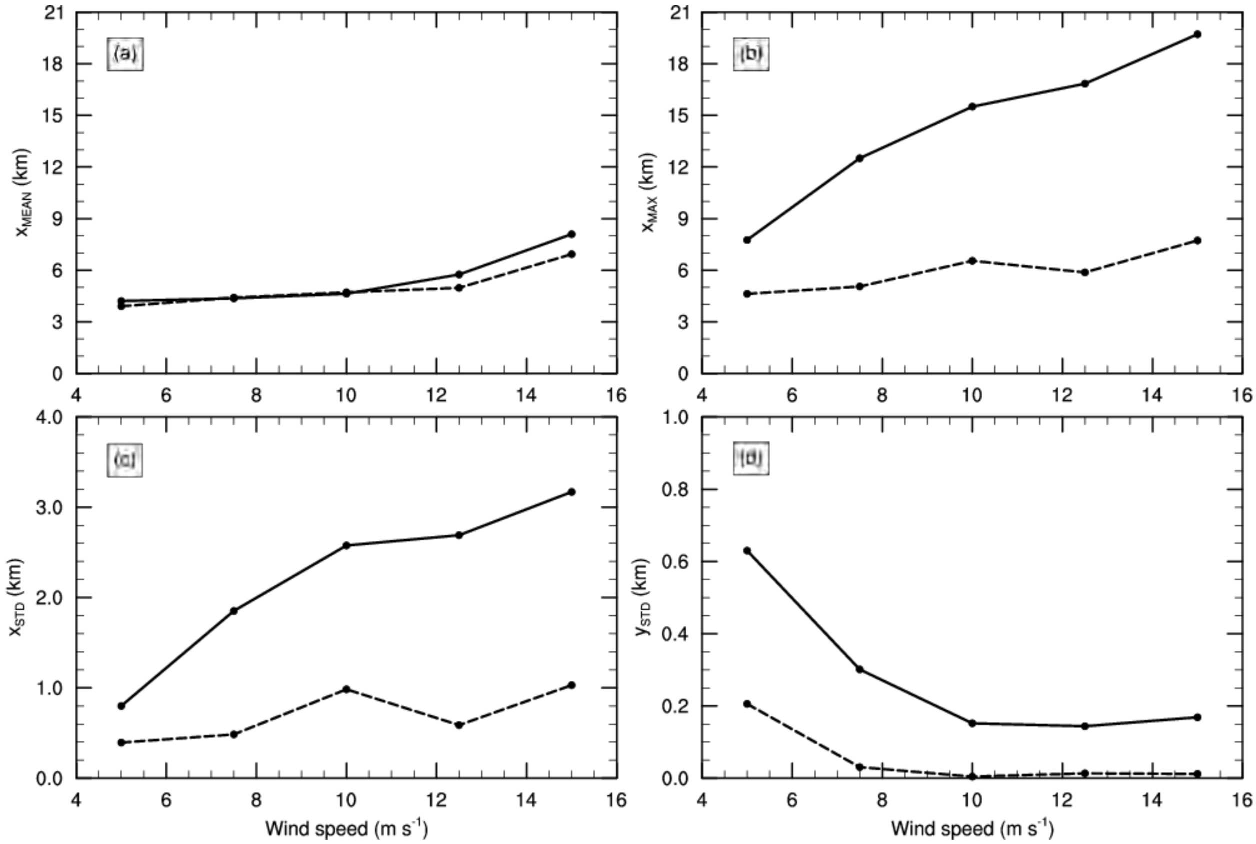

Figure 4: Summary statistics of landing positions for embers lofted by all plumes in background wind speeds from 5 to 15 m s^{-1}. Panels show the (a) mean longitudinal landing position; (b) maximum longitudinal landing position; (c) standard deviation of the longitudinal landing position; and (d) standard deviation of the lateral landing position, all in km. Solid lines represent embers lofted by the time-varying plumes and dashed lines represent embers lofted by the corresponding 1-h mean plumes.

A critical consideration in the potential for firebrands to start spot fires is whether they are still burning when they land. Therefore the flight times of the firebrands lofted by the time-varying weak-wind and strong-wind plumes are presented in Figure 5. Firebrands that are lofted by the weak-wind plume have a relatively long flight time, even if they do not travel a long distance. For example firebrands that are lofted by the weak-wind plume and subsequently travel only 0 to 2 km are in the air for 7.5 to 12.5 minutes, whereas firebrands that are lofted by the strong-wind plume and travel only 0 to 2 km are in the air for a much shorter 1.5 to 3.5 minutes. This is caused by the plume dynamics seen in Figure 1: The weak-wind plume is more upright and has a stronger updraft, causing the firebrands to go almost straight up, reach a greater height and therefore be in the air for longer. This behaviour is confirmed by the trajectory plots of Figure 2. The firebrands that have travelled the furthest (16 to 18 km, in the strong-wind case) have a median flight time of 21.5 minutes and a 1st to 99th percentile range of 19.3 to 23.4 minutes. This is similar to the maximum burnout time of ribbon gum bark observed in the wind tunnel studies of Hall et al. (2015) and would suggest that firebrands taking these trajectories would still be capable of starting spot fires.

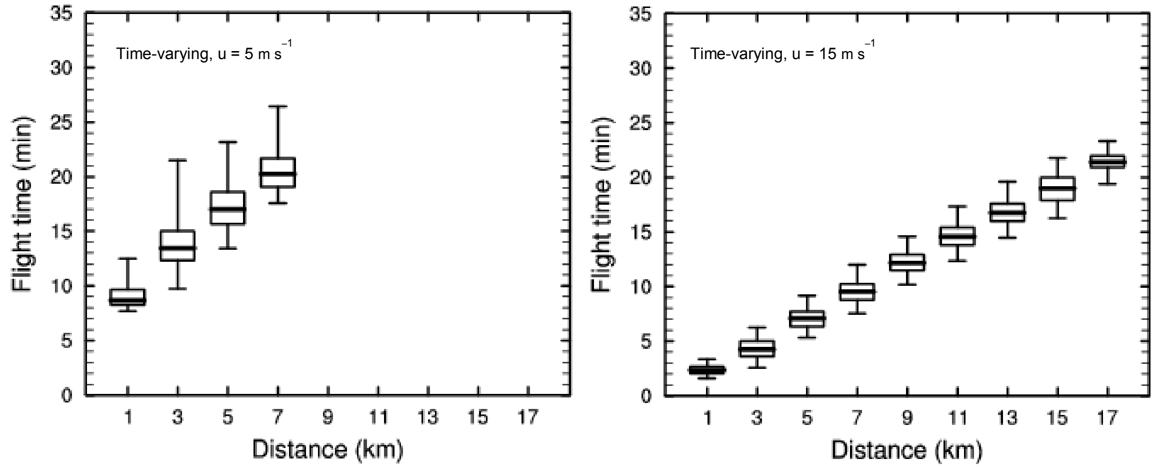

Figure 5: Box and whisker plots of flight times for firebrands lofted by the time-varying plumes under background wind speeds of 5 (left) and 15 (right) m s^{-1}. Flight times are binned according to the distance travelled by the firebrand, at 2-km intervals. The first bin encompasses distances of 0.0 to 2.0 km, the second 2.0 to 4.0 km, and so on. The thick line shows the median flight time and the box spans the interquartile range. Whiskers represent the 1st and 99th percentile flight times.

Summary

We have combined large-eddy simulations of bushfire plumes with Lagrangian particle transport modelling to investigate how turbulent plume dynamics can affect long-range spotting. Plumes exhibited different dynamical and turbulent behaviour depending on the background wind conditions and this consequently leads to differences in firebrand transport. Plumes in weak winds contain a counter-rotating vortex pair which leads to large lateral spread in firebrand landing position. Plumes in strong winds are more turbulent and bent over, leading to more longitudinal spread in firebrand landing position and a greater maximum spotting distance. In-plume turbulence was shown to substantially increase the lateral and longitude spread in firebrand landing position and in the case of plumes in strong background winds, increase the maximum spotting distance by a factor of more than two. Systematic studies such as this will inform the development of better physically based spotting models.

References

Cruz MG, Sullivan AL, Gould JS, Sims NC, Bannister AJ, Hollis JJ, Hurley RJ (2012) Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. *Forest and Ecological Management* **284**, 269–285.

Ellis, PFM (2010) The effect of the aerodynamic behaviour of flakes of jarrah and karri bark on their potential as firebrands. *Journal of the Royal Society of Western Australia* **93**, 21–27.

Gray MEB, Petch J, Derbyshire SH, Brown AR, Lock AP, Swann HA, Brown PRA (2001) Version 2.3 of the Met Office large eddy model: Part II. Scientific documentation. Turbulence and Diffusion Note 276, UK Met Office, 49 pp., Exeter, United Kingdom.

Hall J, Ellis PF, Cary GJ, Bishop G, Sullivan A (2015) Long-distance spotting potential of bark strips of a ribbon gum (*Eucalyptus viminalis*). *International Journal of Wildland Fire* **24**, 1109–1117.

Thurston W, Tory KJ, Fawcett RJB, Kepert JD (2013) Large-eddy simulations of bushfire plumes in the turbulent atmospheric boundary layer. *MODSIM2013, 20th International Congress on Modelling and Simulation,* J. Piantadosi, R. S. Anderssen, and J. Boland, Eds., Modelling and Simulation Society of Australia and New Zealand, 284–289. ISBN: 978-0-9872143-3-1.

Thurston, W, Tory KJ, Kepert JD, Fawcett RJB (2014) The effects of fire-plume dynamics on the lateral and longitudinal spread of long-range spotting. *Proceedings of the Research Forum at the Bushfire and Natural Hazards CRC & AFAC 2014 Conference*, M. Rumsewicz, Ed., Bushfire and Natural Hazards CRC, 85–94, ISBN: 978-0-9941696-3-15.

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Measuring What Didn't Happen: Trying to Objectively Assess Fire Service Bushfire Protection

Musa Kilinc
Country Fire Authority, Melbourne, Victoria, Australia, m.kilinc@cfa.vic.gov.au
Tim Wells*
Country Fire Authority, Melbourne, Victoria, Australia, t.wells@cfa.vic.gov.au
Alen Slijepcevic
Country Fire Authority, Melbourne, Victoria, Australia, a.slijepcevic@cfa.vic.gov.au

Introduction

Historically fire agencies have measured and reported the negative outcomes, or losses, from bushfires. Loss is typically determined by counting the number of fatalities, people injured, livestock injured or killed, properties damaged or destroyed, and the number of hectares burnt. However, such reporting only describes part of the story. Many bushfires have the potential to cause significant loss and damage, but interventions by communities and fire agencies both before and during a fire incident often mean that substantial losses are prevented from occurring. In such cases, the significance of the fire agency prevention and response actions are not adequately captured by current reporting standards. An exploratory project was instigated with the aim of identifying an additional component of measures of 'avoided losses' for broad application in CFA's strategic planning. The term 'avoided loss' refers to any potential losses from an incident that were likely to occur in the absence of prevention, preparedness and response intervention.

Using a case study approach, this project compared observed bushfire behaviour and recorded losses against simulated bushfire behaviour and losses assuming no suppression work was undertaken. Fire incidents from the 2014-15 fire season were used along with the PHOENIX Rapidfire bushfire simulator. The accuracy of the simulated bushfires were assessed, and then the simulated fire outputs from PHOENIX were used to model property impacts and area burnt to produce statistics on 'avoided losses' for each case study.

The aim of this project has been to:

- Prepare a series of case studies describing and calculating the extent of loss avoided through prevention, preparedness and suppression activities
- Identify the best currently available data and test its usefulness for estimating 'avoided losses'
- Explore methods for establishing an automated process for objectively estimating bushfire related avoided loss as a result of fire agencies intervention
- Identify opportunities to improve the accuracy and defensibility of current bushfire and property impact modelling.

* CFA, L4/8 Nicholson Street, East Melbourne VIC 3002, Australia

Method

Overview

Six bushfires were selected for case studies to provide a range of modelling challenges for fires burning under conditions where suppression effectiveness is of interest (locations shown in Figure 1). The case studies were chosen to provide a range of fire environments, fire scales, quality of incident records, quality and number and type of assets exposed.

Fire progression lines were reconstructed for each case study. The fires were then simulated using PHOENIX RapidFire (henceforth referred to as PHOENIX). The accuracy of the simulated bushfires were analysed objectively by using an Area Difference Index (ADI), which assesses the difference between the simulated and reconstructed fire perimeters. The simulated fire outputs from PHOENIX were used in property impact models to produce statistics on 'avoided losses' for each case study.

This study defined two scenarios: (1) an 'actual' scenario that is based on observed events with fire suppression activities; and (2) a 'simulation' scenario assuming no prevention and suppression activities are undertaken. The former indicates where fire spread actually occurred, the latter where it could have spread to and impacted on the community had there been no suppression activity. PHOENIX was used to simulate the potential extent of the bushfire over a 48 hour period from the time of fire ignition for the 'simulation' scenario. The reconstructed fire was used as a reference against which the effects of suppression could be estimated. 'Avoided loss' was then expressed as the difference between the number of properties saved under the 'simulation' scenario and the actual number of property impacts achieved as a result of suppression work.

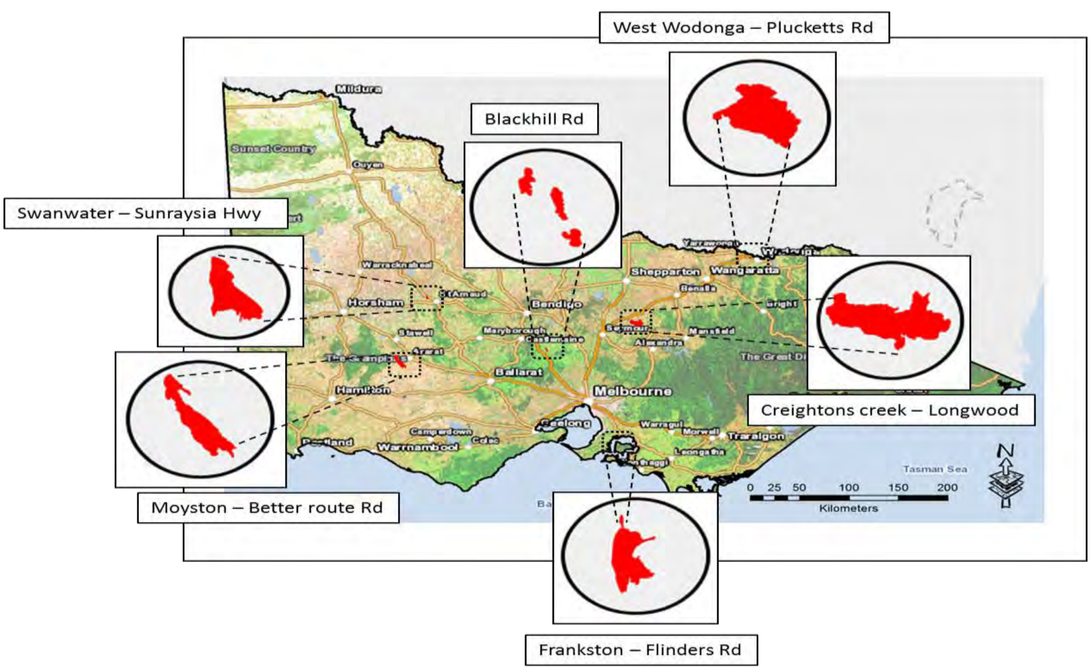

Figure 1: Map showing the location and final fire shape for each case study

Steps taken

The overall method is based on the following steps:

1) Determine the actual fire spread and fire behaviour by reconstructing the fire using fire agency and social media related fire intelligence information sources.

2) Simulate the fire behaviour (assuming no suppression) using PHOENIX multiple times to produced fire perimeters for all possible combinations of model inputs listed below:
    a. Weather input
        i. Automatic Weather Station (AWS) observations
        ii. Numerical Weather Prediction (NWP) forecasts
    b. Grass curing input
        i. CFA curing map
        ii. CFA adjusted curing map
        iii. CFA field observations
    c. Ignition time and location input
        i. Actual time and location as determined during the fire reconstruction
        ii. CFA data obtained from IMS
        iii. DELWP data obtained from Fireweb
    d. Phoenix grid resolution input
        i. 60 m
        ii. 90 m
        iii. 180 m

3) Assess the actual fire spread against the various simulation outputs to determine which modelling method best represents the reconstructed fire behaviour.

4) Determine the difference between the reconstructed fire behaviour and the modelled likely fire behaviour assuming no suppression.

5) Determine the difference between reconstructed (observed/recorded) losses and likely losses from the modelled fire behaviour.
    a. Impact models tested
        i. PHOENIX house loss model
        ii. IB impact model
        iii. WMD property impact model

6) Assign a subjective ‘predictive confidence’ level for each case study based on consideration of anecdotal reports about fire behaviour and suppression effectiveness, accuracy of simulated fire behaviour when compared to observations, variability between different simulations and simulation input data quality.

Assessing actual fire spread against simulations

An Area Difference Index (ADI) measure was used to determine the accuracy of the bushfire simulations (Duff et al. 2012, Duff et al. 2013, Pugnet et al. 2013). The ADI was checked for consistency by measuring the difference in fire direction angle between the simulated and reconstructed fire spread perimeters (Duff et al. 2013). Fire orientation error was determined to identify the consequent differences in fire orientation between the reconstructed and simulated fire spread perimeters as a result of wind trajectory inputs from the weather datasets.

Assessing property impacts

Property impacts were modelled by comparing Victorian property address points (https://www.data.vic.gov.au/) with the bushfire behaviour outputs simulated by PHOENIX. A number of property impact models emanating from previous research studies (Kilinc et al. 2013, Kilinc et al. 2014) were used with the simulation outputs for each case study.

The relationship between Victorian property address points and actual house locations was determined by placing seventeen random quadrats, each measuring 25 hectares within and outside of the simulated PHOENIX fire area. The difference between the Victorian address points and observed house locations (using aerial photography) were calculated to determine a 'loss reduction factor' for each case study.

The final property impact or avoided loss results are presented as the average of the three impact models.

Results

It was found that overall the best performing model combinations were:

- Weather - AWS weather data, which was similar to NWP data for the day of ignition. For simulations longer than 12 hours, AWS weather data performed better than NWP data.
- Curing - The CFA adjusted curing map performed best. It was similar to the CFA field observations.
- Ignition time and location – The data from the fire reconstructions performed much better than either of the agency database data in predicting the impacts.
- Phoenix grid cell resolution – 60 metres performed better than 90 and 180 metres.

The confidence in the fire simulations was generally low (less than 20%), but did reach high (between 60 and 80%) for one of the case studies.

PHOENIX simulations and property impact modelling from the six case studies showed that the total loss avoided as a result of fire agency suppression activities was:

- 282 properties (range 161 and 498)
- approximately 520,000 hectares of land burnt.

More detail about the estimated loss avoided is shown in Table 1 below.

Table 1: Summary of results for the six case studies. Note, the case study titled 'Blackhill' was a series of lightning-strike caused fires in close proximity to each other.

Fire Name	Recorded area burnt (000's ha)	Simulated area burnt (000's ha)	Recorded property loss	Modelled property loss			Avoided area loss (000's ha)	Avoided property loss	Prediction confidence
				Mean	Min	Max			
Creighton's Creek	5.1	8.6	4	33	18	57	3.5	29	Low
Frankston Flinders	0.1	0.1	0	3	1	6	-	3	High
Moyston	5.4	432.3	2	200	117	359	426.9	198	Moderate
Swanwater	0.2	71.9	0	27	15	45	71.7	27	Low
West Wodonga	0.1	17.0	0	0	0	0	16.9	0	Very Low
Blackhill fire No.1	0.1	0.6	0	13	7	21	0.5	13	Low
Blackhill fire No.2	0.1	0.1	0	0	0	0	-	0	Very Low
Blackhill fire No.3	0.1	0.4	0	6	3	10	0.3	6	Very Low
Total	11.2	531.0	6	282	161	498	519.8	276	

Discussion

It is recognised that six case studies constitute a relatively small number of case studies in any one fire season. During the 2014-15 fire season CFA recorded 4327 incidents related to vegetation fires in the Fire Incident Reporting System (FIRS), the dataset used to record characteristics of fire and incidents attended by CFA. Further case studies would be required to estimate the impact of prevention, preparedness and suppression activities on losses avoided within any one fire season. CFA intends to do such analysis in collaboration with a Department of Environment, Land, Water and Planning (DELWP) funded project.

From the study results, it was possible to make some strategic level findings regarding an 'avoided losses' reporting approach in bushfire management:

- Methods and results presented in this study suggest that measures of 'avoided loss' is a possible metric for reporting successful fire response activities by fire agencies. However, currently there is generally low to moderate confidence in results. It is suggested more reliable simulations are necessary, and deeper analysis be undertaken to better understand fire behaviour simulator accuracy.
- Of the three impact models tested in this study, two overestimated the potential property impacts, whilst the WMD model performed the best. However, this model is difficult to automate. It is suggested further investment would be best directed towards localised impact modelling which considers relationships based on the distance between the property and fire in forest vegetation.
- The modelling demonstrated that the DELWP and the CFA ignition data were not suitable for half of the case studies. There were significant errors in the recorded time or

geographic coordinates of the ignition. Recording suitable fire ignition data must be part of a broader plan to conduct avoided loss analyses on a seasonal basis.
- It was difficult to determine whether any Area Difference Index (ADI) discrepancies between observed and simulated fire spread was due to fire observation errors, modelling errors or suppression activities. It is suggested that fire agencies make best efforts to diagnose possible causes of variation in the ADI – be they the underpinning fire spread model, fuel inputs or other elements – and then rectify issues that can be easily addressed.
- If the methods used for this study are further developed to automatically estimate bushfire loss avoided for an entire season it would be preferable, for practical reason, to undertake a single large batch-analysis at the end of the season, rather than many smaller analyses throughout.

Acknowledgements
This work was a collaboration between the CFA Fire & Emergency Management and Business Performance and Strategy directorates, with team members from the Knowledge and Evidence, Fire Behaviour Analysis and Community Capability teams. The project was made possible with significant contributions from Michael Bourne, Bernie Marshall, John Gilbert and Ray Fritz.

References
Duff T, et al. (2012) Procrustes based metrics for spatial validation and calibration of two-dimensional perimeter spread models: A case study considering fire. *Agricultural and Forest Meteorology* **160**: 110-117.

Duff T, et al. (2013) Quantifying spatio-temporal differences between fire shapes: Estimating fire travel paths for the improvement of dynamic spread models. *Environmental Modelling and Software* **46**: 33-43.

Kilinc M, et al. (2013) ‘A scale for determining the destructive potential of bushfires’ Bushfire CRC - Fire severity Technical report 1, Bushfire CRC.

Kilinc M, et al. (2014) ‘A methodology for state wide mapping of bushfire hazard in Victoria’ Australia. Bushfire CRC - Fire severity Technical report 1, Bushfire CRC.

Pugnet L, et al. (2013) ‘Wildland–urban interface (WUI) fire modelling using PHOENIX Rapidfire: A case study in Cavaillon’ France International Congress on Modelling and Simulation, Adelaide, Australia.

Mesoscale Features Related to the Blue Mountains Fires of 17 October 2013 Revealed by High Resolution Numerical Weather Prediction (NWP) Modelling

Simon E. Ching*
Bureau of Meteorology Research and Development, Melbourne, Australia
Bushfire and Natural Hazards Cooperative Research Centre, Melbourne, Australia
South Australia Regional Office, Bureau of Meteorology, Adelaide, Australia

Robert J. B. Fawcett
Bureau of Meteorology Research and Development, Melbourne, Australia

William Thurston, Kevin J. Tory and Jeffrey D. Kepert
Bureau of Meteorology Research and Development, Melbourne, Australia
Bushfire and Natural Hazards Cooperative Research Centre, Melbourne, Australia

Introduction

In October 2013, a number of significant fires broke out in New South Wales, Australia. The most intensive fire activities occurred between 13 and 26 October, when there were 627 incidents and an estimated area of 164 054 ha burnt. The afternoon of 17 October turned out to be the most destructive when the Blue Mountains was heavily affected with more than 200 houses damaged, although, thankfully, no lives were lost (New South Wales Rural Fire Services 2014).

Progression of Fires

The fires in the Blue Mountains region fires include the State Mine Fire and the Mount York Road Fire. The State Mine Fire was ignited on 16 October and spread to the south-east during the night and the morning of 17 October. Later, the fire spread rapidly to the east from about noon, with the estimated area burnt increased from 1036 ha at 11:56 am to 12 436 ha by 9:46 pm Australian Eastern Daylight Time (AEDT, 11 hours ahead of UTC). The Mount York Road Fire was ignited on the afternoon of 17 October. While not as extensive when compared with the State Mine Fire, it had an estimated burnt area of 482 ha by 7:46 am on 18 October (Figure 1).

The areal extension of the State Mine Fire during the afternoon of 17 October was phenomenal – a 12 times increase in burnt area in less than 10 hours (Table 1). It is of both practical and academic interest to investigate if the meteorological conditions had been conducive to the rapid spread of the fire during that day; if so, what were those meteorological conditions? We have tried to answer this question by performing a simulation using a Numerical Weather Prediction (NWP) model with a similar setup for operational purposes but with much higher resolution exceeding operational computing constraints, and have identified several mesoscale features that are of interest.

∗ Corresponding author address: Simon E. Ching, South Australia Regional Office, Bureau of Meteorology, PO Box 421, Kent Town 5071, South Australia, Australia. E-mail: e.ching@bom.gov.au

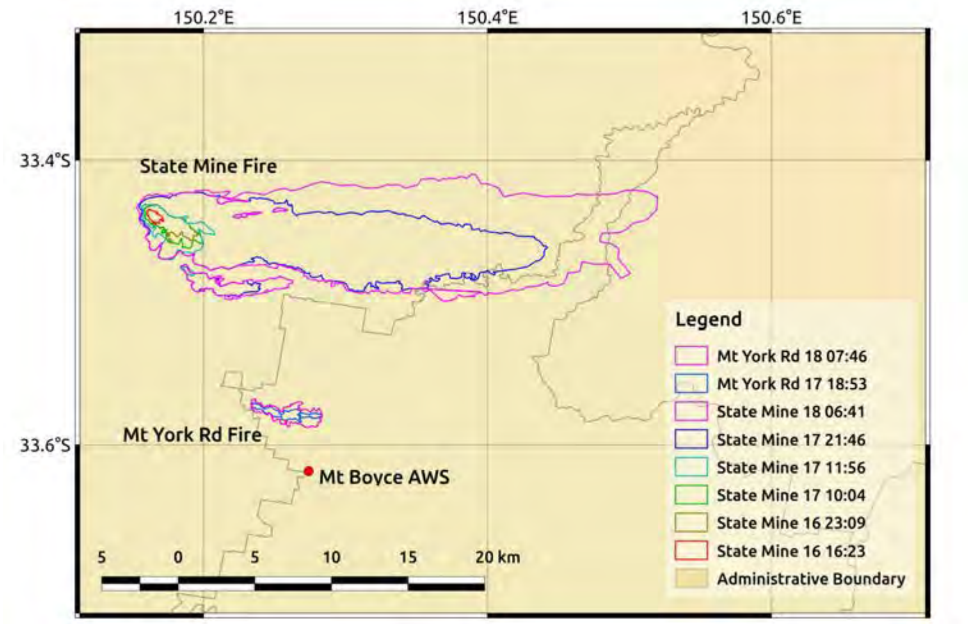

Figure 1: The progression of the perimeters of the State Mine Fire and the Mount York Road Fire. The times are in Australian Eastern Daylight Time (AEDT). Location of Mount Boyce AWS is shown by the red dot.

Meteorological Conditions

Lead Up Conditions

The several months leading up to October 2013 had been quite dry about the Blue Mountains area. The rainfall recorded at Mount Boyce, a hill in the Blue Mountains area with an Automatic Weather Station (AWS) which is closest to the Blue Mountains fire grounds (Figure 1), had been significantly below average from July to October with a total of 81.8 mm against the climatological average of 213.5 mm. The soil dryness from the Australian Water Resources Assessment System (AWRA) (Vase *et al.* 2013) analysis also shows that it was exceptionally dry about the Blue Mountains area in the lead up to the fires (Table 1). The drought factor at Mount Boyce, interpolated from Bureau of Meteorology's national gridded analysis (Finkele *et al.* 2006), was 8.66.

Table 1: Various measures indicating dryness in the Blue Mountains area in October 2013 and the lead up period. All entries are values at Mount Boyce interpolated from the AWRA L4.5 database at 0.25° horizontal resolution, for October 2013 (unless otherwise stated) against previous and subsequent Octobers. Effective Rainfall is the difference between rainfall and evapotranspiration.

Dryness Measure	Value
Top Layer (0 cm to 10 cm) Soil Moisture	4.29 percentile
Top Layer (10 cm to 100 cm) Soil Moisture	2.88 percentile
Rainfall	7.31 percentile
Mid Layer (10 cm to 100 cm) Soil Moisture Anomaly	–41.49 mm
Effective Rainfall Anomaly	–41.55 mm
Effective Rainfall Anomaly August to October 2013	–92.75 mm

Weather of the Day

A cold front passed through New South Wales on 17 October. The wind change accompanying the cold front was a complex one, manifested in the Blue Mountains area as several small abrupt directional changes, embedded within the general trend of north-westerlies gradually backing to south-westerlies throughout the day (Figure 2).

The weather conditions at Mount Boyce on 17 October were characterized by a maximum temperature of 22.5 °C, very dry conditions with dew point temperatures dipping to –7.6 °C around 03 UTC (2 pm AEDT), and windy conditions with one-minute wind speeds reaching 20.6 m s^{-1} and gusts reaching 28.3 m s^{-1} during the afternoon.

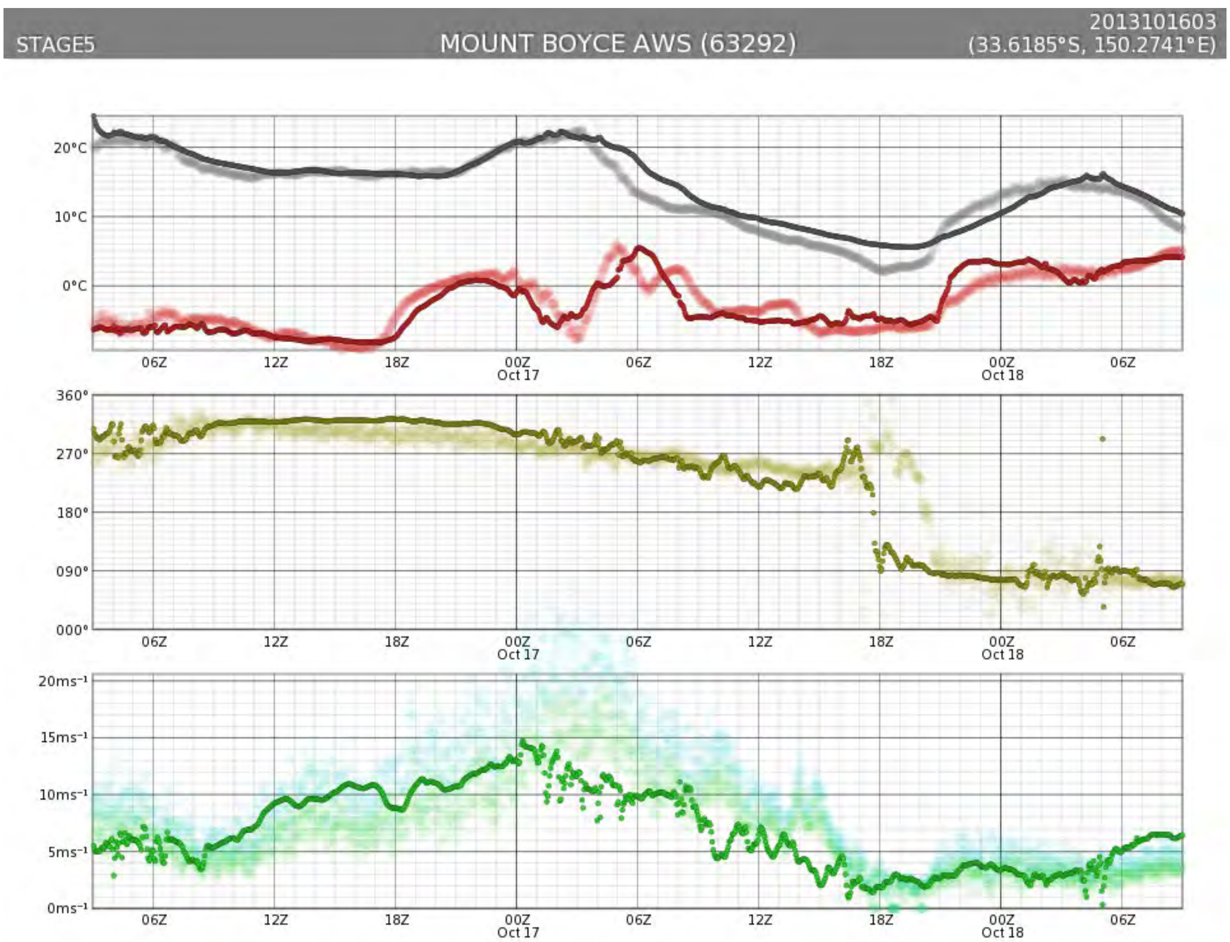

Figure 2: Meteogram of 2-metre temperature (black), 2-metre dew point (red), 10-metre wind direction (gryish yellow), 10-metre wind speed (green) and 10-metre wind gust (cyan) at Mount Boyce from 03 UTC 16 October 2013 to 09 UTC 18 October 2013. Solid dots in the foreground are NWP simulation data (STAGE5 nest). Fainter dots in the background are AWS observations.

NWP Model Configuration

In this study, the simulation was performed using the Australian Community Climate and Earth-System Simulator (ACCESS). The atmospheric component is version 8.5 of the Unified Model developed at the UK Met Office, as implemented at the Bureau of Meteorology. The initial condition was the Bureau's operational global analysis valid at 03 UTC on 16 October 2013, and was run at successively finer nests, beginning with an approximately 40-km mesh on a global domain, down to 4.0 km (STAGE3), 1.3 km (STAGE4) and 440 m (STAGE5) on progressively smaller domains, all with 70 hybrid vertical levels. The global model had a model top of 80 km, with nested models having a model top of 40 km.

Mesoscale Features

Mountain Waves and Downslope Winds

Vertical cross-section from the simulation showed a marked downward extension of the stronger winds aloft in the general vicinity of the fire ground (Figure 3). Examination of the vertical velocity showed a clear mountain wave signature. This pattern persisted from about 23 UTC 17 October to 07 UTC 17 October, which coincided with the rapid fire spread period. This appears to be the cause of the enhanced surface winds and associated gustiness seen in the observational data.

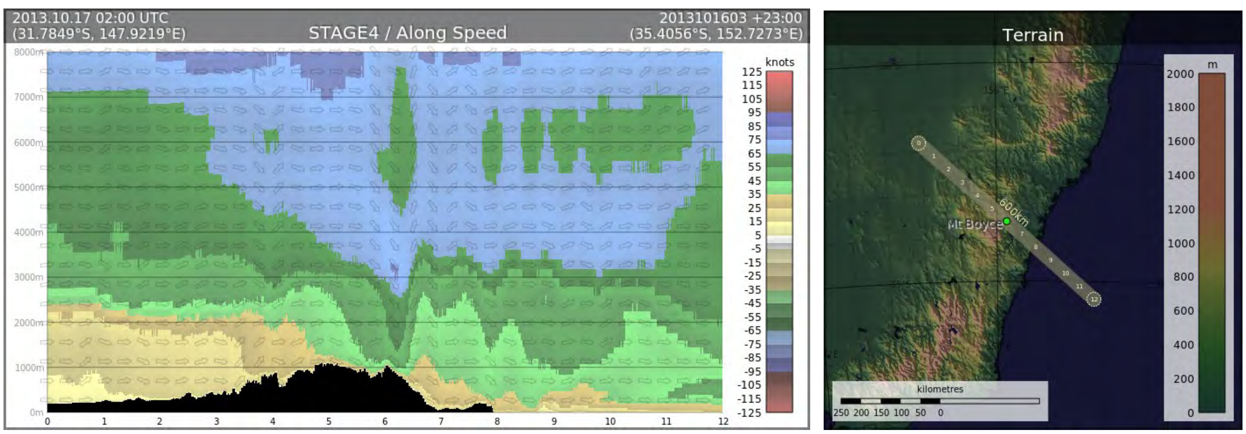

Figure 3. Left: Vertical cross-section of horizontal wind speed along a line through Mount Boyce at 02 UTC 17 October (STAGE4 nest). Positive (negative) values indicate flow from left (right) to right (left). Arrows indicate three-dimensional wind directions projected onto the cross-sectional plane. The figures 0 to 12 along the horizontal axis are position markers 50 km apart. Mount Boyce is located at the position marker 6. Right: Model terrain height and orientation of the cross-section.

The potential for mountain waves to escalate fire behaviour was discussed by Sharples (2009), and they were shown to be responsible for overnight escalations in fires at Margaret River (Kepert and Fawcett 2013) and Aberfeldy (Wells *et al.*, 2014). This case is of particular interest because the phenomenon occurred during the day, rather than at night when the nocturnal inversion provided near-surface conditions favourable for downslope winds.

Dry Slot

Though not reaching the observed Mount Boyce –7.6 °C dew point, a marked northwest-southeast orientated dry slot was present in the simulation from about 23 UTC 16 October to 07 UTC 17 October which passed through the Blue Mountains area around 02 UTC 17 October (Figure 4). The magnitude of the dryness and arrival timing was well represented apart from less abrupt change from drying to moistening than observed. However, a secondary, less marked drying period observed at Mount Boyce AWS around 0630 UTC was not captured by the simulation (Figure 2).

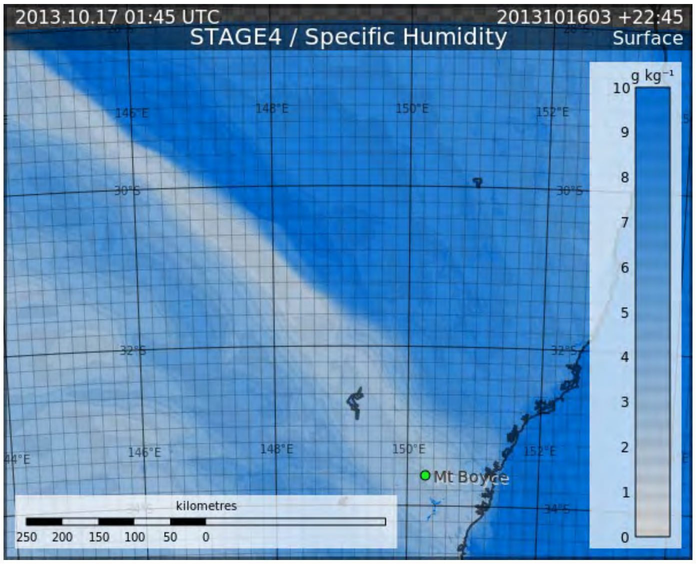

Figure 4. NWP simulated 2-metre specific humidity at 01:45 UTC 17 October 2013 (STAGE4 nest).

Figure 5 shows the vertical cross-section of the dry slot in the simulation. While there was vertical motion in the vicinity of the dry slot, the simulation did not clearly reveal a secondary cross-frontal circulation associated with the dry slot as described by Mills (2005, 2008). Further analysis suggests the dry slot was actually a dry nose of a cooler and otherwise moist airmass spreading from the southwest. Later during the afternoon, the dry slot was dissipated in an interaction with convective activities in the north as it moved into northeastern New South Wales.

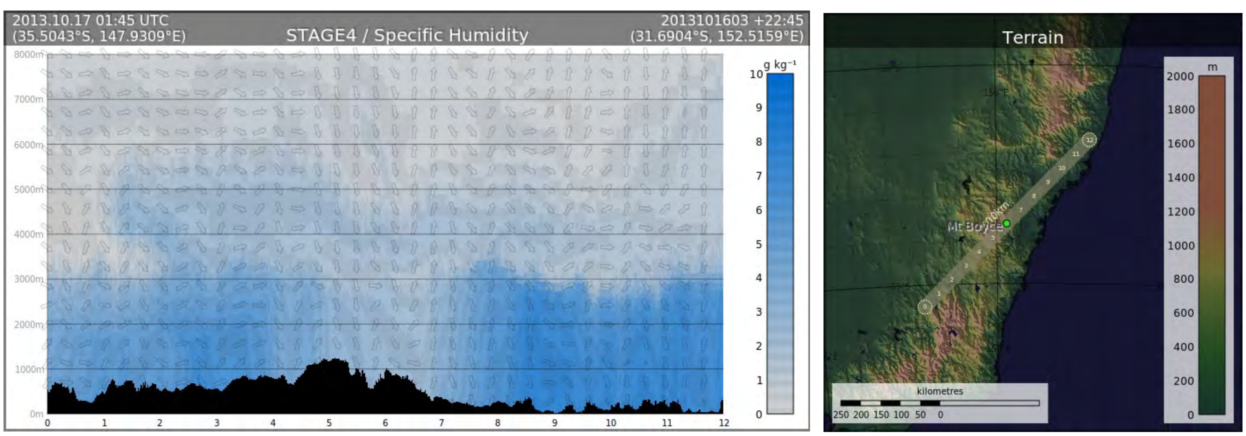

Figure 5: As in Figure 3 but for specific humidity at 01:45 UTC 17 October 2013.

Undular Bore

The formation of the dry nose which acted as a precursor of the dry slot mentioned in the previous section turned out to be related to an undular bore formed upstream the night before when the moist cool change slid into the shallow nocturnal layer over inland Victoria and New South Wales. The passage of the bore raised the leading shallow layer of nocturnally cooled dry air, to a depth of about 2000 m (Figure 6), which formed the cold, dry nose of the cool change. The AWS observations at Kilmore Gap and Yarrawonga were supportive of the revelation by the simulation.

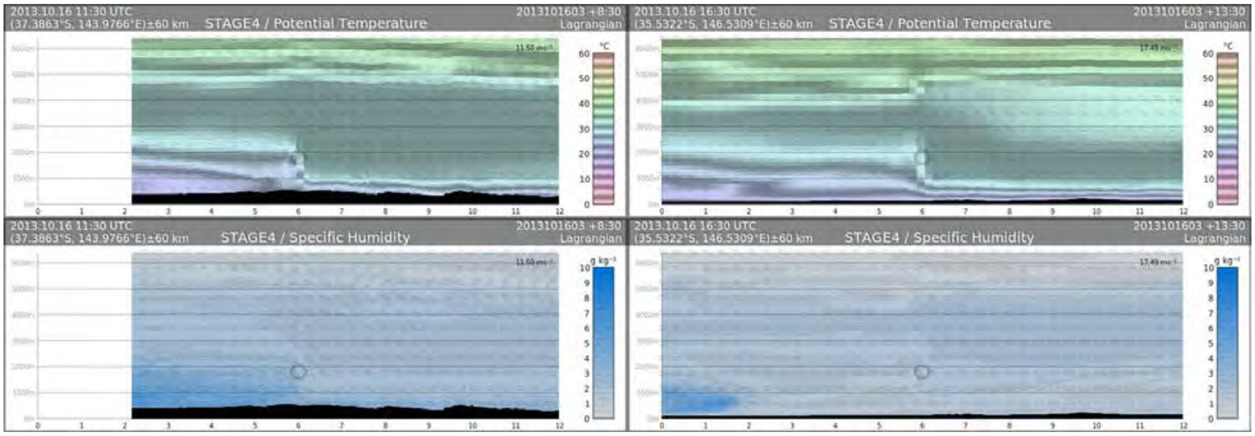

Figure 6: Vertical cross section of potential temperature (top) and specific humidity (bottom) at 11:30 UTC (left) and 16:30 UTC (right). The vertical cross sections are 120 km across, orientated southwest (left) to northeast (right), centred at the undular bore (marked by the faint circle) over a region southwest of the Blue Mountains. The figures 0 to 12 along the horizontal axis are position markers 10 km apart.

References

Finkele, K., G. A. Mills, G. Beard and D. A. Jones, 2006: National gridded drought factors and comparison of two soil moisture deficit formulations used in prediction of Forest Fire Danger Index in Australia, Aust. Met. Mag., 55, 183-197

Kepert, J. D and R. J. B. Fawcett, 2013: Meteorological aspects of the Margaret River fires of November 2011. 20th International Congress on Modelling and Simulation, Adelaide, Australia. The Modelling and Simulation Society of Australia and New Zealand Inc., 180-186

Mills, G. A, 2005: On the sub-synoptic scale meteorology of two extreme fire weather days during the Eastern Australian fires of January 2003, Aust. Met. Mag., 54, 265-290

Mills, G. A., 2008: Abrupt surface drying and fire weather Part 1: overview and case study of the South Australian fires of 11 January 2005, Aust. Met. Mag., 57, 299-309

New South Wales Rural Fire Service, 2014: Bush Fire Bulletin, Volume, 36, No 2/2014

Sharples, J. J., 2009: An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk, International Journal of Wildland Fire, 2009, 18, 737-754

Vaze, J, and Coauthors, 2013: The Australian water resource assessment modeling system (AWRA). 20th International Congress on Modelling and Simulation, Adelaide, Australia. The Modelling and Simulation Society of Australia and New Zealand Inc., 3015-3021

Wells, T., C. S. Yeo and R. J. B. Fawcett, 2014: Meteorological and fire behavioural lessons learned from the Aberfeldy Fire, Victoria, 17 January 2013. Poster, 2014 Conference of the Australian Fire and Emergency Services Council and the Bushfire and Natural Hazards Cooperative Research Centre, Wellington, New Zealand, 2-5 September.

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Modified Fire Behaviour in a Coupled Fire-Atmosphere Model

David Kinniburgh*, Michael Reeder and Jussi Toivanen
School of Earth, Atmosphere & Environment, Monash University, Clayton, Victoria, Australia

Todd Lane
School of Earth Sciences, University of Melbourne, Melbourne, Victoria, Australia

Introduction

The interactions between a bushfire and the surrounding atmospheric environment play a crucial role in the bushfire's behaviour. Energy released from the fire modifies the structure of the surrounding environment, causing fire behaviour to differ than what would be predicted by only considering the far-field atmospheric conditions. This fire-induced flow is a major source of uncertainty in predicting bushfire behaviour. Plume-dominated fires are highly unpredictable (Rothermel 1991). This unpredictability has been hypothesised to be the result of a positive feedback between low-level indrafts supplying oxygen and the updraft of the plume (Banta et al. 1992). It has also been suggested that the presence of pyro-cumulus would exacerbate this positive feedback (Tory and Thurston, 2015). In recent years, numerical coupled fire-atmosphere models have been developed to investigate the effect fire-induced flow has on fire behaviour and we will use a couple fire-atmosphere model to show that evaporatively cooled downdrafts that form gust-fronts at the surface with the potential to push the fire in any direction are a more likely explanation for unexpected fire behaviour.

Numerical Model & Experimental Design

The current research couples a fire spread model to the atmospheric model, CM1 (Bryan and Fritsch, 2002). The fire spread model utilises the McArthur empirical rate of spread formula (Noble et al., 1980). Surface wind speed and temperature required by the spread formula are calculated within CM1 and then communicated to the fire spread model to evolve the fire perimeter. The mass of burning fuel is calculated from the change in the burning area over the timestep and then used to calculate the surface sensible and latent heat fluxes produced by the fire. The flux values are communicated back to CM1 to represent the addition of heat and moisture from a parameterised fire. CM1 integrates the atmospheric variables in response to the heating and moistening of the atmosphere by the fire, closing a coupled fire-atmosphere system.

This work will present results using two different wind profiles, a zero-wind profile and a negatively sheared profile; and three moisture profiles, a dry simulation a low moisture simulation, and a high moisture simulation. To isolate the effect of atmospheric moisture on the fire spread, the latent heat flux in all simulations presented will be neglected.*

* David Kinniburgh, Monash University, Wellington Road, Clayton, Victoria, Australia. david.kinniburgh@monash.edu.au

Results

Zero-wind Simulations

All simulations with zero wind quickly develop a pronounced inflow around the fire perimeter. The plume forms directly above the burning region and cloud quickly develops in the moist simulations. The plume top height increases as the moisture increasing. The fire front is shown to expand at a constant rate in all simulations until an evaporatively cooled downdraft forms in the moist simulations causing rapid fire intensification and fire spread. A comparison between the dry and low moist simulation, Figure 1, illustrates the sudden increase in fire intensity and spread rate for the moist simulation that is not present in the dry simulation.

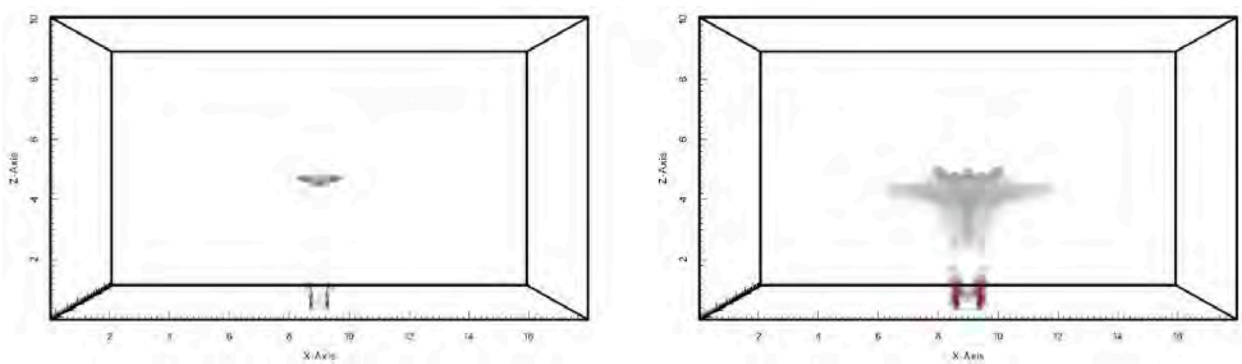

Figure 1: Volume rendered potential temperature perturbation (red) and cloud hydrometeors (grey) after 90 minutes of simulation time for zero-wind dry simulation (left) and low moisture simulation (right).

Negative Shear Simulations

Results from simulations with negative shear also exhibit unexpected behaviour when atmospheric moisture is considered. Initially, all simulations behave like wind-driven fires evolving into the classical parabolic shape, with the exception that the upper plume is advected to the rear of the burning region. Again, convection becomes more vigorous and the plume top height increases as the moisture is increased. Like the zero-wind simulations, there is a change in fire behaviour once evaporatively cooled downdrafts interact with the fire perimeter with fire spread and intensity increasing in the moist simulations. A comparison between the negatively sheared dry and low moisture simulations is shown in Figure 2.

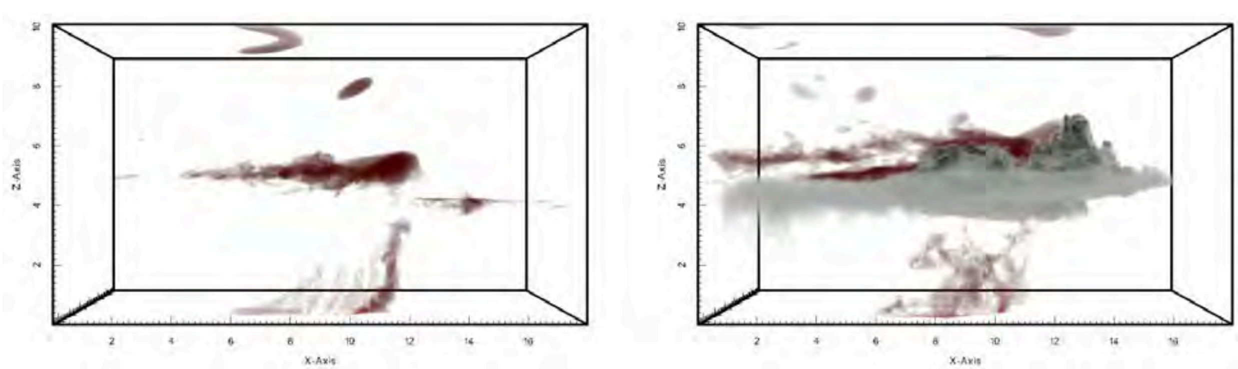

Figure 2: As Figure 1, but for negative shear simulations.

Low-level Wind Field Modification

Lastly, results comparing the low-level horizontal convergence and vertical velocity of the zero-wind simulations show that there is no increase in inflow strength or vertical velocity when a cloud forms until the evaporatively cooled downdraft reaches the surface. Vertical profiles of the vertical velocity show that before the downdrafts form, accelerations in the updraft due to latent heating is limited to the cloud region, too high to affect the behaviour of the fire.

Discussion

The addition of atmospheric moisture to a coupled fire-atmosphere model has shown that atmospheric moisture can play an important role in modifying the behaviour of a fire. In past studies atmospheric moisture has been considered mainly to have an indirect on the fire through the modification of fuel moisture. In contrast, the present study showed that the low-level wind field is unaffected by the formation of the cloud and the associated low-level convergence and the mechanism is evaporatively cooled downdrafts reaching the surface and the subsequent gust-fronts advecting the fire front in an unexpected manner.

References

Banta, R. M., L. D. Oliver, E. T. Halloway, R. A. Kropfi, B. W. Bartram, R. E. Cupp and M. J. Post, 1992: Smoke-column observations from two forest fires using Doppler Lidar and Doppler Radar. *J. App. Met.*, **31**, 1328-1349.

Bryan, G. H. and R. Rotunno, 2002: A benchmark simulation for moist nonhydrostatic numerical models. *Mon. Wea. Rev.*, **130**, 2917-2928.

Noble, I. R., A. V. Bary and A. M. Gill, 1980: McArthur's fire-danger meters expressed as equation. *Aust J. Ecol.*, **5**, 201-203.

Rothermel, R. C., 1991: Predicting behaviour and size of crown fires in the northern Rocky Mountains. *Res. Pap. INT-438. U.S. Dept. of Agiculture, Forest Service, Intermountain Research Station, Ogden UT. 46pp.*

Tory, K. J. and W. Thurston, 2015: Pyrocumulonimbus: A Literature Review, Bushfire and Natural Hazards CRC, Australia.

Monitoring and forecasting fuel moisture content for Australia using a combination of remote sensing and modelling

Marta Yebra*[a,b], Albert van Dijk[a,b] , Xingwen Quan[c,a] and Geoffrey J. Cary[a,b]
a Fenner School of Environment and Society, the Australian National University, Canberra, ACT, Australia.
b Bushfire & Natural Hazards Cooperative Research Centre, Melbourne, Victoria, Australia.
c School of Resources and Environment, University of Electronic Science and Technology of China, Sichuan, China.
Email: marta.yebra@anu.edu.au

Introduction

Fire danger monitoring in Australia involves fire danger indices that consider mainly meteorological conditions, although a simple algorithm is used in the McArthur Forest Fire Danger Index to calculate the 'Drought Factor' value from antecedent weather data, intended as a rough estimate of availability of fuel for combustion. In July 2014, the Australian governments agreed that a new National Fire Danger Rating System (NFDRS) is a national priority (National Fire Danger Ratings Working Group, 2015). The intention of a new system would be to incorporate physically-based models that more accurately predict fire weather, fuel condition, ignition likelihood, fire behaviour, fire suppression and fire impact.

Fuel Moisture Content (FMC), the ratio of water over dry mass, is a critical aspect of fuel condition that influences ignition and the rate of fire spread (Viegas et al., 1992) and hence is important to estimate the risk of unplanned fire as well as plan prescribed burns. Consequently, more accurate observation or estimation of FMC is a key research challenge. In estimating FMC, separate methods are required for live FMC (LFMC) and dead FMC, as they have different water retention mechanisms and respond differently to weather and soil water status. Dead FMC is usually more closely related to atmospheric conditions while LFMC, the focus of this study, is more closely related to soil water availability, and a function of species physiological characteristics and drought adaptation that drives seasonal variation.

This paper presents the first Australia-wide product of LFMC based on the MODIS (Moderate Resolution Imaging Spectrometer) satellite and radiative transfer modelling. We then discuss how LFMC estimates can be assimilated into an ecohydrological forecasting model to produce experimental forecasts of FMC and flammability over the following weeks and months.

Methodology

The methodology used to map LFMC in Australia is based on previous experience in retrieving LFMC in Europe using MODIS reflectance data, ancillary information on live fuel type and Radiative Transfer Model (RTM) Look-up Table (LUT) inversion techniques (Jurdao et al., 2013, Yebra and Chuvieco, 2009, Yebra et al., 2008, Yebra et al., 2013a).

The methodological workflow is shown in Figure 1. Three different reference LUTs, generated using three different RTMs, contain multiple spectra simulated for different moisture contents and fuel types ($LUT_{Grassland}$, $LUT_{Shrubland}$ and $LUT_{Woodland}$). A leaf-level model (PROSPECT; (Feret et al., 2008) and a canopy-level model (SAILH; (Verhoef, 1984) were coupled to simulate the spectra of grasslands and shrublands, whereas PROSPECT was coupled to a geometrical canopy-level model (GeoSail; (Huemmrich, 2001) to simulate the spectra of woodlands/forest.

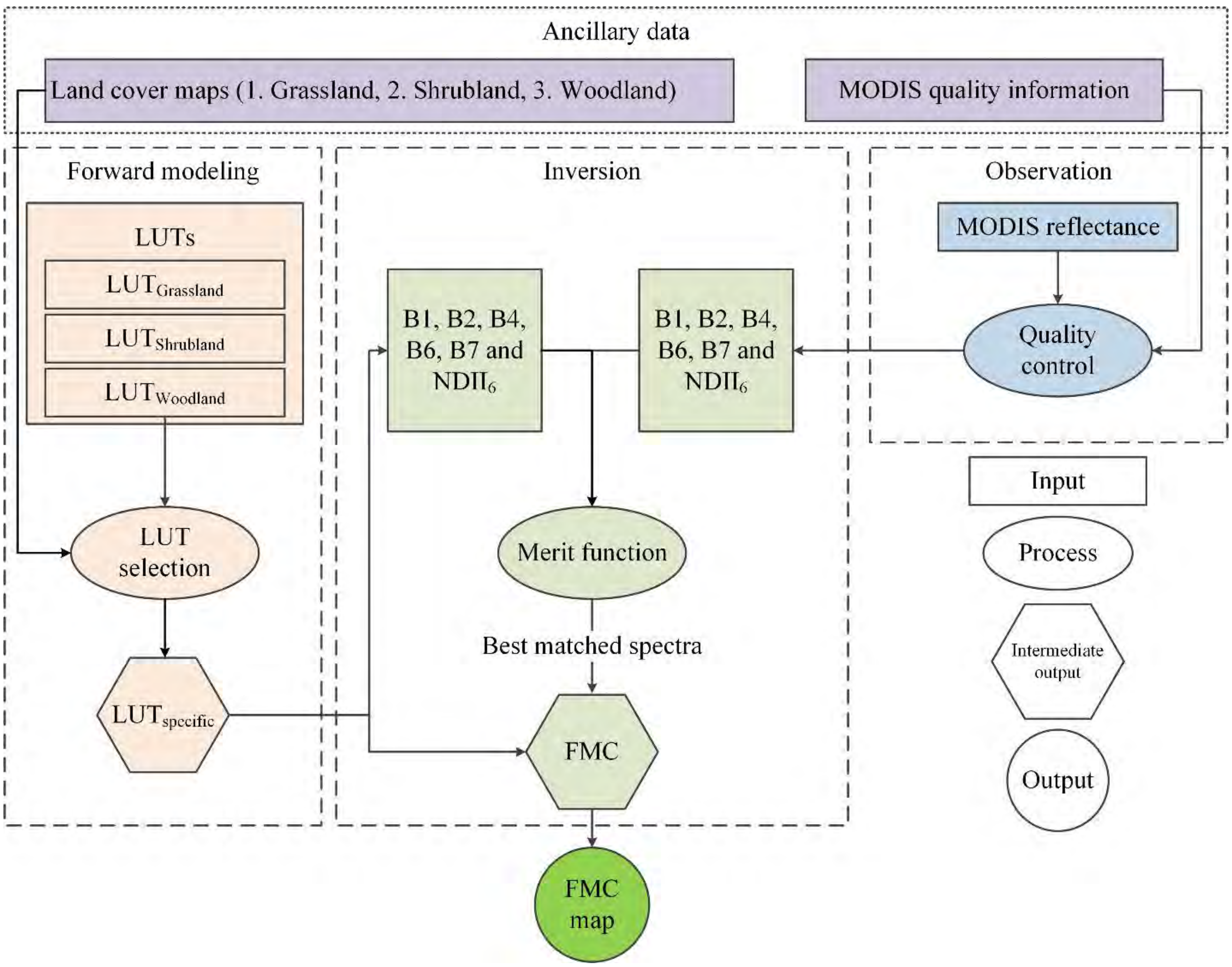

Figure 1: Methodological workflow used to generate a map of live fuel moisture content (FMC) from MODIS, radiative transfer models and land cover data. Forward modelling involves Look-up Tables (LUTs) and inversion involves comparing observed and modeled MODIS reflectance bands (B1 – B7) and the Normalized Difference Infrared Index ($NDII_6$) calculated from these.

For each MODIS (MCD43A4, collection 5) pixel and date, a land cover map (MODIS Land Cover Type product, MCD12Q1) is used to select the reference LUT corresponding to the specific land cover class covering that pixel. All the simulated spectra from the selected LUT are compared to the spectrum of every MODIS pixel that passes the quality control test performed using MODIS quality information obtained from the MCD43A2 product. MODIS bands 1, 2, 4, 6 and 7 as well as the Normalized Difference Infrared Index ($NDII_6$) calculated from bands 2 and 6 (Hunt and Rock, 1989) are used in the comparison. The spectral angle (SA, Eq. 1) was used as the merit function to minimize the differences between observed (satellite image) and simulated (LUT) reflectance and $NDII_6$. The ensemble average of the LFMC of the 40 simulated spectra which are most similar to the MODIS spectrum is selected to represent the final LFMC value of that pixel.

$$SA(\vec{v}, \vec{w}) = cos^{-1}\left(\frac{\vec{v} \times \vec{w}}{\|v\| \times \|w\|}\right) \quad (1)$$

where *v* and *w* are the observed and the reference spectra respectively, both of them considered as an m-dimensional feature vector, with *m* being the number of spectral channels.

Existing field LFMC data collected in grassland (Newnham et al., 2011), shrubland (Caccamo et al., 2012) and forest (Nolan et al., in preparation) environments between 2004 to 2014 were used to validate the algorithm retrievals (Fig. 2). From a total of 416 LFMC measurements, 97 were discarded from the analysis for one or more of the following conditions: (i) poor quality of the reflectance data around the sampling date (assessed from the MCD43A2B4 quality information product); (ii) heterogeneous land cover types; (iii) high-relief topography within the MODIS pixels where the samples were collected; or (iv) anomalous LFMC caused by sampling during or shortly after rainy events (as annotated in the observations of the field collected database). (ii) and (iii) were assessed from high resolution aerial and satellite images from various sources (Google Earth^{TM}, http://www.google.com/earth/).

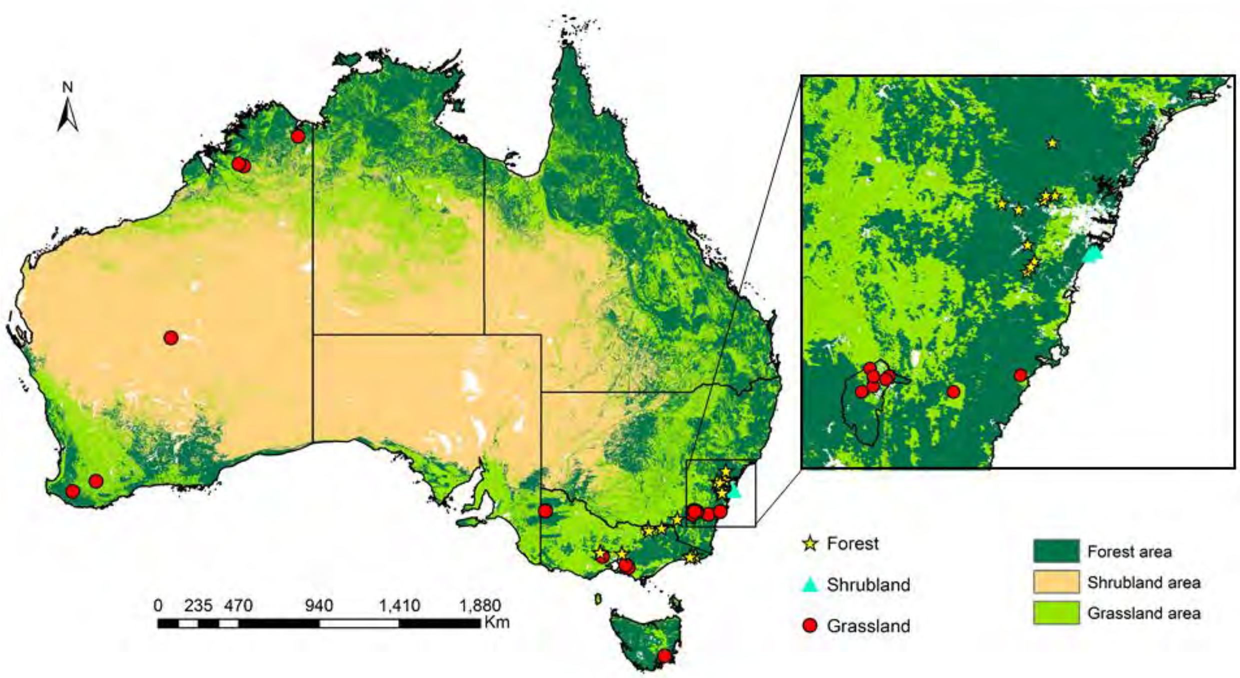

Figure 2: Location of the validation sites for a model of satellite-derived live fuel moisture content

Results

Overall, the algorithm explained 64% of variation in measured LFMC with an RMSE of 31%. Regarding individual fuel types, the seasonality of LFMC for grasslands is more accurately retrieved (R^2=0.66) than for shrublands (R^2=0.02), and forest (R^2=0.01). However, in absolute terms the algorithm produced the best estimates in shrublands (RMSE=14%), followed by woodlands (RMSE=33%) and grasslands (RMSE=39%).

A series of 595 LFMC maps was generated for 13 years of 8-daily MODIS data (2002-2014). An animation of dynamic variation in time and space of the LFMC for Australia for 2002-2014 can be found at https://youtu.be/6h6mgHYiZXQ. Examples illustrating the variation of LFMC during 2013 are shown in Fig. 4. In January 2013, there were low values of LFMC in most of the temperate zones of Australia. The LFMC values in these areas gradually increased until reaching their maximum at the end of winter or beginning of spring (e.g. August/September). Afterwards LFMC started to decrease until the end of the summer when values were the lowest. As expected, the temporal pattern was the opposite in the tropical regions in the north of the country; higher LFMC values were observe during the northern wet season (Dec-March) and lower values during the dry season (April-October). As expected, LFMC values were constantly low in the desert zones.

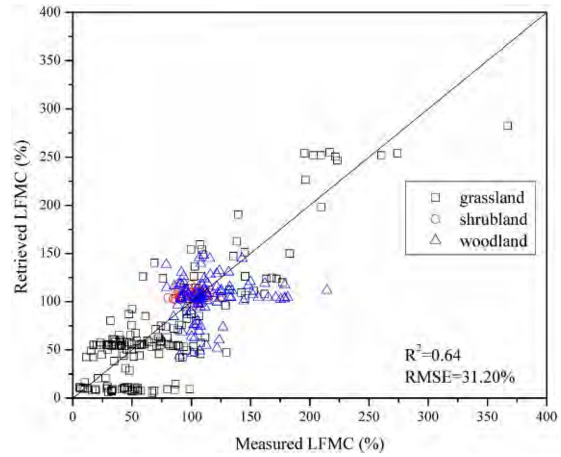

Fig. 3. Relation between measured and retrieved LFMC at all validation sites symbolized by fuel type (grassland, shrubland and forest)

Conclusions and further work

This paper presents the first Australia-wide product of LFMC based on the MODIS imagery, RTM LUT inversion techniques with ancillary information on fuel type. A total of 416 field measurements of LFMC in grassland, shrubland and woodland areas were used to assess the accuracy of the predictive algorithm. The overall accuracy of the algorithm was characterised by an R^2=0.64 and RMSE=31%.

Further work is planned to improve of the accuracy of LFMC estimates by adapting the radiative transfer model and LUT for Australian conditions, as well as deriving LFMC with more spatially detailed satellite observations (ca. 25-m; e.g., Landsat, Sentinel 2). Better temporal resolution (i.e. daily) observations are possible when the new MODIS collection 6 products become fully available in 2016. Furthermore, LFMC has a diurnal cycle, even more so during periods of developing plant water stress. The launch of the geostationary Himawari-8 satellite may allow monitoring of diurnal LFMC dynamics at 2 km resolution. If successful, this development would make it possible to provide early warning of the onset of canopy water stress, and thereby improve flammability forecasts.

Furthermore, we plan to assimilate the remotely sensed LFMC observations in an ecohydrological forecasting model to forecast landscape flammability over the following weeks and months. For this end, we will use the ecohydrological model OzWALD (for "Australian Water And Landscape Dynamics"); a recent further development of the AWRA-L landscape hydrology model (Van Dijk, 2010) used operationally by the Bureau of Meteorology. Relevant modifications already contained in OzWALD include the assimilation of MODIS-derived vegetation leaf area index, albedo and canopy conductance (Yebra et al., 2013b) and the extension of the dynamically-adjusting vegetation model with an explicit description of carbon uptake (Yebra et al., 2015), whereas current work involves the inclusion of dead FMC dynamics (cf. Matthews, 2006). The intention is to use multi-day numerical weather forecasts available from the Bureau of Meteorology to generate FMC forecasts as an input to fire risk assessment and burn planning.

The long-term objective is that a model-data fusion approach to FMC forecasting will be operationally used and integrated with other key fuel structural properties into fire propagation models, to derive more reliable estimates of ignition probability and rate of spread for local conditions.

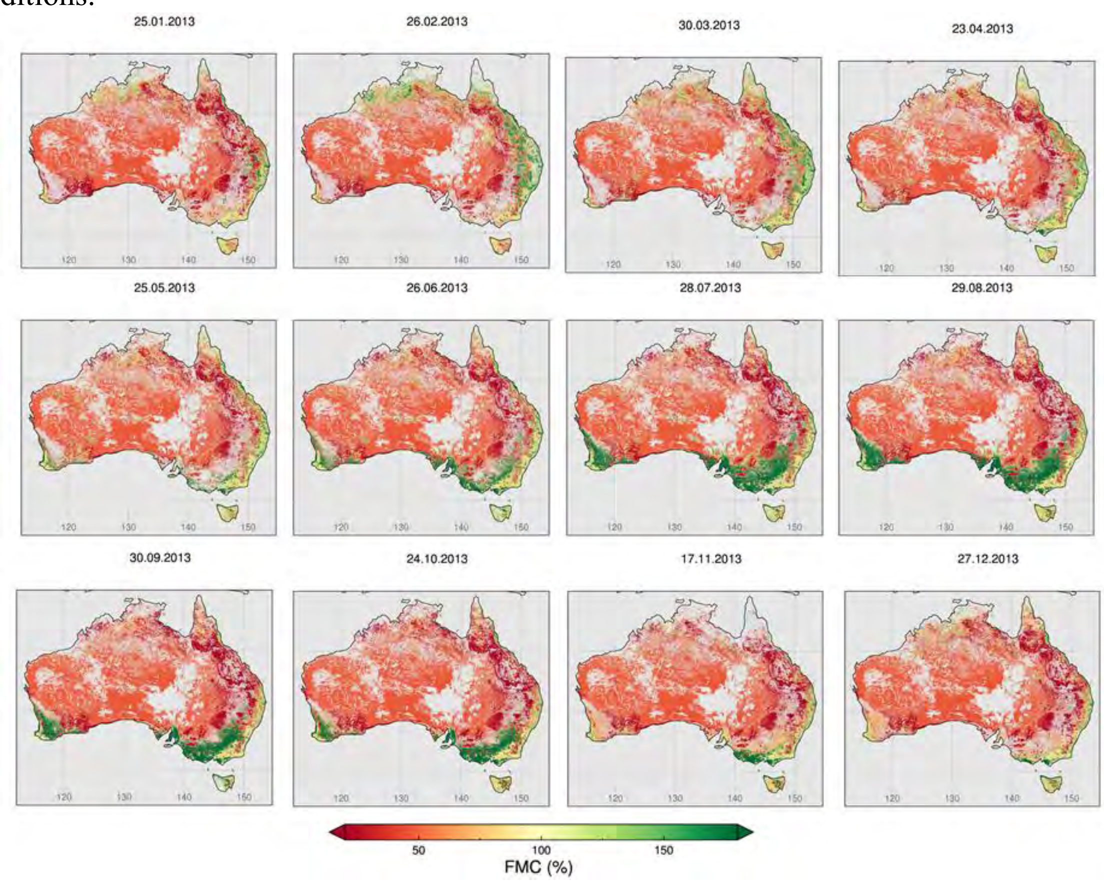

Figure 4. Multi-temporal change in Live Fuel Moisture Content (LFMC) for 2013 for Australia. Shaded areas indicate missing data due to atmospheric contamination and insufficient vegetation cover.

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References

CACCAMO, G., CHISHOLM, L. A., BRADSTOCK, R. A., PUOTINEN, M. L. & PIPPEN, B. G. 2012. Monitoring live fuel moisture content of heathland, shrubland and sclerophyll forest in south-eastern Australia using MODIS data. *International Journal of Wildland Fire,* 21**,** 257-269.

FERET, J.-B., FRANÇOIS, C., ASNER, G. P., GITELSON, A. A., MARTIN, R. E., BIDEL, L. P. R., USTIN, S. L., LE MAIRE, G. & JACQUEMOUD, S. 2008. PROSPECT-4 and 5: Advances in the leaf optical properties model separating photosynthetic pigments. *Remote Sensing of Environment,* 112**,** 3030-3043.

HUEMMRICH, K. F. 2001. The GeoSail model: a simple addition to the SAIL model to describe discontinuous canopy reflectance. *Remote Sensing of Environment,* 75**,** 423-431.

HUNT, E. R. & ROCK, B. N. 1989. Detection of Changes in Leaf Water-Content Using near-Infrared and Middle-Infrared Reflectances. *Remote Sensing of Environment,* 30**,** 43-54.

JURDAO, S., YEBRA, M., GUERSCHMAN, J. P. & CHUVIECO, E. 2013. Regional estimation of woodland moisture content by inverting Radiative Transfer Models. *Remote Sensing Of Environment,* 132**,** 59-70.

MATTHEWS, S. 2006. A process-based model of fine fuel moisture. *International Journal of Wildland Fire,* 15**,** 155-168.

NATIONAL FIRE DANGER RATINGS WORKING GROUP 2015. Scoping a path for a new fire danger rating system. *Bushfire and Natural Hazards CRC and Cube Group.*

NEWNHAM, G. J., VERBESSELT, J., GRANT, I. F. & ANDERSON, S. A. J. 2011. Relative Greenness Index for assessing curing of grassland fuel. *Remote Sensing of Environment,* 115**,** 1456-1463.

VAN DIJK, A. I. J. M. 2010 AWRA Technical Report 3. Landscape Model (version 0.5) Technical Description, WIRADA / CSIRO Water for a Healthy Country Flagship, Canberra.

VERHOEF, W. 1984. Light scattering by leaf layers with application to canopy reflectance modeling: The SAIL model. *Remote Sensing of Environment,* 16**,** 125-141.

VIEGAS, D., VIEGAS, M. & FERREIRA, A. 1992. Moisture Content of Fine Forest Fuels and Fire Occurrence in Central Portugal. *International Journal of Wildland Fire,* 2**,** 69-86.

YEBRA, M. & CHUVIECO, E. 2009. Linking ecological information and radiative transfer models to estimate fuel moisture content in the Mediterranean region of Spain: Solving the ill-posed inverse problem. *Remote Sensing Of Environment,* 113**,** 2403-2411.

YEBRA, M., CHUVIECO, E. & RIANO, D. 2008. Estimation of live fuel moisture content from MODIS images for fire risk assessment. *Agricultural And Forest Meteorology,* 148**,** 523-536.

YEBRA, M., DENNISON, P. E., CHUVIECO, E., RIANO, D., ZYLSTRA, P., HUNT, E. R., DANSON, F. M., QI, Y. & JURDAO, S. 2013a. A global review of remote sensing of live fuel moisture content for fire danger assessment: Moving towards operational products. *Remote Sensing Of Environment,* 136**,** 455-468.

YEBRA, M., VAN DIJK, A., LEUNING, R., HUETE, A. & GUERSCHMAN, J. P. 2013b. Evaluation of optical remote sensing to estimate actual evapotranspiration and canopy conductance. *Remote Sensing of Environment,* 129**,** 250-261.

YEBRA, M., VAN DIJK, A. I. J. M., LEUNING, R. & GUERSCHMAN, J. P. 2015. Global vegetation gross primary production estimation using satellite-derived light-use efficiency and canopy conductance. *Remote Sensing of Environment,* 163**,** 206-216.

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Monitoring live canopy moisture with imaging radars[1]

M. A. Tanase*
School of Ecosystem and Forest Sciences, the University of Melbourne, Australia, mihai@tma.ro
R. Panciera
Cooperative Research Centre for Spatial Information, Melbourne, Australia
K. Lowell,
Cooperative Research Centre for Spatial Information, Melbourne, Australia
C. Aponte
School of Ecosystem and Forest Sciences, the University of Melbourne, Australia

Introduction

An important component of forest fire management systems is fire danger forecasting with most forecasting systems relying on meteorological variables (Chowdhury and Hassan 2014) to estimate fuel moisture content based on drought related indices. Dead fuel moisture is considered the primary danger indicator by most systems (Chowdhury and Hassan 2014). However, in semi-arid environments, variations in live fuel moisture and its spatial continuity are critical factors influencing fire occurrence, intensity and spread with previous work demonstrating an inverse relationship between ignition probability and live vegetation moisture (Dimitrakopoulos and Papaioannou 2001). Since similar atmospheric conditions can result in differentiated effects due to physiological characteristics of individual trees or species-related resistance to drought, estimates of live fuel moisture based on meteorology alone are unreliable (Chuvieco et al. 2009).

Several studies have retrieved live fuel moisture content (FMC) and equivalent water thickness (EWT) using passive optical sensors (Maki et al. 2004). However, monitoring live fuel moisture from optical data has a number of challenges: i) cloud cover which render large areas irretrievable (Leblon 2005), ii) decoupling EWT from dry matter content in the reflectance values (Yebra et al. 2013), iii) confounding effects of leaf area index (LAI) and other canopy variables (Yebra et al. 2013), and iv) low spatial resolution (Leblon 2005). In contrast, active sensors in the microwave region (i.e., synthetic aperture radar - SAR), are insensitive to cloud cover and highly sensitive to materials` water content and have been used to estimate dead fuel moisture in boreal (Abbott et al. 2007) or tropical (Couturier et al. 2001) forests. In addition, current SAR missions such as Sentinel-1 and the second Advanced Land Observing Satellite (ALOS) can achieve high temporal revisit times and at the same time provide high spatial resolutions. Therefore, the aim of this study was to evaluate the opportunity provided by such missions for monitoring live fuel (i.e., canopy foliage) moisture in a semi-arid environment. A set of airborne L-band SAR measurements, similar in characteristics to ALOS-2 mission, was used as a substitute for the satellite data. The specific objective of the study was to evaluate the relationship between live FMC and EWT and different SAR metrics such as backscatter intensities or polarimetric decomposition components.

[1] This study was published in the International Journal of Wildland Fire, vol. 24. The reader is referred to the publisher`s archive for a detailed version of the study.

Materials and methods

Study area and field data

The study area is located in the Murrumbidgee catchment Australia, a fairly flat area with slopes below 5%. The climate is semi-arid and the area is characterized by agricultural and grazing farms interspersed with forests. An 1800 ha forest (mean biomass 60.9 t ha^{-1}) dominated by white cypress pine (*Callitris glaucophylla*) with dispersed (10%) grey box trees (*Eucalyptus microcarpa*) was the focus of this investigation.

A biometric survey was conducted using five circular cluster plots at 12 sites in 2011(Tanase et al. 2014). Leaf sampling was conducted on eight dates at a sub-sample of these sites. At each site one representative white cypress pine tree was selected for sampling. From each tree, leaf samples were collected at 2 and 5 m height (lower and upper canopies). Each sample consisted of 50 to 250 grams of leaves. When present at a site, grey box leaf samples were also collected. Each sample weighed to obtain the fresh weight (FW) and oven dried to obtain the dry weight (DW). Before drying the leaves were spread over white cardboard and vertical photos were taken to calculate leaf surface area. Using FW, DW and leaf area the live FMC (kg kg^{-1}) and EWT (kg m^{-2}) were computed. In total, 88 samples evenly distributed between the lower (2 m) and upper (5 m) forest canopy were collected and processed for the white cypress pine. Additionally, 11 samples were collected at 5 m height (foliage was not present below this height) for grey box trees to assess inter-species differences.

Synthetic Aperture Radar data processing

The SAR data were acquired in 2011 by the Polarimetric L-band Imaging Synthetic aperture radar (PLIS) within the Soil Moisture Active Passive Experiments (SMAPEx) (Panciera et al. 2014). The single-look slant range resolution of PLIS is 6 m while the azimuth resolution is 0.8 m. The sensor was flown eight days at an altitude of 3000 m (Table 1). Two flight lines, flown from different directions, were needed to cover the study area: on the first flight line (FL) both Left (“L”) and Right (“R”) antennas acquired data over the forest (FL1L and FL1R) while on the second flight line the forest was imaged only by the right antenna (FL2R). PLIS polarimetric calibration was accomplished using a modified version of the method described by Ainsworth et al. (2006) while the radiometric calibration was achieved using a set of six Passive Corner Reflectors (PRCs) deployed in a nearby homogeneous grassland field (Tanase et al. 2014).

Two types of metrics were derived from PLIS observations: the first group corresponds to backscatter intensity (i.e., BI metrics) and includes the intensity of individual channels (i.e., HH, HV, VH and VV) and the radar vegetation index (RVI). The second group corresponds to quantities resulting from polarimetric target decomposition (i.e., TD metrics). To compensate for geolocation errors, avoid edge contamination, reduce residual speckle and limit the effect of forest spatial variability the PLIS data extraction was carried out over 0.25 ha areas centred at each sample site. Only pixels falling completely within the extraction area (i.e., around five pixels) were kept and their value averaged. Field and radar data were paired for 11 sites (site 20 was discarded due to partial coverage). Since the SMAPEx campaign focused on soil moisture monitoring forest sampling occurred between PLIS flying days. Therefore, ground data were paired with airborne data acquired within one day which effectively doubled the number of available samples for modelling compared to interpolating ground measurements to flight dates.

Data analysis

Differences in live FMC and EWT between canopy heights (white cypress pine only) were tested for significance using a paired *t*-test for dependent samples while differences between species (5 m height) were tested using a *t*-test. Differences between acquisition dates were analyzed for each species and height separately using analysis of variance (ANOVA) and Tukey-test *post hoc* comparisons. Semi-partial correlation coefficients were used to assess the strength of the relationships between field measurements and radar metrics while live fuel moisture retrieval was carried out using regression-based modelling with cross-validation for each sampled height and at canopy level. Cross-validation (based on bootstrapping) was used to compute root mean squared error (RMSE) and the relative RMSE. Additionally, modeled R^2 and the correlation between predicted and observed values (r) were used to characterize the goodness-of-fit. The data analysis was conducted using two data subsets: all sites (n=45) and only sites acquired during the second airplane pass (FL2, n=23; Fig 1). The split analysis accounted for confounding factors that might affect relationships between ground and airborne data such as: i) forest species composition and field sampling difficulties and ii) airborne sensor characteristics.

Results

Patterns of vegetation and soil water content

Field measurements indicated a 7% decrease in soil moisture and 30% in canopy water content during the campaign (Fig.1 and 2) and high correlations between water content sampled at 2 and 5 m height (r = 0.9). Live FMC did not differ between canopy heights or species ($p>0.5$), whereas EWT was significantly greater at 5 m height when compared to 2 m height for white cypress samples ($p<0.0001$). EWT was also significantly different between the two species ($p<0.002$). Live FMC and EWT varied significantly during the campaign (white cypress), with mean daily values ranging from 0.8 to 1.1 kg kg^{-1} and from 0.3 to 0.5 kg m^{-2} respectively. For grey box such differences were not statistically significant which could be partly attributed to the limited number of samples. However, FMC and EWT temporal trends for grey box seemed consistent with those observed for white cypress (Fig. 1). At species level, only EWT for white cypress was significantly correlated with soil moisture. The joint temporal variation of soil moisture, EWT and PLIS HV scattering during the experiment showed almost perfect correspondence and similar inflection points (Fig. 2, site 38 -- the only site sampled all dates).

Relationships between live fuel moisture and SAR metrics

Airborne SAR data are characterized by wide variations in across-swath incidence angles which affect target scattering properties, i.e., energy return decreases as incidence angle increases. Such signal variations reduce discrimination potential between fuel moisture levels and have to be addressed. One way to address such variations is using the incidence angle as an independent variable. For all SAR metrics radar antenna position was a statistically significant variable suggesting residual calibration differences. A paired t-test performed on the R^2s of the different retrieval models showed statistically significant differences, with R^2s of models including antenna position being on average 10% higher.

Modelling results for EWT (Fig. 3) showed that relative RMSE varied between 15% and 20% with the HH polarization showing the lowest values for both analysis levels. The fit metrics (i.e.,

R^2 and r) were also highest for HH polarization when using either all samples (0.71 and 0.81) or FL2 samples (0.81 and 0.87). Both fit metrics increased with up to 0.2 when using FL2 samples while EWT estimation from volume and dihedral scattering was 2-5% less accurate when compared to backscatter intensities. For FMC, estimation errors were similar (about 10%) with only RVI and surface scattering providing less accurate predictions.

The comparison of EWT and live FMC results showed lower estimation errors for live FMC but higher r values for EWT depending on the analysis level (i.e., *n*=45 and *n*=23). Such differences were observed across all canopy levels but with higher RMSE differences (10%) for the upper canopy (5 m) and higher fit metrics differences (up to 0.2) for the lower canopy (2 m). Examining different sampling heights (results not shown), live fuel moisture in the upper canopy was estimated consistently better with RMSE being lower (up to 4%) and the fit metrics higher (up to 0.3) for live FMC. Such differences were less pronounced for EWT where the RMSE differed by only 1% and the fit metrics by 0.1.

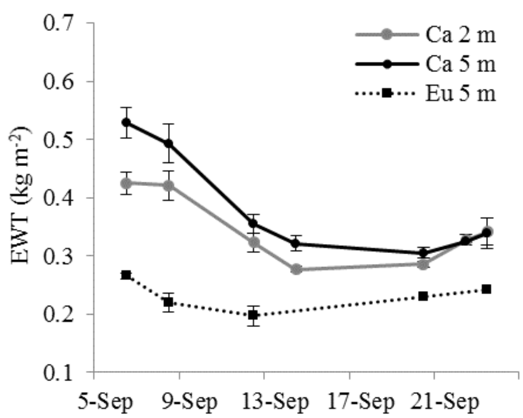

Fig. 1 Equivalent Water Thickness (EWT) temporal variation. The vertical bars represent standard deviation of the mean. Eu stands for grey box while Ca stands for white cypress pine.

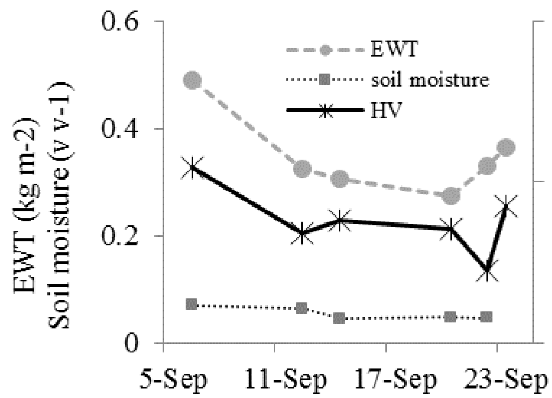

Fig. 2 Joint temporal variation of Equivalent Water Thickness (EWT), L-band radar backscatter intensity (σ°, HV polarization) and soil moisture at site 38.

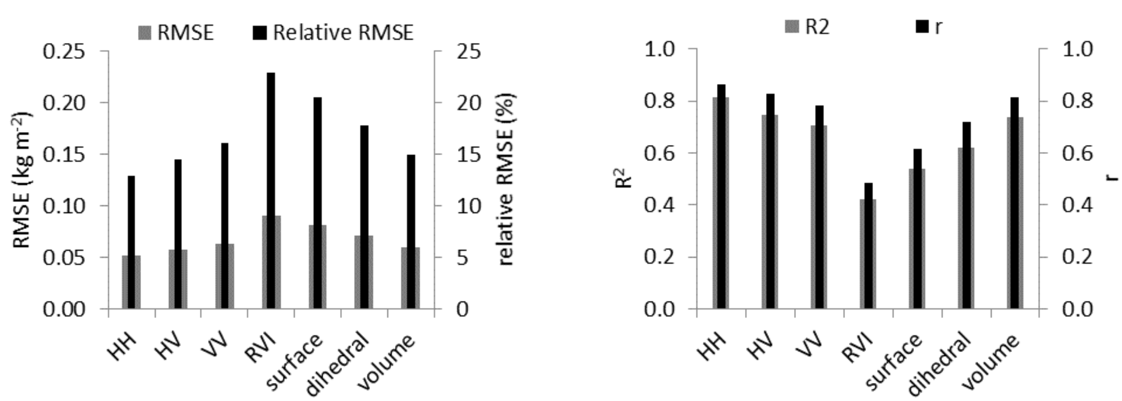

Fig. 3 Statistics for fuel moisture retrieval expressed by the Equivalent Water Thickness (EWT). Only sites located in the second flight line (n=23) were considered.

Discussions

Resource managers use different indices to quantify live canopy moisture. Of the two indices analyzed, EWT values were more stable with between-site variability being low. Moreover, EWT was significantly different for the upper and lower canopies, was correlated to soil moisture, and had generally better model fit statistics except for RMSE. Therefore, information on leaf area should be collected when sampling for live fuel moisture so EWT can be computed. The lower RMSE errors obtained for live FMC suggest that further studies are necessary to recommend one index over the other. Furthermore, different indices may be optimal for different forest types and structures.

Polarimetric decomposition components provided slightly lower estimation accuracies for EWT while for FMC the results were very similar to those obtained from backscatter intensities. This suggests that, in similar environments, live fuel moisture can be monitored using dual polarized L-band datasets routinely acquired by current space borne sensors. Further studies should clarify the utility of fully polarimetric sensors in different environments as well as the most useful polarimetric variables for live fuel moisture monitoring.

Despite the relatively deep L-band penetration and the short trees present in the study area, larger errors were observed when estimating lower canopy fuel moisture for both live FMC and EWT. Two factors may explain such results: i) the reduced moisture content of the lower canopy and, ii) the overall low soil moisture which suggests reduced dihedral scattering. Therefore, the upper canopy should be sampled for the most accurate results in semi-arid areas. The sampling height was also important given that only three meters separated the upper and the lower canopy in this study. The differentiated results suggest that variations in live fuel moisture along canopy are important which is significant for fire risk management since drier lower canopy may ignite more easily from surface fires. The ability to monitor soil moisture is also an important finding due to the direct relationship with fine fuels moisture. However, for taller denser forests soil moisture estimation error might be higher due to stronger signal attenuation. Nevertheless, the relationship observed between EWT and soil moisture may provide a means to spatially estimate fine fuels moisture in taller forests.

Conclusions

This study assessed the relationship between commonly used live fuel moisture indices and radar-derived metrics in a dry forest environment. SAR data were acquired every two to three days using an airborne fully polarized L-band sensor. Field samples of live fuels (i.e., foliage) were collected for two canopy heights. Statistical analysis of the ground dataset showed that EWT was less variable across sites while being significantly different for the two canopy heights analyzed. Models relating EWT and SAR metrics showed slightly better fit statistics when compared to models using live FMC. In general, the SAR data showed potential for live fuel moisture estimation (R^2 = 0.7-0.8) with the conjoint temporal variation of cross-polarized scattering and EWT being remarkably similar. The availability of space-borne SARs with high temporal revisit times provides great opportunities for advancing current knowledge towards operational scenarios where more accurate, spatially explicit live fuel moisture estimates are integrated into operational fire danger forecasting systems.

Acknowledgements

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References

Abbott, K.N., Leblon, B., Staples, G.C., Maclean, D.A., & Alexander, M.E. (2007). Fire danger monitoring using RADARSAT-1 over northern boreal forests. *International Journal of Remote Sensing, 28*, 1317-1338

Ainsworth, T.L., Ferro-Famil, L., & Lee, J.-S. (2006). Orientation Angle Preserving A Posteriori Polarimetric SAR Calibration. *IEEE Transactions on Geoscience and Remote Sensing, 44*, 994-1003

Chowdhury, E.H., & Hassan, Q.K. (2014). Operational perspective of remote sensing-based forest fire danger forecasting systems. *ISPRS Journal of Photogrammetry & Remote Sensing, in press*

Chuvieco, E., González, I., Verdú, F., Aguado, I., & Yebra, M. (2009). Prediction of fire occurrence from live fuel moisture content measurements in a Mediterranean ecosystem. *International Journal of Wildland Fire, 18*, 430-441

Couturier, S., Taylor, D., SIEGERT, F., Hoffmann, A., & Bao M, Q. (2001). ERS SAR backscatter A potential real-time indicator of the proneness of modified rainforests to fire. *Remote Sensing of Environment, 76*, 410-417

Dimitrakopoulos, A.P., & Papaioannou, K.K. (2001). Flammability Assessment of Mediterranean Forest Fuels. *Fire Technology, 37*, 143-152

Leblon, B. (2005). Monitoring forest fire danger with remote sensing. *Natural Hazards, 35*, 343-359

Maki, M., Ishiahra, M., & Tamura, M. (2004). Estimation of leaf water status to monitor the risk of forest fires by using remotely sensed data. *Remote Sensing of Environment, 90*, 441-450

Panciera, R., Walker, J.P., Jackson, T.J., Ryu, D., Gray, D., Monerris, A., Yardley, H., Tanase, M., Rudiger, C., Wu, X., Gao, Y., & Hacker, J. (2014). The Soil Moisture Active Passive Experiments (SMAPEx): Towards Soil Moisture Retrieval From the SMAP Mission *IEEE Transactions on Geoscience and Remote Sensing, 52*, 490-507

Tanase, M., Panciera, R., Lowell, K., Tian, S., Hacker, J., & Walker, J.P. (2014). Airborne Multi Temporal L-band Polarimetric SAR Data for Forest Biomass Estimation in Semi-Arid Forests. *Remote Sensing of Environment, 145*, 93-104

Yebra, M., Dennison, P.E., Chuvieco, E., Riaño, D., Zylstra, P., Jr., E.R.H., Danson, F.M., Qi, Y., & Jurdao, S. (2013). A global review of remote sensing of live fuel moisture content for fire danger assessment: Moving towards operational products. *Remote Sensing of Environment, 136*, 455-468

Next Generation (Australian) National Fire Danger Rating System (NFDRS)
5th International Fire Behaviour and Fuels Conference 2016

Paper prepared by:
Joe Buffone
Chief Officer CFA
(Chair of National Fire Danger Working Group).
Email:j.buffone@cfa.vic.gov.au

This paper is prepared by drawing on extracts from the reports prepared in developing the Road Map for the Next Generation (Australian) National Fire Danger Rating System (NFDRS) on behalf of the National Fire Danger Working Group.

Introduction

Fire Services and emergency service organisations in Australia currently rely on a Fire Danger Rating System that is based on MacArthur's work and has remained largely unchanged since the 1960s. Its limitations, including its inability to be upgraded and capture advances in science, places emergency services, policy makers and communities at unnecessary risk and contributes to greater economic and social dislocation than necessary. At a most general level, it is helpful to keep in mind that the McArthur system was only ever designed to assess the suppression difficulty of fire in the natural environment.

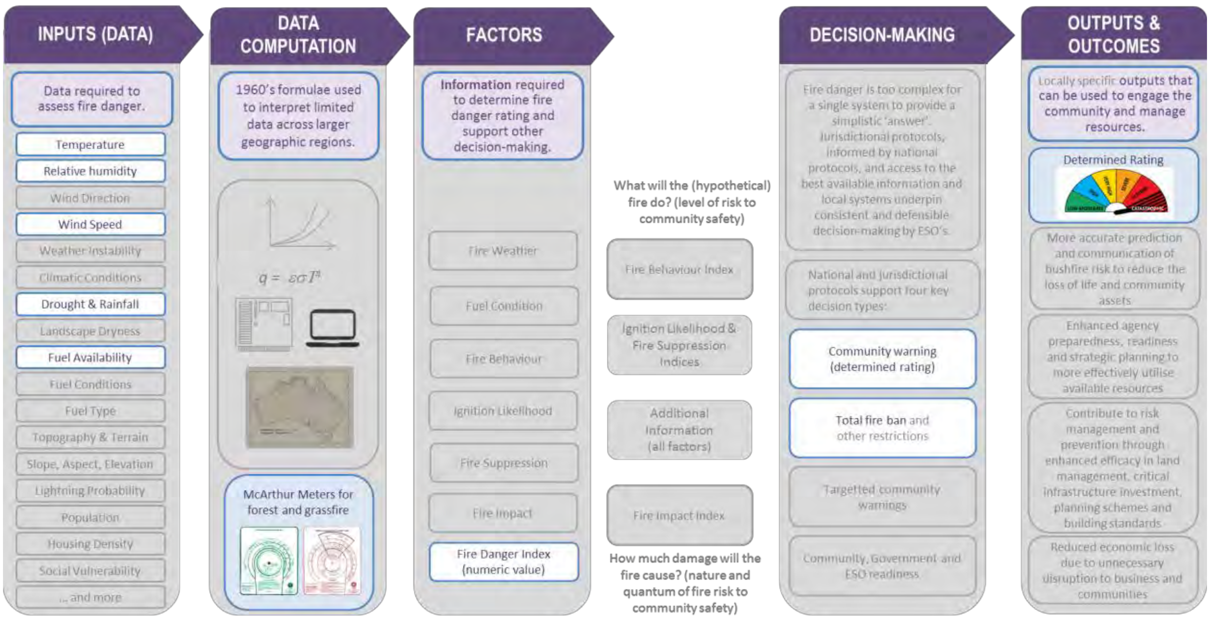

Figure 1: Illustrative representation of Mc Arthur System currently utilised to determine FDR in Australia.

In the wake of the February 2009 Victorian bushfires the resultant Victorian Bushfire Royal Commission identified that: (i) fire danger ratings should be revised to better reflect the higher levels of fire danger being seen in bushfire events; and (ii) fire danger information could be better communicated to the public and through the media.

Progress to Date

To address this, significant work was undertaken to enhance the existing Fire Danger Rating System, this included an FDR of Catastrophic/Code Red to describe and advise when fire conditions are not controllable. In 2014 the NFDRS was determined to be a project of national priority. A National Fire Danger Ratings Working Group, made up of representatives from all jurisdictions (including the Commonwealth), worked together to deliver an overview of costs and benefits of investment, a nationally agreed 'picture' of the design and function of a new Fire Danger Rating System, and a detailed program management plan and 'roadmap' to support its development.

The next generation system will be a contemporary Fire Danger Rating System and draw upon a broad range of data, produce a suite of fire danger indicators, and support practitioners in both strategic and operational response scenarios to make more accurate, informed public safety decisions. The new System will be spatially and temporally enabled and therefore better supporting emergency management organisations to understand and act upon fire risk at a more granular level, vastly improving the accuracy and effectiveness of services.

The NFDRS would ultimately be a nationally consistent technology solution with a single, integrated data model and a common or unified platform. It also acknowledged the implementation Roadmap for the NFDRS solution will leverage existing jurisdictional investment and computational platforms on the pathway to creating a new, purpose built solution.

The benefits of establishing the NFDRS for Australia are substantial. Improved Fire Danger Rating assessment and response will benefit a very broad range of stakeholders either directly, through improved advice and community confidence in that advice, protection of life and property, or indirectly, through improved use of taxpayer funds and resources.

The benefits of the NFDRS can be measured through the impact it will have on reducing the damage and annual cost of fires. Many of the NFDRS benefits flow from three key drivers:

- a reduction in the number, size, intensity and impact of fires;
- the shift to a national system; and
- greater accuracy, risk comprehension and confidence that will result from the new system.

Importantly, the new system will have the ability to deliver incremental benefits. It will be open, adaptive, upgradeable and expandable for continuous improvement allowing for updates and replacements, without impacting other components or requiring a major system overhaul. The design of NFDRS will enable individual jurisdictions to buy-in at an appropriate level for their requirements through incremental investment.

The NFDRS will provide nationally consistent and defensible decision-making for a broad range of community warnings and messages, utilising the best available information in conjunction with local systems. Overall, the NFDRS is a significant and economically viable program that will provide substantial national benefits to Australia as a whole.

NFDRS decision-making

The NFDRS will provide nationally consistent and defensible decision-making for a broad range of community warnings and messages, utilising the best available information in conjunction with local systems.

National and jurisdictional protocols will support decision-makers within emergency service organisations (ESO's) to make decisions regarding the level, nature and quantum or scale of the risk to community safety.

Recognising that fire is too complex for a single system to provide a simplistic 'answer', its intent is to provide cross-jurisdictional agreement on decision-making variables, while still ensuring that locally specific factors can be used to understand and mitigate risks, engage and warn communities and manage resources. Decision-making will be underpinned by agreed processes and protocols used by jurisdictions' Emergency Service Organisations (ESO's) to:

- assess all relevant factors,
- consider real-time needs, and
- determine the appropriate warnings and information to be disseminated to the community and other stakeholders.

An important outcome of this approach is that it ensures that agencies can make consistent and defensible decisions, using the best available information and agreed methods at the time. For strategic use, NFDRS will support decisions on longer term fire prevention and risk mitigation activities such as planned burn programs, land use planning and critical infrastructure protection strategies.

A national approach to decision-making will capture the less formalised approaches that are currently used, while catering specifically for factors that are unique to local regions. Current scientific development, contemporary technology and system capabilities have been considered to inform understanding of how the new system will evolve and the significant positive impacts it will provide at implementation and into the future. Some of the beneficial differences the NFDRS will provide above the current system include:

Capacity to deal with complexity

A modern system will enable a quantum shift in the level of sophistication and accuracy as it will be capable of multivariable analysis using a much broader range of inputs and variables. A feature of the system design is its ability to model different scenarios to better support operational decision-makers.

Modular and open systems design

The system has been designed to be established and matured in a modular fashion and to be developed using open systems technology. In plain terms, this will maximise capacity to connect with a diversity of other systems and to ensure that the system can be modified and improved over time. The current system is incapable of meeting either of these features.

Spatially explicit and temporal

Unlike the current system, the NFDRS will allow agencies, and potentially communities, to analyse and visualise fire danger using a spatial (map based) system. Importantly, its sophistication will also empower decision-makers to consider how risk shifts across time. For example, the level of risk at 10am and at 2pm or at a predicted wind change point, typically differs greatly on a day of high fire danger.

Continuous improvement capability

A contemporary system can be continuously improved through 'learning' based on predicted and actual results. The NFDRS requirements include this important and highly valuable feature.

Based on best available research

The NFDRS will use inputs and calculate algorithms derived from validated scientific research. A significant aspect of the implementation program involves research and development to provide various inputs and raw data sources required for daily operation of the system. Information will be drawn from a broader range and more geographically granular source of inputs that will inform modelling for areas including: fire weather; fuel condition; fire behaviour, ignition likelihood, suppression likelihood and probability of fire impact.

Improved communication and advice for communities

The current system offers a simple and blunt 'rating'. While agencies often supplement this rating with additional advice, community members including businesses and service providers cannot access further information or detail on their specific local risk. The NFDRS will not only provide more localised information and advice, but also offers great potential to provide further

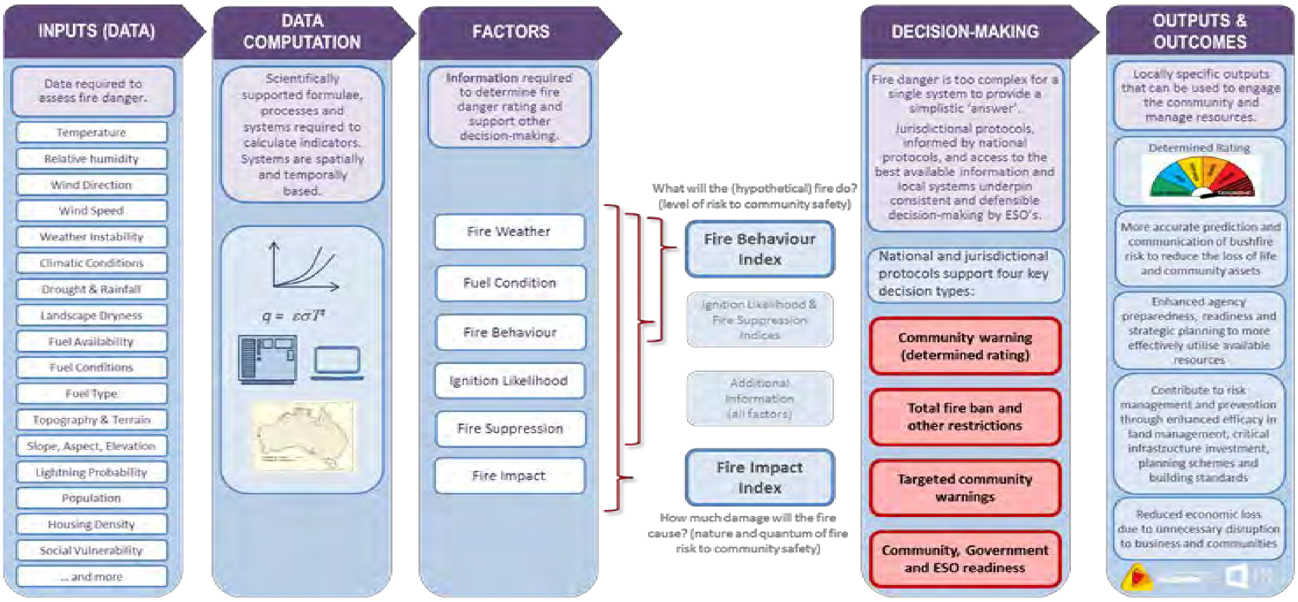

Figure 2: Illustrative representation of the next generation NFDRS.

The NFDRS will provide a paradigm shift in the level of accuracy and sophistication in producing Fire Danger Ratings and all the decisions that flow from them. Robust contemporary scientific inputs and a much more powerful spatial grid (allowing for local rather than regional analysis), where appropriate, and will ensure that operational decisions are significantly more accurate, reliable, objective, and defensible.

This shift supports many of the five benefit areas. With capacity to incorporate existing and future science as it develops, the NFDRS will also be capable of recognising and interacting with other systems. It will provide significantly increased accuracy in:

- **prediction and communication of bushfire risk**. This will assist in reducing both loss of life and community assets;
- **warnings,** both protecting lives and assets or, conversely, reducing unnecessary disruption to business and communities.
- **more effective agency assessment of required resources, readiness, response and strategic planning**. NFDRS will provide greater specificity through spatial and temporal awareness and will better enable emergency services to understand and act upon fire risk at a local, rather than regional level. This will vastly improve the effectiveness of services and have flow on impacts for efficiency of resource allocation.

Understanding risk and building confidence

Crucially, the NFDRS will provide more accurate information and provide the appropriate 'call to action', based on social science findings, thereby providing greater understanding of risk by both emergency services decision makers and the community. Choosing to leave a high fire danger area due to determined rating of extreme or catastrophic conditions is highly disruptive and expensive for individuals and the economy as whole (. But *not* leaving when the situation is critical is potentially far more costly. The public needs to have confidence that when they are asked to leave, that it is not a 'boy who cried wolf' scenario, or their safe response will become increasingly less likely.

Improved information to communities, as well as an increased understanding of risk, is likely to improve household and individual preparation. A plan to stay and defend can be effective for an appropriate level of fire risk where the supporting risk information is clearly communicated. However, where the risk is too high, there is a substantial likelihood that both life and property can be lost. In that scenario, the NFDRS will enable our emergency services personnel and the general public to more accurately assess the level of local fire risk and support these critical decisions.

Interoperability and usability

The development of a modular, open standards system will provide capacity to work with existing systems used by fire services and the Bureau of Meteorology, and emerging operational systems such as the Phoenix Rapid Fire or Aurora predictive fire behaviour applications.
The interoperability factor is crucial. Our current decision making is missing key relevant and up-to-date information. For example, the ability to integrate a broad array of Bureau of Meteorology information to readily support decision-makers prior to a fire danger season or a specific event, assists with both fire prevention and actual response activities.
In addition, the new system will provide clear, simple and relevant outputs making the system more useable by a range of stakeholders, including: the community, emergency service organisations, emergency managers, planners, legislators, business and industry.
The system's capacity to incorporate new scientific advances, new communications methods and technology will bring the additional benefit of increased usability across many different forums.
The lack of current system usability and interoperability means that although there is useful data sets in some areas, they are not effectively linked. For example, our collection of post disaster information in a range of databases means that there is an inability to 'talk' with meteorological databases. The NFDRS will vastly improve our capacity to use existing data, collect cross jurisdictional information and enable causal links to be more easily recognised.

The next steps in Developing NFDRS-From Concept to Prototype:

This will involve the development of a working prototype for the next generation system, within twelve months of the project being endorsed to progress.

The working prototype will continue to build on the pilot fire behaviour indices development work led by NSW Rural Fire Service to date, and this will become the test/development bed for the operational system prototype.

The test prototype will be cut over/transitioned to a production platform, hosted on a system that will meet the agreed future system hosting requirements, and can be built and enhanced in line with the five year roadmap.

Consistent with the developed five year roadmap, the first year of fire science and social research should also be implemented during the one year phase of the project.

- The fire science research will focus on delivering foundational priorities which meet the new system's requirements.

- The social research will focus on delivering evidence and guidance to support effective messages and warnings, and increase community awareness about the new system in the future.

High level tasks for development work of the working prototype are

- Create national base layers, including vegetation and fuel models. These will be based on best available data at the start of the project. Improvement of data sets will take place in years 2-5.
- Determine metrics for the Fire Behaviour Index, informed by the NSW trial and the first year of research
- Produce software to implement the FBI calculations in a development environment
- Create infrastructure to host FBI calculations and derived warning products in a production environment.

Underpinned by the NFDRS Road Map and Conceptual Architecture documents produced for this project the following tasks

- Determine what will be used for FBI and how it will be represented to decision makers
- Develop architecture for calculation of factors and FBI
- Add existing science and data into framework
- Audit data, define requirements for jurisdictions to achieve parity
- Define science requirements for years 1, 2-5

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Opening the treasure trove:
Re-examining A.G. McArthur's experimental fire data

James S Gould
CSIRO Land and Water, Bushfire Behaviour and Risks, Canberra, ACT, 2601
jim.gould@csiro.au

Introduction

Forest fire behaviour research in Australia has evolved over several decades (McArthur 1962, 1967, Peet 1965, 1972, Peet and Sneeuwjagt 1979, 1985, Burrows 1994, 1999, Gould *et al*. 2007, Cheney *et al*. 2012). The pioneering fire behaviour research by McArthur (1962, 1967) was the basis for the Mk 5 McArthur Forest Fire Danger Rating System (McArthur 1973).

McArthur's original experiments were primarily aimed at improving the techniques for fire suppression and controlled burning. His work was conducted on small-scale field experiments of point source ignition under relatively mild burning conditions in which the fire's development was restricted. The limitations of his studies have been discussed by Burrows (1994), Gould *et al*. (1996), Gould *et al*. (2007) and McCaw *et al*. (2008). They concluded that the original forest fire behaviour model (McArthur 1967) that resulted from this work under-estimated fire spread under dry summer conditions (McCaw *et al*. 2008).

One of the possible causes of this under-estimation is that the fires from which the data were compiled were still developing in size and speed (i.e. accelerating), thus were not spreading at their full potential rate of spread, i.e., steady-state. Additionally, it appears that McArthur's experimental data was not fully analysed, possibly because of the specific dual purposes of the experimental fires.

Many of the fires McArthur carried out in the Australian Capital Territory (ACT) were conducted as part of a two-week summer field exercise for students of the Australian Forestry School as part of their fire control subject. Furthermore, a limited number of his experimental fires were conducted in different forest types in Victoria and New South Wales to instruct State fire researchers in experimental techniques so that they could conduct further experimental studies to develop fire behaviour guides for specific fuel types (P Cheney *pers. comm.*). This resulted in a large experimental dataset with limited data analysis. Today this data provides an excellent resource for investigating fire growth and development of point ignition fires in dry eucalypt forest.

This paper presents a summary of the original experimental data predominantly collected under the supervision of A. G. McArthur between 1953 and 1975 and which were digitised and collated into electronic data files for more robust analysis utilising modern statistical methods. This provides an excellent source of empirical data to review the effect of fuel load on rate of spread and highlight the complexity of modelling fire growth, area and perimeter with time since ignition for a range of fuel, weather and topographic conditions, which will be discussed.

Data Reduction

The data for this study were obtained from a number experimental records on fire behaviour, fuel, and weather conditions dating from the early 1950s to the present which were held at CSIRO Land & Water Bushfire Behaviour and RisksTeam, ACT. Specifically, the experimental fires are those conducted by Alan G. McArthur during the 1950s, 1960s and 1970s. These experiments were carried out in open dry eucalypt forest located in ACT (Black Mountain, and Kowen Forest), Victoria (Traralgon and Daylesford), and Western Australia (jarrah forests).

The first phase of the data reduction was the collation of all the experimental fires conducted in dry eucalypt forest (primarily sourced from Alan McArthur's experimental fires). These fires were predominantly lit from a point and allowed to burn for around 30 to 50 minutes, depending on the weather conditions and if the head or flank fire spread was constrained by a track or firebreak. In the majority of these fires the perimeters were marked at two-minute intervals with metal or other markers. At these two minute intervals in-forest wind speed at 1.5 m height was recorded and experienced fire behaviour observers made ocular estimates of fuel continuity, flame height, flame depth, flame length and flame angle of the head fires. Additional notes were made on changes of wind speed and direction, up-draughts, down-draughts, smoke characteristics, spotting and fire behaviour.

After the fire had been extinguished, the positions of the fire perimeter markers were surveyed. The positions of the markers were plotted and fire perimeter isochrones were drawn freehand between the plotted perimeter markers for each time interval. The fire perimeter, fire area, cumulative forward rate and maximum rate of spread were then calculated from these fire perimeter isochrones maps. Figure 1 is an illustrative example of fire isochrones representing the fire perimeter at two-minute intervals. Sullivan *et al*. (2013) provides more detailed description of the methods used during McArthur's experimental fires between 1962 and 1975.

Figure 1. Experimental fire 929 in dry eucalypt forest at Black Mountain, ACT (left) and the fire isochrones represents the fire perimeter at 2-minute intervals (right).

Preliminary findings

Information for each two-minute interval fire observation from the field fire behaviour field sheets and other recorded information for each fire were transferred to electronic data files. The individual fire perimeter isochrones maps were digitally photographed to be included in the metadata for each fire. Some fire records such as the fire area, perimeter and rates of spread were missing and were obtained by analysing digitised fire isochrones maps for this data. In the end, there were over 450 experimental fires collated into five different datasets representing the size of the experiment and the location of the experimental site. Table 1 lists the range of key weather, fuel and fire behaviour experiments conducted in the ACT and Victoria.

The first experimental fires conducted by McArthur in the 1950s were small scale point ignition fires with a burning duration between 1 and 8 minutes spreading up to 13 m from ignition. In the 1960s and 1970s fire experiments were larger in size burning between 4 and 74 minutes depending on the burning conditions and spreading up to 71 m from ignition line (See Table 1).

The duration of the experimental fires conducted near Daylesford, Victoria were similar to the medium-scale fires at Kowen and Black Mountain, ACT. Median values of the fine fuel moisture content of the Daylesford fires were 3% wetter compared to the ACT experiments and the wind conditions were lighter, resulting in a narrower range of spread rates between 0.4 and 4.9 m min^{-1} compared to ACT fires, which were between 0.1, and 16.9 m min^{-1}. Figure 2 illustrates the comparison of the range of the maximum rate of spread by 1.5 m wind speeds of the Daylesford experimental fires with the ACT Black Mountain experiments. There was very little information on the specific location and types of forest where the Daylesford fires were conducted and additional work is required to obtain this information on the location and description of 'Pinchgut' and 'Buckstead' blocks at the time of the Victoria Forestry Commission in the early 1960s.

Exploratory analyses using graphical representations were used to help examine some of the preliminary concepts of fire spread. As an example, we examined how the response variables (e.g. ROS) depends on fuel load (Load) for given intervals of 10 m open wind speed (Wind) and fuel moisture (Moisture). Figure 3 is a coplot of the medium scale fires from Black Mountain experiments. The dependence panels are 6 × 6 array of graphs with the given panels of fuel moisture and in-forest wind speeds. In each dependent panel ROS is plotted against Load for those observations whose value of Moisture and Wind lie within a given interval, thus illustrating how fire spread depends on fuel load, fuel moisture and wind speed under forest canopy. The intervals are shown on the given panel.

The upper left panels of high wind speed and low fuel moisture content in Figure 3 shows a slight increase in rate of spread with increasing fuel load. Overall the rate of spread had a negative correlation with fuel load (r= -0.11) and fuel moisture (r= 0.34). Wind speed was positively correlated (r= 0.34) with fire spread.

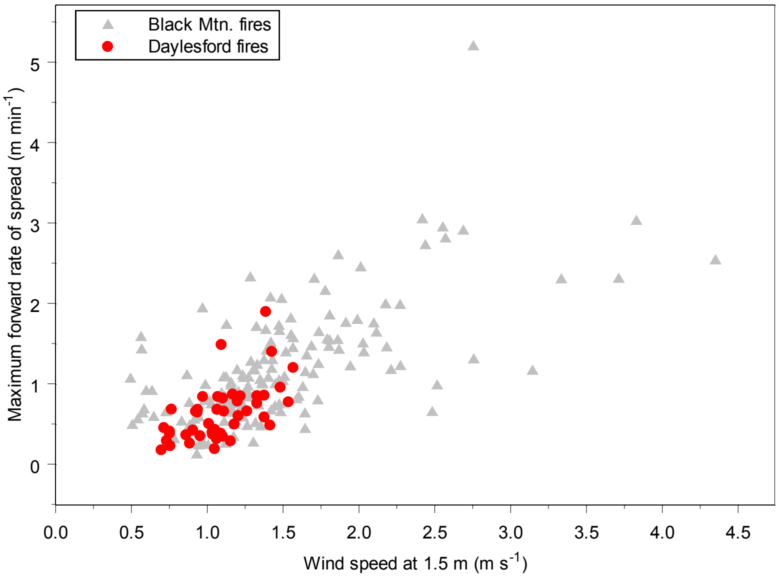

Figure 2. Comparison of the in-forest wind speed at 1.5 m and maximum forward rates of spread from McArthur's experimental fires in dry eucalypt forest at Daylesford, Victoria and Black Mountain, ACT.

Summary

The processes involved in fire propagation during the period between the time ignition occurs until suppression action commences form some of the most critical and significant studies of fire behaviour. During the first 60 minutes or so of a fire's life, suppression forces have their greatest chance of success purely because the fire is still accelerating and has not reached its maximum rate of spread and thus maximum fireline intensity or flame height. These empirical datasets can provide some insight into the different rates of acceleration and fire growth for fires in eucalypt litter fuel. However, further analysis is required to develop a better understanding of on the effects of fuel load, wind speed, fuel moisture and other attributes on fire spread, growth and development for a wide range of fire behaviour conditions. This continuing investigation will provide better knowledge to improve initial response to fires and planning ignition patterns for prescribe burning operations.

Table 1. Weather and fire behaviour data from McArthur's experiments in the ACT and Victoria. Median and range (minimum – maximum)

FIRE BEHAVIOUR PARAMETER	SMALL SCALE EXPERIMENTS KOWEN, ACT 1955 - 1956	MEDIUM SCALE EXPERIMENTS KOWEN, ACT 1957 - 1961	MEDIUM SCALE EXPERIMENTS BLACK MTN., ACT 1960 - 1971	MEDIUM SCALE EXPERIMENTS DAYLESFORD, VIC 1964 - 1966	MEDIUM SCALE EXPERIMENTS TRARALGON, VIC 1962 - 1964
Number of fires	46	191	136	52	29
Number of fire spread observations	284	2280	1951	751	334
Duration (min)	**3.5** (1-8)	**31** (4 – 74)	**30** (10 – 64)	**34** (14 – 60)	**28** (6 – 40)
Ignition length (m) (0=point ignition)	0	0	0	0	0
Mid-flame height wind speed (m s^{-1})	**2.52** (0.31 – 6.3)	**1.8** (0.04 – 6.4)	**1.2** (0 – 4.8)	**1.05** (0.02 – 2.69)	**1.06** (0.22 – 2.29)
Temperature (°C)	**23** (18 – 29)	**22** (10 37)	**22** (10 – 32)	**18** (13 – 24)	**23** (17 – 32)
Relative humidity (%)	**44** (25 – 72)	**40** (9 – 91)	**42** (19 – 68)	**47** (23 – 80)	**50** (29 – 60)
Fuel moisture content (%)	**6.9** (4.5 – 17.6)	**6.9** (3.2 – 22.0)	**7.8** (4.3 – 14.8)	**10.0** (6.2 – 16.0)	**11.3** (8.6 – 18.5)
Fine fuel load (kg m^{-2})	na	na[1]	**1.17** (0.45 – 2.11)	**1.01** (0.6 – 2.67)	**1.25** (0.65 – 1.54)
Maximum distance travelled (m)	**3.1** (0.6– 13)	**22** (1.8 – 63)	**22** (1.2 – 71)	**10.2** (2.9 – 33.1)	**14.5** (4.9 – 32.9)
Slope (°)	0	**10** (-7.5 – 17.0)	**7.5** (2.3 – 21.0)	**5** (-7.0 – 10)	**7.5** (-2 – 9)
Rate of spread (m min^{-1})	**0.8** (0.1 – 16.9)	**0.9** (0.4 – 7.8)	**0.71** (0.01 – 7.2)	**0.61** (0.4 – 4.9)	**0.67** (0.1 – 5.7)
Flame length (m)	Na	**0.6** (0.5 – 5.5)	**0.6** (0.3 – 18.3)	0.45 (0.02 – 6.7)	**1.1** (0.15 – 7.2)

[1] Fuel load was ranked into three major fuel quantity classes: Sparse (S: 0.45 – 0.99 km m^{-2}), Moderate (M: 1.0 – 1.8 kg m^{-2}) and Heavy (H: >1.8 kg m^{-2})

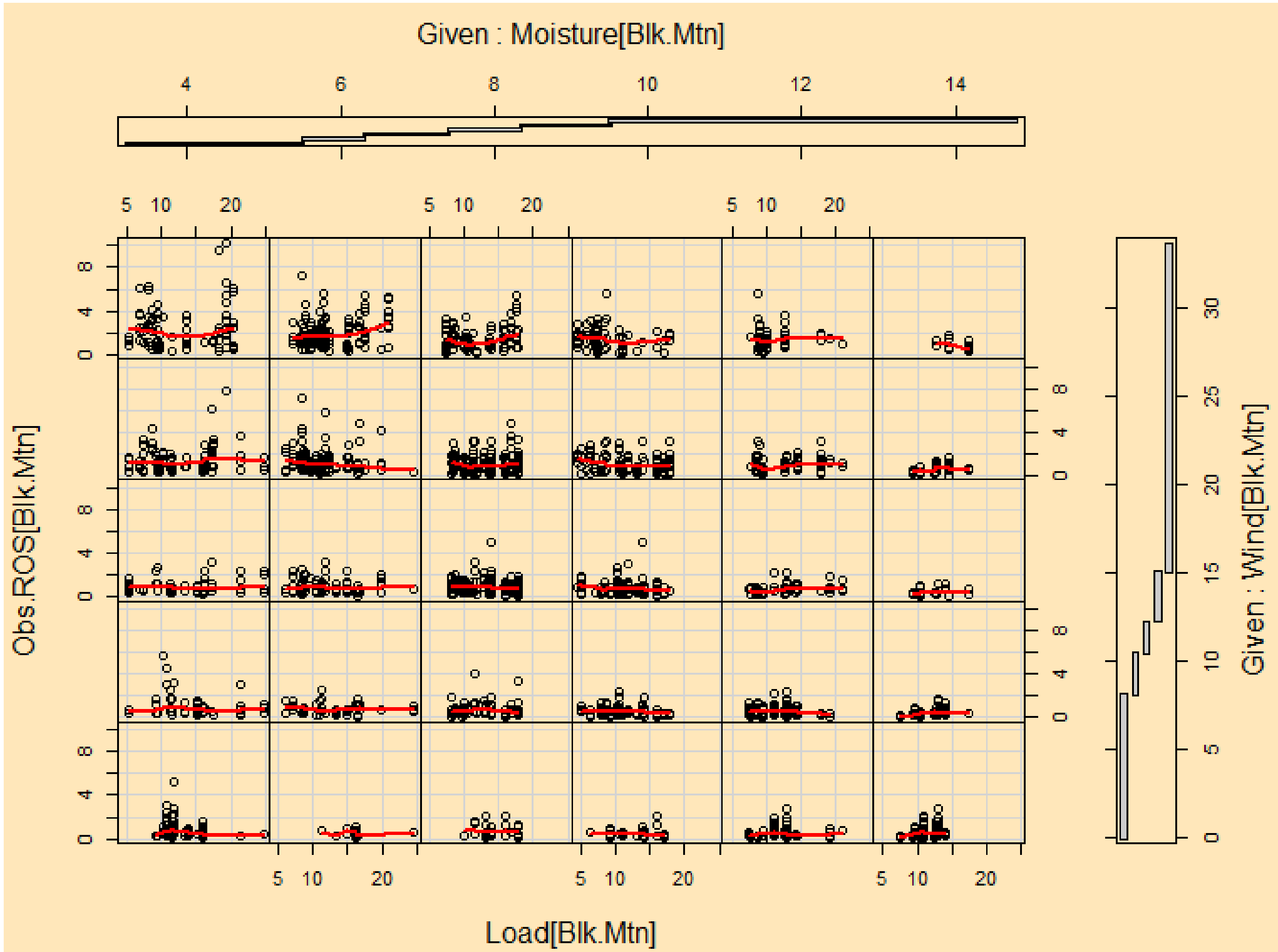

Figure 3. Coplot of Black Mountain, ACT experimental fires (Table 1) illustrating the relationship between rate of spread (Obs.ROS, m min^{-1}) and fuel load (Load, t ha^{-1}) for given fuel moisture (Moisture, %) and open wind speed 10 m (Wind, km h^{-1}) groupings. The Moisture and Wind bars (left to right, and bottom to top respectively) are associated with the dependence panels moving left to right and bottom to top.

References

Burrows ND (1994) Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. PhD Thesis, Australian National University, Canberra, ACT.

Burrows ND (1999) Fire behaviour in jarrah forest fuels: 2. Field experiments. *CALMScience* **3,** 57-84.

Cheney NP, Gould JS, McCaw LW, Anderson WR (2012) Prediction fire behaviour in dry eucalypt forest in southern Australia. *Forest Ecology and Management* **280**, 120-131.

Gould JS, Cheney NP, Hutchings PT, Cheney S (1996) Prediction of bushfire spread. IDNDR Project 4/95. CSIRO Forest and Forest Products, Unpublished Report.

Gould JS, McCaw WL, Cheney NP, Ellis PE, Knight IK, Sullivan AL (2007) Project Vesta- Fire in Dry Eucalypt Forest: Fuel structure, fuel dynamics, and fire behaviour, Ensis-CSIRO, Canberra, ACT and Department of Environment and Conservation, Perth, WA.

McArthur AG (1962) Control burning in eucalypt forests. Forest and Timber Bureau Leaflet 80, Commonwealth of Australia, Canberra, ACT.

McArthur AG (1967) Fire behaviour in eucalypt forests. Forest and Timber Bureau Leaflet 107, Commonwealth of Australia, Canberra, ACT.

McArthur AG (1973) Forest Fire Danger Meter MkV. CSIRO Canberra, ACT.

McCaw WL, Gould JS, Cheney NP (2008) Existing fire behaviour models under-predict the rate of spread of summer fires in open jarrah (*Eucalyptus marginata*) forest. *Australian Forestry* **71**, 16-26.

Peet GB (1965) 'A Fire Danger Rating and Controlled Burning Guide for the Northern Jarrah (*E. marginata*) Forest, of Western Australia. Forests Department Western Australia, Bulletin No. 74.

Sneeuwjagt RJ and Peet GB (1979) Forest Fire Behaviour Tables for Western Australia (2nd edn.). Forest Department of Western Australia.

Sneeuwjagt RJ and Peet GB (1985) Forest Fire Behaviour Tables for Western Australia (3rd edn.). Department of Conservation and Land Management.

Sullivan AL, Cruz MG, Ellis PFM, Gould JS, Plucinski MP, Hurley R, Koul V. (2013) Fire Development, Transitions and Suppression Final Report. Client Report EP1312986. CSIRO Ecosystem Sciences and CSIRO Climate Adaption Flagship, Australia.

Playing With Models: How Risk Analysis Tools Have Been Applied in Tasmania to Evaluate the Most Effective Approach to Fuel Reduction

Rochelle Richards[1]
Tasmania Fire Service, Hobart, Tasmania, Australia, rochelle.richards@fire.tas.gov.au

Samuel Ferguson[1]
Tasmania Fire Service, Hobart, Tasmania, Australia, samuel.ferguson@fire.tas.gov.au

Kylie Cornish[1]
Tasmania Fire Service, Hobart, Tasmania, Australia, kylie.cornish@fire.tas.gov.au

Sandra Whight[1]
Tasmania Fire Service, Hobart, Tasmania, Australia, sandra.whight@fire.tas.gov.au

Grant Williamson[2]
University of Tasmania, Hobart, Tasmania, Australia, grant.williamson@fire.tas.gov.au

Introduction

The state of Tasmania, as a part of southeast Australia, is prone to bushfire and has experienced periodic bushfire events that have caused devastating loss. Fuel reduction burning is one of a range of options that can be used to reduce the risk and impact of bushfires, and to provide safer conditions for firefighting. The Tasmania Fire Service, working with the Parks and Wildlife Service & Forestry Tasmania, are responsible for implementing a fuel reduction program that aims to reduce bushfire risk by reducing fuels that pose a high risk to communities, on all land tenures.

In the lead up to the establishment of the Fuel Reduction Program, Tasmania's State Fire Management Council set out to address the questions: where and how much burning should occur, and how effective is it? To answer these questions, a risk analysis was completed by the State Fire Management Council to inform the development of the program, leading to the publication of the report entitled 'Bushfires in Tasmania: a new approach to reducing our statewide relative risk' (State Fire Management Council 2014).

Methodology

Fifteen fuel treatment scenarios were developed for Tasmania to test different approaches to fuel reduction, specifically targeting high risk areas. These scenarios were run over five years, with risk reduction to human settlement areas measured using Phoenix RapidFire outputs.

The amount of burning under each fuel treatment scenario was guided by recommendations from previous inquiries (Ellis *et al.* 2004, Teague *et al.* 2010). The scenarios included:

- one control scenario that involved no burning;
- six scenarios that involved burning 5%, 2.5% & 1.25% of the treatable fuel regardless of land tenure boundaries ('tenure-blind'), using two methods for selecting high risk areas;
- four scenarios that involved burning 5% & 2.5% of the treatable fuel on public land only, using two methods for selecting high risk areas;
- four scenarios that involved burning treatable fuels within fire management zones (FMZ) around human settlement areas, using five and ten year return intervals in asset protection

[1] GPO Box 1526 Hobart TAS 7001, fuelreductionunit@fire.tas.gov.au, www.fire.tas.gov.au
[2] Private Bag 55 Hobart TAS 7001, grant.williamson@utas.edu.au, www.utas.edu.au

and strategic fuel management zones respectively for the full FMZ scenario, and ten and twenty year intervals in asset protection and strategic fuel management zones respectively for the half FMZ scenario. Again, two methods were used for selecting high risk areas.

Potential burn units were identified by overlaying treatable fuels with roads, tracks, railways & major water features, and ranked using outputs from the Tasmanian Bushfire Risk Assessment Model. Two contrasting methods were used to rank burn units, reflecting the manner in which burns could be selected over time. The first method selected burns based on state-wide risk reduction priorities, which lead to the prioritisation of burn units in southeast Tasmania where much of the Tasmanian population reside. The second method selected burns based only on the priorities within each individual Fire Management Area within Tasmania, of which there are ten. This was considered to more accurately reflect the manner in which fuel reduction priorities would be set by Fire Management Area Committees. Overall, the outcome was to produce fourteen different five year hypothetical burning programs.

The extent of Tasmania's human settlement areas was mapped using building locations, cadastral & census data. This polygon dataset was developed to identify higher densities of buildings and populations rather than individual house locations. The dataset was overlayed with the Phoenix static output grid to identify grid cells that contained human settlement areas. A grid cell was counted as 'impacted' if the modelled intensity for that grid cell exceeded 10,000 $kW.m^{-1}$ or 2.5 $embers.m^{-2}$. These thresholds are the same as those used in the House-Loss-Ratio impact type in Phoenix (Tolhurst & Chong, 2012).

Ignition points were spaced 2.5km apart, resulting in a grid of 11,059 ignitions. In Phoenix, each ignition point was allocated a realistic weather profile based on observations from the nearest relevant weather station. The weather profile represented the 99.0 to 99.5^{th} percentile of summertime weather conditions for the observation area, i.e. conditions that could occur, or be exceeded, approximately three times in an average year. Phoenix was run for each scenario and year, simulating the ignition and spread of each fire individually, as shown in figure 1. The model outputs of fireline intensity, flame height, flame depth, ember density and convection were captured for each Phoenix output grid cell and related to each ignition point, impacted cell, human settlement area, fire management area, fuel reduction burning scenario and fire history/treatment year. A statistical analysis then identified whether the fuel treatment scenarios reduced human settlement area impact, fire intensity and fire area by year five.

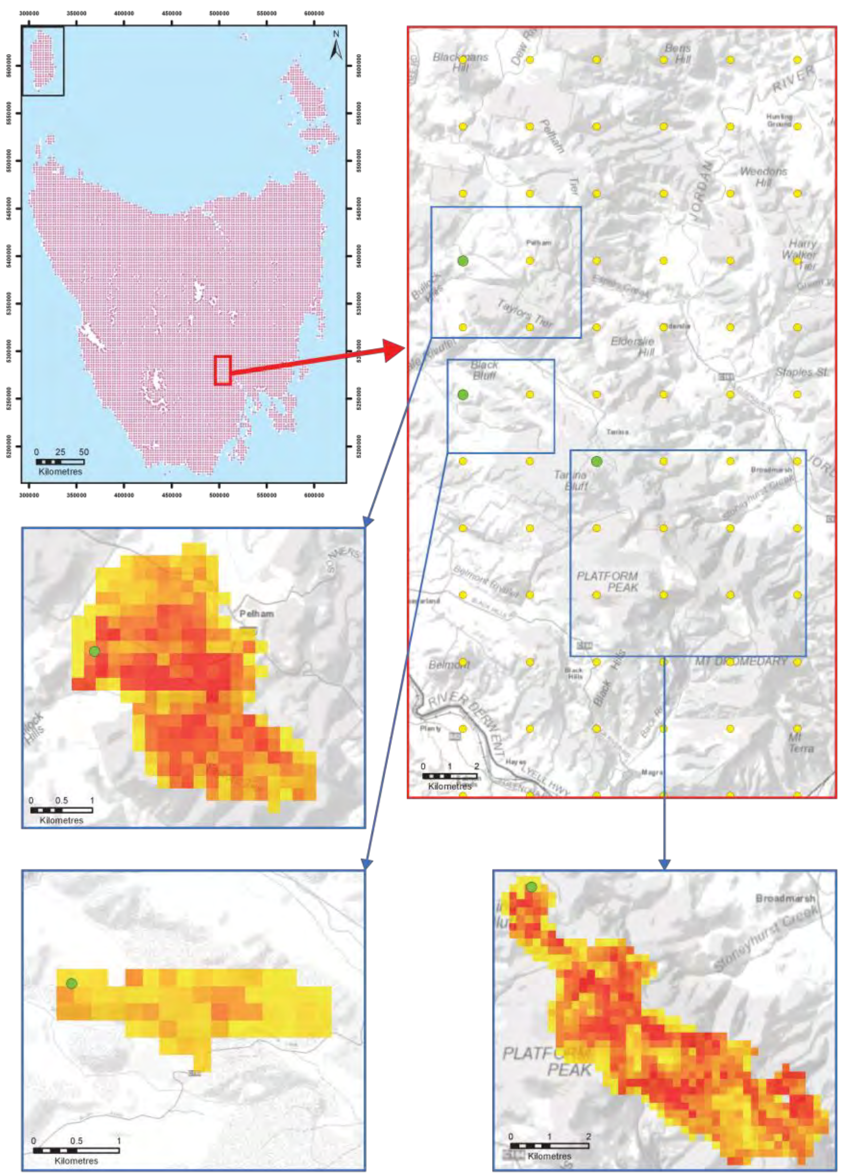

Figure 1. An example of multiple individual PHOENIX RapidFire simulations in the Tasmanian landscape.

Results and Discussion

The risk analysis demonstrated that smaller tenure-blind burning programs were more effective at reducing bushfire impacts than burning solely on public land. The full FMZ scenario was highly effective at reducing impacts, but was considered highly unfeasible due to the financial, ecological and social costs. In contrast, halving the area treated by this scenario each year resulted in the lowest reduction in impacts of all the scenarios that were tested.

All of the fuel reduction burning scenarios, except for the scenario that treated only 2.5% of treatable fuels on public land only, significantly reduced fire behaviour to more manageable levels when compared to no fuel treatment. The greatest effect was a reduction in fire intensity.

Of the scenarios tested, the strategy of burning 31,000 hectares (1.25%) per year of treatable vegetation on both public and private land, where the treatment blocks were prioritised by risk, presented the most effective fuel reduction option given the relative expense, the reduction in relative risk and the increase in ease of suppression in the broader landscape.

Overall, this project demonstrated the importance of a prioritised and strategically targeted fuel reduction burning strategy that applies a tenure-blind approach. These risk analysis products are now being applied to the fuel reduction program to identify high priority areas for treatment, quantify potential risk reductions to human settlement areas, and promote a better understanding of the effectiveness of fuel reduction for reducing bushfire risk. This body of work has also demonstrated that, by strategically identifying areas that are unconstrained by tenure, fuel reduction can be more targeted and effective by reducing bushfire risk at identified high potential ignition sources, as well as close to vulnerable communities.

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References

Ellis S, Kanowski P and Whelan R (2004) 'National inquiry on bushfire mitigation and management.' (Commonwealth of Australia: Canberra)

State Fire Management Council (2014) 'Bushfire in Tasmania: a new approach to reducing our statewide relative risk.' (Hobart, TAS)

Teague B, McLeod R and Pascoe S (2010) '2009 Victorian Bushfires Royal Commission.' (Parliament of Victoria: Melbourne)

Tolhurst K and Chong D (2012) 'PHOENIX RapidFire: user manual – introduction and exercise.' (Melbourne, VIC)

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Quantification of fuel moisture content and identification of critical thresholds for escalation of fire activity in SE Australia's forest regions

Rachael H. Nolan[*1,2,3]
Matthias M. Boer[1]
Victor Resco de Dios[1,4]
Ross A. Bradstock[2]
[1] Hawkesbury Institute for the Environment, Western Sydney University, Richmond, NSW, Australia.
[2] Centre for Environmental Risk Management of Bushfires, Institute for Conservation Biology and Law, University of Wollongong, Wollongong, NSW, Australia
[3] Current address: Terrestrial Ecohydrology Research Group, School of Life Sciences, University of Technology Sydney, Broadway, NSW, Australia, Rachael.Nolan@uts.edu.au
[4] Current address: Department of Crop and Forest Sciences-AGROTECNIO Center, Universitat de Lleida, E 25198 Lleida, Spain.

Introduction

Large, high intensity wildfires pose major threats to people, property and infrastructure and play a pivotal role in shaping many ecosystems worldwide. The incidence of large wildfires is contingent upon the presence of spatially continuous arrays of plant biomass sufficiently dry to burn (Bradstock, 2010). Thus, the moisture content of vegetation and litter (fuel moisture) is an important factor in fire danger indices and a key input to fire behaviour models. However, the extent to which fuel moisture content affects fire activity and behaviour at landscape scales remains poorly quantified because operational methods for the required spatially explicit predictions of fuel moisture content have been lacking. Here, we present recent research on the development and application of a spatially explicit model for prediction of dead fuel moisture. We then combine the dead fuel moisture model with a live fuel moisture model, to determine critical values of fuel moisture associated with large fire events in SE Australia.

Modeling dead fuel moisture

The moisture content of dead fuels, which includes fallen branches and leaf litter, influences the rate of spread and intensity of surface fires (Viney, 1991). Since dead fuel moisture (FM) responds to changes in atmospheric conditions, it is commonly modelled from meteorological variables. Recently, we developed a semi-mechanistic model based on the exponential decline of dead FM with increasing vapour pressure deficit (*D*) and found it had greater accuracy across a range of environments than other commonly used models (Resco de Dios *et al.,* 2015).

In principle, regional scale predictions of dead FM may be derived by combining this *D*-based model with spatially gridded estimates of *D* based on interpolated weather data. However, in practice such estimates may be uncertain in regions where the terrain or vegetation is especially heterogeneous (Nieto *et al*., 2010). This problem may be overcome by predicting FM from remotely sensed *D*, since satellite observations are available with a spatial resolution of 1 km^2 or finer. In this study, we undertake a comparative assessment of predictions of dead FM derived from D sourced from either remote sensing or gridded weather data (Nolan *et al*., 2016).

Relationships between fuel moisture and major wildfires

Fire danger indices condense information about fire weather and fuel dryness, via drought indices. Such drought indices are assumed to characterize the moisture content of live and dead fuels (Bradshaw *et al.*, 1983; McArthur, 1967; Van Wagner, 1987). Correlations exist between major wildfires and fire danger indices, but fire danger indices may lack the accuracy and precision for forecasting the timing and locations of highest potential for wildfires (Caccamo *et al.*, 2012; Resco de Dios *et al.*, 2015). By contrast, studies involving direct estimation of either live (Agee *et al.*, 2002; Dennison *et al.*, 2008) or dead (Dowdy and Mills, 2012; Nash and Johnson, 1996) FM have indicated the potential for non-linear relationships between FM and wildfire activity at local to landscape scales. Thus, thresholds in FM may need to be crossed to provide the potential for the spread of major wildfires. In this study, we test whether thresholds in FM govern area burned by wildfires at a macro-scale (i.e. sub-continental) and whether such thresholds are robust across major variations in climatic and vegetation groups.

Materials and methods

Modeling dead fuel moisture

D is typically calculated from air temperature (T_{air}) and relative humidity (RH) which are used to calculate saturation vapour pressure (e_s) and actual vapour pressure (e_a) (Monteith and Unsworth, 1990). Predictions of D from remotely sensed data were made at a daily time-step with Moderate Resolution Imaging Spectroradiometer (MODIS) products from the Terra satellite, which are available at a 1 km resolution, with overpass time occurring in late morning (approximately 10–11 am local time). We applied two main approaches to calculating D. First, D was calculated following Nieto *et al.* (2010), with land surface temperature (T_{LST}) and the Normalized Difference Vegetation Index (NDVI) used to calculate T_{air}; and total precipitable water (W) used to calculate e_a. We also followed a more parsimonious approach developed by Hashimoto *et al.* (2008), based on an empirical relationship between D, e_s and T_{LST}. These MODIS-based meteorological estimates were validated against the corresponding mean daytime observations from five flux tower sites: three in SE Australia and two in Southern California (see Goulden *et al.,* 2012). The three Australian flux tower sites were situated in either eucalypt forest or woodland, while the vegetation at the two Southern Californian Climate Gradient (SCCG) sites was desert chaparral and desert perennials and annuals respectively.

Gridded meteorological observations of D were obtained from the SILO database (http://www.longpaddock.qld.gov.au/silo/index.html). SILO estimates are based on interpolation of weather station records across Australia on a 0.05° grid (Jeffrey *et al.*, 2001). Daily D was estimated from maximum T_{air} and RH at the time of maximum T_{air}. We used these gridded observations and remotely sensed predictions of D to re-calibrate the dead FM model of Resco de Dios *et al.* (2015). Re-calibration of the dead FM was undertaken with six months of dead FM data obtained from one of the SE Australian flux tower sites. Dead FM was measured with three automated dead FM sensors every 30-60 min, with a fuel moisture sensor connected to a data logger (CS505; Campbell Scientific Inc., Logan, UT, USA). The sensor uses Time Domain Reflectometry (TDR) to measure the moisture content of a 10-hour (13 mm diameter) Ponderosa Pine stick. Validation was undertaken with 15 months of dead FM data from the same flux tower, plus 12 months of data from the two Southern Californian sites. We additionally validated the model with manual measurements of dead FM collected by destructively harvesting fine, dead fuels at an additional 16 sites.

Relationships between fuel moisture and major wildfires

The study area incorporates forests and woodlands across 117 059 km^2 of SE Australia. We obtained fire history datasets from the Victorian Department of Environment, Land, Water and Planning and from the New South Wales Rural Fire Service. The study period covers the 2000 to 2013 fire seasons. This period was chosen because the total area burned was exceptional in recent history (39 642 km^2) and high resolution climatic data and reliable remote sensing imagery, i.e. MODIS, was available.

For each wildfire footprint we calculated the median value of dead and live FM across the footprint. Dead FM was calculated using the *D* model which performed best in the previously described study. Live FM was calculated following the methods of Caccamo *et al.* (2012), and recalibrated using field observations across a wider range of environmental conditions. The live FM model utilized the Normalized Difference Infrared Index (NDIIb6), calculated from the MODIS 8-day composite dataset MOD09A1 (collection 5), with a 1 km spatial resolution. We then calculated the cumulative area burnt by wildfire as a function of FM, following Dennison and Moritz (2009). Briefly, segmented regression was used to fit linear regressions to either side of breakpoints in the data. The number of breakpoints was determined by progressively increasing the number of breakpoints used in fitting the model. The model with the lowest Akaike's Information Criterion (AIC; Akaike, 1974) was selected.

Results

Modeling dead fuel moisture

Performance of the *D*-based model for estimating dead FM was similar when the model was calibrated with remotely sensed data or with gridded meteorological observations. For example at the calibration site the mean absolute error (MAE) of FM sensor data was 2.9% when predicted from MODIS data (T_{LST}), and 2.0% when predicted from gridded meteorological data. However, there was a substantial difference in the number of days dead FM could be calculated from MODIS data and from gridded meteorological data. For example, for the validation of the model with fuel moisture sensor data, gridded meteorological data was available for every day across the validation period (n = 341), whereas MODIS data was available for less than half of the days (n =153), mainly due to cloud contamination.

Relationships between fuel moisture and major wildfires

The relationships between the area burned by wildfire and both live and dead FM were non-linear, with steep rises in area burned evident once FM fell below threshold values (Figure 1).

We identified two thresholds for live FM that demarcated a major increase in area burned, these were at 152.6 ±7.00 % and 101.5 ±0.60 % (Figure 1a). There was an additional threshold identified at 72.4 ±0.37 %, but this was not associated with increasing area burned (i.e. the slope of the regression line was shallower than between the live FM values of 152.6 - 101.5 %). Similarly, there were two thresholds identified for dead FM that demarcated a major increase in area burned, these were at 14.6 ±0.09 % and 9.9 ±0.15 % (Figure 1b).

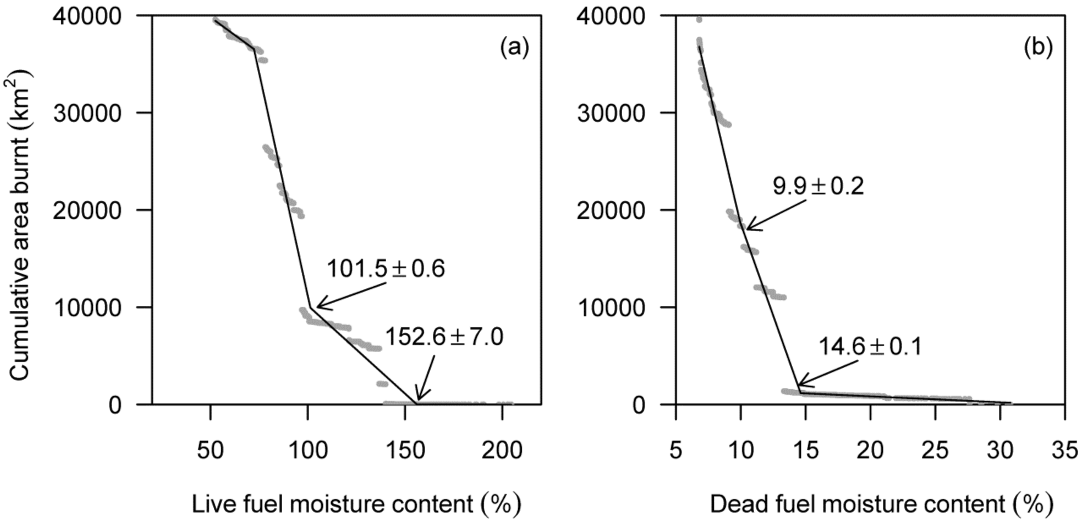

Figure 1: Relationship between live and dead fuel moisture (FM) and cumulative area burnt by wildfire. Fitted to the data are segmented regressions which identify fuel moisture thresholds demarcating a substantial increase in fire activity. The r^2 values for each of the segmented regressions were all ≥0.96.

Discussion

Modeling dead fuel moisture

Predictions of dead FM derived from remotely sensed data or from gridded weather data performed well when compared with *in-situ* observations. Both approaches therefore offer potential for further development and subsequent operational application to predict dead fine FM at large spatial scales. The MAE of the calibrated models was less than 5.0% across a range of fuel classes and vegetation types, which was lower than for other models widely used in fire danger indices (Resco de Dios *et al.,* 2015). The primary advantage of remotely sensed data is its availability across the globe. However, there is a disadvantage with gaps occurring in the data, primarily due to cloud cover. Spatially gridded meteorological datasets may overcome the limitations of remotely sensed *D* and thus be preferable for operational use in monitoring FM, particularly in the fire season. Additionally, there is the potential for predicting *D* and resultant FM from forecasts by meteorological agencies in near real time. In locations where gridded meteorological datasets are less reliable, satellite datasets could be merged with meteorological data, to improve estimation of *D*.

Relationships between fuel moisture and major wildfires

The occurrence of wildfire in forests and woodlands across SE Australia was clearly associated with the incidence of critical thresholds of macro-scale, mean live and dead FM during the 2000 to 2013 fire seasons (Figure 1). Remarkably, the higher dead FM threshold (14.6 %) is similar to that found in subalpine and boreal forests in North America, where dead FM below 14% was associated with increased probability of lightning strikes initiating fire (Nash and Johnson, 1996). This threshold corresponded to a *D* of 1.3 kPa in our study, similar to that found by Williams *et al.* (2015) who showed that annual area burned in South Western USA forests increased rapidly when *D* was between 1.3-1.4 kPa. This suggests that this threshold value of dead FM is applicable across forests and woodlands generally, and not just in the eucalypt forests and woodlands used in this study. For live fuels, the FM thresholds identified at the drier end of moisture values (101.5 %) were similar to results reported elsewhere for forests, with FM thresholds of between 100-120% identified for Pacific Northwest conifer forests (Agee *et al.*, 2002).

A major novel outcome of this study was confirmation of the capacity to monitor rapid transformations in wildfire potential via remote sensing and climatic modelling. This, combined with the potential to forecast *D*, and thus dead FM, provides a significant new capacity for monitoring FM to assist in monitoring, operational planning and risk assessment for major wildfires that is robust across major climatic and vegetation gradients at a sub-continental scale.

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References

Agee, J. K., C. S. Wright, N. Williamson, and M. H. Huff (2002), Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior, *Forest Ecology and Management* **167**(1-3), 57-66.

Akaike, H. (1974), A new look at statistical model identification, *IEEE Transactions on Automatic Control*, **AC19**(6), 716-723.

Bradshaw, L., J. Deeming, R. E. Burgan, and J. Cohen (1983), *The 1978 National Fire-Danger Rating System: Technical Documentation, GTR-INT-169.*, USDA, Forest Service, Ogden, UT.

Bradstock, R. A. (2010), A biogeographic model of fire regimes in Australia: current and future implications, *Global Ecoogy and Biogeography* **19**(2), 145-158.

Caccamo, G., L. A. Chisholm, R. A. Bradstock, and M. L. Puotinen (2012), Using remotely-sensed fuel connectivity patterns as a tool for fire danger monitoring, *Geophysical Research Letters*, **39**.

Dennison, P. E., and M. A. Moritz (2009), Critical live fuel moisture in chaparral ecosystems: a threshold for fire activity and its relationship to antecedent precipitation, *International Journal of Wildland Fire*, **18**(8), 1021-1027.

Dennison, P. E., M. A. Moritz, and R. S. Taylor (2008), Evaluating predictive models of critical live fuel moisture in the Santa Monica Mountains, California, *International Journal of Wildland Fire*, **17**(1), 18-27.

Dowdy, A. J., and G. A. Mills (2012), Atmospheric and Fuel Moisture Characteristics Associated with Lightning-Attributed Fires, *Journal of Applied Meteorology and Climatology*, **51**(11), 2025-2037.

Goulden, M. L., R. G. Anderson, R. C. Bales, A. E. Kelly, M. Meadows, and G. C. Winston (2012), Evapotranspiration along an elevation gradient in California's Sierra Nevada, *Journal of Geophysical Research-Biogeosciences*, **117.**

Hashimoto, H., J. L. Dungan, M. A. White, F. Yang, A. R. Michaelis, S. W. Running, and R. R. Nemani (2008), Satellite-based estimation of surface vapor pressure deficits using MODIS land surface temperature data, *Remote Sensing of Environment*, **112**(1), 142-155.

Jeffrey, S. J., J. O. Carter, K. M. Moodie, and A. R. Beswick (2001), Using spatial interpolation to construct a comprehensive archive of Australian climate data, *Environmental Modelling and Software*, **16**(4), 309-330.

McArthur, A. G. (1967), Fire Behaviour in Eucalypt Forests, Department of National Development Forestry and Timber Bureau, edited, Canberra, Leaflet 107.

Monteith, J. L., and M. H. Unsworth (1990), *Principles of Environmental Physics*, Edward Arnold, London.

Nash, C. H., and E. A. Johnson (1996), Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests, *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, **26**(10), 1859-1874.

Nieto, H., I. Aguado, E. Chuvieco, and I. Sandholt (2010), Dead fuel moisture estimation with MSG-SEVIRI data. Retrieval of meteorological data for the calculation of the equilibrium moisture content, *Agricultural and Forest Meteorology*, **150**(7-8), 861-870.

Nolan, R. H., V. R. de Dios, M. M. Boer, G. Caccamo, M. L. Goulden and R. A. Bradstock (2016), Predicting dead fine fuel moisture at regional scales using vapour pressure deficit from MODIS and gridded weather data, *Remote Sensing of Environment* **174**: 100-108.

Resco de Dios, V., A. W. Fellows, R. H. Nolan, M. M. Boer, R. A. Bradstock, F. Domingo, and M. L. Goulden (2015), A semi-mechanistic model for predicting the moisture content of fine litter, *Agricultural and Forest Meteorology*, **203**, 64-73.

Van Wagner, C. E. (1987), Development and Structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Ottawa, ON, Technical Report 35 pp.

Viney, N. R. (1991), A review of fine fuel moisture modelling, *International Journal of Wildland Fire*, **1**(4), 215-234.

Williams, A. P., et al. (2015), Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States, *International Journal of Wildland Fire*, **24**(1), 14-26.

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Radar Burn Ratio: A novel index for automatic fire impact assessment[1]

M. A. Tanase*
School of Ecosystem and Forest Sciences, the University of Melbourne, Australia, mihai@tma.ro
R. Kennedy
College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, US
C. Aponte
School of Ecosystem and Forest Sciences, the University of Melbourne, Australia

Introduction

Worldwide, about 350 million hectares are affected by fire annually, exerting a potentially major influence on carbon release from terrestrial ecosystems (Simmonds et al. 2005). The assessment of the immediate fire effects is referred to as fire severity, while the assessment of the ecological or environmental response is referred to as burn severity (French et al. 2008). Fire severity can be used to predict ecosystem responses such as soil erosion and post-fire vegetation recovery, which in turn affect water cycles and biodiversity (Benyon and Lane 2013). Furthermore, fire severity is related to impacts in terms of loss of life, properties and suppression costs (Keeley et al. 2008). Therefore, accurate information on fire severity spatial patterns is critical in fire management for evaluating post-fire effects and designing mitigation activities. To estimate landscape level fire severity, systematic field based surveys such as the composite burn index CBI (Key and Benson 2006) were developed and linked with remote sensing datasets from active and passive sensors (Tanase et al. 2010a; Wang and Glenn 2009). Such studies have confirmed the utility of post-fire radar-based metrics for fire severity estimation, particularly at longer wavelengths (Tanase et al. 2010a). However, only methods based on post-fire datasets have been used to estimate fire severity from radar sensors, commonly through empirical modeling using *a priori* information from field based CBI estimates. Therefore, the objectives of this study were to: i) develop a change detection framework (i.e., the Radar Burn Ratio - RBR), for fire severity estimation from radar data; ii) test the accuracy of RBR over a range of fire regimes; iii) calibrate thresholds for standardized RBR to be used for rapid fire severity assessment without the need of *a prior*i data; and iv) compare the accuracy of the standardized RBR against empirical models.

Materials and methods

Materials

Nine fires were selected based on the availability of field estimates of fire severity and L-band datasets from the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR), the most sensitive (to fire impacts) wavelength available on board space platforms. The fires were located in Australia, the United States of America and Spain, and represented variable forest conditions. In Australia, the largest contiguous area affected by fires during Black Saturday (February-March 2009) -- the Kinglake Fire Complex -- was selected. Since the area affected by fire encompassed three forest types with potentially different responses to fire, they were analyzed as three separate fires. In the US, three fires

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located in California (Iron Complex), Oregon (Rooster Rock) and Washington (Columbia River Road) states were selected, while in Spain further three fires were analyzed (Aliaga, Los Olmos, and Zuera). All fires burnt between 2008 and 2010. Over 880 field estimates of fire severity (i.e. CBI or similar) were available through different projects or from governmental agencies (552 in Australia, 126 in US, and 202 in Spain). The study used the CBI values for the plot level as well as the CBI values for the overstory strata (i.e. the average value of the factors scored within the highest tree strata) expected to have a significant influence on the radar signal.

Between six and nine PALSAR fine beam dual (FBD, HH and HV polarizations) datasets acquired up to three years before and after the fire event were used for each fire. The complex radar data, acquired from the same orbital path at each location, were co-registered using as reference the first image of each data series. After co-registration, each image was multi-looked in range (4) and azimuth (20) to obtain a ground pixel spacing of approximately 60 m and the radar intensity was transformed to the radar backscatter coefficient (σ°). The final SAR pre-processing step was orthorectification to the Universal Transverse Mercator (UTM) projection. The Radar Burn Ratio (RBR) was computed as the ratio of average post- to average pre-fire backscattering coefficients except for Rooster Rock and Kinglake fires for which only one post-fire image was acquired under dry conditions. In these cases, RBR was computed as the single date post-fire backscatter divided by the pre-fire average backscatter.

Methods

Fire severity was first estimated through local empirical models calibrated for each fire (i.e. models related field estimates of fire severity to remote sensing data). The relationship between fire severity and RBR_{HV} was studied through scatterplots, while the coefficient of determination (R^2) was used to understand the proportion of RBR_{HV} (i.e., RBR computed for HV polarization) variability explained by changes in fire severity. Fire severity retrieval was carried out using regression-based modeling with cross-validation. Empirical models relating fire severity at plot or overstory levels with RBR indices were developed and tested for each of the nine fires.

Field data needed for local calibration of empirical models are often unavailable or obtained at significant cost. Therefore, estimating fires severity without *a priori* information on local burn conditions is important for a wide range of objectives. This was achieved by calibrating a set of cut thresholds for different remote sensing indices using the available field datasets. For a robust set of thresholds one needs to consider the range of burn conditions present within a fire perimeter (i.e., fire severity), variations in burn conditions across landscapes occupied by a mix of forest species, forest structures and fire regimes as well as variations in environmental (e.g., rainfall) or local conditions (e.g., topography). Such variations result in different RBR ranges, which in turn hinder fire severity retrieval using algorithms based on change values in absolute scale. In this study, the influence of environmental conditions was minimized by an appropriate selection of the radar datasets (dry periods), while topographic effects are eliminated through the use of post- to pre-fire ratios. Compensating for varying RBR ranges across landscapes was achieved by statistical data standardization, which constrains the RBR values to specific scales. Standardization was carried out separately for each fire using RBR values extracted at CBI plot locations to calculate the mean and its standard deviation. Following standardization, *z* scores for each severity class were obtained (at plot and overstory levels) for each fire and environmental condition (dry and wet). The *z* scores were averaged across fires by severity classes and were subsequently used (together with the standard error, α=0.05) to determine the upper and lower variation limits for each severity class. Species specific thresholds (coniferous vs. eucalypt) and environmental conditions thresholds (i.e. dry vs. wet, eucalypt forests only) were also computed.

Once common standardized RBR cut thresholds are defined, a straightforward process allows for mapping fire severity across landscapes by applying the cut thresholds to the standardized RBR pixel values. The most problematic step is determining the mean (μ) and the standard deviation (σ) for standardization data from 'new' fires without *a priori* information from field plots. This was achieved by extracting RBR values for all pixels within each fire perimeter, filtering the values by eliminating outliers (i.e., values below and above the 1st and the 99th percentile), and computing the mean values of five intervals equally spaced between the minimum and the maximum RBR. Such intervals might not correspond directly to pre-defined severity classes (e.g., from CBI data) but they correspond to different severity levels due to the linear relationship between RBR and fire severity. The advantage of such an approach is that the mean of these interval means (fire-wide μ) and standard deviation (σ) are not area dependent (i.e., the mean backscatter over a fire perimeter depends on the number of pixels within each severity class). Using μ and σ, each pixel was standardized and the previously defined standardized RBR cut thresholds were applied to estimate its severity class. The agreement between the fire severity class computed through the standardized model was cross-checked against field data using Cohen`s weighted kappa after reclassifying the continuous CBI interval into five severity classes.

Results

Relationships between RBR and fire severity – Local empirical models

For all fires a linear relationship was observed between fire severity and RBR_{HV} under dry environmental conditions (Fig. 1). With increasing fire severity RBR_{HV} decreased (i.e., scattering reduces due to combustion of vegetation elements). RBR_{HV} dynamic range from unburnt (unchanged) to high severity varied across fires. The radar signal decreased by about 8 dB for the Zuera fire while for the other fires the change was about 3.5 dB except Iron Complex fire, for which the change was about 1.5 dB. Under wet conditions RBR_{HV} presented no sensitivity to fire severity (the slope was close to zero). Similar fire severity levels (i.e. CBI) resulted in a range of RBR_{HV} values independently of forest type (Fig.1). Overall, the highest agreement (i.e., kappa) and model coefficient of determination (R^2) and the lowest estimation error (i.e., RMSE) were observed for the overstory layer which is not unexpected since the radar signal is mostly influenced by the upper part of the canopy. Kappa, R^2, and r values were between 0.06 and 0.1 higher while RMSE was about 0.08 lower when estimating overstory fire severity under dry environmental conditions.

Relationship between RBR and fire severity - Standardized models

The standardization of backscatter change allowed for obtaining similar RBR ranges (Fig. 2). It is evident, when comparing to Fig. 1, that the spread of value among fires was lower and the trend as a function of fire severity was maintained. Overall, substantial agreement (kappa=0.67-0.69) was observed between fire severity estimates based on RBR_{HV} and field data. For RBR indices based on HH polarization and the radar vegetation index (RFDI) the agreement was moderate (kappa=0.45-0.53) and fair (0.36-0.39) respectively under dry environmental conditions (data not shown). However, under wet conditions RBR_{HH} and RBR_{RFDI} based severity

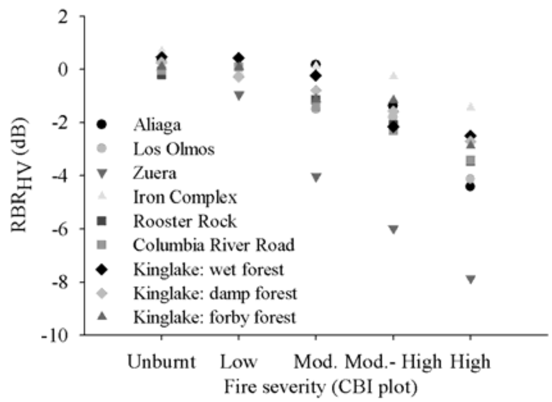

Fig. 1 Relationships between plot fire severity (mean values by severity class and fire) and RBR_{HV} (dry environmental conditions)

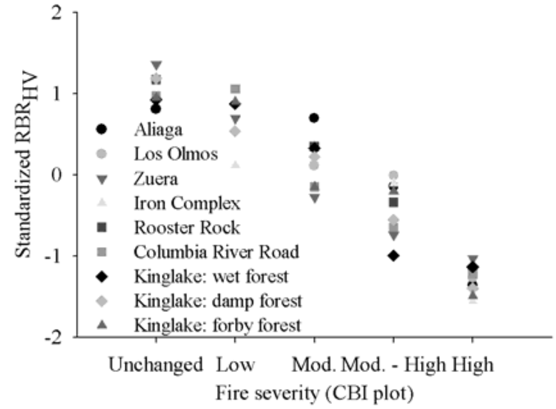

Fig. 2 Relationships between plot fire severity (mean values by severity class and fire) and standardized RBR_{HV} (dry conditions)

estimates provided fair and respectively moderate agreement with the reference data (kappa = 0.30-0.45) as opposed to RBR_{HV} which showed no sensitivity. Using a set of species specific thresholds provided only for a marginal improvement (i.e., kappa by a maximum of 0.1 for RBR_{RFDI} in eucalypt forests) of the estimation accuracy when compared to the common (all forest types) set of thresholds (Fig 3, left panel). Differences were generally higher for RBR_{HH} and RBR_{RFDI} for overstory fire severity. However, a clear pattern was not evident, with kappa values for some fires being higher when using common thresholds.

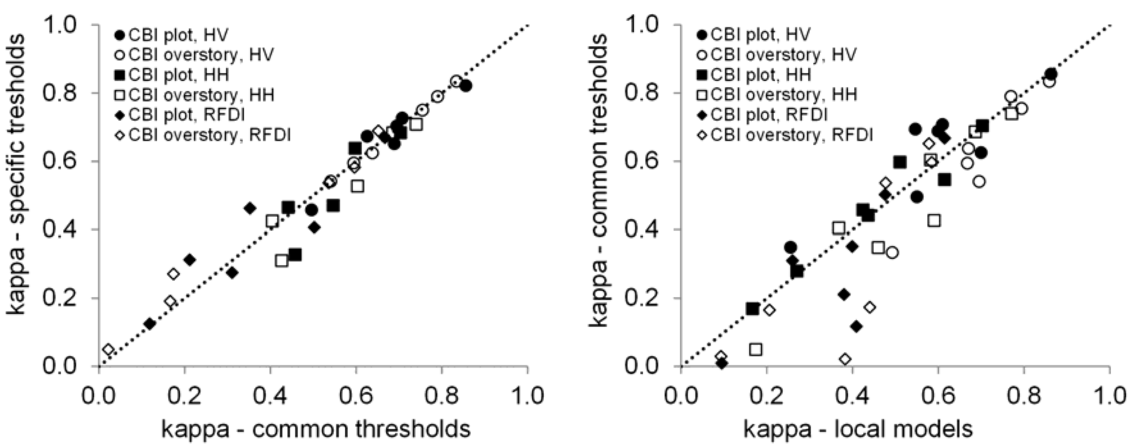

Fig. 3 Cohen`s kappa obtained using common thresholds vs. species specific thresholds in standardized models (left) and local empirical models vs. common thresholds on standardized RBR indices (right).

Local empirical models vs. standardized models for fire severity mapping

The comparison between fire severity estimation accuracy (i.e. kappa) using local empirical modeling vs. using standardized models (with common thresholds) showed fairly similar results, (Fig. 3 right panel). For RBR_{RFDI} empirical modelling provided more accurate fire severity estimation (higher kappa values). Overall, in about 10% of the cases local empirical models provided kappa values at least 0.1 higher, while the opposite was true (at least 0.1 lower) for about 15% of the cases. For RBR_{HV}, plot severity was more accurately estimated using standardized models with common thresholds. Contrarily, overstory severity was better estimated when using local empirical models. However, the average difference in kappa values between the two methods was well below 0.1 for RBR_{HV}. Under wet conditions the average kappa was marginally higher when using standardized models with common thresholds.

Discussions

Previous studies showed that L-band is the most sensitive wavelength to fire effects and its sensitivity does not change significantly across a range of environments, such as Mediterranean and boreal forest (Tanase et al. 2010a; Tanase et al. 2010b). Such studies used locally calibrated empirical models to relate post-fire radar data to field or remote estimates (i.e., from optical indices) of fire severity. However, models based on post-fire datasets need to account for variations in the local incidence angle. By combining pre- and post-fire SAR datasets within a change detection framework (RBR), the effect of local incidence angle was removed, with the radar signal depending only on the forest condition at any given plot. This allowed for the use of simpler and more robust empirical-models when estimating fire severity. It was further shown by this study that RBR indices showed similar trends over a range of fire regimes. This suggests that models to map fire severity over wide areas can be built without needing costly field data.

Overall, the RBR provided a relative measure of fire induced changes, since post-fire information was related to the local pre-fire forest condition at pixel level. The use of pre- and post-fire multi-temporal averages allowed for decreasing pixel-wise speckle noise, which improved fire severity estimation. Parallel analyses (not shown) revealed that correlations between field estimates of fire severity and RBR indices were in all cases higher when using multi-temporal SAR analysis when compared to single date pre- to post-fire image ratios. RBR effectiveness for fire severity estimation was related to forest structural properties, with its accuracy being reduced in forests with high aboveground biomass. The L-band saturation limit at about 100 t ha^{-1} compromised the strength of the relationship between the SAR signal and biomass in such forests. However, it is expected that RBR from sensors with longer wavelengths and thus higher saturation limits (e.g., P-band from the future BIOMASS mission) would provide more accurate results in forests with high levels of biomass.

Local empirical calibration of linear regression models showed that fire severity could be estimated accurately for most of the fires, with RBR indices explaining up to 86% of the observed post-fire forest variability at plot or overstory levels. On average, RBR explained 57% and 65% of the observed post-fire forest variability for plot and canopy levels, respectively. RMSE errors down to 15-20% of the CBI range were observed in this study. Models based on standardized RBR thresholds provided similar estimation accuracies when compared to local empirical models, particularly for RBR_{HV} and plot severity level. Such results suggested that a common set of thresholds could be used to estimate fire severity over wide areas without the need for *a priori* information.

Conclusions

This study provides a significant advance of the current knowledge by integrating pre- and post-fire SAR datasets within a change detection approach, and represents the first attempt to derive standardized thresholds for a rapid fire severity mapping from SAR datasets. Using a novel framework, the Radar Burn Ratio was developed for fire severity estimation using field data from seven forest types with above ground biomass values ranging from 30 to over 500 t ha-1. The study demonstrated that while forest fire regimes might differ, the impact on the radar signal is similar, with RBR showing comparable trends over a wide range of fires. The RBR index most sensitive to fire severity was based on the cross-polarized channel. The methods proposed in this study are particularly valuable for a rapid estimation of fire severity at regional to global levels once a set of pre-calibrated thresholds for the standardized RBR are developed.

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References

Benyon, R.G., & Lane, P.N.J. (2013). Ground and satellite-based assessments of wet eucalypt forest survival and regeneration for predicting long-term hydrological responses to a large wildfire. *Forest Ecology and Management, 294*, 197-207

French, N.H.F., Kasischke, E.S., Hall, R.J., Murphy, K.A., Verbyla, D.L., Hoy, E.E., & Allen, J.L. (2008). Using Landsat data to assess fire and burn severity in the North American boreal forest region: an overview and summary of results *International Journal of Wildland Fire, 17*, 443-462

Keeley, J.E., Brennan, T., & Pfaff, A.H. (2008). Fire Severity and Ecosystem Responses Following Crown Fires in California Shrublands. *Ecological Applications, 18*, 1530-1546

Key, C.H., & Benson, N.C. (2006). Landscape assessment (LA) Sampling and Analysis Methods. In D.C. Lutes, R.E. Keane, J.F. Caratti, C.H. Key, N.C. Benson, S. Sutherland, & L.J. Gangi (Eds.), *FIREMON: Fire effects monitoring and inventory system* (pp. 1-55). Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Gen. Tech. Rep. RMRS-GTR-164-CD

Simmonds, P.G., Manning, A.J., Derwent, R.G., Ciais, P., Ramonet, M., Kazan, V., & Ryall, D. (2005). A burning question. Can recent growth rate anomalies in the greenhouse gases be attributed to large-scale biomass burning events? *Atmospheric Environment, 39*, 2513-2517

Tanase, M.A., de la Riva, J., Santoro, M., Le Toan, T., & Perez-Cabello, F. (2010a). Sensitivity of X-, C- and L-band SAR backscatter to fire severity in mediterranean pine forests. *IEEE Transactions on Geoscience and Remote Sensing, 48*, 3663-3675

Tanase, M.A., Santoro, M., de la Riva, J., Kasischke, E., & Korets, M.A. (2010b). L-band SAR backscatter prospects for burn severity estimation in boreal forests. In, *ESA Living Planet Symposium*. Bergen, Norway: ESA Publications Division

Wang, C., & Glenn, N.F. (2009). Estimation of fire severity using pre- and post-fire LiDAR data in sagebrush steppe rangelands. *International Journal of Wildland Fire, 18*, 848-856

REDUCING INCONSISTENCIES OF GRASSLAND CURING ASSESSMENT BETWEEN MULTIPLE JURISDICTIONS ACROSS AUSTRALIA

Danielle Wright*, Alex Chen, Rachel Bessell, Susan Kidnie, David Nichols, Alen Slijepcevic

Country Fire Authority, Burwood East, Victoria, Australia, *d.wright@cfa.vic.gov.au

Abstract

In Australia, the degree of grassland curing (senescence) is an essential component in fire behaviour models and in Grassland Fire Danger Index (GFDI) calculations. Between states and territories, methods used to assess grassland curing vary from use of either satellite imagery or ground-based visual observations. Such variation causes inconsistent GFDI values across the continent, and inhibits the continuity of GFDI values at state/territory borders. These techniques alone also have inherent limitations, leading to inaccurate GFDI calculations. From the ground, visual observations are subjective, and have high variability in accuracy. Ground-based observations (using visual estimates, destructive sampling or Levy rod sampling) do not cover the whole state or territory and can be spatially unrepresentative of curing across the landscape. Satellite observations provide a curing value for every gridded cell across the state; however, changes in curing may not be captured entirely by satellite in the event of consecutive days of cloud cover. Satellite models tend to under-estimate curing if woody vegetation and secondary grass growth is present, and tend to over-estimate curing in regions with water-bodies, urban areas, sand dunes and landscapes covered by yellow flowers.

In 2013, a combined approach for estimating grassland curing was developed and deployed operationally in the state of Victoria, Australia. The inherent limitations of other practices were lessened by merging weekly ground-based observations with near real-time satellite data. Since 2014, the combined approach is being trialled for other states and territories across Australia; however, inconsistencies remain apparent at state/territory borders. This paper describes a proposed technique to minimise the inconsistencies of curing between jurisdictions. The proposed technique entails the influence of ground observations across state/territory borders. With ongoing support from multiple fire management agencies, GFDI calculations will become more accurate and consistent across the continent.

Introduction

In Australia, the Grassland Fire Danger Index (GFDI) is determined by several inputs including the degree of grassland curing, defined as the proportion of senescent material in a grassland (Cheney and Sullivan, 2008). Throughout Australia, techniques used to assess grassland curing vary between states and territories. The variation in techniques causes inconsistent GFDI values across the continent, and inhibits the continuity of GFDI values at state/territory borders. Additionally, inaccurate assessments and poor spatial coverage of curing measurements provide imprecise information for determining fire danger ratings. In the state of Victoria, the Country Fire Authority (CFA) developed a combined approach for estimating curing that entails the use of satellite observations adjusted by observations from ground observers. Using MODerate resolution Imaging Spectroradiometer (MODIS) satellite data, a satellite model was derived, named MapVictoria, based on historical satellite and ground-based observations. With use of the new satellite model (MapVictoria), an integrated model was developed, named the Victorian Improved Satellite Curing Algorithm (VISCA), combining near real-time MODIS satellite data with weekly observations of curing from the ground (Martin et al., 2015). The VISCA model was automated through the development of an online system. At the beginning of the 2013/2014 fire season, the VISCA model, accompanied by the online system, was deployed in operations for accurate fire danger calculations of grasslands in Victoria.

Since 2014, with support from the Commonwealth Attorney General's Department National Emergency Management Projects (NEMP), CFA has collaborated with fire agencies from multiple jurisdictions to offer the combined approach of grassland curing assessment to other states and territories as a pilot trial. Participating states and territories include Queensland, New South Wales, Australian Capital Territory, South Australia and Tasmania. Prior to the 2017/2018 fire season, it is envisaged that the VISCA model and online system will be developed for these jurisdictions as an operational product. For each jurisdiction, trial grassland curing maps have been provided (by CFA) on a weekly basis. While the same approach has been trialled for each state and territory, ground observations have only influenced the VISCA model within each jurisdiction. The discontinuity at state/territory borders therefore remains apparent. This paper describes the development of a proposed technique whereby ground observations can be utilised across state/territory borders. The proposed technique will minimise inconsistencies of curing assessment between jurisdictions and will improve the spatial coverage of ground observations particularly in remote areas. The technique will also support the standardisation of national curing assessment.

Previous techniques

Fire management agencies across Australia have historically used either ground-based visual observations or satellite observations alone for operational curing assessment. From the ground, visual observations are subjective, and therefore have high variability in accuracy. As indicated by Anderson et al. (2011), Levy rod observations (Levy and Madden, 1933) are more accurate than visual observations however the Levy rod technique is not operationally feasible for weekly estimates by volunteer observers. Regardless of which ground-based method is used, ground-based observations do not capture variation in curing levels across the whole landscape (Anderson et al., 2011). Satellite observations provide a curing value for every gridded cell across a state or territory; however, changes in curing may not be captured entirely by satellite in the event of consecutive days of cloud cover. Satellite models may underestimate curing owing to woody vegetation and secondary grass growth, and may overestimate curing owing to water-bodies, urban areas, sand dunes, bare soil and even landscapes covered by yellow flowers which result in inaccurate curing estimates (Newnham et al., 2010).

Current technique

Ground observations

The combined approach of curing assessment has worked successfully in Victoria since the 2013/2014 fire season. In addition to the MapVictoria model, derived specifically for

Victorian grasslands, the VISCA model is supported by accurate ground-based observations through the establishment of a network of volunteer observers and the development of training products. For the current trial, the Victorian approach has been offered to other jurisdictions. Visually assessed curing observations are entered online once a week from over 450 observation sites across Queensland, New South Wales, Australian Capital Territory, South Australia and Tasmania. For each jurisdiction, ground observations are validated by operational personnel and are utilised in the VISCA model to adjust the MapVictoria satellite observations.

Satellite observations

Using a direct feed of MODIS satellite data, the Bureau of Meteorology process and update 500m MapVictoria data on a daily basis, with “no data” pixels representing water-bodies or cloud cover. As an example, mosaicked MapVictoria data and ground observations are presented in Figure 1 from January 31st 2016 to February 4th 2016.

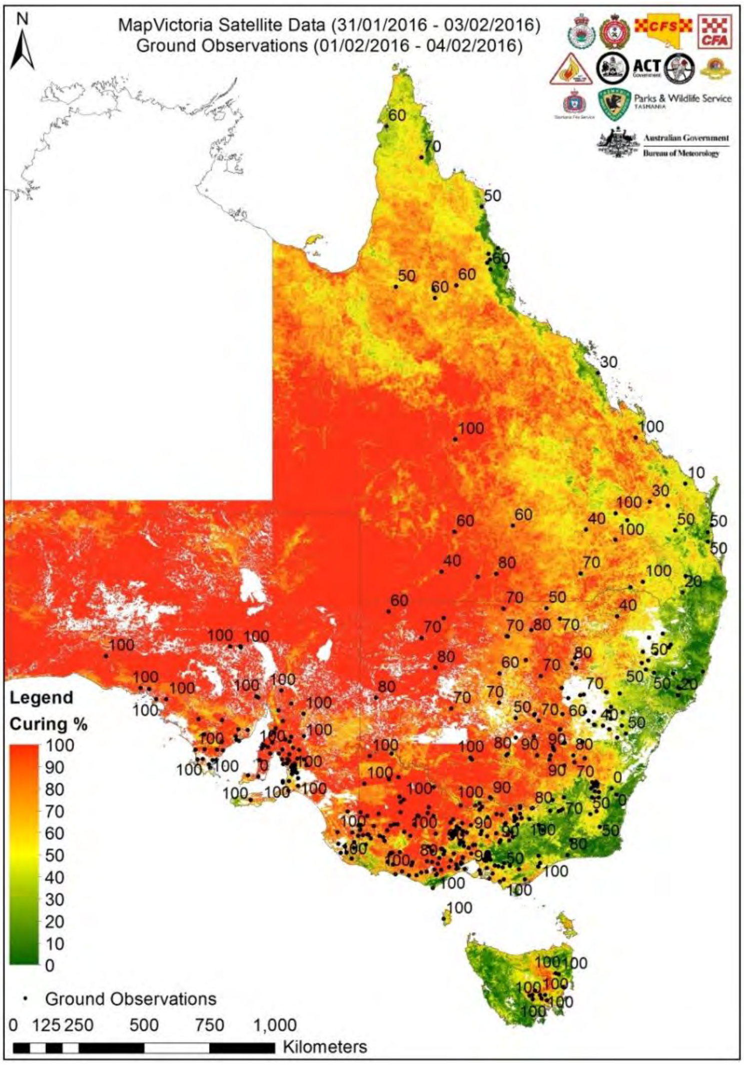

Figure 1 MapVictoria Satellite Curing Data processed (by the Bureau of Meteorology) on the following dates: 31/01/2016 (VIC), 02/02/2016 (QLD/TAS), 03/02/2016 (ACT/NSW/SA) and Visually Assessed Curing Observations validated online on the following dates: 01/02/2016 (VIC), 03/02/2016 (QLD/TAS), and 04/02/2016 (ACT/NSW/SA).

For the extents of Queensland, Victoria and the Australian Capital Territory the satellite observations are filled by older satellite observations in the presence of cloud cover. Every filled MapVictoria dataset is accompanied by a satellite data age file, which comprises the age of each observation (in number of days) for every 500m pixel. The satellite data age file is used in the VISCA model to increase or decrease the influence that each ground observation has on the VISCA model as older satellite observations are less reliable. For the extents of New South Wales and South Australia, the MapVictoria data are not filled, and therefore contain "no data" pixels in the presence of cloud cover.

The satellite observations and ground observations in Figure 1 are collated from different dates as the curing maps are provided for each jurisdiction on different days of the week; Monday for Victoria, Wednesday for Queensland and Tasmania, Thursday for New South Wales, Australian Capital Territory and South Australia. Evidently in Figure 1, the inland areas comprise MapVictoria curing values of 100% and point observations of varying values. In some cases, the satellite values agree with the ground observations, however in other cases, the MapVictoria observations are over-estimating curing. This is due to the sparse spatial coverage of grass and high exposure of bare soil. Ground observations are vital in such areas to adjust the over-estimating satellite values.

Automated online system

In Victoria in 2013, the online system was developed and deployed to Victoria's CFA website to facilitate an automated operational workflow for VISCA curing map production. The system's workflow progresses from signing up new observers, to capturing and collating field observations, to producing a VISCA curing map for Victoria. The system can be accessed using web browsers across different platforms including personal computers, tablets and smartphones. For five other jurisdictions, the automated online system is being trialled for data entry and automated VISCA map production. A prototype of the online system comprises a web portal, a cloud-based database and application server, and a geo-processing service, residing in a low-cost, low maintenance, and scalable cloud computing platform.

VISCA

For each jurisdiction, the satellite and ground observations (Figure 1) are combined to produce six VISCA curing maps, shown (as a mosaic) in Figure 2. With the exception of Tasmania, inconsistency at state/territory borders remains evident.

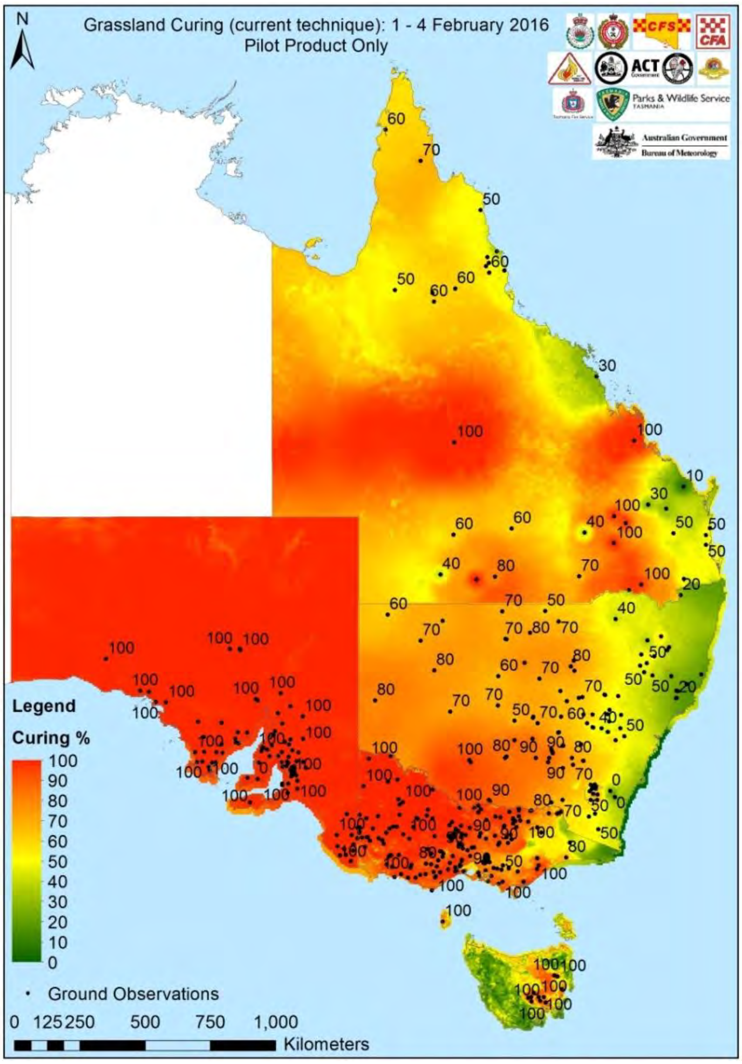

Figure 2 Current technique for VISCA Grassland Curing Mapping (01/02/2016 – 04/02/2016)

Proposed technique

In 2016, revised versions of the VISCA model and online system will be developed and deployed for each jurisdiction. The revised versions entail a proposed technique whereby ground observations can be shared across state/territory borders. Using the online system, operational personnel will be able to select which observation sites can be viewed by other states and territories. Additionally, operational personnel will be able to select which observations from other jurisdictions they wish to use for their jurisdictional curing map. Testing the proposed technique for the first week of February 2016, Figure 3 presents a mosaic of the proposed VISCA maps using all ground observations presented. Assuming all jurisdictions wish to use all or most observations from other jurisdictions, the continuity of curing across state/territory borders has greatly improved.

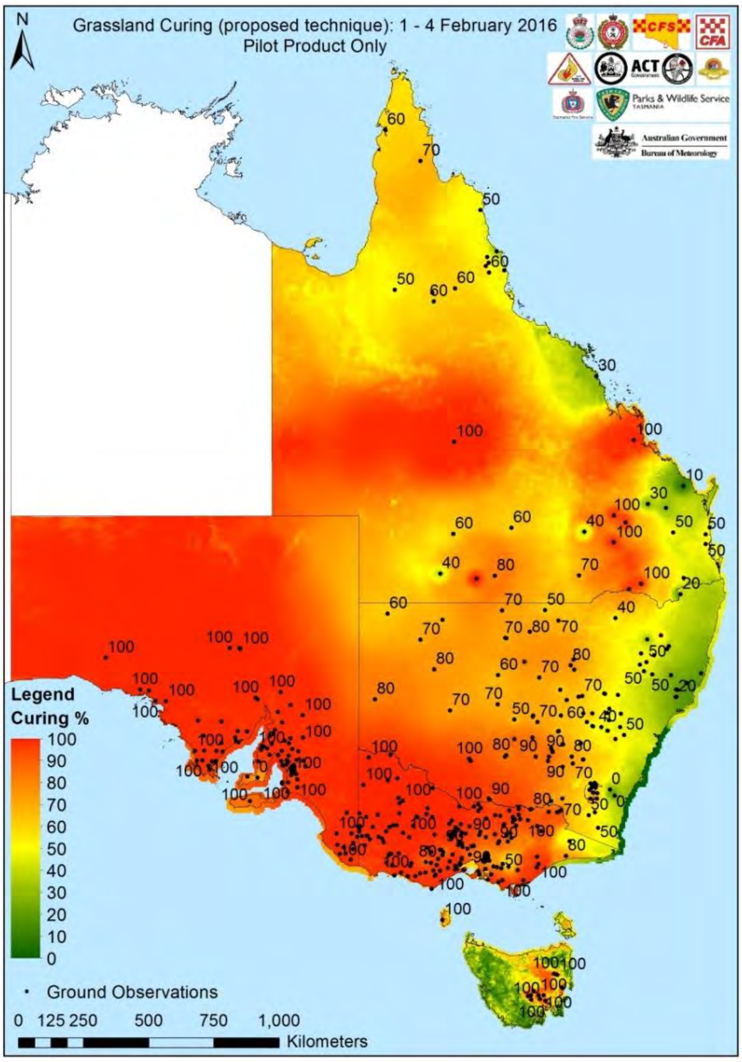

Figure 3 Proposed technique for VISCA Grassland Curing Mapping (01/02/2016 – 04/02/2016)

Conclusions

In Victoria, CFA has contributed to improved GFDI calculations through the development and deployment of an effective automated technique for operational curing assessment. Across Australia, methods used to assess grassland curing vary between states and territories. Inconsistent methods can result in inconsistent GFDI values at state/territory borders. Inaccurate assessment of grassland fuels result in inaccurate FDRs. To support the standardisation of curing assessment, multiple state fire and land management agencies are participating in the NEMP project. By trialling the VISCA model and the online system in multiple jurisdictions, the project will provide accurate and consistent GFDI calculations across multiple states and territories. At the completion of the trial, the VISCA model and online system will be available to each jurisdiction for operational use. The combined efforts of the NEMP project will result in more accurate and spatially representative grass fuel information being used in fire danger indices across the country.

Acknowledgements

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References

Anderson SAJ, Anderson WR, Hollis JJ, Botha EJ (2011) A simple method for field-based grassland curing assessment. *International Journal of Wildland Fire* **20**: 804-814.

Cheney P, Sullivan A (2008) ‘Grassfires – Fuel, Weather and Fire Behaviour, 2nd Edn.’ (CSIRO Publishing: Melbourne)

Levy EB, Madden EA (1933) The point method of pasture analysis. *New England Journal of Agriculture* **46**, 267-279.

Martin D, Chen T, Nichols D, Bessell R, Kidnie S, Alexander J (2015) Integrating ground and satellite-based observations to determine the degree of grassland curing. *International Journal of Wildland* Fire **24**:329-339.

Newnham GJ, Grant IF, Martin DN, Anderson SAJ (2010) Improved Methods for Assessment and Prediction of Grassland Curing - Satellite Based Curing Methods and Mapping. Bushfire Cooperative Research Centre Project A1.4 Report. (Melbourne).

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Results of a formal trial for predicting blow-up fire events

Rick McRae*
ACT Emergency Services Agency, Canberra, ACT, Australia, rick.mcrae@act.gov.au
Jason Sharples
UNSW Canberra, ACT, Australia.
Laurence McCoy
NSW Rural Fire Service, Sydney, NSW, Australia.

Introduction

In order to test the results of recent scientific advances in the understanding of extreme wildfires, we have been conducting a formal multi-jurisdiction operational trial of a predictive model. The model looks at the potential for blow-up fire events. The trial involves ACT Emergency Services Agency, NSW Rural Fire Service and UNSW Canberra. It is linked to the formal cross-border MOU between NSW and ACT.

The model includes aspects of the formation of deep flaming and the instability environment. Elevated fire danger serves only as a precursor for activation of the model. The trial has run for the last three austral summers, and a number of critical events have been captured.

With the end of summer the trial outcome is now being evaluated. If successful, the trial would be a significant advance in our management of the most damaging class of wildfires.

Definitions:

Blow-up event: A part of a fire that becomes coupled with the atmosphere as a result of deep flaming in a suitable instability environment.

BUFO: The Blow-Up Fire Outlook project (see References).

Extreme fire: A large fire that includes one or more blow-up events (not necessarily at the same time).

FBAN: Fire behaviour Analyst - a specialist analysing the fire environment and predicting fire behaviour for an Incident Management Team

PyroCb: The most extreme manifestation of violent pyro-convection above an extreme fire - a fire thunderstorm.

Methodology:

BUFO works by:

1) Evaluating fire weather forecast grids from the Australian Digital Forecast Database for initial trigger conditions. This uses fire agency viewers, BoM viewers and direct feeds into mapping software.

2) Applying the flowchart to forecast conditions as spatial overlays. The aim is to produce

map areas that meet the model output at specific times.

3) Discussing these results with stakeholders.

4) Comparing the overlay results against situational information - fires, hotspots, imagery, weather observations, radar, etc.

5) If a fire is in the areas with potential for blow-ups then a warning is issued for that fire and passed on to the fire's FBAN.

Results of the formal trial:
The trial has run between December 2013 and March 2016. For the ACT and NSW there have been 19 days when the initial conditions for the model have been met, or nearly met and conditions have warranted an analysis.

In that period 3 alerts were issued. 2 blow-up events were detected. The Probability of Detection was 100%. The False Alarm Rate was 33%.

The context of the trial can be judged from the national pattern of notable wildfires. There were 2 extreme wildfire events in the 2013/2014 season, neither in the BUFO project domain (both were in Victoria). The same was true of the 5 major wildfire events in the 2014/2015 fire season (3 in Victoria, 1 in SA and 2 in WA). Four major wildfire events occurred in the season just finished, again outside the project area (2 in Victoria, 1 in SA and 1 in WA). It is clear that a broader implementation would be required to have a useful likelihood of capturing future major widlfires. In the last 12 months some interim modeling was conducted across a broader area.

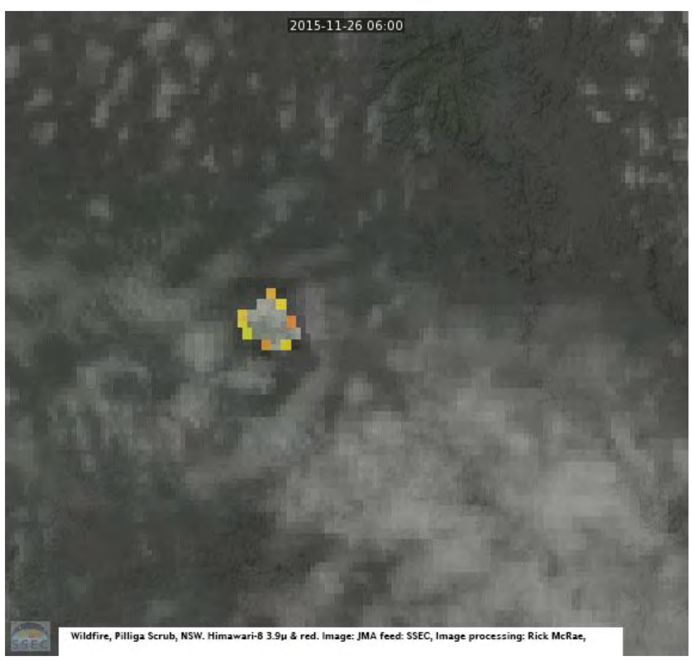

Figure 1. Himawari-8 imagery of a fire for which an alert had been issued.

The trial outcomes are currently being considered. Options are:

- The project has suitable Probability of Detection and False Alarm Rate to be considered successful. The trial will be concluded and BUFO will be made operational.

- The project has not yet accumulated enough data to be concluded. It will be continued.

- The project has POD and FAR that are not suitable for operationalising. It will be concluded. The methodology will need to be reviewed.

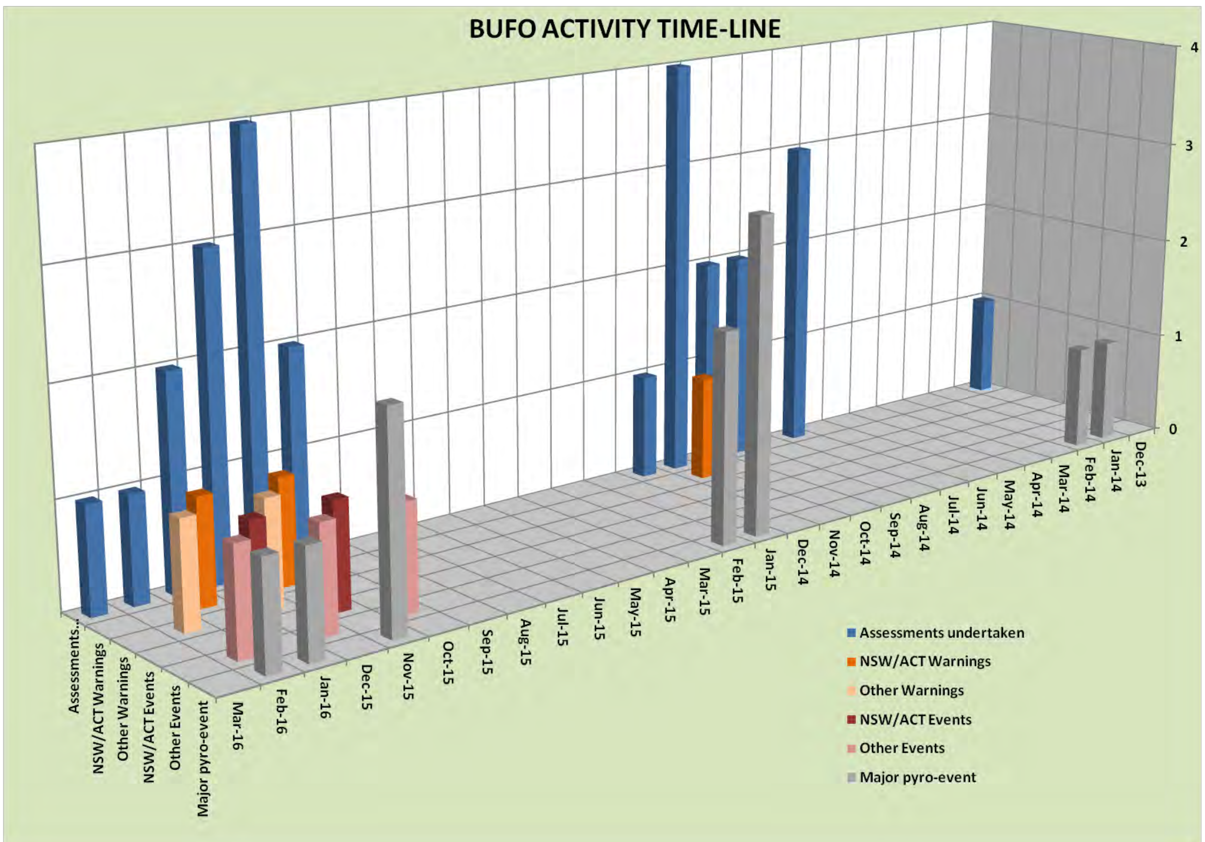

Figure 2: BUFO trial activity timeline. Only the last 12 months looked at areas outside of NSW/ACT.

Implications:

Current results indicate that there would be some significant implications arising from the BUFO Project:

1) On days of elevated fire danger with numerous fires on the landscape, it is practical to anticipate the development of a blow-up fire event.

2) The BUFO methodology could form a platform for implementing future improvements in our understanding of blow-up and pyroCb events.

3) A greater ability to predict a fire's blow-up potential could have significant downstream effects. These could range from strategic prioritisation of resources to early warning of communities. This will aid in mitigation of the biggest source of residual risk from bushfires for Australia's rural and peri-urban communities.

4) The FBAN and Predictive Services capabilities being developed across the sector can and should consider using this BUFO methodology.

Conclusion:

A useful level of skill has been demonstrated for anticipating fires that become blow-up events. The setting of a landscape with elevated fire danger and a number of fires can be analysed to identify where risks to the community and fire crews are most dangerous.

This work implements peer-reviewed scientific research, and has the ability to include future work as we improve our knowledge of the drivers of the most dangerous fires.

References

McRae, R.H.D. & Sharples, J.J. (2013). A process model for forecasting conditions conducive to blow-up fire events. *Proceedings, 2013 MODSIM Conference, Adelaide*.

McRae, R.H.D. & Sharples, J.J. (2014). Forecasting conditions conducive to blow-up fire events. *CAWCR Research Letters*

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Retrospective Bush Fire Protection Standards for Existing Development

Jon Gaibor
New South Wales Rural Fire Service, Lidcome, NSW, jon.gaibor@rfs.nsw.gov.au

Abstract
In August 2002, the New South Wales (NSW) government introduced legislation to proactively address the bush fire risk to life and property in interface areas throughout NSW. The legislation prescribes performance standards for new development covering a range of different measures including construction standards and setback distances.

However, many existing developments located in bush land interface areas in NSW have not been designed in accordance with these standards. Generally, existing developments often offer little or no protection against bush fire. In many cases, these properties will contain assets that have minimal setbacks from potential bush fire hazards and construction standards that do not adhere to current bush fire building requirements.

The key legislation relating to bush fires in New South Wales is the *Rural Fires Act 1997*. Part 4 of the Act outline responsibilities for land owners and public authorities in regard to preventing bushfires and minimizing the danger and spread of bushfires. In meeting, these responsibilities land owners and public authorities undertake works to protect properties however to date there has been a lack of guidance in determining the required treatment.

To address the gap for existing development the NSW Rural Fire Service have developed a guideline which sets out a practical and robust methodology that allows for the consistent application of protection measures for existing development at risk of bush fire across the State of NSW. For the purpose of the guideline existing development is defined as those properties, which have not been built with regard to Planning Fire Bush Fire Protection and AS3959.

The guideline outlines protection measures for existing development including; residential dwellings, vulnerable community assets such as schools, hospitals and nursing homes (Special Fire Protection Purpose Facilities) and major buildings (eg. commercial and industrial buildings).

Challenges in developing the guideline.
A key challenge in developing the guideline was balancing conflicting priorities. Protection outcomes often can conflict with environmental protection outcomes and peoples values can vary significantly. The cost of protection outcomes also needs to be balanced between asset owners, adjoining landowners and public authorities. To assist in balancing these priorities it was recognised that there was a need to base the approach on current scientific research.

Bush fire research in the last decade has identified a number of key elements in managing the impact of bush fires on communities, particularly along the bush land interface. The research has highlighted the value of undertaking risk treatment strategies in interface areas in order to protect life and property from bush fire.

Research undertaken by the Bushfire CRC (2010) into house losses during the 2009 Victorian 'Black Saturday' bush fires indicate that in the townships of Marysville and Kinglake, up to 60% of the houses that were lost were within 10 metres of bush land (Chen & McAneney 2010). Additional research by Gibbons et. al. (2012) suggests that the implementation of a fuel reduced zone up to 40 metres from houses has potential to reduce house loss by 43%. In both cases, the research suggests that buildings in close proximity (less than 40 metres) to bush land were impacted by a combination of bush fire attack mechanisms, with flame, radiant heat and embers playing a role in house loss. Recent work undertaken by the University of Wollongong (Price and Bradstock 2013) also reinforces the concept that separation of assets from unmanaged vegetation is an essential part of reducing the risk of life and property loss from bush fire.

It is also important that the nature of ember attack is taken into account when considering the protection of existing development from bush fire. Analysis of past bush fire events indicates that embers and wind born debris are the most prevalent attack mechanism on houses in Australian bush fires and are responsible for over 90% of houses loss (Potter & Leonard 2010). Work in this area indicates that embers can travel significant distances (up to 700m) from bush land areas and impact properties (Chen & McAneney 2010). Therefore, whilst maintaining separation between assets and bush fire hazards is an important measure, it must be coupled with appropriate development design in order to protect against embers and effectively reduce the bush fire risk.

In summary, the research referenced above reinforces the following principles in managing bush fire risk to communities**:**

- Providing separation between assets and bush fire hazards is an important aspect of reducing the risk of life and property losses from bush fire.
- Ember attack can affect properties over significant distances (up to 700m) and is responsible for a large portion of house ignitions. Combining fuel management with improved construction standards will provide increased protection against bush fires.
- Fuel management treatments alone will not always be effective during Severe to Catastrophic fire weather conditions.
- Treatment strategies such as suppression, ignition management, preparedness, community education, planning and building improvements will assist in further reducing the bush fire risk to life and property.

The above principles have been used to provide a basis for developing standards for bush fire protection measures, which combines appropriate separation distances with ember protection measures.

Determining appropriate separation distances for Residential Development

Determining the appropriate minimum separation distances (referred to as Asset Protection Zone (APZ) in NSW) is calculated using recognised bush fire attack modeling. The calculations are based on a predetermined radiant heat target and FDI value, which are fundamental inputs to bush fire attack modeling.

The APZ distances for residential development aim to achieve radiant heat of less than 19 kWm^{-2} and a Forest Fire Danger Index (FFDI) of 50.

A radiant heat target of less than 19 kWm^{-2} is based on information provided in Table A3.4.2 of *Planning for Bush Fire Protection* 2006 (page 3 of Addendum Appendix 3) regarding the impact of different levels of radiant heat on building elements. This table states that the integrity of buildings will be threatened when exposed to radiant heat loads greater than 19 kWm^{-2}. Whilst some building elements may still be affected at a radiant heat load below 19 kWm^{-2}, the implementation of building upgrades can be applied to reduce the risk of building ignition at these levels. These building upgrades are considered a reasonable and practical measure for an asset owner to undertake. The need to undertake building upgrades to complement the APZs promotes the concept of shared responsibility in bush fire management.

A FFDI of 50 is the point at which a Severe Fire Danger Rating is activated. It is also the point at which:

- Fire Weather Warnings are issued & Total Fire Bans are declared
- Community advice is issued through the various media outlets on the heightened risk of bush fires
- The Bush Fire Survival Plan provides specific messages to the community on actions to take to survive a bush fire
- Level 1 Operational Readiness is triggered for NSW RFS State, Regional and District Offices

Given the alignment of FFDI 50 (i.e. adopting an FFDI of 50) with existing community messaging and operational triggers, it was considered a most suitable benchmark to adopt for existing residential development.

The Forest Fire Danger Index of 50 and 19 kWm^{-2} benchmarks operate on the theoretical premise that the APZs and building upgrades would provide bush fire protection to the dwelling up to a FFDI of 50. These measures will also create a more manageable environment where mentally and physically prepared residents have an opportunity to stay and defend their homes at FDR's below Severe.

For Fire Danger Ratings of Severe and above, residents will still need to make a decision on the appropriate actions to take based on their individual circumstances as per their Bush Fire Survival Plan. During these heightened fire weather conditions, the APZs and building upgrades provided for by the acceptable approach will provide a reduction in radiant heat and a defendable space which will enhance the ability of residents and fire fighters to implement active protection measures. Table 1 outlines the minimum APZ's based on the above rational for some representative vegetation classes in NSW.

Table 1 –Asset Protection Zone Distances (m) for Existing Residential Development

Vegetation Community	EFFECTIVE SLOPE (DEGREES)				
	Upslope/Flat	**>0-5**	**>5-10**	**>10-15**	**>15-20**
North Coast Wet Sclerophyll Forest Overall Fuel Load: 28.99 t/ha	19	24	30	37	46
Sydney Coastal Dry Sclerophyll Forest Overall Fuel Load: 24.3 t/ha	18	23	28	35	44
Western Slope Woodlands Overall Fuel Load: 14.4 t/ha	10	13	16	21	27
Short Heath Overall Fuel Load: 15 t/ha	11	13	14	17	19

Promoting Ember Protection Strategies for Existing Residential Development

In addition to the APZ measures the guideline promotes the position that management of bush fire risk is a *shared responsibility* and an adjoining land owner / manager should not be solely accountable for providing adequate bush fire protection to adjacent assets. The building owner / occupier also has a responsibility to protect their own asset by incorporating bush fire protection measures appropriate for the environment in which the building is sited. Protection measures may include upgrades to the construction standards along with ongoing building and property maintenance.

To support this, the property owner is provided with information regarding their risk and actions that they can undertake which will complement and further protect their property. A focus of this information is upgrades than can be undertaken to improve the ember protection of the property.

Determining appropriate separation distances for Existing Special Fire Protection Purpose (SFPP) Development

The APZ distances for SFPP aim to achieve a radiant heat target of less than 10 kWm^{-2}, coupled with a design FFDI of 100 for nominated[1] onsite refuge buildings.

The focus of the bush fire protection measures for an on-site refuge is life safety. This is due to the vulnerable nature of occupants and the limitations associated with their relocation during a bush fire event. *Planning for Bush Fire Protection* 2006 establishes a robust position for the protection of new SFPP development that is based on life safety. It designates a radiant heat target of less than 10 kWm^{-2} for these types of developments which has been adopted for the purposes of an on-site refuge for existing SFPPs.

The design FFDI 100 is the point at which a Catastrophic FDR is activated. This FFDI combined with a radiant heat load of less than 10 kWm^{-2} ensures that on-site refuges remain as viable shelter options up to a Catastrophic FDR.

[1] The nominated on-site refuge is the building or part of a building that has been identified as the shelter option in the Emergency Management and Evacuation Plan.

Assets that are not designated as an on-site refuge within an existing SFPP development do not have the same life safety requirements. Therefore, APZs that are commensurate with existing residential development are considered appropriate for other occupied buildings within an existing SFPP. Table 2 outlines the minimum APZ's for On-site refuges in SFPP.

Table 2 –APZ Distances for Onsite Refuges in Special Fire Protection Purpose Facilities

Vegetation Community	EFFECTIVE SLOPE (DEGREES)				
	Upslope/Flat	**>0-5**	**>5-10**	**>10-15**	**>15-20**
Sydney Coastal Dry Sclerophyll Forest Overall Fuel Load: 24.3 t/ha	62	74	89	100	100
Western Slope Woodlands Overall Fuel Load: 14.4 t/ha	40	49	59	72	86
Grassland Overall Fuel Load: 6t/ha	36	40	46	51	57

Promoting Ember Protection and Emergency Management Arrangements for Existing SFPP

As with the approach for residential development the APZ measures are supported by promoting the position that management of bush fire risk is a *shared responsibility.* The guideline promotes that ongoing building and property maintenance combined with suitable Emergency Management arrangements are critical actions, which also need to be undertaken by the facility management.

The NSW RFS has developed a Bush Fire Emergency Management and Evacuation Plan Guideline for SFPP developments and this will provided to facility managers to assist them in preparing a Bush Fire Emergency Management and Evacuation Plan. This Bush Fire Emergency Management and Evacuation Plan will need to identify a suitable on-site refuge. The facility manager is also provided with information regarding the risk to the facility and actions that they can undertake which will complement and further protect the facility. A focus of this information is upgrades than can be undertaken to improve the ember protection of the facility.

Providing an Alternate Approach for when environmental constraints restrict work

In developing the guideline, it was recognised that in some circumstances APZ distances would not be able to be achieved due to site limitations such as terrain, threatened species and Endangered Ecological Communities. The guideline has alternate approaches for each development type. These approaches detail additional protection measures which offset the lack of separation. The alternate approach for residential development is explained in more detail below

A first step in applying the alternate approach is to establish what the largest achievable APZ is, and based on this, what would be the resultant radiant heat rating on the asset. Based on this resultant radiant heat the property is classified into either 19-29 kWm^{-2} or greater than 29 kWm^{-2}. For assets that fall into the 19-29kWm^{-2} category the following additional treatments are recommended;

- The Asset Protection Zone fuels are managed at a higher intensity. The whole APZ should be maintained as an Inner Protection Area (ie Canopy cover <15% & shrub cover <5%).
- The property owner should receive a tailored community engagement activity which includes a property inspection from an experienced officer to provide specific and tailored advise about what measures would be most beneficial for the land owner to undertake to upgrade the building elements of their property
- The resident should also be provided with assistance to complete their Bush Fire Survival Plan

For properties which have a resultant radiant heat of greater than 29kWm^{-2} the above measures apply along with the following additional to treatments;

- A prescribed burn proposal should be developed for the area and submitted to the local Bush Fire Management Committee (BFMC) so that it can be assessed along with other proposals for inclusion in the BFMC's annual works or contingency program.
- A detailed assessment of factors surrounding the property such as road access, fire trail access, vegetation proximity under power lines and condition of adjacent Asset Protection Zones to the property are also inspected to see if any improvements can be made.

Conclusion

Protecting existing development presents a major challenge. The use of radiant heat modeling for determining the calculation of APZ's provides a practical basis for determining the required works in bush land interface areas. The additional focus on shared responsibility and of improvements to and directly around the asset will further enhance the protection to individual assets. For officers of fire agencies and land managers the guideline will provide transparent and consistent decision making for the application of bush fire protection measures to existing development throughout NSW.

References

Chen K, McAneney J (2010) Bushfire Penetration into Urban Areas in Australia: A Spatial Analysis, Report to Bushfire CRC (Melbourne, VIC)

Potter M, Leonard J. (2010), Spray system design for ember attack – Research findings and discussion paper. Report to Bushfire CRC (Melbourne, VIC)

Gibbons P, van Bommel L, Gill AM, Cary GJ, Driscoll DA, et al. (2012), Land Management Practices Associated with House Loss in Wildfires. *PLoS ONE* **7**, e29212

Price O, Bradstock R. (2013), The efficacy of fuel treatment in mitigating property loss during wildfires: Insights from analysis of the severity of the catastrophic fires in 2009 in Victoria, Australia, *Journal of Environmental Management* 113. 146-157

Price O, Bradstock R (2013b), Landscape Scale Influences of Forest Area and Housing Density on House Loss in the 2009 Victorian Bush Fires. *PLoS ONE* **8**, e73421

Review of 20 years of progress in wildfire modelling using a fully physical approach

Dominique Morvan
Aix-Marseille Université CNRS, Centrale Marseille, M2P2 UMR 7340, Marseille, FRANCE,
domnique.morvan@univ-amu.fr

In 1996 A.M. Grishin has published in English a monograph entitled "Mathematical modelling of forest fires and new methods of fighting them", the publication of this book (the first edition in 1992, was in Russian) by the Tomsk State University and resulting from the initiative of Franck Albini as an editor, can be considered as the first reference book at the origin of the applications of turbulent multiphase flows to the understanding of wildfire behaviour.
Besides the presentation of the mathematical formulation developed to simulate numerically all the physical mechanisms contributing to the propagation of a forest fire, i.e. the degradation of a forest fuel, the mechanisms of heat transfer between the flame and the solid fuel, the interactions between the vegetation and the atmospheric boundary layer ..., this monograph (p.367) constitutes also a precious source of information where were collected numerous experimental data in connection with this very complex physical problem.
This presentation constitutes a review of the major contributions in wildfire modelling using a physical approach published these last 20 years since the publication of the A.M. Grishin's monograph in 1996 (Grishin 1996).
As suggested by Weber (Weber 1991) and few years after by Sullivan (Sullivan 2009), wildland fire spread models can be classified in three categories: physical models, empirical or semi-empirical models and contagion models. All these different classes of fire models have their own scale of using (from large scale wildfire forecasting to local scale fire safety engineering). In this sense, they can be considered as complimentary, and therefore they have all their own domain of application: one single tool would not be able to cover the large range of scales characterizing wildfires.
Wildfire modelling is a very complex problem, it includes numerous sources of non-linearity, such as the decomposition by pyrolysis of the solid fuel, the radiation heat transfer between the flame and the vegetation, the turbulence of the gas flow around the fire, the gaseous combustion, and so on … Because of that, empirical approaches based on statistical analysis of experimental data bases, have been for a long time privileged in comparison with more physical approaches based on the resolution of the balance equations governing this physical system.
Unfortunately, as in meteorology, it is impossible to construct a database covering the variability of situations (in terms of fuel, topography, atmospheric conditions …) encountered during the propagation of a forest fire. The extrapolation from one situation to another one, for the prediction of the behaviour of a fire, is highly speculative, this explain the relative failure observed in solving this problem following this way.
The comparison of a set wildfire models with real observations collected on the field (Malibu fire in October 1996), has clearly shown that the minimal level of accuracy (with a relative error still equal to 100%!) was achieved when at least the wind vector acting on the fire front (such as in the Rothermel's model) (Rothermel 1972) was calculated in taking into account of the local topography through an atmospheric CFD model (Hanson et al 2000).
At the end of the nineties, the increase of computational power has allowed to progress towards more physical wildfire models following two ways:

(I) In connecting large mesoscale atmospheric flow model with a simplified semi-empirical fire front model (more or less similar to the Rothermel's model).
(II) In developing in 2D and 3D a multiphase, fully physical wildfire model (more or less as detailed in the Grishins' monograph) (Larini et 1998, Morvan et al 2013, Mell et al 2007).

The first approach (I) has been mainly initiated by the community "physics of the atmosphere". The atmospheric boundary layer flow problem was generally solve in using a mesoscale non-hydrostatic model such as WRF (Mandel 2008, Coen 2005) or MESO-NH (Filippi et al 2011) coupled to a more or less empirical/physical fire front model (BEHAVE, FOREFIRE) (Rothermel 1972, Balbi et al 2009). To compensate the uncertainties coming from the simplified fire model, the position of the fire front can be dynamically corrected using a data assimilation procedure, similar to the approach adopted for the meteorological predictions. Because this approach do not explicitly resolve the combustion process in the flame (the flame is reduced to a prescribed surface heat source on the ground), it is mainly adapted to study the behaviour at large scale of the thermal plume coming from the fire (see Figure 1). Its extension to predict the trajectory of the smoke plume could be also envisaged with a great interest if the emission factors were sufficiently well known (which is far to be the case for the moment).

The second approach (II) has been developed by the fluid mechanics community. It includes much more details of the complex interaction between a wildfire and a vegetation cover, such as the drag effect induced on the turbulent atmospheric flow by the vegetation, the degradation (by drying, pyrolysis and combustion) of the vegetation, the turbulent combustion in the gaseous phase (the flame) and the consequences in terms of soot production and radiation heat transfer … Compared to the method (I), the gap in terms of complex physics is really huge and the computational effort necessary to describe all these phenomena at a correct length scale has also increased substantially! The great advantage with this second approach is that the dimensions (the flame geometry) and the behaviour of the fire front is directly predicted by the model itself (it is not prescribed empirically). With this approach, we can theoretically access to all modes of interaction between the fire and the atmosphere (including the wind) and more generally to the whole interactions between the fire and the external conditions (structure and state of the solid fuel, topography …) governing to the behaviour of the fire front (see Figure 2). However this enthusiasm must be moderated, because of the level of uncertainties characterizing the behaviour of nonlinear physical systems. And in practice this kind of models must be reserved to simulate wildfires at a local scale (<500 m) and the interactions with potential target such as vegetation, buildings … located ahead of the fire front. Despite these limitations, this approach has known a great interest, especially to study the behaviour of the fire at a local scale (Morvan 2013 and 2014, Mell et al 2009) for problems relative to fire safety engineering inside the Wildland Urban Interface (WUI) (Morvan 2015, Mell et al 2010).

In some manner, the approach proposed Linn in FIRETEC (Linn 1997, Linn et al 2005) can be considered as a mix between (I) and (II), i.e. as in method (I) the flame is not explicitly calculated, however as in (II) the heat release by the fire is calculated from an energy balance inside the vegetation layer. In fact, the degradation of the solid fuel and the combustion process were supposed to occur in the same computational cell, without any transport step in the gas phase. The fact that the low Mach number approximation, was not implemented in FIRETEC constituted also a great limitation for the mesh size (around 1 m due to CFL restriction), which potentially could limit the use of the model for relatively high vegetation layers (such as a forest

cover) (Linn et al 2005, Pimont et al 2009) to have more than one cell inside the vegetation layer, even if some applications has been proposed for fire propagating through grassland and shrubs (Linn et al 2012).
Because approach II has the objective in describing in detail the heat transfer by convection and radiation between the flame and the interaction in volume between the atmospheric flow and the vegetation stratum, this approach is subject to more severe constraints in term of mesh size compared to approach I. These constraints result from the physical length scales characterizing the physical mechanisms governing the ignition and the propagation of forest fires, such as the extinction length scale for the radiation heat transfer, the atmospheric boundary layer flow and its interaction with the vegetation stratum, the integral turbulence length scale … (Morvan 2011).
The capabilities of the two classes of wildfire models (I and II) are summarized in Table 1. This comparison has allowed to identify clearly what models resolve or not the gaseous combustion (the flame), which represents an essential feature to study the interaction and the propagation of a wildfire fire inside the wildland urban interface (WUI) (Mell et al 2010). Another important point concerns the possibilities offered by the method (I) of study problems at large scale such as the impact of wildfires at regional scale, for example the trajectory of smoke plume in the vicinity of an urban zone or near an airport.

Conclusions
This short review has allowed to identify the progress done in terms of wildfire modelling during the last 20 years, since the publication of the Grishin monograph. The analysis of the literature published on this subject, highlights two classes of models, for two domains of applications. From this bibliography analysis, it is clear that the study of this very complex problem cannot be solved with a single universal tool, the needs of engineering approach and basic researches, do not concern the same level of details in the description of physical mechanisms contributing to the behaviour of forest fires.

Acknowledgements
I would like to thank all people who have contributed to the illustration of this paper, especially JB Filippi from the CNRS and the University of Corsica and S. Méradji from the University of Toulon.

	3D Fuel/ABL	Flame	3D Fuel/Fire	Large scale potential
WFR-FIRE (I)	No	No	No	Yes
MesoNH-ForeFire (I)	No	No	No	Yes
FIRETEC (I/II)	Yes	No	Yes	No
WFDS (II)	Yes	Yes	Yes	No
FIRESTAR (II)	Yes	Yes	Yes	No
FIRELES (II)	Yes	Yes	Yes	No
ForestFireFOAM (II)	Yes	Yes	Yes	No

Table 1: Synthetic capabilities of various physical wildfire models.

References

A.M. Grishin and F. Albini (Editor) (1996) Mathematical Modelling of Forest Fires and New Methods of Fighting them. Tomsk State University, Tomsk.

Weber RO (1991) Modelling fire spread through fuel beds. *Progress in Energy and Combustion Science* **17**, 67-82.

Sullivan AL (2009) Wildland surface fire spread modelling 1990–2007: 1 physical and quasi-physical models. *International Journal of Wildland Fire*, **18(4)**, 349–368.

Sullivan AL (2009) Wildland surface fire spread modelling 1990–2007: 2 empirical and quasi-empirical models. *International Journal of Wildland Fire*, **18(4)**, 369–386.

Sullivan AL (2009) Wildland surface fire spread modelling 1990–2007: 3 simulation and mathematical analogue models. *International Journal of Wildland Fire*, **18(4)**, 387–403.

Rothermel RC (1972) A mathematical model for predicting fire spread in wildfire fuels. USDA Forest Service Research Paper INT-155, Intermountain Forest and Range Experiment Station, Ogden, UT.

Hanson PH, Bradley MM, Bossert JE, Linn RR, Younker LW (2000) The potential and promise of physics-based wildfire simulation. *Environmental Science & Policy*, **3**, 161-172.

Larini M, Giroud F, Porterie B, Loraud JC (1998) A multiphase formulation for fire propagation in heterogeneous combustible media. *International Journal of Heat and Mass Transfer,* **41(6-7)**, 881-897.

Morvan D, Méradji S, Mell W (2013) Interaction between head fire and backfire in grasslands. *Fire Safety Journal*, **58**, 195-203.

Mell W, Maranghides A, McDermott R, Manzello SL (2009) Numerical simulation and experiments of burning douglas fir trees. *Combustion and Flame*, **156**, 2023-2041.

Mell W, Jenkins MA, Gould J, Cheney Ph (2007) A physics-based approach to modelling grassland fires. *International Journal of Wildland Fire*, **16**, 1–22.

Mandel J, Bennethum LS, Beezley JD, Coen JL, Douglas CC, Kim M, Vodacek (2008) A wildland fire model with data assimilation. *Mathematics and Computers in Simulation*, **79(3)**, 584-606.

Coen JL (2005) Simulation of the Big Elk using coupled atmosphere-fire modelling. *International Journal of Wildland Fire*, **14**, 49–59.

Filippi JB, Bosseur F, Pialat X, Santoni PA, Strada S, Mari C (2011) Simulation of coupled fire/atmosphere interaction with the MesoNH-ForeFire models. *Journal of Combustion*, **2011**, Article ID 540390, 13 pages.

Balbi JH, Morandini F, Silvani X, Filippi JB, Rinieri F (2009) A physical model for wildland fires. *Combustion and Flame*, **156(2)**, 2217-2230.

Morvan D (2013) Numerical study of the effect of fuel moisture content (FMC) upon the propagation of a surface fire on a flat terrain, *Fire Safety Journal*, **58**, 121-131.

Morvan D (2014) Wind effects, unsteady behaviours and regimes of propagation of surface fires in open field. *Combustion Science and Technology*, **186(7)**, 869-888.

Morvan D (2015) Numerical study of the behaviour of a surface fire propagating through a fuel break built in a Mediterranean shrub layer. *Fire Safety Journal*, **71**, 34-48.

Mell WE, Manzello SL, Maranghides A, Butry D, Rehm RG (2010) The wildland-urban interface fire problem current approaches and research needs, *International Journal of Wildland Fire*, **19(2)**, 238-251.

Linn RR (1997) A transport model for prediction of wildfire behaviour, PhD thesis University of New Mexico, LANL.

Linn RR, Winterkamp J, Colman JJ, Edminster C, Bailey JD (2005) Modeling interactions between fire and atmosphere in discrete element fuel beds. *International Journal of Wildland Fire*, **14**, 37-48.

Pimont F, Dupuy JL, Linn RR, Dupont S (2009) Validation of FIRETEC wind-flow over a canopy and a fuel-break. . *International Journal of Wildland Fire*, **18**, 775-790.

Linn RR, Canfield JM, Cunningham P, Edminster C, Dupuy JL, Pimont F (2012) Using periodic line fires to gain a new perspective on multi-dimensional aspects of forward fire spread. *Agricultural and Forest Meteorology*, **157**, 60-76.

Morvan D (2011) Physical phenomena and length scales governing the behaviour of wildfires: a case for physical modelling. *Fire Technology*, **47**, 437-460.

Zhou X, Mahalingam S, Weise D (2007) Experimental study and large eddy simulation of effect of terrain slope on marginal burning in shrub fuel beds. Proceedings of the Combustion Institute, **31**, 2547–2555.

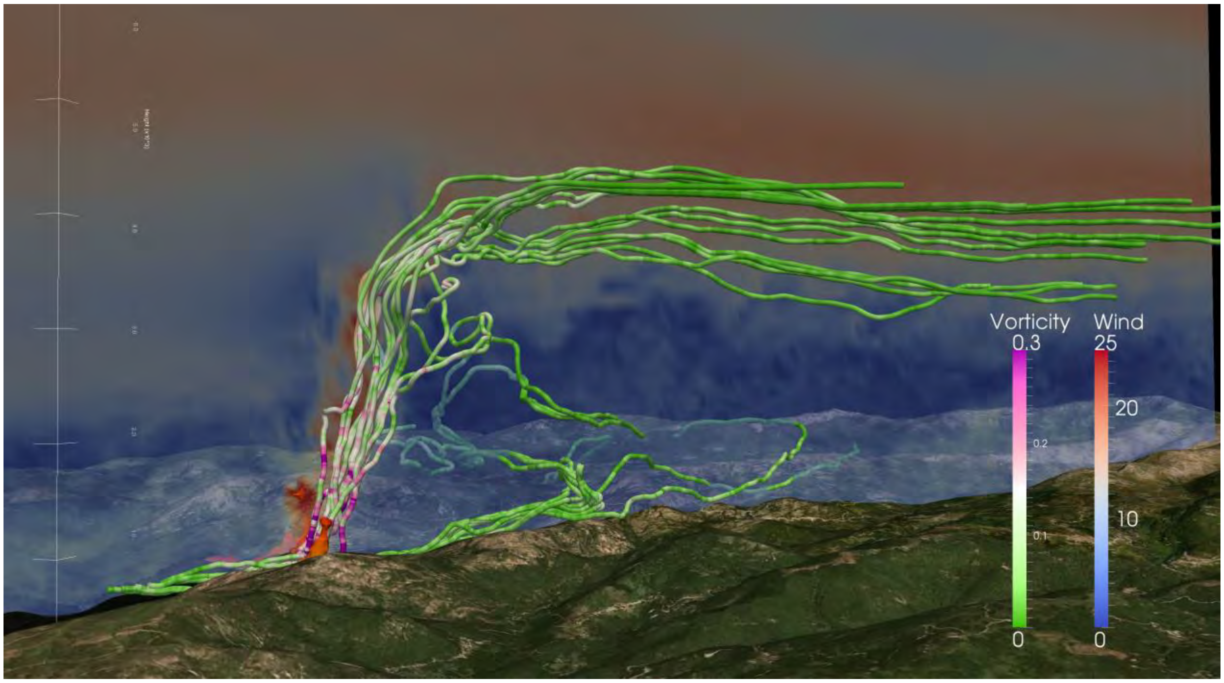

Figure 1: Large scale simulation of a thermal plume above a wildfire in Corsica using MesoNH-ForeFire (courtesy of JB Filippi et al, University of Corsica).

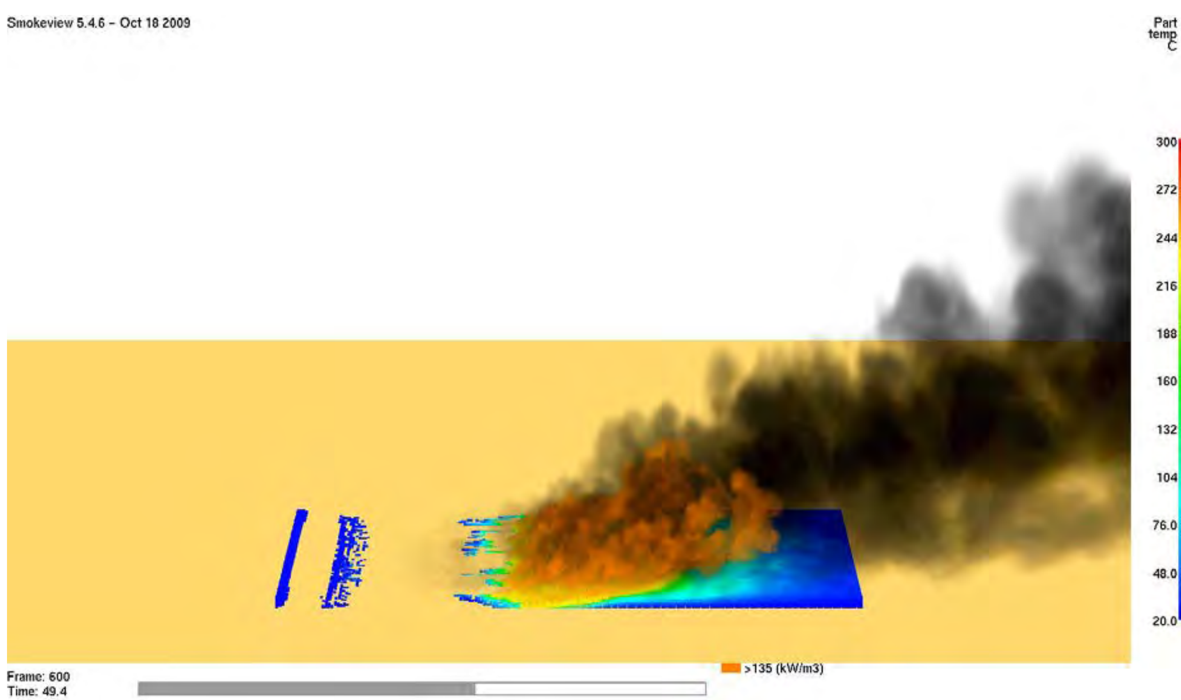

Figure 2: WFDS 3D simulation of a surface fire propagating through a grassland (Morvan et al 2013).

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Seasonal forecasting of fire weather based on a new global fire weather database

Andrew J. Dowdy*
Australian Bureau of Meteorology, Docklands, Victoria, Australia

Robert D. Field
Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA
NASA Goddard Institute for Space Studies, New York, NY, USA

Allan C. Spessa
Department Environment, Earth & Ecosystems, The Open University, Milton Keynes, UK
Department Atmospheric Chemistry, Max Planck Institute for Chemistry, Mainz, Germany

Introduction

Seasonal forecasting of fire weather is examined based on a recently produced global database of the Fire Weather Index (FWI) system beginning in 1980. Seasonal average values of the FWI are examined in relation to measures of the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The results are used to examine seasonal forecasts of fire weather conditions throughout the world.

Data and methods

FWI data are obtained from the Global Fire Weather Database (GFWED) as described by Field et al. [2015]. The data have a spatial resolution of 0.667 degrees in longitude and 0.5 degrees in latitude. Seasonal average values of the data for December, January and February (DJF), March, April and May (MAM), June, July and August (JJA) and September, October and November (SON) are examined here for the period from 1983 to 2014. The FWI data are based on wind speed, relative humidity and temperature (obtained from the NASA Modern Era Retrospective-Analysis for Research and Applications, MERRA [Rienecker et al. 2011]) together with precipitation from a gridded analyses of land-based rain gauge data (obtained from the Climate Prediction Center, CPC, of NOAA [Chen et al. 2008]).

The El Niño-Southern Oscillation (ENSO: as represented by the NINO3.4 index) and the Indian Ocean Dipole (IOD: as represented by the Dipole Mode Index, DMI) are examined based on sea-surface temperature (SST) data obtained from the CPC. Seasonal averages of these indices are used here for the DJF, MAM, JJA and SON seasons.

* Bureau of Meteorology, GPO Box 1289, Melbourne, VIC 3001, Australia. E-mail: A.Dowdy@bom.gov.au

Hindcasts (i.e., reforecasts) of NINO3.4 values were obtained from NOAA for the 1996-2010 period, based on forecasts of the tropical Pacific SSTs [Xue and Leetmaa, 2000]. Seasonal average values are used here for the DJF, MAM, JJA and SON seasons, with the hindcast values based on a three-month lead time prior to the start of a season (e.g., values for the DJF season are based on initial conditions for the preceding September).

The sample Pearson's correlation coefficient, r, is used to examine the dependence between datasets. The 95% confidence level is used to examine the significance of results, determined using a nonparametric bootstrap method based on 10 000 random permutations of the data, with two-sided confidence intervals based on percentiles.

Results

Large-scale drivers of fire weather variability

Figure 1 shows the relationship between ENSO and the FWI. The correlations are calculated individually for each grid point of the study region. Correlations are based on seasonal values throughout the 32-year study period (from 1983 to 2014) and are calculated individually for each season. Figure 2 is similar to Figure 1, but for the relationship between IOD and the FWI.

The correlations shown in Figures 1 and 2 indicate that for each of the four seasons, ENSO appears to have a stronger and more widespread influence than the IOD in general throughout the world. Additionally, the significant relationships that do occur between DMI and the FWI are broadly similar to the results for NINO3.4 in some cases (noting that ENSO and IOD are somewhat related [Allan et al. 2001]). Hence hereafter the focus is on the ENSO/FWI relationship.

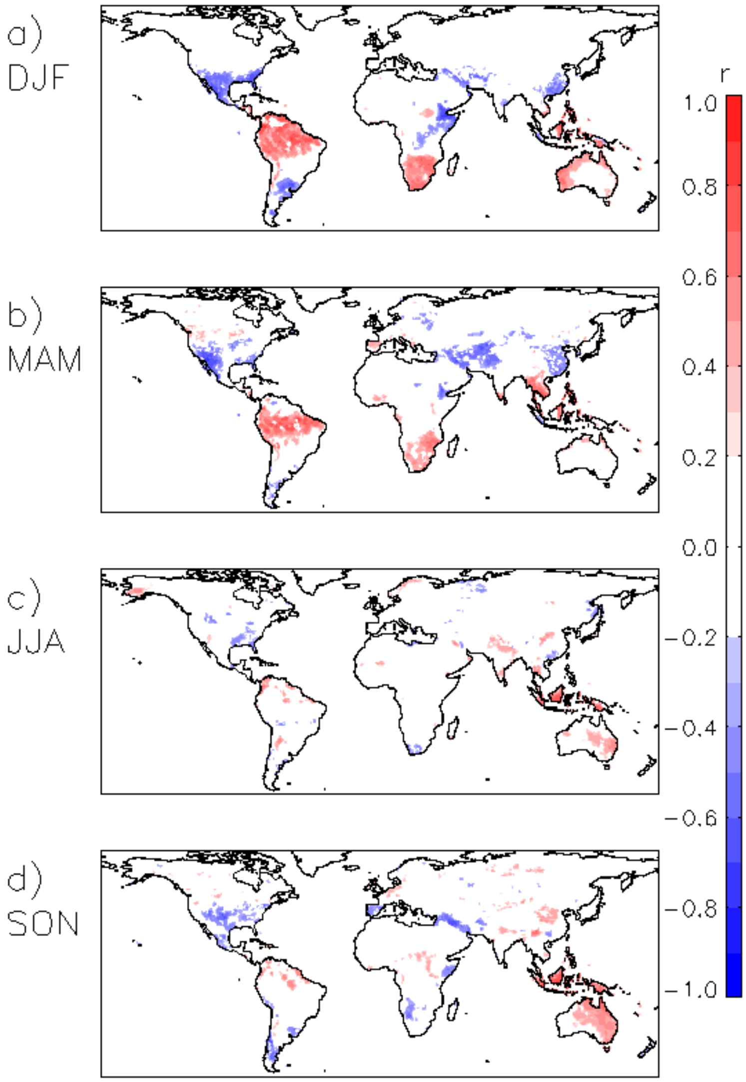

Figure 1: Correlations between seasonal mean values of FWI and NINO3.4 (as an indication of ENSO conditions) for the period from 1983 to 2014. The correlations are shown for locations where the relationship is significant at the 95% confidence level, calculated individually for each season: DJF (a), MAM (b), JJA (c) and SON (d).

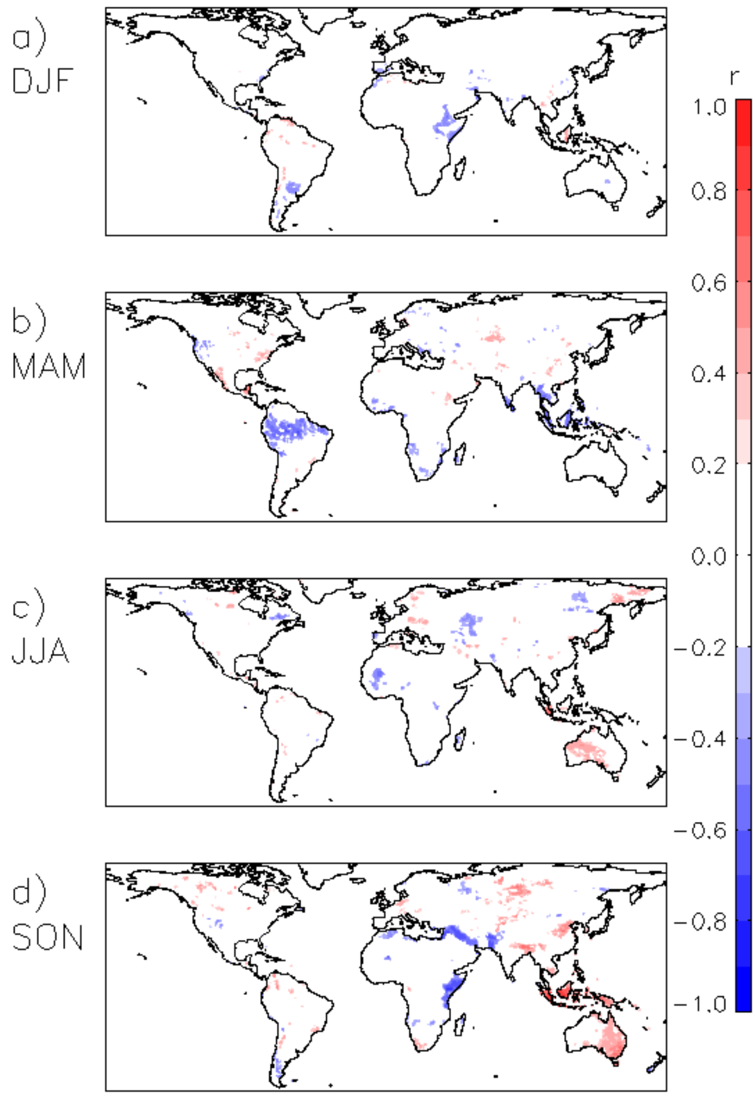

Figure 2: Correlations between seasonal mean values of FWI and DMI (as an indication of IOD conditions) for the period from 1983 to 2014. The correlations are shown for locations where the relationship is significant at the 95% confidence level, calculated individually for each season: DJF (a), MAM (b), JJA (c) and SON (d).

Predictability

Predictions of FWI values, as either higher or lower than their seasonal median value, are considered here based on whether the hindcast NINO3.4 values are higher or lower than their seasonal median value. For example, in cases where a positive correlation occurs (from Fig. 1) a high FWI value would be predicted if the hindcast NINO3.4 value is high, with the converse being the case for negative correlations.

Figure 3 shows the prediction accuracy, calculated as the number of correct predictions divided by the total number of predictions during the period 1996-2010. The accuracy is higher in general for DJF, MAM and SON than for JJA. The low accuracy during JJA is associated with a period of low hindcast skill for NINO3.4 in the months preceding the JJA season (i.e. March, April and May) and is an example of the challenges that remain in understanding ENSO variability and predictability. There are a number of cases where the accuracy of the predictions is relatively high (e.g., above 80%) throughout large geographic regions, such as in northern and eastern Australia for the SON season.

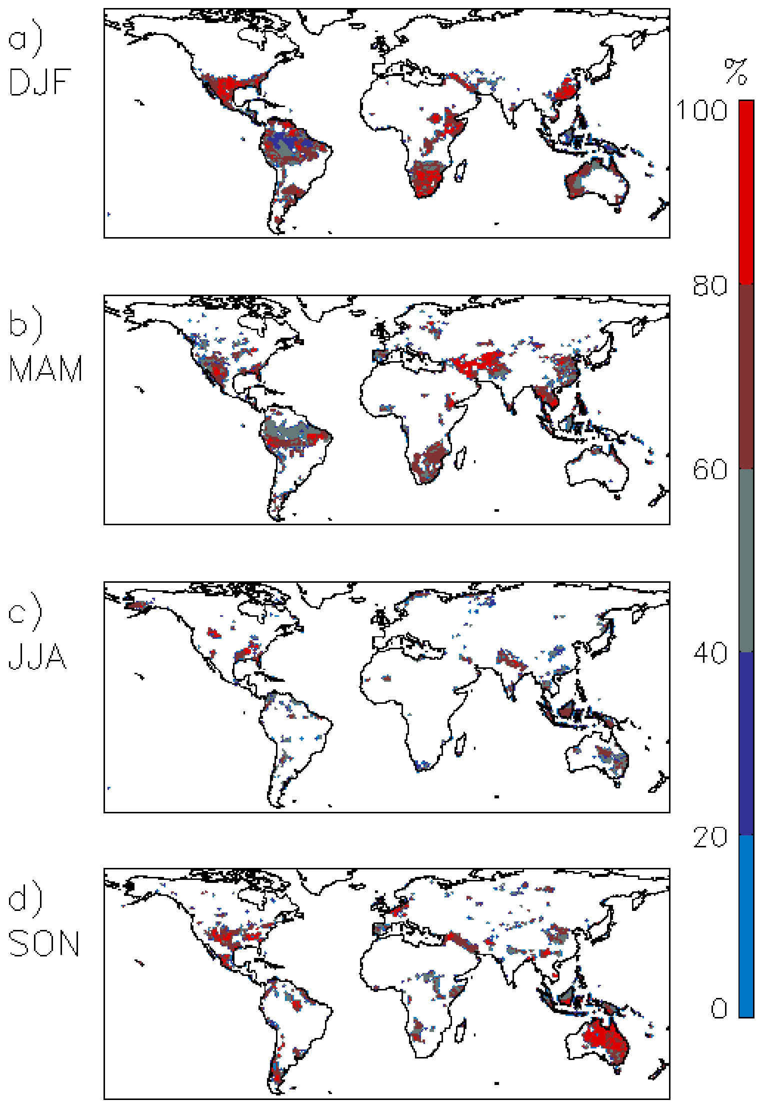

Figure 3: Seasonal prediction of global fire weather, with a lead time of 3 months. The accuracy of the forecast is shown here as the percentage number of predictions that are correct, based on predictions of FWI values as either above or below the seasonal median value, for the period from 1996 to 2010. This is shown for locations where a significant relationship exists between FWI and the NINO3.4 index (from Fig. 1).

Conclusions

A recently produced database of the Fire Weather Index (FWI) system was used to examine seasonal forecasting of fire weather conditions. ENSO was found to have a stronger and more widespread influence on fire weather conditions than IOD in general throughout the world. As ENSO can be predictable several months in advance in some cases, this relationship was used to examine seasonal predictions of fire weather conditions. The results indicate considerable accuracy in predicting the upcoming seasonal fire weather conditions for various seasons and regions throughout the world.

Acknowledgements

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References

- Allan RJ, Chambers D, Drosdowsky W, Hendon H, Latif M, Nicholls N, Smith I, Stone RC, Tourre Y (2001) Is there an Indian Ocean dipole and is it independent of the El Niño-Southern Oscillation? *CLIVAR Exchanges* **6**, 18-22, ISSN 1026–0471.

- Chen Y, Randerson JT, Morton DC, DeFries RS, Collatz GJ, Kasibhatla PS, Giglio L, Jin Y, Marlier ME (2011) Forecasting Fire Season Severity in South America Using Sea Surface Temperature Anomalies. *Science* **334**, 787–791, doi:10.1126/science.1209472.

- Field RD, Spessa AC, Aziz NA, Camia A, Cantin A, Carr R, de Groot WJ, Dowdy AJ, Flannigan MD, Manomaiphiboon K, Pappenberger F (2014) Development of a global fire weather database for 1980–2012. *Natural Hazards and Earth System Sciences* **2**, 6555-6597.

- Rienecker MM, et al. (2011) MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *J. Climate* **24**, 3624–3648, doi:10.1175/jcli-d-11-00015.1.

- Xue Y, Leetmaa A (2000) Forecasts of tropical Pacific SST and sea level using a Markov model. *Geophysical. Research Letters* **27**, 2701-2704.

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Sensitivity of Atypical Lateral Fire Spread on Lee Slopes to the Fire Environment and Fire-Atmosphere Coupling

Jason Sharples*
University of New South Wales, Canberra, Australia
Colin Simpson
University of New South Wales, Canberra, Australia
Jason P. Evans
University of New South Wales, Sydney, Australia

Introduction

Wildland fires have been observed to advance rapidly across steep lee-facing slopes, in a direction that is approximately perpendicular to the background wind. Although a theory explaining this atypical behaviour was first proposed several decades ago by Countryman (1971), it has received little attention in the fire science and fire management communities. After a number of atypical lateral fire spread events were observed to have a considerable impact in the 2003 Canberra bushfires, there has been renewed interest in this atypical lateral fire spread. More recent bushfires, such as the Wambelong Campground fire in January 2013 near Coonabarabran NSW, and subsequent inquiries have further highlighted the importance of the atypical lateral spread phenomena in the development of extreme fires.

Atypical lateral spread has been studied in the laboratory by Raposo et al. (2015), who found that the rate of lateral advance of the fire depended on the strength of the prevailing winds. Using a coupled fire-atmosphere model, Simpson et al. (2013) reproduced lateral fire spread that qualitatively matched that observed in wildfire cases and demonstrated that the effect was dependent upon wind speed. Furthermore, they demonstrated that such behaviour was a consequence of the three-way coupling between the wind, the terrain and the fire, and as such constituted an instance of dynamic propagation. Dynamic modes of fire propagation are currently beyond the scope of operational fire spread models, and so they present a serious issue when dealing the fire spread prediction. Moreover, atypical lateral spread has been characterised as a form of extreme fire behaviour.

In this paper we summarise the use coupled fire-atmosphere models to investigate the sensitivity of atypical lateral spread characteristics to the fire environment and to fire atmosphere coupling. In particular, we summarise the dependence of lateral spread on topographic slope and aspect, wind speed and atmospheric coupling with the fire.

Coupled fire-atmosphere modelling

Numerical simulations of lateral fire spread were performed using version 3.5 of the Advanced Research Weather and Forecasting (WRF) model (Skamarock et al., 2008), coupled the WRF-Fire wildland fire physics module (Coen et al., 2013). The WRF model is run in large eddy simulation (LES) configuration (Moeng et al., 2007) and can be used to model turbulent atmospheric flows as it explicitly resolves large-scale atmospheric eddies and applies a subfilter-

* *Corresponding Author:* j.sharples@adfa.edu.au

scale stress model to sub grid-scale motions. WRF utilizes fully compressible non-hydrostatic equations and a mass-balanced terrain-following coordinate system.

WRF-Fire uses a two-dimensional level set method implementation of Rothermel's semiempirical fire spread model (Rothermel, 1972):

$$R = R_0(1 + \phi_W + \phi_S),$$

where R is the rate of spread and R_0 is that in the absence of wind or slope. The slope and wind correction factors, ϕ_S and ϕ_W respectively, are calculated using the outward pointing normal components, relative to the fire region and mid-flame height winds at each point along the perimeter.

The coupling between the fire and the atmosphere is realised through the pyrogenic release of sensible and latent heat (determined by the fire spread module) into the bottom layer of the atmospheric model at each time step. The fire-modified, or pyrogenic, winds can subsequently affect the fire spread allowing for direct modelling of the two-way coupling between the fire and the atmosphere.

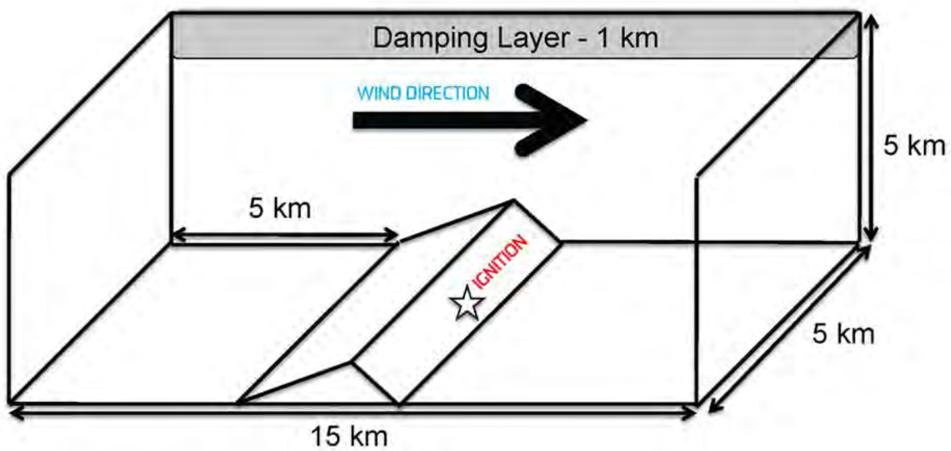

Figure 1. Coupled fire-atmosphere model domain showing the idealized triangular ridge and a leeward ignition point.

Figure 1 illustrates a typical model domain set-up with a leeward ignition of the fires. Windward ignitions were also considered. The ambient wind is given by:

$$U(z) = P_z(u_0\hat{\boldsymbol{x}} + v_0\hat{\boldsymbol{y}}),$$

with

$$P_z = \begin{cases} \left(\frac{z}{200}\right)^{\frac{1}{7}} & , z \leq 200 \\ 1 & , z > 200 \end{cases}$$

where u_0 and v_0 are the horizontal wind components along the x (west to east) and y (south to north) axes, respectively. The reference wind speed U_0 and the wind direction δ relative to the terrain aspect are given by

$$U_0 = \sqrt{{u_0}^2 + {v_0}^2}$$

and

$$\delta = \tan^{-1}\left(\frac{v_0}{u_0}\right)$$

such that $\delta = 0$denotes a background wind direction perpendicular to the ridge.

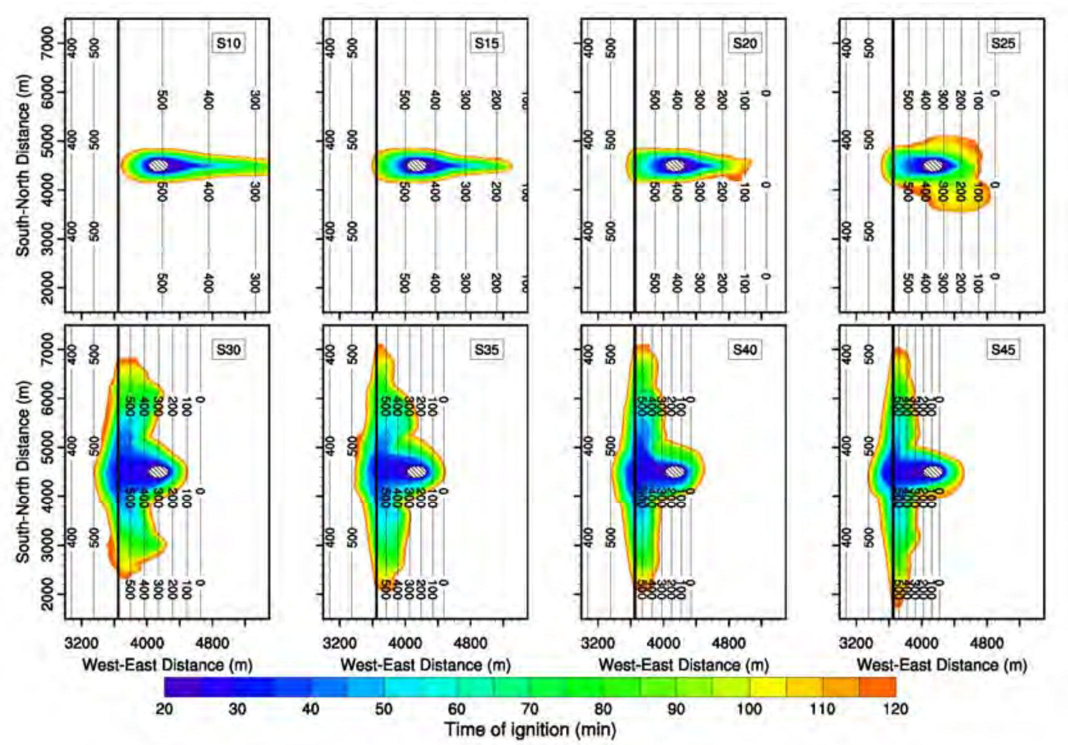

Figure 2. Results of the coupled fire-atmosphere simulations examining the sensitivity of the lateral spread to topographic slope. The slope angle is identified in each panel; for example, 'S20' indicates a leeward slope angle of 20°. The colour shading indicates time since ignition. Wind speed and direction are constant across each panel.

Results

Figures 2 and 3 present some of the results obtained in the sensitivity studies. The sensitivity of the modelled lateral spread to topographic slope can be seen in Figure 2, which shows that no lateral spread occurs when the leeward slope is less than 25°. For the cases above 25° the fire propagation exhibits a significant lateral spread component. The slope threshold of about 25° indicated in these simulation results are broadly consistent with that determined by Sharples et al. (2012) using observations of the Canberra wildfires.

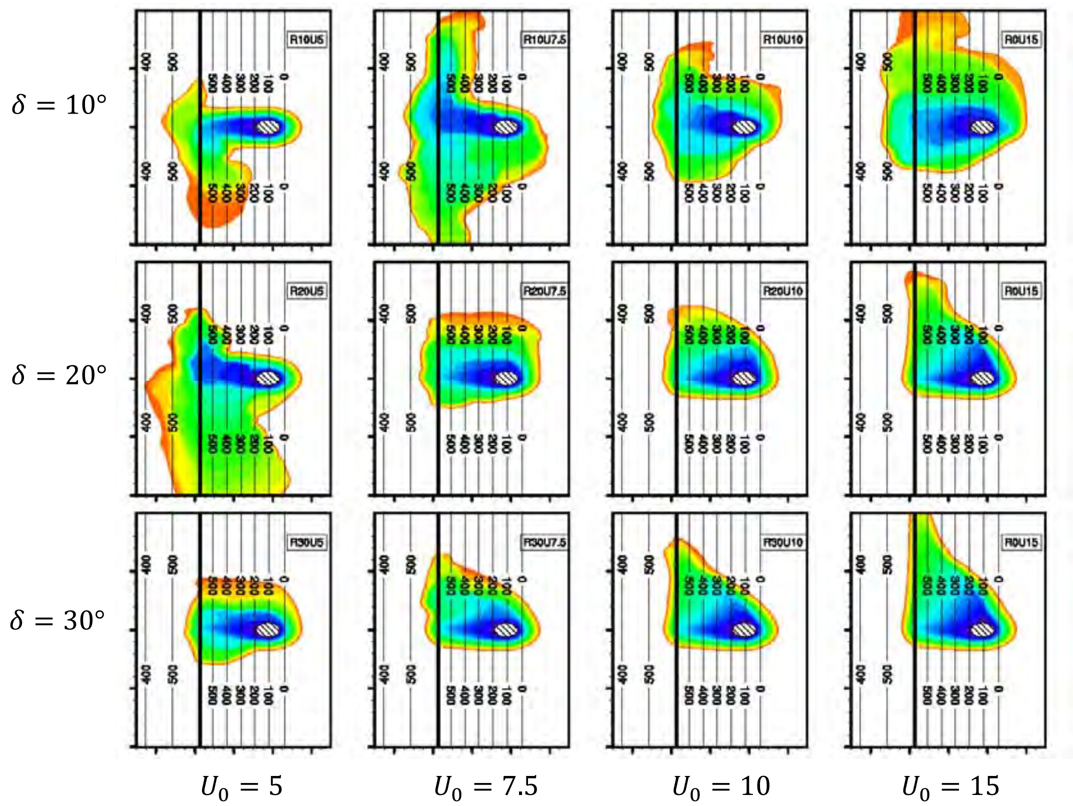

Figure 3. Results of the coupled fire-atmosphere simulations examining the combined sensitivity of the lateral spread to wind speed (m s^{-1}) and topographic aspect relative to wind direction. The slope angle is held constant in each panel. The colour shading is the same as it was in Figure 2.

Figure 3 shows the combined sensitivity of the lateral spread to wind speed and wind direction. For $U_0 = 2.5$ m s^{-1} (results not shown) there is no lateral fire spread regardless of the value of δ. Similarly, no lateral fire spread was observed for δ =0° and U_0 = 5 and 7.5 m s^{-1}, indicating no significant coupling between the fire and the atmosphere. The simulation results also indicated little to no pyrogenic vorticity was generated in these cases. By contrast, in all other cases fire-atmosphere coupling leads to dynamically driven lateral fire spread. However, the characteristics of the leeward pyrogenic vorticity vary markedly with U_0 and δ. For more details the reader is referred to Simpson et al. (2016).

Conclusions

Based on these sensitivity studies and earlier descriptions of the lateral spread phenomenon, we conclude that the atypical lateral fire spread is predominantly driven by pyrogenic vorticity, which can manifest as rotating columns of air above the fire that can drive intermittent and rapid fire spread laterally across a lee slope. Although these simulations are highly idealised, they provide useful insights into the dynamic and potentially dangerous nature of fire spread that can occur in complex terrain.

Acknowledgments

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References

Coen, J., Cameron, M., Michalakes, J., Patton, E., Riggan, P., and Yedinak, K. (2013) WRF-Fire: Coupled weather-wildland fire modelling with the Weather Research and Forecasting model. *Journal of Applied Meteorology and Climatology*, 52: 16–38.

Countryman, C.M. (1971) *Fire whirls… why, when and where*. General Technical Report, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.

Moeng, C., Dudhia, J., Klemp, J., and Sullivan, P. (2007) Examining two-way grid nesting for large eddy simulation of the PBL using the WRF model. *Monthly Weather Review*, 135: 2295–2311.

Raposo, J. R., Cabiddu, S., Viegas, D. X., Salis, M. and Sharples, J.J. (2015) Experimental analysis of fire spread across a two-dimensional ridge under wind conditions. *International Journal of Wildland Fire*, 24: 1008-1022.

Rothermel, R. (1972) *A mathematical model for predicting fire spread in wildland fuels*. Report, Intermountain Forest and Range Experiment Station, Research Paper INT-115, Forest Service, US Department of Agriculture, USDA Forest Service, Ogden.

Sharples, J., McRae, R., and Wilkes, S. (2012) Wind-terrain effects on the propagation of large wildfires in rugged terrain: fire channelling. *International Journal of Wildland Fire*, 21: 599–614.

Simpson, C.C., Sharples, J.J., Evans, J.P. and McCabe, M.F. (2013) Large eddy simulation of atypical wildland fire spread on leeward slopes. *International Journal of Wildland Fire*, 22: 282-296.

Simpson, C.C., Sharples, J.J., and Evans, J.P. (2016) Sensitivity of atypical lateral fire spread to wind and slope. *Geophysical Research Letters*. doi: 10.1002/2015GL067343.

Skamarock, W., Klemp, J., Dudhia, J., Gill, D., Barker, D., Duda, M., Huang, X.-Y., Wang, W., and Powers, J. (2008) *A description of the Advanced Research WRF Version 3*, Report, NCAR.

Sharing Responsibility: Who is Ready for a More Meaningful Partnership?

Delene Weber*

Natural and Built Environments Research Centre, University of South Australia, South Australia, Australia, delene.weber@unisa.edu.au

Emily Moskwa

Natural and Built Environments Research Centre, University of South Australia, South Australia, Australia, emily.moskwa@unisa.edu.au

Douglas K Bardsley

School of Geography, Environment and Population, University of Adelaide, South Australia, Australia, douglas.bardsley@adelaide.edu.au

Guy M Robinson

School of Geography, Environment and Population, University of Adelaide, South Australia, Australia, guy.robinson@adelaide.edu.au

Introduction

Juxtaposed against the unpredictable nature of fires is the almost predictable nature of people: under-prepared, optimistic and emotionally attached to their land. As more and more people move into peri-urban spaces, a series of risks increases. Ironically, the biodiversity in the forested areas that attracts many people is often threatened by the development of these spaces, and in turn the vegetation can expose residents to greater risk. There is a need to modify the "cycle of predictability" where people have good intentions but haven't utilised or prioritised available time to clear gutters, mow lawns, or make investments likely to improve the safety of themselves and their communities (Demarque et al., 2013). Our study revealed only 4.8% of people considered themselves well prepared for the current fire season. This paper explores what could be improved to share responsibility and create fire-smart peri-urban communities that are pro-active in protecting biodiversity and preventing bushfires.

Background

This paper reports part of a larger study funded primarily by the Australian Research Council (project LP130100406) examining bushfires and biodiversity, and specifically strategies to optimise conservation outcomes in peri-urban areas. The project explored perceptions of vegetation management regimes in peri-urban areas facing high bushfire risk in the Adelaide and Mount Lofty Ranges and the Eyre Peninsula. It addressed a "wicked problem" related to the increasing number of people living in peri-urban areas: namely the need for protection and conservation of large tracts of vegetation in these areas, which often contain important and unique biodiversity; and the increased fire risk associated with this scenario, which is exacerbated by climate change.

Catastrophic fires in peri-urban regions of Australia are reframing perceptions of what constitutes effective vegetation management (Bardsley et al., 2015). The Country Fire Service (CFS) warns that South Australia can expect serious bushfires in six or seven out of every ten years. South Australia experiences hot and dry summers with mild winters and moderate rainfall. The state recorded lower than historical average rainfall from 2012 to 2015 with Bureau of Meteorology data showing that the number of days exceeding 40°C has increased annually from 2011. Communities living in the Adelaide and Mount Lofty Ranges and Eyre Peninsula have experienced destructive bushfires causing loss of life and extensive property damage. At the time of commencing the study in January 2014, the recent fire history of the two areas was quite distinct. In 1983, over 160,000ha of the Adelaide and Mount Lofty Ranges were burnt and 28 fatalities were recorded. The Lower Eyre Peninsula has experienced more recent fires, notably in 2005 where bushfires burnt over 77,000ha and resulted in nine fatalities (CFS 2012). Part way through the study, in January 2015, the Sampson Flat fires burnt more than 20,000 hectares and destroyed 27 houses. With such major risks to place, property and people, the management of vegetation for bushfire risk mitigation is highly contentious, and improved partnerships to share the responsibility of bushfire and biodiversity management are needed (Bowman et al., 2013).

The increasing vulnerability of human settlements to dangerous bushfires in South Australia, as with much of the Mediterranean biome, reflects various factors, including:

- Urban spaces and individual dwellings are becoming increasingly embedded in fire-risk areas;
- Suburban areas are becoming more wooded, and often planted with more flammable species;
- Extended droughts have increased the flammability of forests, woodlands, heathlands and grasslands within or adjacent to urban centres; and,
- Climate change is associated with more extreme weather events resulting in higher average summer temperatures that extend fire-risk periods, and large high pressure systems leading to more extremely hot wind events (Bardsley & Rogers 2011; Pyne, 2009; Sherrah, 2009).

Study and Method

The project was conducted by the Universities of South Australia and Adelaide in partnership with the South Australian Department of Environment, Water and Natural Resources (DEWNR) and two regional Natural Resource Management (NRM) Boards (the Adelaide and Mount Lofty Ranges and Eyre Peninsula). The South Australian CFS was represented on our Steering Committee, and we also worked closely with six local government authorities within our study sites of the Adelaide and Mount Lofty Ranges and Lower Eyre Peninsula.

In November-December 2014 we conducted a postal survey of 3000 households, receiving 988 responses (c30%). Apart from general demographic and locational questions, respondents were asked about their perceptions of value and risk in relation to local vegetation; their past or likely future actions in response to risk and biodiversity values; where they gain information about fire and biodiversity management issues; and, what they would consider appropriate policy goals around management of native vegetation. They were also asked a series of questions about climate change, place attachment and trust in the CFS and DEWNR.

In addition to the large resident survey, we conducted 25 interviews with local government representative and residents, as well as 10 focus groups with CFS and DEWNR employees and local residents. This paper is based on the results of data collected from the focus groups, interviews and surveys and was motivated by a question from a DEWNR fire manager asking if a group of people exist who are ready for a more sophisticated level of information regarding fire behaviour. Qualitative data were analysed for content using Nvivo while quantitative data were analysed using SPSS. The multivariate data reduction technique of factor analysis was applied as a means of summarizing variation in responses to 7-point Likert scale questions. Factor analysis was performed using principal components with a varimax rotation (Robinson, 1998) and included the following items.

- Motivations for residing in an area (14 questions)
- Emotional place attachment (4 questions)
- Place dependence (4 questions)
- Development preferences (4 questions)
- Preferences for vegetation management (23 questions)
- Trust in CFS (13 questions)
- Trust in DEWNR (13 questions)
- Knowledge of biodiversity (1 question)
- Knowledge of bushfire management (1 question)

Results – Public Perspectives

The results of the factor analysis revealed six factors that explain 65.84% of variance amongst the input variables. These factors are described below.

Land Management Advocacy

This factor accounted for 19.9% of variance and loaded on statements such as trust in the agencies, particularly in relation to the training of CFS and DEWNR (0.71 and 0.74), place attachment (0.63) and support for prescribed burning (0.62).

Anti-management

This factor accounted for 15.7% and loaded on items such as low knowledge of bushfire management (0.62), low acceptance of prescribed burning (0.71), low acceptance of vegetation clearance (0.70), low acceptance of biodiversity taking precedence over bushfire risk mitigation (0.74) and high acceptance that current attention to bushfire risk is excessive (0.57).

Relax and Escape

Accounting for 8.8% of variability, this factor loaded on relaxed lifestyle (0.74) and escape from urban life (0.78). It also loaded negatively on the item "residents should be restricted to plant only Australian plants" (-0.76)

Place Dependence

This factor accounted for 8.0% of variation. It loaded on all place dependent items (>0.7) plus one place identity item (0.65) and on the statement "I would prefer to see more of the location protected from development" (0.68).

Detached

This factor loaded on the statement "I would prefer this area to be less forested" and negatively loaded on the emotional place attachment statements. It accounted for 7.3% of variance.

Work and Family oriented

This factor accounted for 6.1% of variation and loaded on "good environment to bring up children", "I live here for work reasons" and also "vegetation should focus on removing non-native species".

These factors go some way in explaining the different types of issues that communication specialists need to address. To further understand these groups, relationships between the factors and variables of interest were explored using analysis of variance (ANOVA).

While the survey data suggest six main factors explain around two-thirds of the variance, a series of focus groups and interviews revealed two additional groups that may warrant further attention.

The Vulnerable

The first of these additional groups we have labelled as, "The Vulnerable". They include elderly people no longer able to maintain their property in a fire safe manner; children; women who feel they have insufficient physical strength to carry out fire duties or who have not recognised that "leaving with the children" is not always an option; and new immigrants who are isolated socially and not aware of the fire danger (Whittaker et al., 2012).

Busy Urbanites

The second group we have labelled as "Busy Urbanites". They are people who have often recently moved to the peri-urban areas, and who may not have recognised the inherent risks in such areas. While some people may term group as apathetic or in denial, the consensus seemed that they were generally people who maintained a busy urban lifestyle in a peri-urban area and simply hadn't given the topic of fire risk sufficient attention.

This information has provided us with valuable insights in terms of differences within the public which could help to build more tailored and successful strategies related to both fire management and biodiversity conservation. However, it was clear from the focus groups that improved partnerships among agencies could also improve outcomes.

Results - Agency Perspectives

The two key fire management organisations within South Australia are the Department of Environment, Water and Natural Resources (DEWNR), and the Country Fire Service (CFS). Focus groups with both organisations suggested deep respect for the work of one another. It was clear however, that there had been limited formal meetings between the groups despite clear synergies and benefits of such an arrangement. Similarly, there seemed room for improvement within both organisations in terms of communications among various sections of the organisation. For example, community education officers really had their "finger on the pulse" of the level of public knowledge and concern on a wide variety of fire-related issues and appeared well positioned to take a much more pro-active role in setting agendas.

The public trust in each of these organisations was high (averaging 5.82 for the CFS and 4.75 for DEWNR on a 7-point scale where 1=strongly disagree and 7=strongly agree, n=620). It is not surprising that the value was higher for the CFS given 14.2% of respondents were members of the CFS and it is likely through social networking that a large number of our sample had direct experiences with members of the CFS. It should also be noted that

DEWNR staff comprise the largest CFS crew in the state and attend fires in CFS rather than DEWNR uniforms, so it is likely that the public have limited knowledge of the full role and expertise of DEWNR in fire management. Ironically, this high level of trust may be related to the lack of fire preparation reported by many respondents.

Local councils were perceived as being the most effective entity for making decisions about reducing bushfire risk by 50.3% of the sample population (n=976). Interestingly some councils, notably Onkaparinga council, were mentioned specifically by many members of the public and various different organisations, suggesting the model used in that council was particularly effective. Further investigation revealed this particular council places high emphasis on consultation and building relationships with various organisations and fire officers appeared to have higher visibility within the community. It also appeared to be resourced more appropriately with full-time staff dealing with fire management throughout the year. Of interest, several council staff working in fire management expressed awe in a training session conducted for them by DEWNR fire experts and reflected that they learned a great amount in a short time period. Given the apparent faith the public puts in councils, it would seem prudent to use DEWNR staff to improve the capacity of this group.

Several other organisations, such as SA Water and the Department of Planning, Transport and Infrastructure (DPTI), are involved in fire and yet it seemed partnerships with CFS and DEWNR were less than optimal. Specifically, opportunities existed for improvement in weed management after burning conducted by SA Water that could be addressed by a stronger partnership with DEWNR. During a number of focus groups, the role of planning legislation managed by DPTI was discussed, with frequent suggestions relating to a need for improved collaboration between DPTI and DEWNR when approving developments adjacent to protected areas and a general need for greater knowledge about fire among urban planners.

Implications and Recommendations

Four key recommendations are suggested:

(1) *Acknowledge different market groups within the general public*

The data suggest that communication strategies tailored to specific groups is possible and may be more likely to succeed. Of particular interest is the land management advocate group, who may be good candidates for more sophisticated fire information. Other groups, such as the "vulnerable" may be well suited to a community-funded project that provides assistance in risk mitigation – for example use of partnering with Rotary volunteers or scouts to audit and improve properties before the fire season.

(2) Leverage the CFS Credibility

The credibility of the source of information is acknowledged as a critical first step in any persuasive communication model. The extremely high level of trust in the CFS suggests people may be more likely to engage with public communication coming from this source. We recommend this is an area where organisations such as DEWNR and local councils could benefit from co-badging of materials. This could be very important in terms of biodiversity conservation as using the CFS brand to leverage DEWNR expertise in weed control and fuel management in general, could help to move the public into a more sophisticated understanding of fire behaviour.

(3) Resource organisations so they can optimise outcomes

Acknowledge the expertise of DEWNR in terms of fuel management and biodiversity conservation and resource the agency appropriately. There is great unmet potential in terms of weed management, in particular directly after a controlled burn and this is not being optimised.

The public who participate in CFS-organised community groups are more confident and prepared. There is a great opportunity through these groups to increase the level of knowledge of fire behaviour and build the cohort of well-informed citizens capable of extending important messages via social networks.

(4) Use expertise effectively
Capitalising on existing expertise could improve fire management and biodiversity protection. For example, CFS partnering with universities to train planners in fire management could build capacity within policy makers and regulators. DEWNR staff training council fire officers who are seen to be most influential could expand overall knowledge and capacity in fire management and its interaction with biodiversity.

In conclusion, many people within the public want to be more engaged in fire management. While some want to a process to complain about neighbours, and others want to display some award for being "fire smart", almost all shared a concern for their vulnerability to a fire and this unites them and provides an excellent opportunity to build future partnerships focused on shared responsibility (see Brady and Webb, 2013; McLennan and Eburn, 2015).

References

Bardsley DK. & Rogers G. (2011). Prioritizing engagement for sustainable adaptation to climate change: an example from natural resource management in South Australia. *Society and Natural Resources* 24: 1-17.

Bardsley DK., Weber D., Robinson GM., Moskwa E. & Bardsley A.M. (2015) Wildfire risk, biodiversity and peri-urban planning in the Mt Lofty Ranges, South Australia. *Applied Geography*, 63: 155-165.

Bowman DM., O'Brien JA & Goldammer JG (2013) Pyrogeography and the global quest for sustainable fire management. *Annual Review of Environment and Resources*, *38*(1): 57-80.

Brady D & Webb N (2013) Communicating bushfire safety in Australia: the challenge for government of increasing community participation. *Asia Pacific Media Educator, 23*(2): 351-365.

Country Fire Service (CFS) (2012) http://www.cfs.sa.gov.au/site/home.jsp

Demarque C, Apostolidis T & Joule RV (2013) Consideration of future consequences and pro-environmental decision making in the context of persuasion and binding commitment. *Journal of Environmental Psychology*, 36: 214-220.

McLennan BJ & Eburn M (2015) Exposing hidden-value trade-offs: sharing wildfire management responsibility between government and citizens. *International Journal of Wildland Fire*, 24(2): 162-9.

Pyne SJ (2009. The human geography of fire: a research agenda. *Progress in Human Geography* 33: 443-446.

Robinson GM (1998) *Methods and techniques in human geography*. John Wildey & Sons, Chichester and New York.

Sherrah M (2009) A fresh approach to development assessment in bushfire protection areas. *The Australian Journal of Emergency Management* 24: 11-16.

Whittaker J., Handmer, J & Mercer D (2012) Vulnerability to bushfires in rural Australia: A case study from East Gippsland, Victoria. *Journal of Rural Studies*, 28(2): 161-173.

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Simulation Analysis-based Risk Evaluation (SABRE) Fire. Operational Stochastic Fire Spread Decision Support Capability in the Queensland Fire and Emergency Services

Ben Twomey MSc. (OR & Stats)*, Inspector Andrew Sturgess
Queensland Fire and Emergency Services (QFES), Kedron, Queensland, Australia,
*ben.twomey@qfes.qld.gov.au andrew.sturgess@qfes.qld.gov.au

Introduction

The Fire Impact and Risk Evaluation Decision Support Tool (FIRE-DST) was a "proof-of-concept" system created by Geoscience Australia under a Bushfire Cooperative Centre (CRC) project during 2011-2012. It brought together the Australian Bureau of Meteorology's new "high resolution" ACCESS (Australian Community Climate and Earth-System Simulator) weather prediction system, the Phoenix RapidFire (referred to as Phoenix) model, Commonwealth Scientific and Industrial Research Organisation (CSIRO) building vulnerability assessment model, infrastructure and demographic databases provided by Geoscience Australia and CSIRO's smoke dispersion model. (French, Cechet, Yang, & Sanabria, 2014).

The broader FIRE-DST concept was generally well received by fire and emergency management agencies. The FIRE-DST was able to, but specifically avoided defining and sampling the full probability distributions of the various inputs to Phoenix (French, Cechet, Yang, & Sanabria, 2014) during its Kilmore fire validation project. It instead used a basic sensitivity analysis approach, at low resolution for key inputs to the Phoenix simulator. Despite this, it did show how even a basic sensitivity analysis approach can produce a valuable, probabilistic fire spread prediction. It also provided examples of associated visual decision support products. The overall FIRE-DST concept was effectively considered 'proven', but there was no follow-on project or effort to 'operationalize' the capability, and what was created was not available or suitable for adoption by fire agencies for operational use or further development.

In this presentation we introduce the Queensland Fire and Emergency Services (QFES) approach to leveraging simulation-based outputs for operational decision making incorporating lessons learned from the FIRE-DST. QFES is creating an *all hazards*, operational decision support system known as Simulation Analysis-based Risk Evaluation (SABRE). The first operational capability within SABRE is known as SABRE Fire, and it has been undergoing prototyping and operational evaluation on live bushfire incidents since October 2015. While sharing some similar, high level goals with the FIRE-DST, SABREs conceptual architecture and aims differ significantly. SABRE aims to permit open and easy definition and management of uncertainties in input data for any suitable hazard simulation. Like the FIRE-DST, it employs Monte Carlo sampling to generate many trials of a deterministic simulation (Phoenix) with inputs randomly drawn from definable probability densities vice single, best estimate forecast values. It then translates the multiple outputs into intuitive and interactive decision support tools based on risk while ensuring this is done consistently, robustly and within useful operational timelines.

On prediction errors

In the context of operational simulation-based predictions, the quality of prediction products is directly proportional to two main things:

1. Model errors – For the purposes of this presentation, model errors encompass the validity and level of fidelity of the simulator, its internal models, methods and how the model/simulator is used.
2. Input data errors - For the purposes of this presentation, input data errors describe the difference between stated input (forecast) data and the real world data that actually occurred in the phenomenon being modelled.

Both of the error types above can be thought of as comprising a total error signal in final prediction products. The final proportions of the total error signal due to both types of error is not fixed or known with certainty. Anecdotally in QFES' experience, the input data error component probably comprises greater than 50% or 60% of the total prediction error signal under most conditions, on average.

Model errors
QFES has had little to no ability to directly control model errors through changes to the models and simulation tools themselves. Developers of fire spread simulators usually publish their general methods and validation efforts in peer reviewed journals, and are usually engaged in constant refinement to reduce their levels of model error. QFES mainly attempts to manage model errors procedurally through actions like adopting new versions, and only using particular simulators under conditions where they have been shown to be fit for purpose and sufficiently valid in the past.

Input data errors
Within QFES, the management of input data is seen as more directly controllable. Significant improvements have been made in accessing gridded weather forecast data, and the use of air operations has improved the fidelity of starting / current state fire locations and timing on some fires. QFES weather forecasters from the Bureau of Meteorology (BOM) review, advise on and directly modify the gridded weather data, and can assign confidence levels to the weather data as part of the prediction process. QFES is always striving for methods that improve input data collection and accuracy. Despite constant improvement efforts though, QFES acknowledges that none of these can consistently provide a suite of perfectly accurate input data in all circumstances.

Consequences of errors
Estimates and forecasts of inputs are usually single point values that fall within an uncertainty range that will usually contain the true, real world value. Prior to August 2015, QFES operational fire spread predictions used *best estimate* data to create a single *best estimate* fire spread map (manual or simulation-based) that was then used to support decision makers as part of a larger fire behaviour report. This has been viewed in QFES as an excellent and valuable step relative to not employing structured simulation-based predictions at all, but it shifted the primary question about process improvement. The question then became if the decision maker only gets the *best estimate* map, how do they know how inaccurate the prediction map might be if the original input data estimates were inaccurate, and how should they manage the fire, and community warnings to properly account for that uncertainty? There is a high likelihood that best estimate products will be somewhat inaccurate, but will be *reified* (to make something concrete or real) by the decision maker. Thus the potential impacts of uncertainty on fire spread are at risk of effectively being eliminated from that part of the decision making process using these products.

What does input data uncertainty look like?

To better account for how inaccurate a prediction might be, and to more meaningfully carry this through to the decision maker, the input data needs to move from single best estimates to probability densities describing the uncertainty ranges around them. One significant problem is that the shape of these distributions is largely unknown, and in some circumstances is possibly unknowable with precision. So the basic options for a path forward in light of this come down to:

1. Continuing to avoid characterising the input errors at all, and persisting with single best estimate approaches. This effectively treats uncertainties as zero, even though it is known that they must always be greater than zero, sometimes significantly greater. It effectively continues to outsource interpreting uncertainty impacts to the decision maker, ostensibly without them realising it.

2. FBANs estimate the input error ranges around the best estimates as probability densities based on professional judgement, and where possible on published, peer reviewed data. Then, carry these through to decision products in a way that enables decision makers to intuitively weigh their decisions based on estimated risk.

The creators of SABRE are not claiming to know the 'true' input data probability densities with accuracy and precision. Instead, they have adopted the view that not dealing with input data uncertainties *at all* is more dangerous and less defensible than estimating their shape and magnitudes and carrying these through to quantify their likelihoods and impacts on fire spread prediction products. Given SABRE Fire creates its uncertainty ranges around the best estimates anyway, the best estimate is still going to show up as being greater than about 50% likely in SABRE Fire products. SABRE Fire does not seek to change the best estimate or improve it, but rather it puts *weighted error bars* around it. In the process of doing this, it is contended that a much more useful information set can be made available at the point of decision, and in planning. The ultimate test is how much more useful the products are considered to be by decision makers.

SABRE provides a capability that enables easy and rapid implementation of research findings associated with defining these uncertainty distributions and seamlessly incorporating them into the FBAN process. In the absence of definitive research, QFES' approach is a mix of estimation based on professional judgement and using published uncertainty range data for curing, drought factor and some fuel loads. SABRE is also planning to create a historical data archive enabling ongoing comparisons of forecast inputs to observed values so these uncertainty ranges can be quantified through ongoing empirical analysis.

SABRE Fire

Uncertainty range estimation

In SABRE Fire, defining input probability densities begins by assuming that the best estimate data as the most likely value to be observed in the real world. Most data inputs to fire spread simulators are averages either across a defined area (such as slope and fuel loads) or across time (such as average wind speed and direction). Being forecast average values, SABRE Fire assumes these can be described using normal distributions, with the best estimate value as their mean. Their standard deviation for each level of certainty is usually described as a percentage of the mean, and SABRE Fire has six certainty levels assignable: certain, very high, high, moderate, low and very low.

SABRE Fire randomised inputs

SABRE Fire currently randomises the following input data to Phoenix and assumes each defined value is independent of the others in its time series. The user can switch on or off any of these as deemed necessary. Every input data type enables the user to easily reconfigure the type and magnitude of the distributions for each certainty level:

1. Wind speed. Certainty levels defined as a function of original wind speed. This allows the user to describe certainty levels for low wind speeds being different from higher wind speeds in as much granularity as desired.
2. Local wind direction. Each time stepped wind direction is randomised independently, again with certainty levels defined as a function of the above wind speed. Wind direction becomes less certain at lower speeds, and SABRE enables this to be accounted for in as much granularity as desired.
3. Prevailing wind direction. Every individual time stepped wind direction is altered by the same single randomised value, effectively changing the prevailing direction equally across time. This is achieved by designating one or more segments of time as discrete wind direction periods. Prevailing wind is independently randomised for each defined wind direction period.
4. Weather change timing. The user can define weather change start, most likely and end times in the wind direction stream. This forms a triangular distribution in time, and SABRE then randomly draws the change time from that distribution and interpolates the new time steps within it. The result is a randomised wind direction stream that changes the arrival timing of a forecast wind change based on the defined timing window.
5. Curing and drought factor. There has been some published research into forecast versus actual curing and drought factor. Both of these items are currently represented as uniform distributions as a function of their original values, and cite their published sources.
6. Ignition time. Uniform random distribution of minutes before the original ignition time. E.g. if original ignition time was 11am, and the user defined window was 60 minutes, each trial fire will have an ignition time that is equally probable between 10am and 11am.
7. Ignition location. SABRE randomises the ignition point or polygons locations independently in the X and Y directions using a normal distribution with a mean distance from the original point of zero. The user describes the absolute distance of the standard deviation of the possible error in each direction.
8. Fuels. Fuel loads are randomised based on certainty categories described by the standard deviation of their c and k factors in the fuel reaccumulation formulas used for each fuel layer. SABRE is awaiting empirically derived confidence interval data for these values for some fuel types that will be published in the coming year.
9. Wind reduction factor (WRF). SABRE describes WRF as uniformly distributed between a minimum and maximum, but as a function of the original WRF value. As WRF goes up, its level of certainty can decrease. SABRE enables this to be accounted for in as much granularity as desired

Main lessons from the FIRE-DST and elsewhere

The authors don't claim to know the FIRE-DST project deeply. From what literature could be accessed, the creators of SABRE adopted the following principals, some of which were derived from the good work undertaken in the FIRE-DST project.

1. In contrast to the FIRE-DST, SABRE has adopted an open, modular framework approach vice a closed application approach. This enables the addition or replacement of key components like fire simulators, visualisation environments etc. more easily.

2. SABRE executes and manages results processing locally inside the QFES firewall, and publishes just processed results data to the cloud-based decision support environment which will be available to anyone who is granted access, and has a 3G/4G smart device or computer with a web browser.

3. The SABRE Fire ensemble manager has a fully configurable interface for defining probability densities around input data values. This enables tailorable representation of the input errors and their likelihoods. The distribution types and the methods for arriving at their arguments are easily configured and updated.

4. SABRE employs the concept of *user groups* to present selected information at the appropriate level of detail and in the appropriate way to suit the particular decision maker and user need. Some users need to undertake detailed and in depth analysis (e.g. FBAN) and get more information, others need high level information only.

5. While Phoenix is the current bushfire simulation tool used inside SABRE Fire, the framework has the ability to, and will incorporate other fire simulators as they become suitable. It is also designed to operate across other hazards that are suitably underpinned by fit for purpose simulation tools. Other hazards currently being explored include bushfire smoke, flood and storm tide.

At present SABRE Fire does not randomise data at the gridded level. So weather, curing and drought factor data are extracts from the point of ignition and are applied to the entire fire. This is managed procedurally for large fires. Future versions of SABRE will aim to randomise values at the gridded level, removing this as a limitation.

Conclusion

This presentation contends that of the total error signal in simulation-based prediction products, at least 50% or 60% is anecdotally attributable to input data errors, on average. It also contends that in relation to simulation-based bushfire decision support products, *estimating* input data uncertainty and using Monte Carlo methods to manage it before the point of decision is more useful, defensible and less dangerous than using a single best estimate which does not account for uncertainty at all. The FIRE-DST has clearly outlined why uncertainty management is so important, and has provided useful lessons in how it might be managed in an operational context. SABRE is the *all hazards*, QFES response to the problem of managing input data uncertainty in simulation-based decision support products, of which SABRE Fire is the first hazard type to be used operationally. SABRE Fire has been used on about twenty fire incidents to date, with more than 30 individual scenarios published and used. The next phases of SABRE Fire will see probabilistic fire spread data integrated with life, property and environment data to yield a richer set of risk-based decision support products. It will also explore grid level randomisation, and the integration of CSIROs Spark fire spread simulator. Some of the SABRE Fire decision support products are shown in Figures 1 and 2 below, with Figure 1 overlaying several linescans to indicate prediction performance.

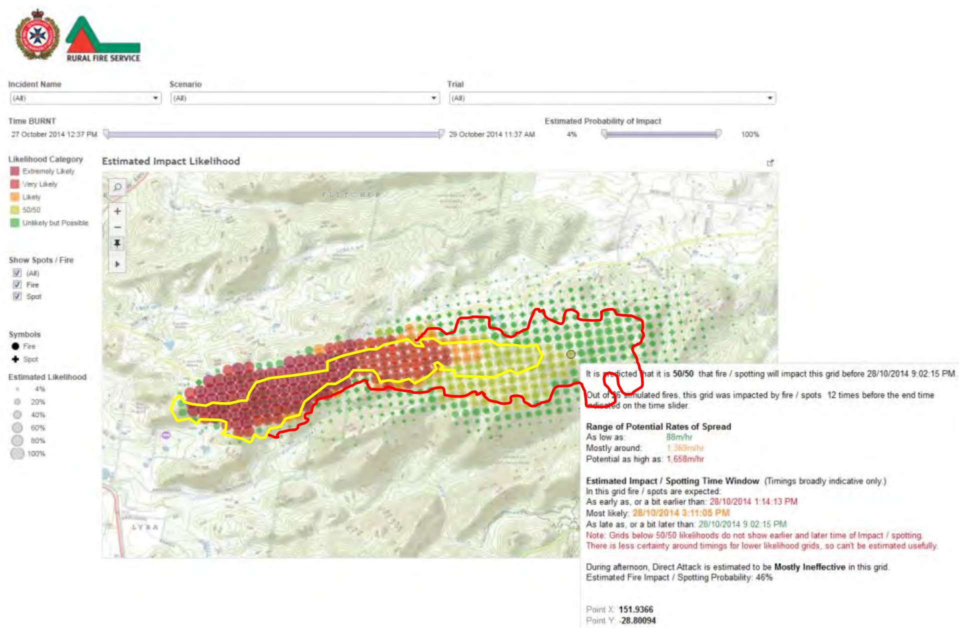

Figure 1 - SABRE Fire, fire impact probability overlay and tool tip box (which appears when points are moused over) showing the 2014 Ballandean fire reconstruction. Yellow line indicates linescan of actual perimeter 28hr after prediction start time, and red line is the linescan of actual fire perimeter 47hr after prediction start time.

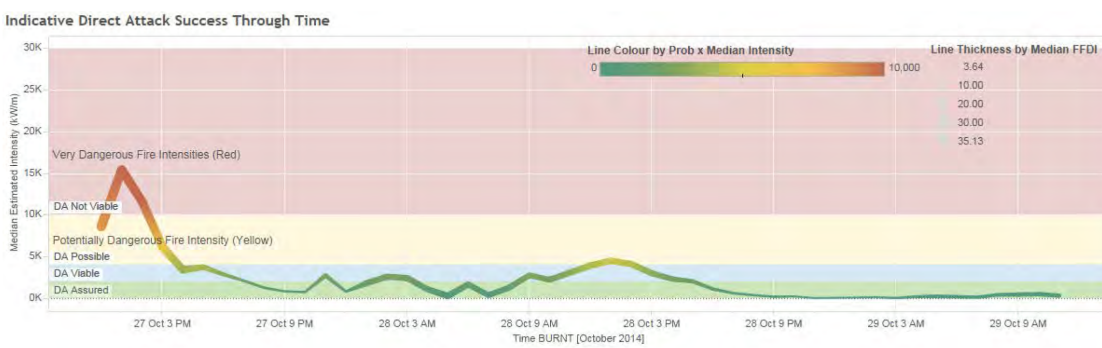

Figure 2 - SABRE Fire, indicative direct attack success through time chart showing indicative time windows where direct attack strategies are likely to be more successful on the 2014 Ballandean fire.

Citations

- *Report*
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SURFACE FUEL LOAD MODELLING WITH LIDAR DATA: A CASE STUDY OF UPPER YARRA RESERVOIR AREA, VICTORIA, AUSTRALIA

Yang Chen*[ac], Xuan Zhu[a], Marta Yebra[bc], Sarah Harris[ac], Nigel Tapper[ac]

a. School of Earth, Atmosphere & Environment, Monash University, Melbourne, VIC, Australia
b. College of Medicine, Biology & Environment, ANU, Canberra, ACT, Australia
c. Bushfire & Natural Hazards CRC, Melbourne, VIC, Australia

Introduction

Accurate quantification of forest surface fuel is important in bushfire behaviour prediction, potential fire hazards assessment and fuel hazard-reduction (McArthur, 1967; Anderson, 1982; Gould et al., 2008). Traditionally, surface fuel load is determined by field sampling, oven drying, and weighing (McArthur, 1962; McCarthy, 1996; McCarthy et al., 1998), which can be time consuming and labour intensive at large scales. As a quick and feasible alternative, McArthur's positive relationships between surface litter fuel load and litter-bed depth have been used to support fuel hazard-reduction burns in Eucalypt forests in Australia, instead of directly measuring fuel load (McArthur, 1962; Birk and Simpson, 1980). Several studies (Olson, 1963; Birk and Simpson, 1980; Raison et al., 1983; Raison et al., 1986; Burrows, 1994) have described and modelled surface fuel load through a general form of the exponential function of fuel accumulation models with time since fire as the independent variable to predict fuel growth of different vegetation communities (Gould et al., 2011). Time since fire is the initial key indicator to fuel accumulation; recent studies have been shifting to environmental indices - based surface fuel load estimation (Bresnehan, 2003; Gilroy and Tran, 2009). Since surface fuel load accumulation depends on rates difference between fuel accession and decomposition (Agee et al., 1973), which is further reliant on the results of a complex interaction of separate and related influencing factors (e.g. forest type, productivity of understorey and overstorey, density of canopy and environmental conditions) of the accumulation (Hogg and Kirkpatrick, 1974; Miller and Urban, 2000; Bresnehan, 2003).

In this study, the Light Detection and Ranging (LiDAR) technique was used to estimate some of the influencing factors due to its ability to provide three-dimensional information to quantify forest structural characteristics and terrain features with high spatial accuracies (Lefsky et al., 1999; Lovell et al., 2003; Riaño et al., 2003; Coops et al., 2007). The LiDAR derived surface fuel depth, surface fuel percentage cover, canopy density and topography (e.g. slope, aspect and elevation), and previous disturbances (e.g. years since last fire and burn types) along with direct measured fuel moisture content and dry fuel load were used to develop a predictive model to estimate surface fuel load in the Upper Yarra Reservoir area, Victoria, Australia through multiple regression. Unlike the fuel accumulation studies, it also evaluated how the spatial variation in surface fuel load relates to the separate and related influencing factors across the study area.

Methods

Study Site and Data Collection

This study used the Upper Yarra Reservoir Park as a case study area to model forest surface fuel load through multiple regression analysis. A total of forty-one sample sites were selected to have different fire history, burn types, fuel types, and terrain features using a stratified systematic sample design. The total surface fuel load at each site (0.5 m

*Yang Chen, yang.chen2@monash.edu
Room 224, BLDG 28, 9 Rainforest Walk, School of EAE, Faculty of Science, Monash University, Wellington Rd, Clayton, Victoria, 3800, Australia

* 0.5 m) was weighed directly, as the weight (g) comprising dry weight and moisture content. Dry weight (g) was measured after oven drying for 24 hours at 105 °C (Loomis and Main, 1980; Pook, 1993; Pook and Gill, 1993; Cheney and Sullivan, 1997). Fuel moisture content was calculated by subtracting oven-dried weight from the total weight of surface fuel load. Terrestrial LiDAR (Zebedee) was applied to measure surface fuel depth and its percentage cover. Airborne LiDAR data was used to calculate canopy density and topographic variables.

Model Development

Modelling of forest litter-bed fuel load was accomplished in iii stages of multiple regression analysis (Graybill, 1970).

i. Modelling the forest fuel depth-to-load (*FD* to *DW*) relationship with the influence by years since last fire (*YSF*) (McArthur, 1962; Agee et al., 1973; Sneeuwjagt and Peet, 1985; Chatto, 1996; McCarthy, 1996; McCarthy, 2004; Gilroy and Tran, 2009);
ii. Introducing more quantitative variables in the model, as interactions with *FD* and *YSF*, including canopy density (*CD*), surface fuel moisture content (*MC*), surface fuel percentage cover (*PC*), elevation (*E*), aspect (*A*) and slope (*S*);
iii. Introducing types of burn and fuel as qualitative variables in the models as interactions with these existing independent variables, in order to account for differences among forest fuel types (*FT*) as well as burn types (*BT*);

Each component of *DW* was modelled using stepwise procedures to identify the best subset of independent variables at the statistical significance level of 0.05. To keep the number of variables manageable, we used the first-order interaction terms for independent variables, and omitted high-order terms to the model. In order to limit overfitting problems, the leave-one-out cross-validation was then used to verify the result of the finalised multiple linear regression model.

Findings and discussion

The stepwise procedure was used to produce estimates of the model coefficients to select the important variables, and the finalised predictive model is described below.

$$ln\,(DW) = 3.608 + 0.004 * YSF * FD + 0.001 * CD * E + 0.13 * FD * FT + 0.001 * MC$$

The model suggests that fuel load is primarily influenced by surface litter-bed depth, years since fire, canopy density, elevation, forest fuel type, and fuel moisture content. Surface litter depth and years since last fire are more significantly related to quantities of litter fuel load than others.

Our model produced R^2 value of 0.9, *RMSE* values of 4.5 g and a prediction error of 4.1 g/m^2. This study introduced more influencing factors, including canopy density, fuel type, burn type, surface fuel moisture content, surface fuel percentage cover, and topography, compared with McArthur’s depth-to-load relationships and Gilroy and Tran (2009)’s model. By directly applying McArthur’s depth-to-load model with our data, it overestimated surface fuel load and also produced a R^2 value of 0.65 and a *RMSE* value of approximately 40 g. Gilroy and Tran (2009)’s model produced a value R^2 of 0.706 and a *RMSE* value of 35.4 g with our data.

Conclusion

Quantifying surface fuel load is an ongoing requirement for fire authorities and fire management agencies, due to its significance in predicting fire behavior, and assessing potential fire risks. This study developed a predictive model of forest surface fuel load for the Upper Yarra Reservoir area using multiple regression analysis. LiDAR data were

*Yang Chen, yang.chen2@monash.edu
Room 224, BLDG 28, 9 Rainforest Walk, School of EAE, Faculty of Science, Monash University, Wellington Rd, Clayton, Victoria, 3800, Australia

used to provide canopy density, topography, fuel depth and fuel percentage cover with high spatial accuracy. The results of this study suggest that these important fuel characteristics, environmental factors and fire disturbance can be used to predict spatial variation in forest fuel load as an efficient method to assist forest fuel and fire related management activities across the local area. The predictive model can be used to assist forest fuel management, to estimate suppression difficulties, to predict ongoing fires for operational activities, and to assess potential fire hazards across study area.

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Reference

Agee JK, Wakimoto RH, Darley EF, Biswell HH (1973) Eucalyptus fuel dynamics, and fire hazard in the Oakland hills. *California Agriculture,* **27,** 13-15.

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. *The Bark Beetles, Fuels, and Fire Bibliography***,** 143.

Birk EM, Simpson R (1980) Steady state and the continuous input model of litter accumulation and decompostion in Australian eucalypt forests. *Ecology***,** 481-485.

Bresnehan SJ. (2003) An assessment of fuel characteristics and fuel loads in the dry Sclerophyll Forests of South-East Tasmania. University of Tasmania.

Burrows ND. (1994) Experimental development of a fire management model for Jarrah (Eucalyptus Marginata Donn ex Sm.) forest. PhD, Australian National University.

Chatto K (1996) Fuel hazard levels in relation to site characteristics and fire history: Chiltern Regional Park case study. Parks Victoria.

Cheney P, Sullivan A (1997) 'Grassfires: fuel, weather and fire behaviour.' (CSIRO PUBLISHING)

Coops NC, Hilker T, Wulder MA, St-Onge B, Newnham G, Siggins A, Trofymow JT (2007) Estimating canopy structure of Douglas-fir forest stands from discrete-return LiDAR. *Trees,* **21,** 295-310.

Gilroy J, Tran C A new fuel load model for eucalypt forests in southeast Queensland. Royal Society of Queensland.

Gould J, Mccaw L, Cheney PN, Ellis P, Kinight KI, Sullivan A (2008) 'PROJECT VESTA: FIRE IN DRY EUCALYPT FOREST.' CSIRO)

Gould JS, Mccaw WL, Cheney NP (2011) Quantifying fine fuel dynamics and structure in dry eucalypt forest (Eucalyptus marginata) in Western Australia for fire management. *Forest Ecology and Management,* **262,** 531-546.

Graybill FA (1970) 'Theory and Application of the Linear Model.' (North Scituate, Mass: Duxbury Press)

Hogg A, Kirkpatrick J (1974) The phytosociology and synecology of some southern Tasmanian eucalypt forests and woodlands. *Journal of Biogeography***,** 227-245.

Lefsky MA, Harding D, Cohen WB, Parker G, Shugart HH (1999) Surface Lidar Remote Sensing of Basal Area and Biomass in Deciduous Forests of Eastern Maryland, USA. *Remote Sensing of Environment,* **67,** 83-98.

Loomis RM, Main WA (1980) Comparing jack pine slash and forest floor moisture contents and National Fire Danger Rating System predictions. *USDA Forest Service research paper NC-United States*.

Lovell J, Jupp DL, Culvenor D, Coops N (2003) Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests. *Canadian Journal of Remote Sensing,* **29,** 607-622.

Mcarthur AG (1962) 'Control burning in eucalypt forests.' (Forestry and Timber Bureau. Leaflet: Canberra, Australia)

*Yang Chen, yang.chen2@monash.edu
Room 224, BLDG 28, 9 Rainforest Walk, School of EAE, Faculty of Science, Monash University, Wellington Rd, Clayton, Victoria, 3800, Australia

Mcarthur AG (1967) Fire behaviour in eucalypt forests. Forestry and Timber Bureau Leaflet 107, Commonwealth Department of National Development, Canberra ACT.

Mccarthy GJ (1996) Assessment of Overall Fuel Hazard for a Site and its Implications for Both Strategic Fuel Management and First Attack Success Probability. 13th Conference on Fire and Forest Meteorology. Lorne, Australia: International Association of Wildland Fire.

Mccarthy GJ (2004) 'Surface fine fuel hazard rating: forest fuels in East Gippsland.' (Department of Sustainability and Environment: East Melbourne, VIC)

Mccarthy GJ, Tolhurst KG, Chatto K (1998) Overall fuel hazard guide. Victoria Fire Management. East Melbourne, VIC: Department of Natural Resources & Environment.

Miller C, Urban DL (2000) Connectivity of forest fuels and surface fire regimes. *Landscape Ecology,* **15,** 145-154.

Olson JS (1963) Energy Storage and the Balance of Producers and Decomposers in Ecological Systems. *Ecology,* **44,** 322-331.

Pook E (1993) Empirical models evaluated for prediction of fine fuel moisture in Australian Pinus radiata plantations. *New Zealand Journal of Forestry Science,* **23,** 278-297.

Pook E, Gill A (1993) Variation of live and dead fine fuel moisture in Pinus radiata plantations of the Australian-Capital-Territory. *International Journal of Wildland Fire,* **3,** 155-168.

Raison R, Woods P, Khanna P (1983) Dynamics of fine fuels in recurrently burnt eucalypt forests. *Australian Forestry,* **46,** 294-302.

Raison RJ, Woods P, Khanna PK (1986) Decomposition and accumulation of litter after fire in sub-alpine eucalypt forest. *Australian Journal of Ecology***,** 9-19.

Riaño D, Meier E, Allgöwer B, Chuvieco E, Ustin SL (2003) Modeling airborne laser scanning data for the spatial generation of critical forest parameters in fire behavior modeling. *Remote Sensing of Environment,* **86,** 177-186.

Sneeuwjagt RJ, Peet GB (1985) Forest Fire Behaviour Tables for Western Australia, 3rd ed. Perth, Western Australia: Department of Conservation and Land Management.

*Yang Chen, yang.chen2@monash.edu
Room 224, BLDG 28, 9 Rainforest Walk, School of EAE, Faculty of Science, Monash University, Wellington Rd, Clayton, Victoria, 3800, Australia

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The Effect of Curing on Fire Behaviour in Grasslands

Susan Kidnie*[A], Miguel Cruz[B], David Nichols[A], Richard Hurley[B], Jim Gould[B], Rachel Bessell[A], Alen Slijepcevic[A],

[A] Country Fire Authority, Burwood East, Victoria, Australia
[B] CSIRO, GPO Box 1700, Canberra, ACT, Australia

Introduction

Knowledge of the annual growing cycle of grasslands is a key aspect to understanding fire susceptibility in grasslands. As grasses senescence, the fuel moisture content gradually decreases and the proportion and amount of dead material increases, raising the general "flammability" of a grassland fuel type (Cheney and Sullivan 2008).

The proportion of dead fuel material in a grassland is typically described as the curing level (expressed as a percentage) (Luke and McArthur 1978; Anderson *et al*. 2011). Grass curing is considered to have a strong effect on fire behaviour in grasslands (McArthur 1966). In Australia, the degree of curing has been used as an input into the calculation of grassland fire danger ratings and grassfire rate of spread. The ability to accurately assess the degree of curing and understand how curing affects fire behaviour is therefore very important for fire agencies fire danger predictions throughout the fire season.

Senescence of grass fuels and landscape level grass curing is a complex and dynamic process that modifies a fuel bed's ability to support active fire propagation in multiple ways. By measuring curing as the proportion of dead fuel, the impact of curing on fire behaviour is reduced to a single number and ignores the more complex dynamics involved in the senescence process. Between 2012 and 2016, a series of paired experimental burns were carried out across eastern Australia to (1) better understand curing dynamics, (2) quantify the degree of curing above which sustained fire propagation is expected to occur and (3) determine the damping effect of live grass fuels on the relative rate of fire spread, the curing factor.

Methods

Study Sites

Experiments were conducted at five sites across eastern Australia. Sites were located at: Wangaratta South, Victoria (36°24'17''S, 146°14'57'' E), Wendouree, Victoria (37°31'12''S, 143°48'3''E), Tamworth, New South Wales (31˚2'15"S, 150˚54'47"E), Toowoomba, Queensland (27˚30'39"S, 151˚52'48"E) and Braidwood, New South Wales (35°18'56"S, 149°43'22"E). Average site fuel loads ranged from 0.24 kg m^{-2} (at Braidwood) to 0.46 kg m^{-2} (at Wangaratta South) and sites were selected to be representative of pastures in the area.

Curing Dynamics

Curing assessments were conducted by visually assessment (CFA 2014) and destructive sampling. Destructive sampling considered grass fuel components partitioned into four distinct fuel categories: (i) old dead, (ii) new dead, (iii) senescing and (iv) green. Old dead

*Susan Kidnie
Country Fire Authority
8 Lakeside Drive Burwood East VIC 3151, s.kidnie@cfa.vic.gov.au

(*od*) is the grass fuel component from the previous year's growth. Fuel particles of this component have a colour varying from light to dark brown or grey, depending on species and age. New dead (*nd*) is the dead fuel component from the current season's growth. These fuels are usually attached to living fuel and maintain their vertical structure. There is no remaining green chlorophyll pigment present. Thus, they appear bleached and the stalks break easily. Moisture content in the *od* and *nd* fuel components closely follows environmental conditions. Senescing (*sen*) fuels are undergoing transition from live to dead. Fuel colouration in the senescing category depends on the amount of chlorophyll pigment remaining and can range from pale green to green-yellow or yellow in colour. Components in this category do not break as easily as *nd* fuels but they are not as as lush as green fuels. Green (*g*) fuel is the component that is green in colour and does not show any obvious physical signs of plant tissue deterioration or aging. Leaves in the green category are generally soft to the touch and stalks show visible moisture if broken.

Experimental Burns

The experimental approach relied on two different sets of field experiments, one for fire sustainability and another to address fire propagation. The fire sustainability experiments comprised 'go/no-go' experiments burned under low curing levels. These experiments aimed to explore the likelihood of sustained fire propagation in the early stages of plant curing (i.e. a degree of curing of 20 to 50%). These were followed by the fire propagation experiments aimed at quantifying the effect of the degree of grass curing on the rate of fire spread and associated fire behaviour characteristics (e.g. flame height, flame front residence time).

The fire sustainability experimentation involved individual plots approximately 20 x 20 m (0.04 ha) in size ignited under a range of environmental conditions and curing levels. The ignition line was set on the upwind side of the plot in order to capture the wind-driven fire propagation.

The experimental design for the fire propagation component of the study called for simultaneous fires conducted in 100% cured (control, obtained by killing the pasture with herbicide) and partially cured (treatment, natural cured state) plots over a range of curing levels (see Figure 1). Over 100 plots were ignited measuring approximately 33 x 33 m (0.1 ha) in size at 5 sites across eastern Australia.

Figure 1: Example of a plot layout with herbicide treated, fully cured plots are at the top of the picture and untreated, partially cured plots in the foreground.

Results

Analysis of the complete set of burns is not yet complete. The following results represent a combination of the data – the range of conditions and curing values represent all of the burns, but the proposed curing coefficient was developed using only Victorian burn data (Wangaratta and Wendouree sites).

Curing Dynamics

Our study identified that visual assessment of the degree of curing tend to result in over-estimates of the proportion of dead fuels. These results are contrary to other studies, which have found that visual assessment resulted in underestimates of the degree of curing (Pairman *et al*. 1995, Anderson *et al*. 2011). This bias could be due to two factors: (i) previous studies have likely included what we defined as senescing fuel in the dead category, thus increasing the curing value used to compare to visual estimates; and (ii) between approximately 30 and 70% visual curing, there is actually very little change in the proportion of new dead fuel, suggesting that what is commonly identified visually as dead fuel, is in reality senescing fuel. Issues with species differences, season of growth and growth rate as a result of site productivity, precipitation, climate, stocking and competition will affect the amount of grass present and visual perception of the degree of curing.

We also noticed it was difficult for visual assessors to incorporate the proportion of old dead fuels in their visual estimation of curing in certain situations. In high productivity areas, the current season's growth tends to obscure the old dead fuel that typically is horizontally oriented and close to the ground. The largest error predominantly occurred early in the curing season with visual assessors estimating curing at about 30% when the actual curing level was around 50%. This error was largest in non-disturbed areas, such as where grazing is absent, and at low curing values. In these situations, the proportion of old dead grasses is relatively high, leading to larger under prediction bias. By 30 to 40% cured, the proportion of senescent fuels has increased and the visual curing bias switches to an overestimation due to the inaccurate categorisation of senescent fuel as dead fuel.

Fire Behaviour

We conducted over 10 fire spread sustainability tests. These test fires were initiated when the visual degree of curing reached 30%. All of the tests resulted in sustained fire propagation.

Over 50-paired experimental fire plots were burned to quantify the effect of the degree of curing level on the spread rate of grassfires. Wind speeds measured at 2-m height above ground during the experimental fires ranged from approximately five to 40 km h^{-1}.Dead fuel moisture content ranged from approximately 2 to 13 % of the oven dry weight.

Using data from the Victorian burns only, the curing coefficient (the rate of spread of the partially cured plot divided by the rate of spread of the fully cured plot) varied between 0.04 and 0.77. The variation in the curing coefficient was best explained by degree of curing level ($r = 0.899$; $p<0.0001$) and the visual assessment curing estimate ($r = 0.852$; $p = 0.0002$). Overall fuel moisture content, a parameter integrating both the proportion of live and dead fuel components and their respective moisture contents was also significantly related to the curing coefficient ($r = -0.631$; $p = 0.021$). Interestingly, the proportion of senescing fuels, and the moisture content of senescing, green or live fuels were not related to the curing coefficient.

A new curing coefficient function has been developed using the Victorian data to estimate the damping effect of the degree of curing on fire spread rate in partially cured grasslands. The shape of the model took into consideration knowledge that the curing effect on fire spread rate asymptotes when the curing level approaches 90% (Cheney *et al.* 1993, 1998). The other constraint imposed was that marginal fire propagation was expected to occur at a curing level of about 20%, although admittedly we do not have rate of fire spread data for curing levels lower than 40%.

The model was developed using non-linear regression analysis relying on a sigmoidal relationship (see Cheney *et al.* 1998) between the degree of curing and the curing coefficient:

$$\Phi C = a/[1 + b \exp(-k\ (C - Cx))\ ] \qquad [1]$$

where *Cx* is the curing extinction coefficient (i.e. the threshold below which no fire spread will occur) and C is the current level of curing. Assuming a *Cx* of 20%, the estimated coefficients (and standard error) were: a = 1.036 (0.0241), b = 103.989 (48.916) and k = 0.0996 (0.012). All coefficients were significant at a 0.05 alpha level. This model function yielded an RMSE of 0.055, an MAE of 0.03 and a MAPE of 18%. Residuals analysis showed no deviation from normality and no significant relationships with other variables available for analysis. Thus, no other variables were added to the model.

Discussion

Our experimental design called for a substantial number of fire spread sustainability test fires conducted in grasslands with curing levels of around 30%. This level of curing wasn't possible at the Queensland and New South Wales sites predominantly because of the high proportion of old dead fuel across the sites being around 40% of the overall fuel load. The initial test fires in Victoria, however, with degree of curing levels varying between 21% and 30%, did in fact achieve sustained fire propagation. From these results, the spread sustainability experiments were halted, as it was not possible to carry out further tests with lower curing levels due to the progress of the senescence process. The results are in line with the assumption of Wotton *et al.* (2009) and contrary to the expectation used in Australia that fires would likely not propagate when the grass degree of curing level is lower than 50% (Cheney 1997; Cheney *et al.* 1998; Cheney and Sullivan 2008). Despite the low dead fuel loads associated with these experimental fires, which varied between 0.07 and 0.1 kg m^{-2}, enough energy was generated from the combustion of these fuels to sustain fire propagation. The results from the fire propagation experimental fires showed that the two curing coefficient functions currently used in Australia (McArthur (1966) and Cheney *et al.* (1998)) lead to an under-prediction of fire spread rate potential in southern Australia pastures. We proposed a new parameterization of a sigmoid shaped curing coefficient function based on the data collected from the Victorian experimental burns. Comparison between the damping effect of our function and those of McArthur (1966) and Cheney *et al.* (1998) showed that the new function would predict fire spread rates to be approximately 10 to two times faster at degree of curing levels between 50 and 80%.

Our results from the Victorian experiments failed to find a significant effect of the live fuel moisture content per se in damping the rate of fire spread in grasslands. The overall fuel moisture content, a metric largely determined by the amount of live fuels and associated moisture content was found to be significantly related to the curing coefficient, but with a smaller effect than the degree of curing level alone. This result might imply that it is the quantity of dead fuels that is the primary variable determining fire propagation in fuel beds made up of live and dead plant components. The effect of live fuel moisture by itself has no relation to the observed damping effect as the quantity of fuel involved in combustion is unknown.

Future Work

We will merge the Victorian, Queensland and New South Wales datasets to investigate if the function developed for Victoria as wide applicability, or if there is a need to update the function. Analysis of the effect of curing on flame height and fire growth will also be determined from the extended grass fire behaviour dataset.

References

Anderson SAJ, Anderson WR, Hollis JJ, Botha EJ (2011) A simple method for field-based grassland curing assessment. *International Journal of Wildland Fire* **20**, 804-814.

CFA (2014) Grassland Curing Guide. Fire and Emergency Management, Country Fire Authority. (Burwood East VIC).

Cheney NP (1997) Effective grass curing on firespread and fire danger rating. In “Grass curing workshop”. 27 August, Aspendale, Victoria, Australia.

Cheney NP (1993) Fire behaviour in tropical grasslands. Page 9-16 in Proceedings of the workshop “Fire on conservation reserves of Tropical Australia. July 1993, Malanda, Queensland, Australia.

Cheney NP, Gould JS, Catchpole WR (1998) Prediction of fire spread in grassland. *International Journal of Wildland Fire* **8**, 1-13.

Cheney P, Sullivan A (2008) Grassfires: fuel, weather and fire behaviour, 2nd edition. (CSIRO: Collingwood, Victoria)

Luke RH, McArthur AG (1978) Bushfires in Australia. Australian Government Publishing Service. (Canberra, ACT)

McArthur AG (1966) Weather and grassland fire behaviour. Commonwealth of Australia, Forestry and Timber Bureau, Leaflet 100 (Canberra, ACT)

Pairman D, Barens EJ, Fogarty LG (1995) Initial evaluation of satellite derived NDVA to estimate fuel moisture content in grassland. New Zealand Forest Research Institute, Project Record Number 5291. (Rotorua, New Zealand)

Wotton BM, Alexander ME, Taylor SW (2009) Updates and revisions to the 1992 Canadian Forest Fire Behaviour Prediction Systems. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Information Report GLC-X-10. (Sault Ste Marie, ON)

There are No Boundaries: the South Para Collaborative Fire Management Plan

Aidan Galpin*
Department of Environment, Water and Natural Resources,
South Australia, Australia, aidan.galpin@sa.gov.au

Introduction – Shared Responsibility

After the 2009 Victorian Bushfires, shared responsibility became a principle of the resilience based approach to disaster management (Dr B McLennan & Prof J Handmer 2014; Parliament of Victoria 2010). Until this time, South Australian public land management agencies managed their respective lands independently.

In 2012, the Heads of Agencies responsible for public land management in South Australia (the South Australian Country Fire Service (CFS), Department of Environment, Water and Natural Resources (DEWNR), ForestrySA, and SA Water) agreed to the *Code of Practice for Fire Management on Public Land in South Australia 2012 - 2016* (DEWNR *et al.* 2012). The Code of Practice commits the four agencies, CFS, DEWNR, ForestrySA, and SA Water to collaborate and support one another in landscape-scale prevention and suppression of bushfires (DEWNR *et al.* 2012).

An outcomes of this approach was agreement to develop the *South Para Collaborative Fire Management Plan* (SPFMP), covering over 20 000 hectares of public land managed by the four agencies in the South Para area of the Mount Lofty Ranges (Figure 1).

Figure 1: South Para Fire Management Plan Area

The Challenge
The Adelaide and Mount Lofty Ranges are unique and home to one of the most complex landscape in South Australia. The relatively high rainfall and hilly topography, along with the Mediterranean climate makes the region ideal for agriculture and primary production (DEH 2010). The diversity of landscapes within a comparatively small area also supports a diverse array of ecosystems and species. It is home to half of the state's species of native plants and three-quarters of its native birds, many of these species are endemic to the region or geographically separated from other state or interstate populations, which is reflected in the Mt Lofty Ranges forming one of the fifteen National Biodiversity Hotspots (AMLR NRM Board 2014; Department of the Environment 2006). The area also supports a diverse range of economic activities and industries, which contributes significantly to the state's economic health and social wellbeing.

Historically, up to 87% of the native vegetation has been cleared (DEH 2010), resulting in the extinctions some species and the decline of others. The remaining native vegetation across the Adelaide and Mount Lofty Ranges acts as a stronghold for a number of endemic threatened species and ecological communities.

The South Para planning area contains the largest contiguous expanse of remnant native vegetation in the Adelaide and Mount Lofty Ranges (DEWNR 2016), providing an ever present bushfire fuel hazard, that requires careful management to balance the needs of the community, infrastructure, environment, and the implementation of adequate bushfire prevention measures. As a result, a range of lands have been included in the plan that are managed for various outcomes including, conservation, recreation, forestry, or catchment management purposes. This includes:

- plantation forests and Native Forest Reserves (which are proclaimed for conservation purposes) within the Mount Crawford Forest Reserve managed by ForestrySA,
- Reservoir Reserves managed by SA Water,
- Conservation Parks and Recreation Park managed by DEWNR,
- selected Crown land managed by DEWNR, and
- privately owned Heritage Agreements adjoining public land.

Further, the planning area is home to a number of significant and at risk assets, which may be impacted by bushfire, including:

- significant townships and regional communities,
- remnant native vegetation,
- national and state significant species and ecological communities,
- Aboriginal and non-Aboriginal cultural heritage and assets,
- a significant proportion of Adelaide's fresh water supply and infrastructure,
- ForestrySA plantations and associated assets,
- significant horticulture, agriculture and viticulture production, and
- an increasing peri-urban interface.

Considering the complexity of the planning area, it was identified as a priority for fire management planning due to the potential for bushfire to threaten the above values and assets, in particular, the local community (such as Williamstown and other centres), essential infrastructure, Adelaide's drinking water catchment, commercial forestry plantations, and threatened species and ecological communities. Incorporated into the tenure blind approach, was the inclusion of privately owned Heritage Agreement areas declared under the *Native Vegetation Act 1991 (SA)*, where land owner consent was provided.

The SPFMP emphasises the protection of human life as the highest priority, proposes strategies to reduce the risk of bushfires threatening assets and infrastructure and provides direction for land managers in the protection and enhancement of environmental values. While there is an understanding that not everything can be protected, a balance has been sought to ensure that values and assets across the landscape have been assessed and addressed where the risk meets or exceeds High (DEWNR 2015).

A Multi Agency Approach – There Are No Boundaries

The collaborative approach by multiple state agencies to develop the SPFMP is a first for fire management planning in South Australia. The SPFMP will provide a strategic, tenure blind landscape scale approach, which extends bushfire risk management activities and works across public land management boundaries in order to provide a more consistent risk mitigation approach across the landscape.

This approach was founded on the development of the Code of Practice (DEWNR *et al.* 2012) and DEWNR's existing fire management planning methodology (DEWNR 2015). Agencies dedicated and tasked officers to contribute to the collaborative development of the plan. Risk assessment workshops were undertaken with the four agencies to identify the risk to Life, Property and the Environment from both bushfire events and prescribed treatments. This allowed fire vulnerable species to be addressed. Where the risk to an identified asset or value met or exceeded High, the SPFMP identified a mitigating action.

The results were spatially represented through a series of Fire Management Zones (Figure 2), that covered the publically management lands, irrespective of land management boundaries, and facilitates the ability for the extension of these zones across adjoining private lands, this being the end goal. The SPFMP informs annual works programs, which are entered through the Fire Information Management System database (DEWNR 2014) to track and map completed mitigation works. This data can then be used to inform Incident Management Teams during bushfire events to support decision making around suppression strategies.

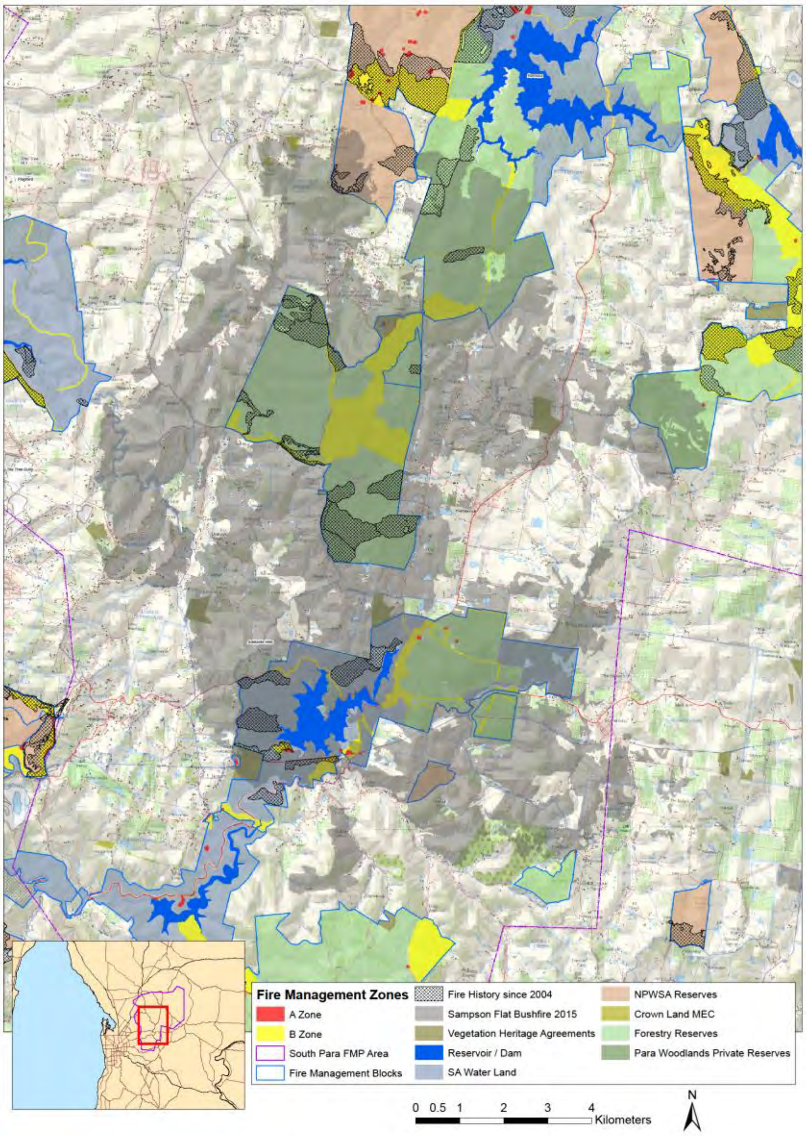


Figure 2 – South Para Fire Management Zoning

In November 2014, The HoA endorsed the SPFMP for public release, in doing so committing the agencies to deliver as much of the recommended treatments as time, resourcing and weather allowed.

On Friday 2 January 2015, the bushfire potential within the planning area became a reality when the Sampson Flat bushfire burnt 12,569 ha from Parra Wirra to Cudlee Creek and Hermitage to Forreston, over six days. Large areas of Millbrook Reservoir Reserve and Mount Gawler Forest Reserve, and part of Para Wirra Recreation Park were burnt at varying intensities. Reported losses from this event included 28 houses, 11 businesses, 103 sheds and other buildings.

The collaborative response and suppression efforts during the Sampson Flat event are a reflection of the commitment and cooperation from the Head of Agencies, and the CFS as the lead response agency. A review of the 2015 Sampson Flat bushfire showed that prevention works implemented across public land tenures contributed to reducing fire severity in several locations, contributing to the eventual containment and control of the bushfire (Figure 3).

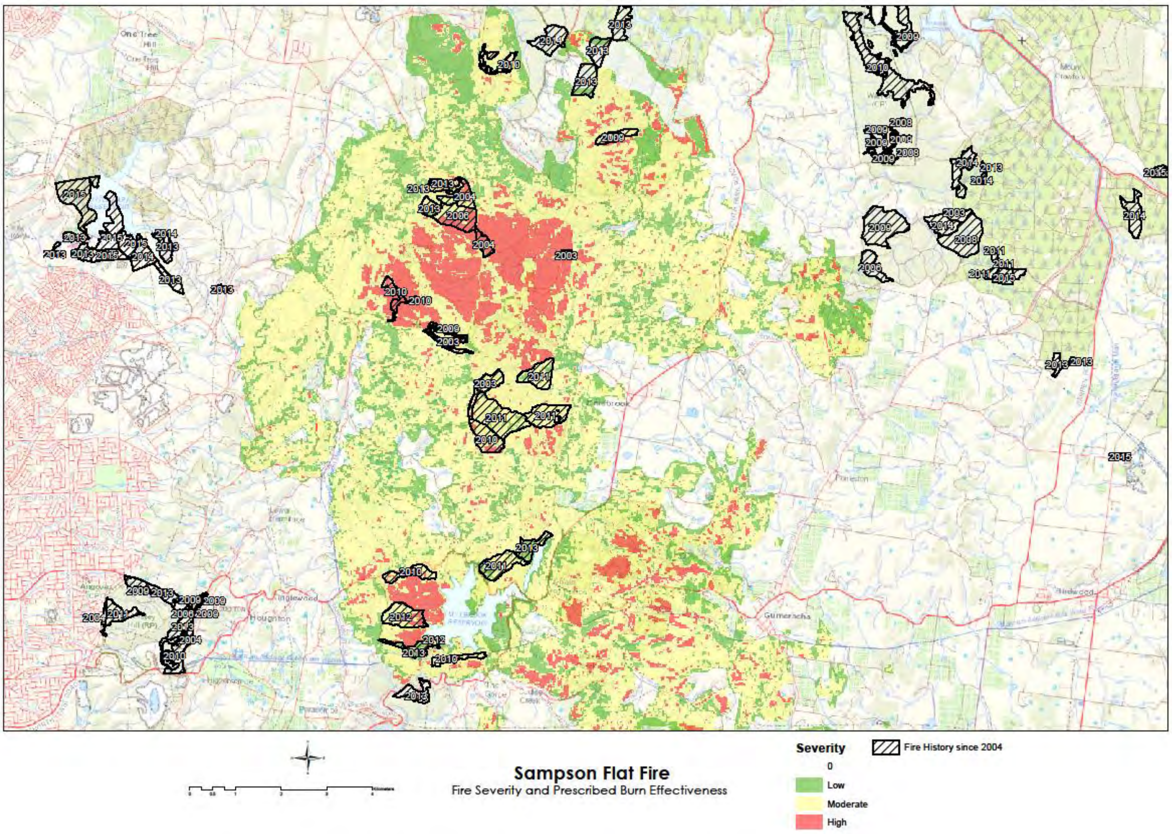


Figure 3: Fire Severity Mapping Across Mount Crawford Native Forest, Millbrook Reservoir Reserve, and Para Wirra Recreation Park with Fire History

A review of the SPFMP was undertaken after the Sampson Flat Bushfire, with some minor amendments made.

There have been many challenges throughout the development of this plan, including shared ownership, the shared commitment to invest the required resources, and the shared acceptance of releasing the information publicly. All this along with a major review of the SPFMP in response to the 2015 Sampson Flat bushfire, which impacted significantly on the planning process.

The benefits of working collaboratively on the Plan has been the improved resourcing ability and resource efficiency, improved knowledge across land tenures, and the increased effectiveness of mitigating actions as a result of strategically implemented, compatible and complementary works, which were demonstrated during Sampson Flat (Figure 2).

The Future – Whole of Landscape

To continue the evolution of bushfire management planning in South Australia, the Country Fire Service is now facilitating the development of Bushfire Area Management Plans (BMAPs) across settled areas of the state. The aim of the BMAPs is to assess the risk to life, property and the environment at the local and landscape scale. This has provided the opportunity to identify the risk to the broader landscape and apply prevention measures, such as bushfire management zones, improve access and egress, access to water, and/or improve major infrastructure across the landscape over public and private land. The risk assessments and strategic planning already undertaken within the SPFMP will complement the development of these plans.

The implementation of cross-tenure bushfire mitigation strategies (e.g. prescribed burning), as identified within the BMAP, will present many serious challenges. Currently very little prescribed burning is undertaken on private land to complement the state government program. In response to this, DEWNR and the CFS have commenced work on a joint project (Private Lands Burning Project) which seeks to identify and address challenges/issues including:

- Who will fund the implementation of strategic cross-tenure prescribed burns?
- Who will be liable for any damages caused in implementing cross-tenure prescribed burns?
- What impediments currently exists for private landholders and CFS Brigades to undertake appropriate prescribed burns on private land?
- How will the environmental impacts of prescribed burns be mitigated against across all land tenures?
- How should State Government firefighting resources best be utilised to treat fuels across the landscape?

Conclusion

The final goal of a truly tenure blind model to enable effective bushfire management across the landscape is to bring about true shared responsibility by all landowners and stakeholders (Dr B McLennan & Prof J Handmer 2014). Our biggest challenge moving forward will be altering or creating a new social licence to operate and support burning across private lands, one which the Burning on Private Lands Project will seek to stimulate and contribute to.

References

AMLR NRM Board 2014, *Adelaide and Mount Lofty Ranges Natural Resources Management Plan 2014-15 to 2023-24*. Department of Environment, Water and Natural Resources, Government of South Australia, Adelaide.

DEH 2010, *Informing Biodiversity Conservation for the Adelaide and Mount Lofty Ranges Region South Australia: Priorities, Strategies and Targets*. Government of South Australia, Adelaide, Department for Environment and Heritage.

Department of the Environment 2006, *Australia's 15 National Biodiversity Hotspots*, Australian Government.

DEWNR 2014, *FIMS User Guide*. Department of Environment, Water and Natural Resources, Government of South Australia, Adelaide.

DEWNR 2015, *Fire Policy and Procedure Manual 2014/15*. Department of Environment, Water and Natural Resources, Government of South Australia, Adelaide.

DEWNR 2016, *South Para Collaborative Fire Management Plan*. Department for Environment, Water and Natural Resources, Government of South Australia, Adelaide.

DEWNR, ForestrySA, SA Water & CFS 2012, *Code of Practice for fire management on public land in South Australia 2012 - 2016*, Government of South Australia, Adelaide.

Dr B McLennan & Prof J Handmer 2014, *Sharing Responsibility - More Than a Slogan*, 128, Bushfire Cooperative Research Center, and Australasian Fire and Emergency Services Authorities Council, Melbourne, Victoria.

Parliament of Victoria 2010, *2009 Victorian Bushfires Royal Commission: Final Report Summary*. State Government of Victoria, Melbourne.

Translating Science Into Practice: Building Networks And Landholder Capacity

Craig Welden*
South East Queensland Fire and Biodiversity Consortium
Brisbane, Queensland, Australia.
cwelden@seqcatchments.com.au

Samantha Lloyd
South East Queensland Fire and Biodiversity Consortium
Brisbane, Queensland, Australia.
slloyd@seqcatchments.com.au

Introduction

Sustainable and effective land management is a constant juggle, trying to manage a range of competing threats, obligations and assets. Fire, being both a positive and negative force in the Australian landscape, is one of the most challenging land management issues. Dangerous bushfire weather is set to worsen with climate change, in particular the number of high risk fire weather days and fuel accumulation (Hughes and Fenwick, 2015, Steffen and Fenwick, 2016). This places landholders under increasing pressure, with the majority of bushland in Australia in private ownership and/or management and not managed by state or federal agencies (e.g. approximately 93% of land within Queensland is in private ownership and/or management) (Geoscience Australia, 1993). The key to better managing this growing threat is working in partnership with private landowners to support effective programs that translate science into practice for beneficial onground fire management, biodiversity and agricultural outcomes. There is a great deal of knowledge out there in the community, and as scientists and land managers we need to get a lot better at building trust and initiating partnerships that empower land managers and allow for improved, sustainable management of fire in the Australian landscape.

The South East Queensland Fire and Biodiversity Consortium (SEQ Fire and Biodiversity Consortium) was established in 1998 and aims to translate science into practice for improved fire management, fire ecology and biodiversity conservation in south-east Queensland (SEQ) through education, engagement, applied research and representation. The SEQ Fire and Biodiversity Consortium is hosted by SEQ Catchments (the regional Natural Resource Management NRM body for South East Queensland), is supported by a further 17 organisations (local government, state government and utility) and is non-government. This sponsorship model supports 18 long-term partnerships and has resulted in numerous collaborations and networks supporting government land managers, private landowners, utility providers, Traditional Owners, students and researchers.

Figure 1 Rural Fire Service Queensland (RFSQ) Voluntary Community Educators demonstrating fire behaviour and spread with the use of the RFSQ portable fire simulator. Photo C. Welden

The SEQ Fire and Biodiversity Consortium provides a range of very popular services and products for its supporting organisations (and their respective land holders), including one-day forums (a mini-conference), a weekly *E-news* service, research paper reviews, a Research Student Scholarship Program and one day private property Fire Management Planning Workshops (Figures 1, 2 and 3). Since 2010, the SEQ Fire and Biodiversity Consortium has delivered ten forums to over 1000 attendees, devolved $10,000 in funds to four research students and delivered 55 workshops and talks to approximately 1370 participants in eleven local government areas. This paper looks specifically at the importance, function and potential of the private property Fire Management Planning Workshops to engage with stakeholders, share knowledge, build partnerships and better integrate science, conservation and fire management practices for improved landholder capacity and ongound outcomes.

Figure 2 SEQ Fire and Biodiversity Consortium Property -level Fire Management Planning Workshops are attended by a broad range of people and presenters including Rural Fire Service Queensland personnel and Local Government Officers. Photo C. Welden

Prevention and Preparedness

Prevention and preparedness are the first two areas of operation of The Comprehensive Approach to risk management, known as the Prevention Preparedness Response and Recovery (PPRR) model (Rogers, 2011). The PPRR model has been used by emergency services across Australia for decades, with much success. Australian communities and government agencies are very good at response and recovery, but there is much more work to do with respect to prevention and preparedness. This is especially true for private landholders, who despite their best efforts may not always have access to information or support services (The State of Queensland. Queensland Audit Office, 2014, Shindler et al., 2009) While it is recognised that actions of prevention and preparedness will not necessarily prevent bushfires, these actions may lessen the impacts on life, property assets and the environment (Halliday et al., 2012). It is the experience of the SEQ Fire and Biodiversity Consortium, that despite a willingness and enthusiasm to learn (which is duly acknowledged), many landholders have a lack of understanding and capacity to carry out effective fire management planning or other prevention measures (namely hazard mitigation for bushfire) (Halliday et al., 2012, Gooding et al., 2014). Yet this is vital with respect to effective sustainable fire and land management, and biodiversity conservation at both the property and catchment level..

Our Workshops

The SEQ Fire and Biodiversity Consortium Property Level Fire Management Planning Workshops are delivered in partnership with relevant agencies and aim to assist landholders and land managers to reduce the threat from bushfires, whilst understanding the vital role of fire in Australian bush and at the same time conserving the diversity and abundance of native plants and animals. The workshops are an intensive seven hours and provide landholders with:

- information on fire behaviour, fuels, safety (QFES Prepare, Act, Survive campaign), permits, land management, ecology, fire regimes (i.e. season, frequency, intensity and extent);
- the necessary maps and information to develop a fire management plan for their property;
- the relevant contacts within their local council and Rural Fire Brigade; and

- Improved confidence and capacity to undertake fire management planning within the context of sustainable land management.

(adapted from Jakes and Sturtevant, 2013).

Table 1. The SEQ Fire and Biodiversity Consortium Property-level fire management planning workshops provide participants with the necessary tools to create property maps and break their properties up into management zones. Participants are then asked to consider actions required for each of these management zones that are then put into a work plan. The property-level fire management workshops are intended to “fit easily” into a Sub-catchment Fire Management Planning process.

Specifically, the SEQ Fire and Biodiversity Consortium Property Level Fire Management Planning Workshops provide landholders with the relevant information on prevention and preparedness and facilitate their understanding of the impacts of these measures on “whole of landscape” bushfire mitigation (see table 1). Moreover, the workshops assist landholders in their understating of the role of fire in supporting biodiversity conservation and maintaining heathy ecosystems at a local, catchment and landscape scale. Recent research has found that people who plan for bushfires are more likely to implement prevention measures that may lessen the impacts on life, property assets and the environment (Gooding et al., 2014, Eriksen and Gill, 2010). The significance of the environmental benefits of these efforts are widely acknowledged but few programs have the resources or capacity to measure these outcomes (with the exception of the NSW Hotspots Fire Project).

Fire Management Planning and Sustainable Land Management

One of the key threatening processes to biodiversity conservation is either too frequent fire to infrequent fire. We have found though our property-level fire management planning workshops, that the majority of participants do not use fire as a tool, consequently some vegetation types on these properties may be suffering from too infrequent fire. Just over the border in New South Wales, results from a study in Byron Shire (Baker and Catterall, 2015) have challenged the belief that high frequency fire dominates the landscape, and they have found vegetation change as a result of lack of fire.

For most landholders, fire is but one element in land management. Land holders and land managers alike must consider other time competing, but often complimentary, areas of action including weeds, pests, erosion, protection of biodiversity assets,(Halliday et al., 2012). It has been recognised that fire management workshops that integrate "whole of land management" strategies, such as fire and weeds, improve outcomes for land managers and also assist with bushfire risk reduction strategies (Jakes and Sturtevant, 2013). Moreover, programs that incorporate fire management into catchment level sustainable land management extension programs, such as the SEQ Fire and Biodiversity Consortium Property Level Fire Management Planning Workshops and SEQ Catchments' Coordinated Fire Management Planning, assist in hazard identification, subsequent bushfire mitigation planning and allow for facilitation of catchment level fire management planning that compliment agricultural, peri-urban and conservation values.

Figure 3 RFSQ Voluntary Community Educator (RFSQ VCE), Jan Blok and Craig Welden assisting landholders in creating a fire management map of their property. Photo, Nadine Anderson (RFSQ VCE)

References

BAKER, A. G. & CATTERALL, C. 2015. Where has all the fire gone? Quantifying the spatial and temporal extent of fire exclusion in Byron Shire, Australia. *Ecological Management & Restoration,* 16**,** 106-113.

ERIKSEN, C. & GILL, N. 2010. Bushfire and everyday life: Examining the awareness-action 'gap' in changing rural landscapes. *Geoforum,* 41**,** 814-825.

GEOSCIENCE AUSTRALIA. 1993. *Land Tenure Australia* [Online]. Available: http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_a05f7892-b790-7506-e044-00144fdd4fa6/Australian+Land+Tenure+1993 [Accessed 31/03/16 2016].

GOODING, O., STEVENSON, I., ANDREWS, L., PARKER, W., WOUTERS, M., WELDEN, C. & GREIVE, B. Where Red Meets Green, Balancing Fire Risk and Biodiversity in an Urbanising Landscape using a comparison of Interstate Programs. AFAC14 After Disaster Strikes, Learning from Adversity., 2014 Wellington. Bushfire and Natural Hazards CRC, 52.

HALLIDAY, L. G., CASTLEY, J. G., FITZSIMONS, J. A., TRAN, C. & WARNKEN, J. 2012. Fire management on private conservation lands: knowledge, perceptions and actions of landholders in eastern Australia. *International Journal of Wildland Fire,* 21**,** 197-209.

HUGHES, P. & FENWICK, J. 2015. The Burning Issue: Climate change and the Australian bushfire threat.: Climate Council of Australia.

JAKES, P. J. & STURTEVANT, V. 2013. Trial by fire: Community Wildfire Protection Plans put to the test. *International Journal of Wildland Fire,* 22**,** 1134-1143.

ROGERS, P. 2011. Development of Resilient Australia: enhancing the PPRR approach with anticipation, assessment and registration of risks *Australian Journal of Emergency Management, The,* Volume 26

SHINDLER, B. A., TOMAN, E. & MCCAFFREY, S. M. 2009. Public perspectives of fire, fuels and the Forest Service in the Great Lakes Region: a survey of citizen–agency communication and trust. *International Journal of Wildland Fire,* 18**,** 157-164.

STEFFEN, W. & FENWICK, J. 2016. The Hottest Year on Record (Again). . Climate Council of Australia.

THE STATE OF QUEENSLAND. QUEENSLAND AUDIT OFFICE 2014. Bushfire prevention and preparedness. Brisbane The State of Queensland.

Trials, Tribulations and Triumph: Lessons Learnt from Tenure-blind Fuel Reduction in Tasmania.

Sandra Whight
Tasmania Fire Service, Hobart, Tasmania, Australia, sandra.whight@fire.tas.gov.au

Introduction

Fuel-reduction burning is a recognised technique for reducing the rate of spread and intensity of bushfires, minimising damage, and provide fire-fighters with safe opportunities to contain and extinguish future fires. Burning is considered the most cost-effective tool available for managing broad areas of vegetation fuel loads in the landscape. Consequently most state and territory governments in Australia have policies and programs around burning.

In response to the Victorian Bushfires Royal Commission (Teague *et al*, 2010), the State Fire Management Council Tasmania was tasked to analyse the extent and effectiveness of Tasmania's fuel reduction burning. Building on work pioneered by the then Department of Environment and Primary Industries Victoria (2013), a comprehensive bushfire risk assessment for Tasmania was undertaken which tested the effectiveness of different approaches to bushfire risk reduction through fuel reduction burning (State Fire Management Council 2014). The subsequent report to the Tasmanian government recommended a strategic, tenure-blind approach to treating fuel in the landscape. The timing of this advice combined with a change in Government, who by policy committed to a four year whole-of-government, tenure-blind strategic fuel-reduction program.

The overarching objective of the program is to reduce the bushfire risk to Tasmanian communities. Subordinate objectives are to: target fuel reduction on areas that have the maximum risk reduction benefit to Tasmanian communities; facilitate local level involvement in identifying target areas for fuel reduction; build capacity in fuel reduction in both the public and private sectors; and, improve public understanding of matters relating to fuel reduction. After 18 months of implementation, there are lessons to share from the Tasmanian experience. This program has required a cultural change not only for the broader public, but also the agencies engaged to deliver it. Considerable effort has been spent engaging with the community, working with private land owners to not only access their land, but set fire to it. How are priorities determined in a transparent way? How do you manage different legislative challenges, land use values, and the breadth of opinions ranging from those who favour no burning, to those for whom there will never be enough?

The challenge of complexity

There is a reason why planned burning largely takes place on public land. Operational challenges aside, it is simpler and relatively straight-forward – the land management objectives are clearly defined and responsibilities and accountabilities generally well defined in either management plans or legislation. Prior to the commencement of this program, not unexpectedly the majority of burning was occurring on public land, often for purposes other than community risk reduction (though certainly not always), and in areas that are remote from communities.

In Tasmania 42% of treatable fuels are on private land, and these areas also present some of the greatest bushfire risk to communities (State Fire Management Council, 2014). Burns remote from interface zones are typically less complex and less expensive when compared to burning that occurs in close proximity to communities. Therefore a strategically planned fuel reduction burning program based on community risk reduction required resourcing over and above historical levels – and 28.5 million dollars over four years was committed by government to implement their fuel reduction policy. Looking at the experiences from interstate, it was apparent that it takes approximately three years to build up an expanded fuel reduction burning program. Furthermore, an ongoing and long-term commitment is required to effectively reduce long-term bushfire risk – so demonstrable success is required in the first four years to justify future funds. As a whole-of-government program the governance structure has not been straight-forward. A high level steering committee has been established, which reports to 3 Ministers – though one Minister has been clearly identified as accountable. The finances and project manager sit in one Department, whilst the operational team sits within another.

Figure 1 is a schematic of the planned burning process. What is notable from this diagram is how actually "setting fire to the bush" is only one step in a detailed process. Yet this is often the primary focus of community expectations and performance indicators.

The challenge of managing expectations

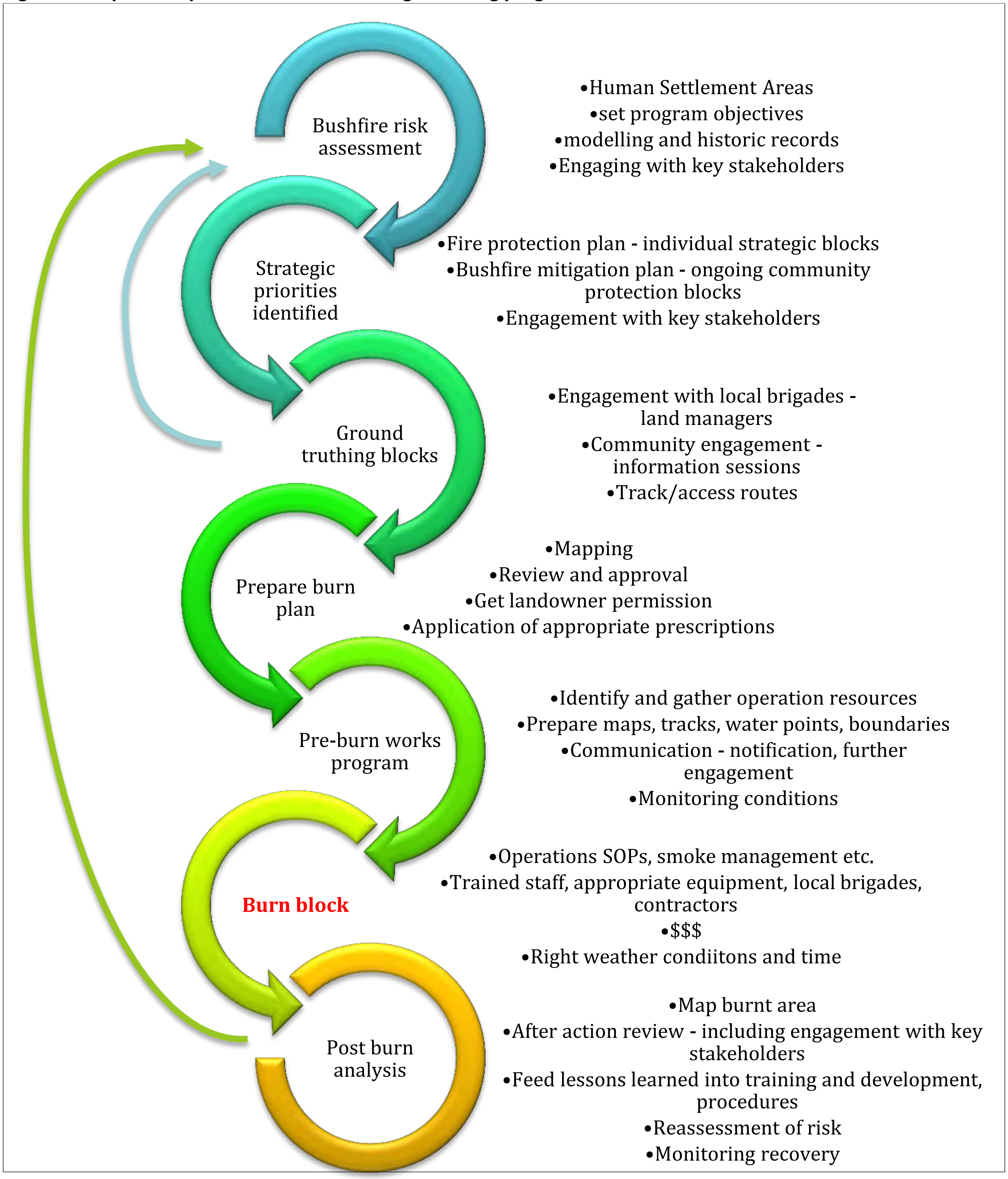
In Figure 1, the first 4 steps are the most time consuming, and one of the most critical part of the whole program is the stakeholder and community engagement. The best planned and operationally sound program can still fail if its objectives are poorly communicated and the concerns of the community and key stakeholders are not appropriately addressed.

A comprehensive engagement program has been required. Some of the key issues that have required consideration (any many are still works in progress) include:

- community acceptance of an expanded planned burning program
- determining priorities across multiple tenures and multiple land managers
- explaining the limitations of different mitigation activities; some areas will always be prone to high bushfire risk even after all mitigation options have been implemented
- access to private lands to undertake risk mitigation activities
- liability, authority and accountability for when burns escape, as well as reopening areas for access and use
- smoke and public health impacts
- the effects of an expanded fuel reduction burning program on other burning programs that are regulated by smoke restrictions – yet have very different objective (eg silviculture)
- the visual impacts of smoke and charring in the landscape, including their effects on tourism
- balancing risk mitigation actions with environmental impacts; and
- workforce capacity to implement a program of this scale.

While some legislative tools and policies were already in place, an implementation framework and business plan was developed that endeavoured to build on collaboration, cooperation, and a whole-of-community acceptance of bushfire risk. It is fair to say there have been mixed successes in this area – a program of this nature is bringing cultural change and that is a process that can't be rushed. However, from the outset it was necessary to kick early goals whilst simultaneously building: a new team; relationships both internally and externally; and, capacity across the whole fire management sector.

Figure 1: Steps for implementation of a strategic burning program.



The challenge of setting priorities
The agencies most closely involved in bushfire management in Tasmania are the Tasmania Fire Service, Forestry Tasmania and the Parks and Wildlife Service. An Inter-Agency Fire Management Protocol is signed each year that is effectively the operating agreement between the three agencies. The protocol underpins the cooperation that exists between the agencies to ensure the suppression and management of bushfire in Tasmania is safe, efficient and cost-effective. Through this arrangement there is collaboration in: training; identification of risk and mitigation; some planned burning operations; and, bushfire suppression. In addition to the three main agencies, bushfire prevention and response activities are also undertaken by private land owners, private forest companies, contractors, and some local governments (for example Hobart City Council). These groups are important partners in bushfire management in Tasmania, and particularly with the forest contractors, undertake the same training and use the same incident management systems for bushfire suppression.

The State Fire Management Council is an independently chaired council provided for under Section 14 of the *Fire Service Act 1979*, with its functions set out in Section 15 of the Act. The Council brings together representatives of the Tasmanian Farmers and Graziers Association, the Local Government Association of Tasmania, the Forest Industries Association of Tasmania, Forestry Tasmania, the Tasmania Fire Service, and the Parks and Wildlife Service; under an independent chairperson. Reporting to the Council are 10 Fire Management Area Committees, for the state with boundaries based on bushfire risk and topography, largely aligning to local government boundaries. The focus of these committees is to prepare a fire protection plan for their area, through the identification and prioritisation of bushfire vegetation risks, and prioritisation of strategic works to mitigate these risks. The approach undertaken within these committees is tenure blind, and it is through these groups that priorities are identified.

The risk modelling work as outlined in the introduction provides the risk context for prioritising mitigation activities. The results of the analysis can be used to identify the most effective areas for strategic mitigation programs, and to underpin Fire Management Area fire protection plans. Within the committees there is a place for modification and negotiation of these priorities, as consideration is given to local knowledge and more detailed localised plans; including Community Bushfire Mitigation Plans, area specific fire protection plans and Community Protection Plans.

It is fair to say that it is still early days. Fire Management Area Committees in their current form have only been in place for 2 years. A long term commitment has been made to implement a centrally coordinated fuel reduction burning program that incorporates the entire fuel reduction burning management process, including an ongoing commitment to improve strategic selection of burning priorities.

The challenge of burning on private land
One of the largest challenges in this area is the time it takes – to build trust, relationships, manage legitimate land owner concerns, assess each property and clearly explain the burning process. It is through engagement we have been able to gain permission to burn on private land – the largest block achieved to date has been 700 hectares within 20km of Hobart. The landowner in this situation was aware of their responsibility to the community to manage the risk, and

welcomed participation in the fuel reduction program. Endangered species present on the block were managed through good planning, close liaison with threatened species experts and using an appropriate lighting strategy. Most landowners have responded with similar support. Not all though, and at this stage there is enough to be done that staff move on. There are legal instruments that can be applied to force involvement, however this approach is considered at odds with the program objectives and not a constructive approach to encouraging community participation.

Considerable time has been spent working through the legal questions that arise when burning on freehold land. In particular the questions associated with liability protections to employees, the authority by which such burning can be undertaken and who pays for inadvertent damage that might occur.

The liability protections for employees are relatively straight-forward. As is usual in the workplace, staff (volunteers, etc) working in the course of their employment (e.g. carrying out a burn) and acting in good faith will not be personally liable for damage they cause. If they are negligent, their employer will usually be vicariously liable for the damage.

The *Fire Service Act 1979* is the principal piece of legislation that applies when considering liability (in particular section 121), and there are powerful protections in place protecting the Tasmania Fire Service from damages which have been tested in some of the highest courts in Australia. However, a more conciliatory approach has been taken to entice private land owners to give consent to a fuel reduction burn on their land. A written agreement is entered into with the land owner, where the fire agency burning commits to pay for specified inadvertent damage – and a pre-burn property assessment is undertaken that is signed by both parties. It is not a perfect solution, and there is a measure of risk involved and need for trust between all parties. This risk however must be balanced against the larger risk of doing nothing, and dealing with the consequences of bushfire impacts instead.

Conclusion

After only 18 months, there is still a long way to go with this program. This paper only touches on the challenges that are still being overcome. The number one lesson though is the importance of engagement – across every level. There will always be challenges, and rather than letting these be the reason to stop, it is important to take the time to keep talking, listening and working through each issue as it arises.

References

Department of Environment and Primary Industries (2013) Victorian Bushfire Risk Profiles: A Foundational Framework for Strategic Bushfire Risk Assessment (Victorian Government, Department of Environment and Primary Industries. East Melbourne).

Teague B, Mcleod R, Pascoe S. (2010) The 2009 Victoria bushfires Royal Commission Final Report. (Government Printer for the State of Victoria. Melbourne)

State Fire Management Council (2014) Bushfire in Tasmania: A new approach to reducing our statewide relative risk. (Tasmania Fire Service. Hobart, Tasmania)

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User oriented verification of fire spread models

Paul Fox-Hughes*
Bureau of Meteorology, Hobart, Tasmania, Australia, p.fox-hughes@bom.gov.au
Nathan Faggian
Bureau of Meteorology, Melbourne, Victoria, Australia, n.faggian@bom.gov.au
Chris Bridge
Bureau of Meteorology, Melbourne, Victoria, Australia, c.bridge@bom.gov.au
Elizabeth Ebert
Bureau of Meteorology, Melbourne, Victoria, Australia, e.ebert@bom.gov.au
Howard Jacobs
Bureau of Meteorology, Melbourne, Victoria, Australia, h.jacobs@bom.gov.au
John Bally
Bureau of Meteorology, Hobart, Tasmania, Australia, j.bally@bom.gov.au

Introduction

The Bureau of Meteorology is undertaking a project to evaluate the performance of a number of fire predictive models in use, or in development, in Australia. The evaluation aims to identify strengths and weaknesses of the models being studied, and to establish standardisation of both evaluation framework and test data sets. This will assist in the development of a robust and defensible transition into operational use of new models and new versions of existing models.

Fire behaviour models have become an important part of the response to bushfires in Australia and in other fire-prone regions, used to enhance the protection of communities and of assets, both natural and human. They have also assumed an important role in risk assessment and pre-season management activities. The degree of sophistication of such models varies dramatically from simple algorithms through to complex, fully coupled three dimensional fire-atmosphere models. The latter, with currently available hardware, cannot run in real-time and so most agencies employ empirically-derived fire spread models (Sullivan 2009).

There are a number of spatial fire behaviour models currently used in Australia, developed for different environments and under different circumstances, employing several algorithmic approaches. Australis was developed in Western Australia, and uses a cellular automata approach to fire spread (Johnston et al. 2008), while Phoenix models fire spread using the Huygens' wavelet principle, and is most frequently used in south-eastern Australia. Prometheus (Tymstra et al. 2010) was developed for Canadian conditions, employing the same underlying approach as Phoenix, but with a different fuel model. It has been applied in New Zealand and in some parts of Australia, particularly Tasmania. Recently, the Spark fire simulator framework has been developed to allow the application of different fire/fuel models for different situations, based on a level-set approach (Hilton et al. 2015).

While such fire predictive models have been introduced as additional guidance into operational use in many jurisdictions, there has been no clearly defined process for operational acceptance. New versions of models are sometimes introduced, without a clear statement of the degree to which they are an improvement over previous versions, and there has been no objective assessment of whether a particular model is superior to others in particular circumstances, or that the model and its operating environment are sufficiently robust to support critical decision-making. There is now a general recognition that a clearly defined, objective and defensible process is required for the testing of fire predictive models prior to their introduction into operations, as is the norm in many other software development domains. As a result, the New South Wales Rural Fire Service, with support of the Australasian Fire and Emergency Services Council (AFAC), has requested the Bureau of Meteorology to conduct an evaluation of the performance of the four predictive models or frameworks mentioned above, to identify a standard approach to verification of fire predictive models and to commence the collation of a set of standard case studies against which future models can be evaluated and improved. This paper describes the progress to date towards these goals.

The paper is structured as follows. We first identify the various types of data that are available and required to complete a suitable evaluation of model performance. We then briefly discuss the type of metrics that can assist in the evaluation process, informed largely by recent fire-spread simulator literature. We highlight the difficulty of fairly comparing quite different models, developed for different circumstances, and, finally, point to possible future approaches to data and evaluation of fire predictive models.

Data

A number of data types are generally required to model fires and to evaluate the modelling software. Topography, fuel type and load, and weather data are necessary, at least (Chong et al. 2012, Kelso et al. 2015). There are, as is to be expected, uncertainties with each of these input layers, and there has been a lack of standardisation of fuel classification across jurisdictional boundaries (see e.g. Gould and Cruz 2012). For all events which may be used as evaluation test cases, we will have available weather data (otherwise the events would not be considered), and for some events there is very high resolution modelling of the weather available. Ironically, however, such very high resolution data (with grid size of the order of 440m) may not be the most suitable for evaluation as large fires influence the surrounding atmosphere, changing the winds compared to conditions without a fire present (Chong et al. 2012). In addition, there will have to be careful assessment of areas previously burnt, and of areas burnt as part of fire suppression (back burning, for example).

The project aims to evaluate model performance over at least ten cases, across a range of environments and, ideally, at different levels of fire severity. Fire managers across Australia have been requested to put forward cases that they believe would provide a useful test of the fire predictive models, and for which adequate supporting data is available.

In selecting cases for the evaluation, the quality of the underlying data sets has been ranked by the data custodians according to reliability ratings suggested by Cruz et al. (2012) to attempt to identify cases for which the best-quality data is available.

Key to the evaluation process, of course, is the availability of fire activity data, against which model fire predictions can be compared. Fire predictive models may output a variety of fire behaviour, including rates of spread, fire intensity, flame height and level of spotting. Because of operational pressures during going fires, however, fire behaviour data is generally not routinely recorded, and only the fire boundary position is available at different times during the course of a fire. This paucity of data is particularly evident when the fire is predominantly fuelled by grass, as such fires usually run very rapidly. As with the earlier datasets discussed, however, boundaries may be recorded with varying degrees of accuracy. Particularly in fast-moving fires, fire position may be estimated from verbal reports or other indirect sources. The definition of the fire boundary itself can sometimes be confusing, as fires spot ahead of a main fire front, and burn into previously untouched areas to its rear. Aircraft line scans are generally held to be the best-quality data for locating fire boundaries, however even these can be misleading, occasionally identifying hot smoke ahead of a fire as the surface-active fire zone. For the purposes of the project, we will define the fire boundary as that which agency fire behaviour analysts have identified as most likely, often by reconstruction of the most likely fire boundary at different times during the progression of the fire. Given the paucity of data on other fire behaviour characteristics, we will not attempt to verify other outputs of fire predictive models in this initial project.

Another form of data important for the project is information on the modes of use by fire agencies of fire predictive models. Unless the evaluation of models is focussed on the ways that they are actually used, that evaluation will be at best of limited value (Murphy 1993). The project team have generated a number of core use case flowcharts in discussion with RFS staff (Fig. 1), validated in discussion with managers from other jurisdictions at a workshop held at RFS headquarters in February 2016.

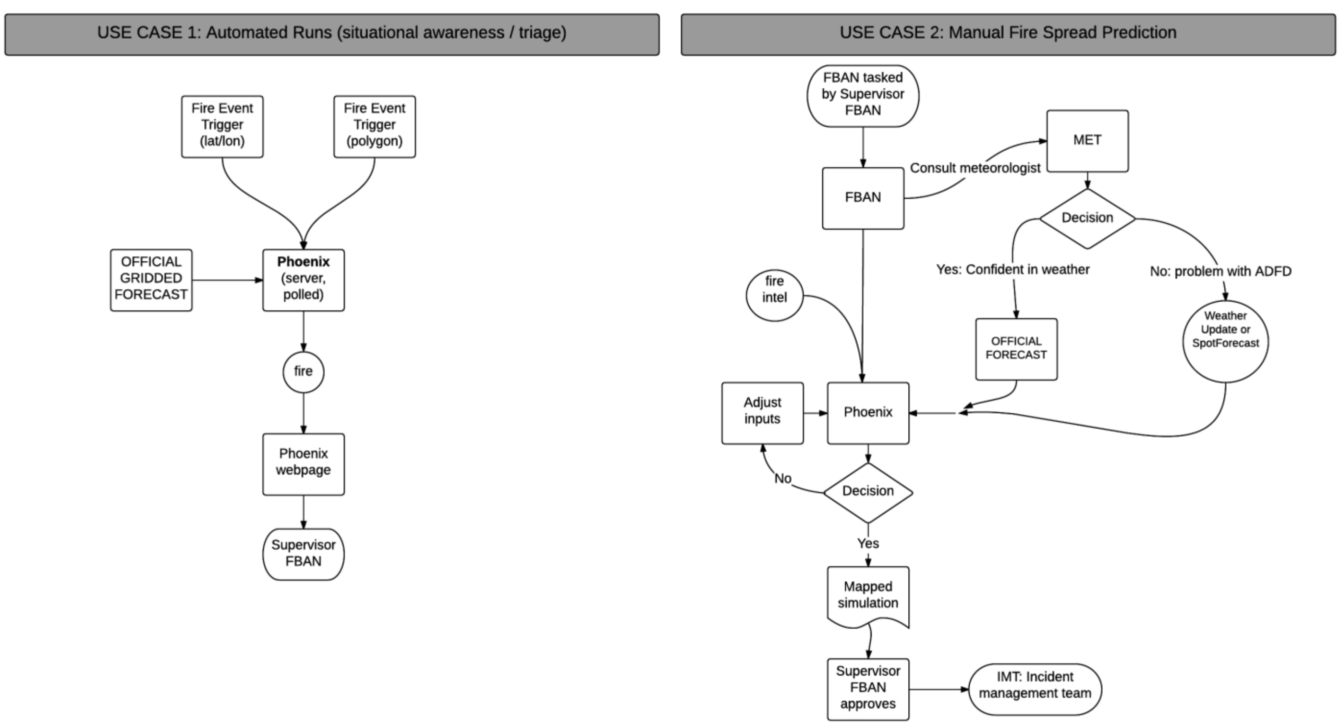

Figure 1. Samples of use cases for fire predictive models: (1) automated runs to assess the need for further investigation by fire behaviour analysts, and (2) more detailed analysis of individual fires, with input from fire weather meteorologists.

Metrics

Early attempts to validate fire predictive models used quite simple metrics. There has been more recent work on validating the performance of individual models, using a range of metrics both in Australia (e.g. Duff et al. 2012, Kelso et al. 2015) and Europe (Fillippi et al. 2014), some of which were developed specifically for fire behaviour studies, such as the arrival time agreement and shape agreement (Fillippi et al. 2014) and Procrustes-based metrics (Duff et al. 2012). Spatial verification of forecasts has occurred in other fields as well, including weather forecasting of rainfall (e.g. Ebert 2008). Some metrics developed in this area may be applicable to the fire spread case although as Duff et al. (2012) note, nature of the initiation and spread mechanisms are somewhat different.

It is unlikely that any single metric will be sufficient to evaluate the range of fire behaviour or meet the requirements of fire agency staff for information on models performance. The project will start with simple metrics such as the Area Difference Index (ADI, Chong et al. 2012, Figure 2), which measures the disagreement between the predicted and observed fire areas. Through a process of testing and stakeholder consultation, additional metrics will be selected. Use of an appropriate range of metrics, together with a broad choice of test cases across a range of environments, will ensure that the model inter-comparison is fair.

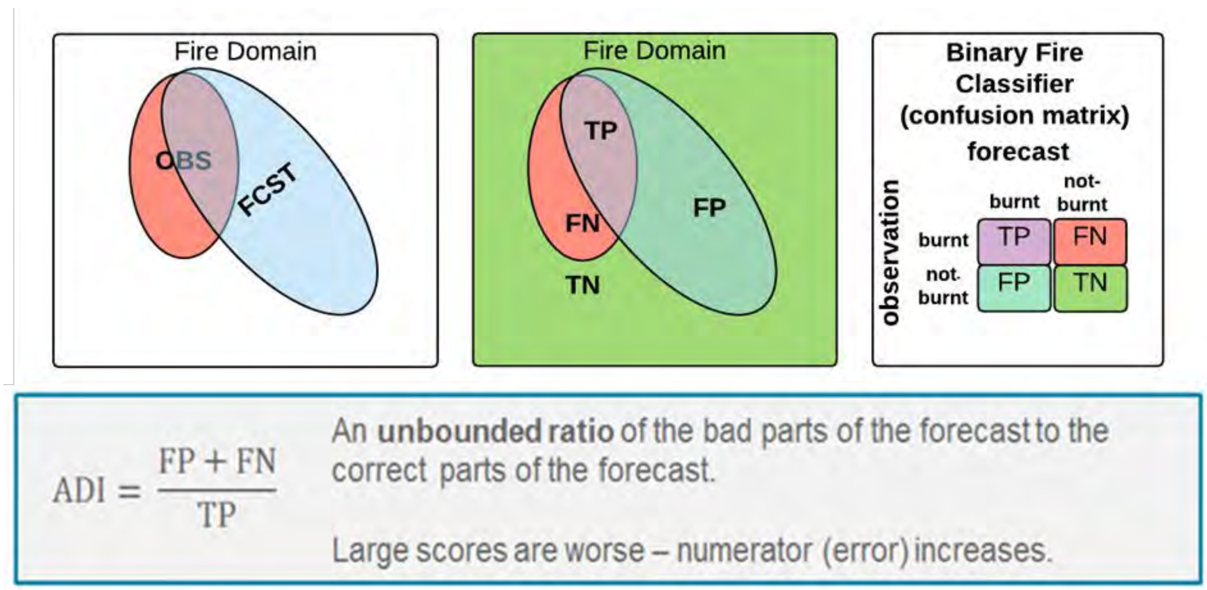

Figure 2. Definition of the Area Difference Index (ADI). The left-hand top image shows idealised observed and modelled fires, the middle image shows the same, but with a fire domain defined, and ADI regions defined. The top-right image shows the classification matrix for the ADI, and the bottom panel displays the ADI formula with an explanation of its range. TP, FP, FN, and TN refer to true positive, false positive, false negative, and true negative, respectively.

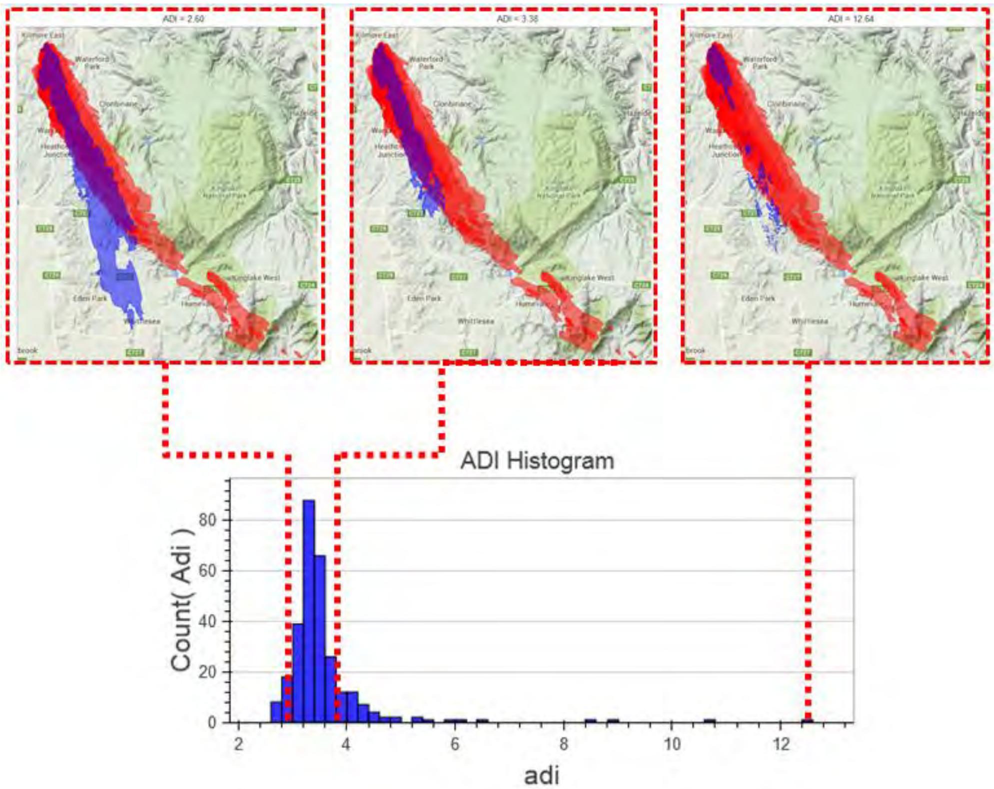

Figure 3. Exploratory analysis of Phoenix ignition point sensitivity for the Black Saturday 2009 Kilmore East fire. Best, average and worst fire scars (blue) are illustrated in comparison to the actual (red) fire. Their positions are shown on a histogram of ADI values computed for 300 ignition locations randomly varied on a 100m radius of the accepted ignition point. Results are very preliminary, illustrating some of the approaches to evaluation to be explored.

Further, we will test the sensitivity of fire predictive models to variation in a number of input parameters. For example, initial testing of Phoenix shows considerable sensitivity to ignition location (Figure 3), as a result of the ignition point's proximity to a potential barrier to development (a road). We will also document the features of each of the models being evaluated, as a guide for users, e.g., whether the model includes a spotting capacity, and approaches to downscaling weather and other data.

Discussion

The fire predictive services evaluation project is still in its initial stages. We are accumulating data for a test set of (at least) ten case studies. We are examining currently used evaluation metrics, and assessing whether we can contribute usefully to that area (for example, it may be worth defining "fuzzy" metrics, where the success of fire simulations is weighted higher if they are close to observed fires, even if the overlap between simulation and observation is not high). We have established an evaluation framework, where hundreds of simulations can be run simultaneously, to permit an assessment of simulation sensitivity to initial conditions. There is still much to be done, however, and we look forward to a constructive engagement with simulation developers and fire practitioners to provide an initial benchmark of the current state of fire predictive modelling in Australia.

References

Chong, D, Duff, T Tolhurst, K (2012) 'Evaluation of weather data at different spatial and temporal scales on fire behaviour prediction using PHOENIX RapidFire 4.0 – Kilmore Case Study'. Bushfire CRC Technical Report. (Melbourne, VIC)

Duff TJ, Chong DM, Taylor P, Tolhurst KG (2012) Procrustes based metrics for spatial validation and calibration of two-dimensional perimeter spread models: A case study considering fire. *Agricultural and Forest Meteorology* **160**, 110-7.

Ebert EE (2008) Fuzzy verification of high-resolution gridded forecasts: a review and proposed framework. *Meteorological Applications* **15**, 51-64.

Filippi JB, Mallet V, Nader B (2014) Representation and evaluation of wildfire propagation simulations. *International Journal of Wildland Fire* **23**, 46-57.

Gould J, Cruz M (2012) Australian Fuel Classification: Stage II. CSIRO Ecosystem Sciences and Climate Adaption Flagship Report No. EP126505. (Canberra, ACT)

Hilton JE, Miller C, Sullivan AL, Rucinski C (2015) Effects of spatial and temporal variation in environmental conditions on simulation of wildfire spread. *Environmental Modelling & Software* **67**, 118-27.

Johnston P, Kelso J, Milne GJ (2008) Efficient simulation of wildfire spread on an irregular grid. *International Journal of Wildland Fire* **17**, 614-27.

Kelso JK, Mellor D, Murphy ME, Milne GJ (2015) Techniques for evaluating wildfire simulators via the simulation of historical fires using the AUSTRALIS simulator. *International Journal of Wildland Fire* **24**, 784-97.

Murphy AH (1993) What is a good forecast? An essay on the nature of goodness in weather forecasting. *Weather and forecasting* **8**, 281-93.

Sullivan AL (2009) Wildland surface fire spread modelling, 1990–2007. 2: Empirical and quasi-empirical models. *International Journal of Wildland Fire* **18**, 369-86.

Tymstra C, Bryce RW, Wotton BM, Taylor SW, Armitage OB (2010) Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Northern Forestry Centre Information Report NOR-X-417. (Edmonton, AB)

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Using bushfire characterisation to foster shared responsibility in a high risk community

Suriya Vij*
Department of Environment, Land, Water and Planning, Melbourne, Victoria, Australia,
suriya.vij@delwp.vic.gov.au

Context

People are increasingly inhabiting fire-prone landscapes in Australia as well as the United States of America and elsewhere around the world (Moritz *et al.* 2014). Fires are increasing in size, occurrence and frequency due to the negative effects of climate change in these areas. Studies show that more and larger fires are already occurring with unprecedented fire behaviour, and this trend is predicted to continue (Clarke *et al.* 2011; Liu *et al.* 2013; Kalabokidis *et al.* 2015). The negative impacts of fire, then, are becoming increasingly common so that living with bushfire is more difficult (Moritz *et al.* 2014).

Responsibility for increased risk to human lives must be shared between government and the people at risk. To be able to share responsibility with a community, agencies must get to know that community and understand its diversity, resources, vulnerabilities, values and people. One approach is to integrate planning, fuel management, fire suppression, building standards, and knowledge of fire and ecosystem dynamics together with agency and community knowledge and values (Moritz *et al.* 2014).

Warburton is located along the Yarra River, about 70 km east of Melbourne in Victoria, Australia. It is a stunning location nestled between mountain ranges covered with tall Mountain Ash (*Eucalyptus regnans*) trees and temperate rainforest. This topography and vegetation type also makes it a high bushfire risk area as there is potential for large, landscape fires with significant ember attack and convection. Additionally, since the town is surrounded by wet forest that is largely not suitable to treat with planned burning, risk reduction for Warburton needs to take a broader approach considering all mitigation options.

To share responsibility people must first share knowledge and education is key to this broader approach. This study aimed to combine bushfire scenario workshops with leading bushfire modelling technology in a multi-agency and community group environment in a novel approach to not only educate but to build lasting relationships, enable continuous learning and empower communities. Focusing education work in the Warburton area for this study was strategic. Firstly, as mentioned, it is a high bushfire risk area. Secondly, it is a location where a lot of successful bushfire education and development work had already been started by the Yarra Ranges Council. There was a great opportunity to build on this work and the existing strong relationships with the other emergency and government agencies and community groups in the area. The challenge was to go beyond the people who are already interested, engage the broader community and establish an environment where communities help to manage bushfire risk.

*address: 609 Burwood Highway, Knoxfield VIC 3180, email: suriya.vij@delwp.vic.gov.au, web: delwp.vic.gov.au

A process of learning through doing

A working group was formed and we created a four step process of developing bushfire knowledge and seeking community input with a bushfire scenario at the centre. This process built on several community events:

1. the annual Country Fire Authority (CFA) Brigade pre-season information session for the community,
2. a CFA bushfire planning workshop to create personal fire safety plans,
3. the bushfire scenario as an opportunity to test those plans, and
4. a follow-up session to help make sense of what happened at the scenario, whether their plan worked or not, and provide more information and space for discussion.

The key driver behind bringing agencies, government and community together was the bushfire scenario workshop. These scenarios have been done around Victoria, including in the Surf Coast Shire, and are consistent with good risk communication principles where the method of communication is key: the process is interactive; the practitioner strives to understand the context of the risk; information is honest, timely, accurate and reliable; uses credible sources and authority figures are used where appropriate; and communication occurs before and during a crisis, treating risk communication as a process (Steelman and McCaffrey 2013). Critically, the Warburton scenario used visual outputs from bushfire modelling programs to enable participants to 'live through a bushfire' and picture events as they unfold. The four step process incorporated ideas from bushfire simulations, strategic conversations, personal fire safety plans and community-based emergency management planning. The goal was to empower the community as well as provide information.

The Department of Environment, Land, Water and Planning (DELWP) uses Phoenix RapidFire bushfire simulation model (Phoenix) (Tolhurst *et al.* 2008) to simulate how a bushfire responds to changing fuel, terrain and weather inputs as it moves across a landscape. It has been tested and updated against data from real fire events such as the 2009 Black Saturday bushfires and is used to analyse the risk of bushfires across the state, including where the worst fires start, which areas are most impacted and where fires build intensity and convection. The aim is to better understand our bushfire risk so that we can better manage it. Phoenix can also be used as an excellent visual tool for discussing bushfire risk with the community. Phoenix facilitates a deeper connection and understanding of bushfire risk because it explicitly demonstrates the realism of an event, and thus how the event would impact people and what they value. It provokes great conversation and thought processes around personal safety, personal emergency planning and community emergency planning.

There were seven agencies and over a dozen people involved in the working group for this entire developmental process. These included DELWP, Parks Victoria, the local CFA Brigade, Regional CFA staff, the Warburton Emergency Planning Group (a community group), Victoria Police, VicSES and Yarra Ranges Council. There were additional groups that came in and out of the process as needed, like the Committee for Economic Development and Tourism Victoria. As a working group we identified the shared objectives for the scenario and what specifically we wanted to test.

The objectives were to:

- increase bushfire preparedness in a high risk area,
- clarify the roles of the different groups and agencies in a bushfire,
- build on existing bushfire information sources to consolidate learning,
- provide an opportunity for the community and agencies to learn through experience,
- promote individual ownership and develop shared responsibility between communities and agencies,
- demonstrate the workability of bushfire plans, and
- help people work through when their trigger is to leave.

We wanted the scenario to consider:

- a broader range of possible bushfire scenarios, as current education is largely focussed on Black Saturday,
- a possible fire scenario ignition at Launching Place/Don Valley, Mt Little Joe or Millgrove,
- that a fire could be caused by things other than arson or lightning, for instance by a welder, or your neighbour,
- a manageable and realistic situation, occurring on a day with weather conditions that occur every year,
- the possibility of multiple ignitions,
- the Millgrove fire refuge and how it may be affected during a fire, for instance traffic issues,
- the community safer place at the footy oval, as this is the first fire season that it has been in place,
- access issues such as the two bridges crossing the Yarra – and a potential bottle neck,
- consideration of community resources and capability,
- information sources during an event, in particular reinforcing which radio stations to listen to,
- difficulties in getting information – internet access, mobile phone blackspots. And what other ways can you get information?
- the effectiveness of people's plans by allowing time to talk through at the end whether people's plans worked or not, and why or why not. Did they have a Plan B, C, D?
- when do you stop the scenario? It would be good to include some bushfire recovery information and planning– what do you or agencies do after a bushfire?

As a result of these considerations, we selected a fire simulation that was at Forest Fire Danger Index of 50, a situation right on the border of Very High and Severe fire danger ratings that would occur multiple times per bushfire season. This bushfire would cut off Warburton Highway within a few hours of the fire starting – the only way in and out of Warburton. We did not want a scenario that completely destroyed Warburton and overwhelmed participants, rather one that empowered people to action. The scenario is shown in Figure 1.

The follow-up session was held three weeks later, to provide enough time for participants to reflect on and make sense of the scenario. It was designed to address the broad issues raised during the scenario and via a feedback survey received afterwards.

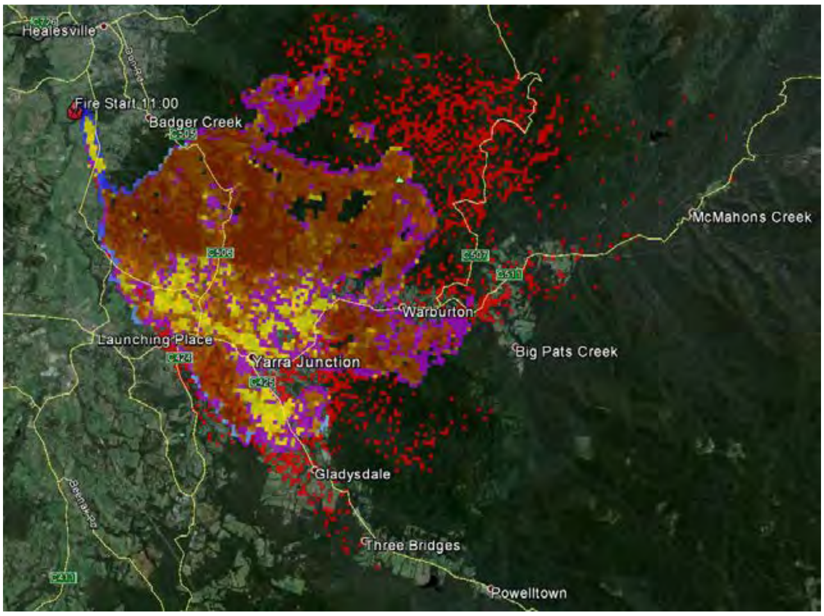

Figure 1: Phoenix RapidFire was used to simulate a bushfire impacting Warburton, Victoria, to help residents test their bushfire plans in a scenario session

Outcomes and discussion

In total 90 people attended the two identical scenario sessions, run on the same day – one in the afternoon and one in the evening. Participants mostly live in Warburton, with some coming from neighbouring communities such as Millgrove and East Warburton, and others from further afield such as Reefton and Healesville. Promotion of the sessions was through local channels, via Facebook pages of the Brigade and Emergency Planning Group, flyers, word of mouth and a variable message board in the main street of town. It was key to have locals involved who could speak to their friends and relatives about it, and the organisers also spoke with many people on the phone.

When creating the scenario, the working group realised that we were incorporating ideas that need further explaining, so we started with an overview of fire danger ratings and places of last resort, both of which sparked excellent questions and discussion. This allowed us to move smoothly through the scenario and focus on the flow of the story. A key benefit of the scenario approach is that it allows us to communicate a dynamic science by telling a story, and making it visual, interactive and experiential. It also enabled us to deliver a huge amount of information in a short space of time in a relevant, coherent and interesting way.

Feedback from the event was overwhelmingly positive, with comments such as 'it was an excellent session, the best and most realistic opportunity we have had to understand the risks we run.' Some participants reported that they had gone home and changed their personal fire safety plans. Participants better understood the emergency warning system and the need to leave early if they plan to leave. There were additional areas for discussion that participants wanted to cover and it also highlighted some of the shortcomings of the information and warnings systems in Warburton. Leaving time between events enabled us to build these topics into the follow-up session.

A key outcome of the scenario was that people were able to learn from each other – from people they trust, others in their community, as well as a whole panel of bushfire managers and experts. It has also contributed to building community trust in the agencies, which is key to social acceptability of the work we do (Olsen and Sharp 2013), in fire prevention, preparedness, response or recovery.

The follow-up session was run more on the principles of a strategic conversation. That is, understanding who is in the room, making connections and learning from each other, and talking about whatever is relevant to the group (Campbell *et al.* 2012). The issues discussed were:

- we will (stay and) survive; late leavers,
- is leaving early yesterday? Vulnerable people and those without cars,
- recovery this way,
- our community is prepared; communication; what are our neighbours doing?
- visitors in bushfire weather.

At the end of a workshop there is often pressure to identify actions and a person to be responsible for them, but in the real world everyone rarely agrees, the people in the room are not necessarily the ones to take action and sometimes further reflection is needed before action (McWaters and Moore 2016). Instead we asked the group, 'what happens next?' This open ended question prompted the slightly awkward space of shared responsibility – and some excellent ideas about what everyone can do, for example, speaking to someone about bushfire they haven't previously. The follow-up session provided the participants with the tools to take action themselves and the agency contacts to get things done, as well as influencing agencies' actions, for example through additional communication tools.

Conclusions

There are tenuous links between providing information and action. Risk communication programs typically assume that 'advising people of their risk and what they should do to manage that risk … will motivate people to act' (Smith 1993 in Paton *et al.* 2008, p. 41). However, the literature shows that this relationship is more complex (Kumagai *et al.* 2004; McCaffrey 2007) and depends on varying perceptions of risk, physical and social environments and personal characteristics (MacDougall *et al.* 2014).

The interactive, visual and experiential format of the scenario and follow-up session provided the space, information and tools to empower participants to make sense of their bushfire risk themselves and take action themselves, by working through the process and their own triggers and drivers.

This kind of work has been done well elsewhere too. We took the idea and built on it, incorporating fire conversations, simulations, Phoenix, personal fire safety plans and community-based emergency management planning. The difference here is that the goal was to empower the community to make change, as well as providing information. This was largely through lengthening the process to enable this change, that is, the pre-sessions and follow-up session.

However, collaboration is neither easy nor quick. For this scenario we built on opportunities and benefits created by existing relationships between agencies and with the community. This enabled the groups to provide a unified front and communicate science through a visual and interactive experience that enabled change in the community – individuals re-planning and understanding warnings; community educating each other and understanding what they need; and the emergency planning group linking effectively with agencies. The amount of effort is warranted by the long-term benefits, displaying shared responsibility in practice. DELWP will continue to use this type of approach focusing on communities at risk who are ready to talk in more detail about bushfire management in their area.

References

- Campbell, C, Campbell, M, Blair, S (2012) 'Guiding principles: Facilitating learning, understanding and change through relationships'. (Victorian Government Department of Sustainability and Environment, Melbourne)
- Clarke, HG, Smith, PL, Pitman, AJ (2011) Regional signatures of future fire weather over eastern Australia from global climate models. *International Journal of Wildland Fire* **20**, 550-562.
- Kalabokidis, K, Palaiologou, P, Gerasopoulos, E, Giannakopoulos, C, Kostopoulo, E, Zerefos, C (2015) Effect of climate change projections on forest fire behaviour and values-at-risk in southwestern Greece. *Forests* **6**, 2214-2240.
- Kumagai Y, Carroll, MS, Cohn, P (2004) Coping with interface wildfire as a human event: lessons from the disaster/hazards literature. *Journal of Forestry* **102(**6), 28-32.
- Liu, Y, Goodrick, SL, Stanturf, JA (2013) Future U.S. wildfire potential trends projected using a dynamically downscaled climate change scenario. *Forest Ecology and Management* **294,** 120-135.
- MacDougall, C, Gibbs, L, Clark, R (2014) Community-based preparedness programmes and the 2009 Australian bushfires: policy implications derived from applying theory. *Disasters* **38(**2), 249-266.
- McCaffrey, S (2007) Understanding public perceptions of wildfire risk. In 'Wildfire risk: human perceptions and management implications'. (Eds W Martin, C Raish, B Kent) pp. 11-22. (Resources for the Future, Washington DC)
- McWaters, V, Moore J (2016) 'Creative Facilitation'. (http://creativefacilitation.com/free-book)
- Moritz, MA, Batllori, E, Bradstock, RA, Gill, AM, Handmer, J, Hessburg, PF, Leonard, J, McCaffrey, S, Odion, DC, Schoennagel, T, Syphard, AD (2014) Learning to coexist with wildfire. *Nature* **515**, 58-66.
- Olsen, CS, Sharp, E (2013) Building community-agency trust in fire-affected communities in Australia and the United States. *International Journal of Wildland Fire* **22**, 822-831.
- Paton, D, Burgelt, PT, Prior, T (2008) Living with bushfire risk: social and environmental influences on preparedness. *The Australian Journal of Emergency Management* **23**(3), 41-48.
- Steelman, TA, McCaffrey, S (2013) Best practices in risk and crisis communication: Implications for natural hazards management. *Natural Hazards* **65**, 683-705.
- Tolhurst, KG, Shields, BJ, Chong, DM (2008) Phoenix: development and application of a bushfire risk management tool. *The Australian Journal of Emergency Management* **23(**4), 47-54.

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Using fire line geometry to model dynamic fire spread

Jason Sharples*
University of New South Wales, Canberra, Australia
James Hilton
CSIRO Data 61, Clayton South, Australia
Andrew Sullivan
CSIRO Land and Water, Black Mountain, Australia
Claire Miller
CSIRO Data 61, Clayton South, Australia
Christopher Thomas
University of New South Wales, Canberra, Australia

Introduction

The propagation of a wildfire is driven by a range of effects including convection, radiation and spot fire formation. The combined influence of these effects governs the evolution of a fire, which can include dynamic variation in the shape of the fire perimeter and in the rate of spread. However, it is difficult to fully parametrise the complex interactions between each of these processes in order to predict subsequent fire behaviour. While three-dimensional physical models that explicitly account for the processes governing fire spread are able to capture some elements of dynamic behaviour, their computational demands mean that they are not generally suitable to support operational fire spread prediction. Indeed, operational fire prediction currently relies on two-dimensional, empirically based models, which assume that fire spread takes place in a state of quasi-equilibrium. This modelling compromise is adequate in the majority of circumstances but can result in an under-appreciation of the potential for fire spread when dynamic fire propagation mechanisms are in effect. Coupled fire-atmosphere models, which combine empirical or semi-empirical fire spread models with atmospheric models offer an intermediate modelling option, but these models are still quite computationally expensive and too immature for operational use.

In this paper we explore the use of geometric aspects of the fire perimeter to model the dynamic evolution of a wildfire. In particular, we consider the inclusion of fire line curvature in a computationally efficient two-dimensional modelling framework.

Dynamic fire behaviour and fire line geometry

The propagation of a fire perimeter is driven by the transfer of heat from the combustion zone of the fire to adjacent unburnt fuel, primarily in the form of radiation and convection. Despite the many experimental and computational studies that have examined the relative contribution from each to fire propagation, the relative strengths of these factors across the various length scales relevant to fire propagation are yet to be definitively understood. However, there is broad agreement that the intrinsic geometry of a fire line can influence the subsequent evolution of the fire. Figure 1 illustrates the effect that fire line geometry can have on fire propagation by contrasting the behaviour of a straight-line fire with that of a circular arc of fire. The figure

* *Corresponding Author:* j.sharples@adfa.edu.au

shows the evolution of the two fire lines, as simulated using a coupled fire-atmosphere model. Although such a model does not explicitly include the effects of compounded radiation or spot fire formation, the model does indicate that variations in fire line geometry can result in significant differences in the pyro-convective dynamics that drive the overall propagation of the fire. The simulations were conducted with fire-atmosphere feedback enabled (red curves) and disabled (blue curves). The differences in the coupled and uncoupled simulations demonstrate the effect of the pyro-convective coupling between different parts of the fire lines. For the case of the straight-line fire (Figure 1a) there is negligible difference between the coupled and uncoupled simulations, while for the curved fire line case (Figure 1b) the inclusion of pyro-convective coupling results in a considerably different pattern of fire propagation.

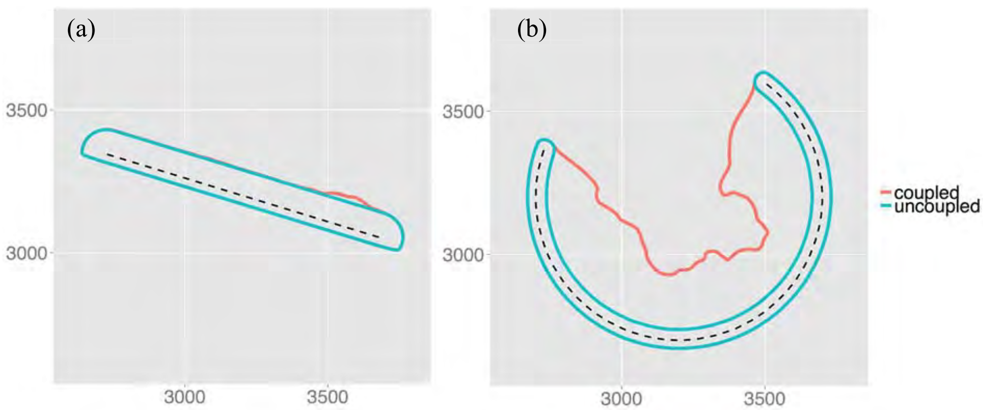

Figure 1. Coupled fire-atmosphere model simulations of (a) a straight-line fire, and (b) a circular arc fire. In each panel, the black dashed line indicates the initial line of ignition. Both simulations assume zero ambient wind.

A number of authors have considered using characteristics of the geometry of a fire line to account for dynamic variations in rate of spread. In particular, Weber (1989), Cheney et al. (1993) and Cheney and Gould (1995) have all discussed the effect of fire line curvature on fire propagation. Fire line curvature κ can be defined as the (negative of) the divergence of the fire line's unit normal vector: $\kappa = -\nabla \cdot \hat{\boldsymbol{n}}$. In his investigations of physical models for radiative heat transfer effects in the absence of wind, Weber (1989) noted a link between positive curvature and the acceleration of a fire originating from a point ignition. Cheney et al. (1993) and Cheney and Gould (1995) noted similar effects in wind-driven experimental fires, in which fires with lower local (positive) curvature spread faster than those with higher local curvature. Furthermore, Cheney and Gould (1997) observed that fires ignited from a long (> 200 m) line with low positive curvature reached their potential maximum rate of spread faster than smaller fires with higher positive curvature.

In his study of 'jump fires' Viegas et al. (2012) noted that the point of intersection of two fire lines that had merged at some oblique angle advanced more rapidly than other parts of the fire. Sharples et al. (2013) demonstrated that the dynamic fire behaviour reported by Viegas et al.

(2012) could be reproduced qualitatively using a mathematical model, in which the local rate of fire propagation was proportional to the negative curvature of the fire line.

Mathematical model

We propose a mathematical model for fire propagation based on the level set method (Sethian, 2001). The level set method is a general method for modelling the motion of an interface subject to a given speed imposed around the interface. The interface in this case is the boundary between regions that are burnt and regions that are unburnt, and the zero level set represents the current fire perimeter, as shown in Figure 2. The speed of the interface in this case is the local rate of spread of the fire.

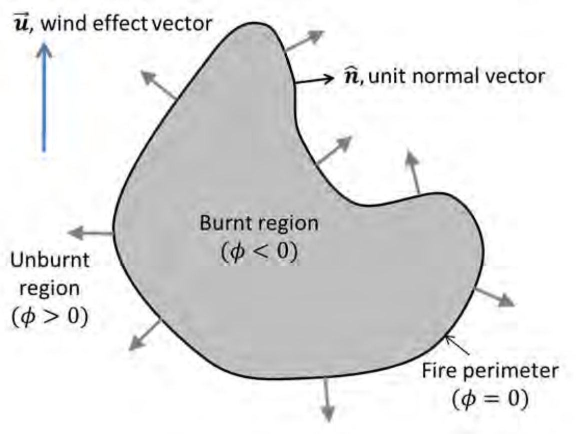

Figure 2. Interface (black curve) between burnt (light grey area) and unburnt regions representing a fire perimeter. The level set method calculates the distance ϕ from the interface, where $\phi < 0$ within the interface and $\phi > 0$ outside.

The level set method models the time evolution of the distance function ϕ via the partial differential equation:

$$\frac{\partial \phi}{\partial t} + s|\nabla \phi| + \vec{\boldsymbol{u}} \cdot \nabla \phi = 0,$$

where s is the normal (i.e. outward) speed of the interface and $\vec{\boldsymbol{u}}$ is a vector that characterizes the influence of the ambient wind. We consider the motion of the interface evolving with a curvature dependent speed defined by

$$s(\alpha) = \alpha \kappa,$$

which is then advected by a vector $\vec{\boldsymbol{u}}(\gamma)$ that depends on the ambient wind field. The parameters α and γ define the overall model.

Results

Figure 3 shows model simulations of experimental grassfires (Cruz et al. 2015). Figure 3a shows the evolution of the interface according to the model defined by $\alpha = 0$ and $\gamma = 1.2$; that is without incorporating any effect due to the curvature of the fire line. Alternatively, Figure 3b shows the evolution of the interface according to a model that incorporates fire line curvature dependence, defined by $\alpha = 1.5$ and $\gamma = 1.2$. As can be seen the inclusion of a curvature dependent rate of spread results in an improved fit between the observed and modelled fire perimeters.

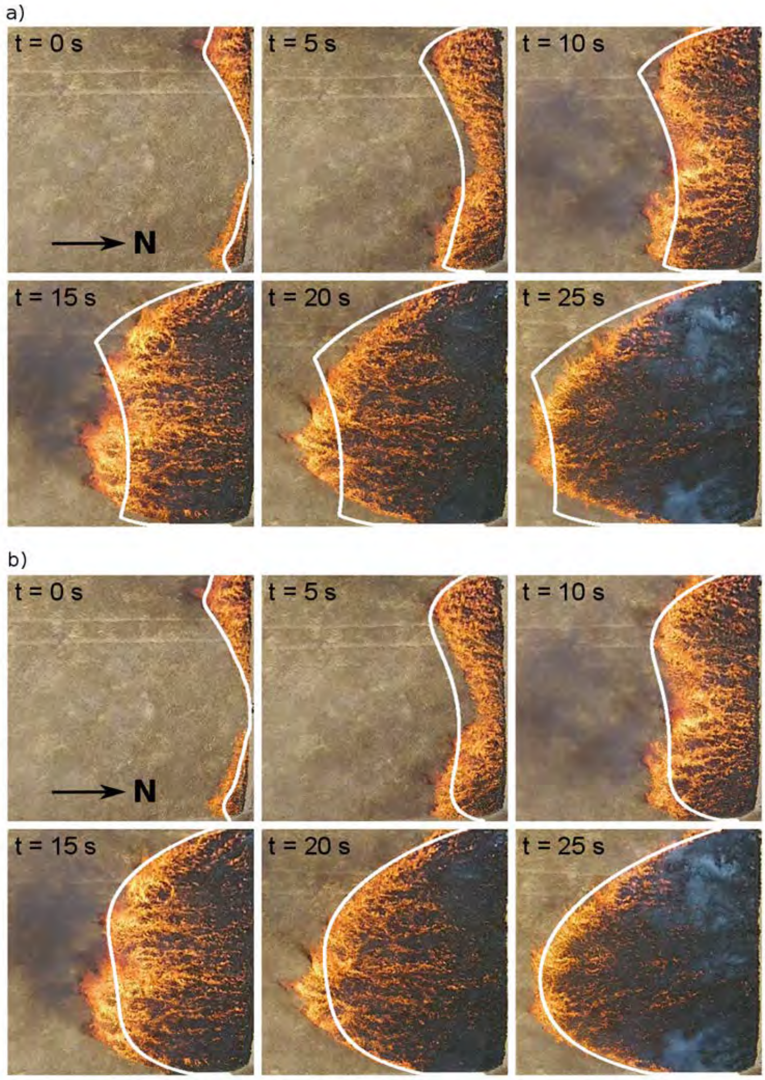

Figure 3. Series of fire spread images at 5 s intervals from t = 0 from experimental fire. (a) Isochrones in solid white line from level set method with no curvature effects incorporated ($\alpha = 0$, $\gamma = 1.2$). b) Isochrones in solid white line from level set method with curvature effects incorporated ($\alpha = 1.5$, $\gamma = 1.2$).

Conclusions

We considered a two-dimensional mathematical fire propagation model that incorporates geometric aspects of the fire perimeter to model the dynamic evolution of a wildfire. Specifically, we found that incorporation of curvature dependence in a fire propagation model provides closer agreement with the observed evolution of experimental fires than models without curvature dependence. The local curvature parameter may represent compounded radiation and convective effects near the fire perimeter. Our findings provide a means to incorporate these effects in a computationally efficient way and may lead to improved prediction capability for rate of spread models and other fire behaviour characteristics.

Acknowledgments

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References

Cheney, N. P. and Gould, J. S. (1995) Fire growth in grassland fuels. *International Journal of Wildland Fire*, 5(4):237-247.

Cheney, N. P. and Gould, J. S. (1997) Fire growth and acceleration. *International Journal of Wildland Fire*, 7(1):1-5.

Cheney, N. P., Gould, J. S., and Catchpole, W. R. (1993) The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *International Journal of Wildland Fire*, 3(1):31-44.

Cruz, M. G., Gould, J. S., Kidnie, S., Bessell, R., Nichols, D., and Slijepcevic, A. (2015) Effects of curing on grassfires: II. Effect of grass senescence on the rate of fire spread. *International Journal of Wildland Fire*, 24(6):838-848.

Sethian, J. (2001) Evolution, implementation, and application of level set and fast marching methods for advancing fronts. *Journal of Computational Physics*, 169:503-555.

Sharples, J. J., Towers, I. N., Wheeler, G. E., Wheeler, V.-M., and McCoy, J. A. (2013) Modelling fire line merging using plane curvature ow. In Piantadosi, J., Anderssen, R. S., and Boland, J., editors, 20th International Congress on Modelling and Simulation, pages 256-262. Modelling and Simulation Society of Australia and New Zealand.

Viegas, D. X., Raposo, J. R., Davim, D. A., and Rossa, C. G. (2012) Study of the jump fire produced by the interaction of two oblique _re fronts. Part 1. Analytical model and validation with no-slope laboratory experiments. *International Journal of Wildland Fire*, 21:843-856.

Weber, R. O. (1989) Analytical models of fire spread due to radiation. *Combustion and Flame*, 78:398-408.

USING MAPS TO SUCCESSFULLY DISPLAY COMPLEX BUSHFIRE BEHAVIOUR ATTRIBUTES IN VICTORIA

Frazer Wilson, Joanna Wand, Hayley Coviello, Suriya Vij, Emily Borton

Department of Environment, Land, Water and Planning / Forest Fire Management Victoria
Knoxfield, Victoria, Australia,

frazer.wilson@delwp.vic.gov.au

Introduction

Context

Bushfire is a significant risk to millions of Victorians both across the state and within the East Central bushfire risk landscape area, Victoria, Australia (Figure 1). Up until recently knowledge of bushfire risk has been limited to anecdotal evidence and best guesses. Using maps and spatial information from Phoenix Rapidfire (Tolhurst et al. 2008) modelling within the East Central Bushfire Risk Landscape (ECBRL), bushfire risk has been presented to fire agencies and municipalities using best available science, and purposed to provide support and advice in a meaningful format. In 2014 ECBRL, one of seven risk landscapes across Victoria, produced a Strategic Bushfire Management Plan. Using this modelling that became the Forest Fire Management's (FFM) (the agency responsible for fire on Public Land in Victoria) strategy for reducing the risk to life and property within the East Central landscape.

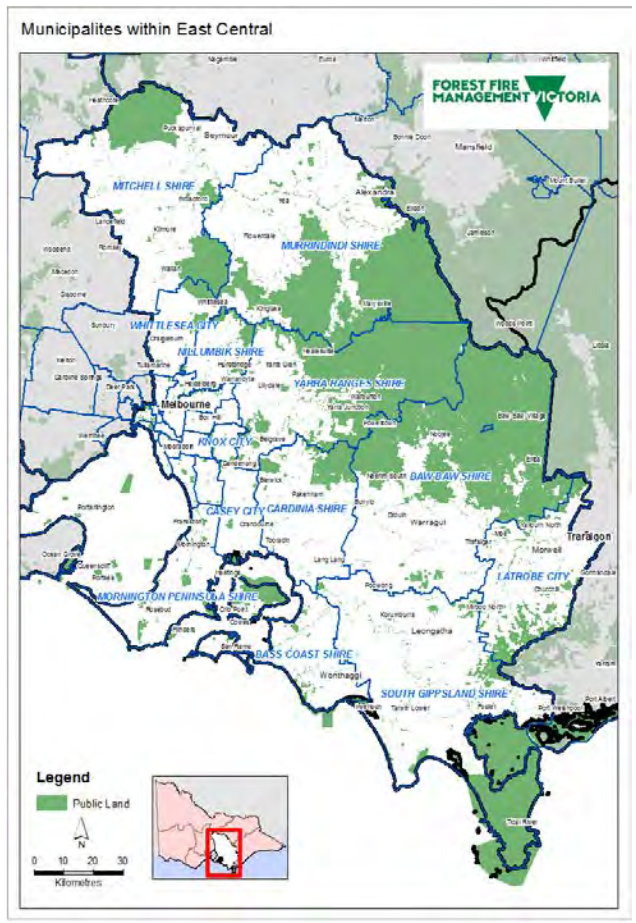


Figure 1: Map of Municipalities within the East Central Bushfire Risk Landscape Area

The Problem

The ECBRL team, using Phoenix Rapidfire modelling, retains incredibly large amounts of data on fire behaviour in large databases. This data can only be accessed by the team's Bushfire Risk Analysts.

A real issue is to determine how to deliver large amounts of information to other agencies, especially municipalities, who have a role in fuel management. The ECBRL team

Frazer Wilson - frazer.wilson@delwp.vic.gov.au
609 Burwood Highway, Knoxfield, Victoria, Australia 3180
http://bushfire-planning.delwp.vic.gov.au

needed a method to assist agencies to use the data from the Strategic Bushfire Management Plan to reduce the risk of fire to life and property but without having to field constant individual requests from other agencies. Additionally, we asked how could we get this information to municipalities and present it in a format that they can easily use? It was not possible to simply ask municipalities what they wanted, due to the very specific and continually evolving nature of risk modelling. To further complicate the matter, those working outside of FFM had had no previous exposure to risk modelling and were not sure what risk products were even possible to produce, therefore this project was created.

Project Aims

This project had two key aims:

1. Produce risk analysis products at the municipal scale that communicate results from the Strategic Bushfire Management Plan.
2. Collaborate with municipalities to produce the products to assist in improving our relationships with municipalities as a key stakeholder.

How we undertake modelling and what makes it so complex

The East Central team used the fire characterisation software Phoenix Rapidfire (Tolhurst et al. 2008) created by Melbourne University. Bushfire modelling for the entire landscape involves modelling 40,262 individual fire simulations using the software on a 1km grid, an example shown in Figure 2. Running all of these fires creates up to 25GB 'Allcells' table output which provides fire behaviour information at a 180m x 180m resolution. Information includes: Fire Intensity, Flame Heights, Flame Depth, Ember Density, Convection and possible Asset Losses.

Figure 2: An example of a 1km set of fires over the landscape

One of the key benefits of using Phoenix Rapidfire for modelling is its ability to model variations in fuel loads in different scenarios. Scenarios we have analysed include a range of weather options at different Forest Fire Danger Index levels as well as different fire histories. The fire histories were sometimes actual historical fire histories based on a specific year but sometimes theoretical fire history options are used, based on what may occur in future events. For every variation in fuel or weather, or any other change, all 40,262 fires then need to be modelled again repeatedly.

The Phoenix Rapidfire Allcells outputs are then uploaded into a multi-terabyte PostgreSQL database where further analysis is done and the data is cut down into varying scales, including municipal and locality scales, and modified into a range of products, some of which are described below.

Creating Risk Profile Reports

What first?

There are examples of things that have occurred before. similar to these Risk Profile Reports, this included the initial internal 2013 East Central Risk Profile Report which was 141 pages, and extremely wordy, had limited mapping content and was not well received. The internal Alpine Greater Gippsland Risk Profile report in 2014 was spatial heavy but did not include text descriptions about the maps with a purely internal FFM audience in mind and was created at the FFM Fire District scale.

Knowing that municipalities had limited access to our modelling programs and outputs, we met with the Yarra Ranges Shire Council's fire and biodiversity staff with a catalogue of every product we knew how to make at the time.

The ECBRL team discussed every risk analysis product developed individually to gauge the usefulness of each product to the municipalities and to float the idea of putting it all together in one document at the municipal scale.

Consultation remained important during the production of a document with relevant risk analysis products, with regular meetings scheduled with councils to assist in product development. The process involved discussions on every aspect of all risk analysis products, including the format of the report to the colours on maps and which maps were not required. The final document became the "Risk Profile Report".

Making it Spatial

While with a bit of SQL coding information from the PostgreSQL database, data can be imported into ArcMap to become spatial files. Converting this data into useful information requires further interpretation and feedback from municipalities.

Every detail down to colour schemes were carefully selected to provide not only maximum understanding of the information presented but to also meet accessibility requirements. Additionally, end user expectations needed to be considered. An example final product is displayed in Figure 3,the Impact Risk map for the Warburton area. This map shows there where the highest bushfire risk is to life and property is in the landscape. A few options were created for the symbology for this map including one that was shades of blue. Clear feedback was about the understanding of the colour red. Red represents fire, red represents danger and maps were always considered clearer using a black to yellow scale.

Many of the maps deliberately use 'fuzzy boundaries' for varying reasons. While the fires in Phoenix use an ignition grid of 1km by 1km, the outputs of Phoenix are in a 180m by 180m resolution. There is a danger with this that people may attempt to look to the individual pixel level. The data when aggregated out, for example to locality level, is reflective of the risk within the locality but the outputs were not designed for pixel level detail.

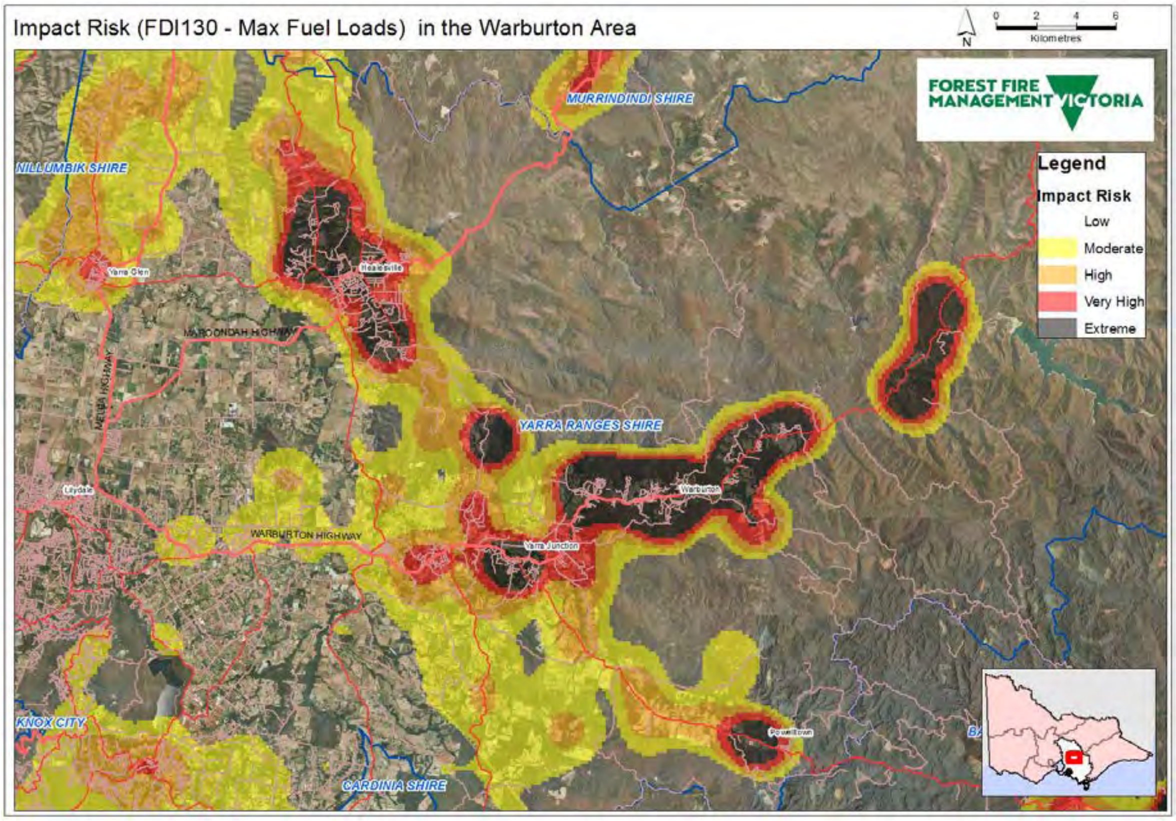


Figure 3: Impact Risk map for the Warburton Area (FDI130 Scenario with Maximum Fuel Loads)

Some maps such as Ignition Threat maps shown in Figure 4 use the 1km by 1km grid and display how many properties would be destroyed from that simulated fire. There is an inherent risk in providing this level of data as, eventually, these reports may end up with users without being delivered with the hours of conversations and discussions we had with municipalities about the assumptions and limitations behind the maps. Also, some maps indicate ignition points where bushfires can cause serious damage and many have expressed concern over passing this information to arsonists.

Therefore the centre points have been slightly adjusted and of the original coloured point locations have been converted into squares covering the entire 1km x 1km area. Thereby not identifying the exact location of the Phoenix fire location.

The Final Product

The final product was a set of individual reports covering the eleven municipalities who requested one, each of approximately 60-70 pages. The report, as well as all of the spatial data related to it, was then provided to the Municipal Fire Management Committees for use within their committees. These committees include the Country Fire Authority, Parks Victoria, the Department of Environment, Land, Water and Planning, local governments and all other key stakeholders that my need the report and the data. The reports are internal in nature but parts are often used to assist in community engagement publically where useful.

The reports contain a wide range of products beyond what is discussed here, including sections on Fire Ecology, Overall Fuel Hazard, discussions around existing known risk and an analysis on the town with the largest bushfire risk within the municipality.

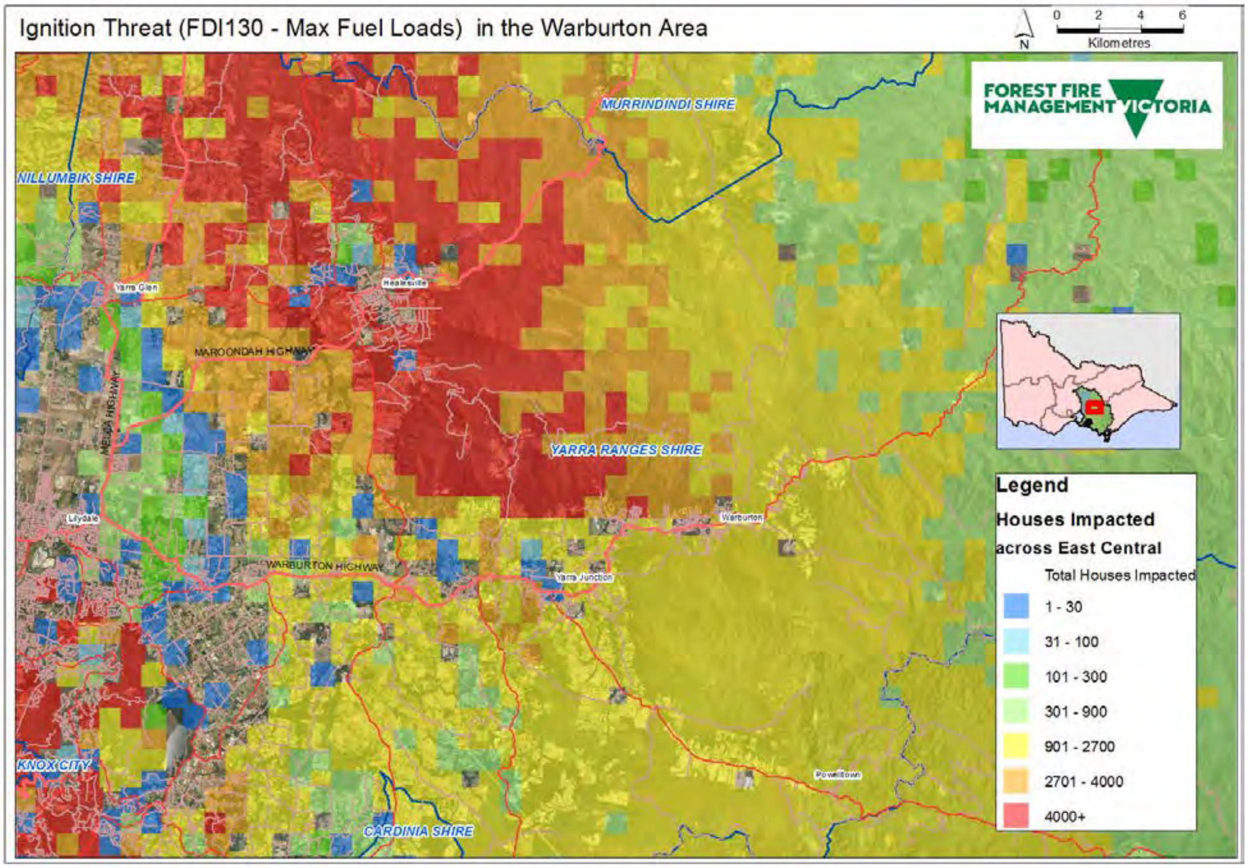


Figure 4: Ignition Threat map for the Warburton Area (FDI130 Scenario with Maximum Fuel Loads)

Continuous Improvement

The Risk Profile reports are a snapshot in time based on current science. As a part of our monitoring and evaluation reporting planning, a web-survey was undertaken with the municipalities and the Country Fire Authority. Figure 5 (and the quotes beneath it) show the responses on the topic of the maps produced from Phoenix modelling. The responses were either positive or neutral, which was a very positive outcome and emphasised the importance of the initial consultation that process with each municipality.

"(The Maps) provide a good overview to enable a landscape approach to strategic planning." - Manningham City Council

"(The Document) provides a level of background to make more holistic decisions in developing mitigation works and community engagement activities."
- Baw Baw Shire Council

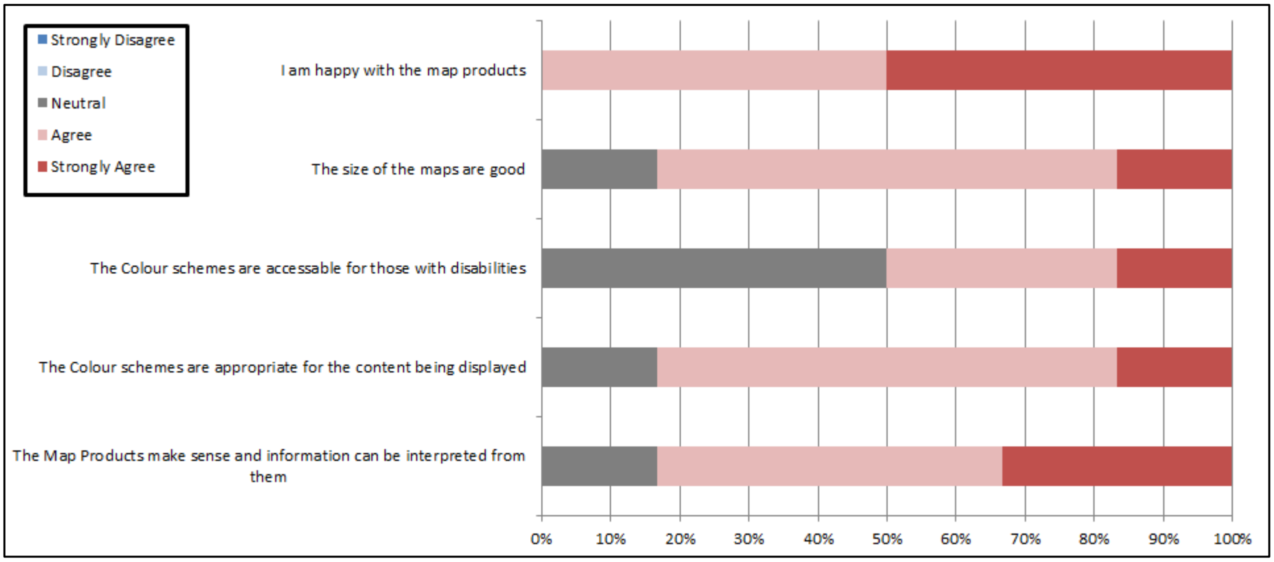


Figure 5: Web-survey results regarding the map products (Number of responses = 10)

Conclusion

Through this process the East Central team has developed a document, the Risk Profile Report, that can be used by Forest Fire Management and other government agencies and the process can be repeated into the future. Because of extensive consultation before the report was created we have received positive feedback and strengthened our connections with municipalities by providing them with relevant and useful information and including them in discussions.

We have come a long way quite quickly presenting this type of bushfire behaviour attributes in such a way that can be used at the municipal scale to represent the Strategic Bushfire Management Plan. However there will still be ways to make this information even easier to use in the future. Prioritising spatial information as a method of representing bushfire risk has proven to be very effective.

Acknowledgements

From FFM: Peter West, Stephanie Carr, Michael May, Andrew Blackett, Andy Ackland, Jaymie Norris. Yarra Ranges Shire Council's Fire & Emergency Management staff, Yarra Ranges Shire Council's Environmental staff and all other Municipalities and the Country Fire Authority that participated in this risk modelling process.

References

Tolhurst, KG, Shields, BJ & Chong, DM 2008, 'Phoenix: development and application of a bushfire risk management tool', *The Australian Journal of Emergency Management,* vol. 23, no. 4, pp. 47-54.

Which Configurations Cause Entrapment Risk?

Sébastien Lahaye*[a], Thomas Curt[b], Christelle Hély [c]
[a]Bouches-du-Rhône Fire Service, Marseille, France, slahaye@sdis13.fr
[b]IRSTEA, Aix-en-Provence, France, thomas.curt@irstea.fr
[c]ISEM, Montpellier, France, christelle.hely-alleaume@univ-montp2.fr

Introduction

Forest fires in southern Europe are characterized by their high intensity and rapid spread. The most devastating fires occur in the hot and dry summer, especially during windy episodes (Curt *et al.* 2013). Furthermore, threatened issues are increasingly important. The growth of population in recent decades has created an extension of the wildland-urban interfaces.
This population, often rural background-free, is poorly aware of the fire risk and prevention methods. It entirely relies on Fire Services to protect. Firefighters should thus engage to stop fire progression before it threatens populated areas, regardless of the violence of fire. This is why many stakeholders are trapped by the fire line and smoke. The consequences can be severe and even fatal (Viegas and Simeoni 2011).
Some studies in Europe have described in detail accidents in order to reconstruct the concatenation of events and human behavior that lead to tragic consequences (Viegas *et al.* 2009). Two scientific hypotheses are now trying to explain how fire suddenly turned to accident causing intensity. The first considers that a number of entrapments could be the result of a sudden and massive inflammation of fuel distilled volatile organic compound gases (Carbonell *et al.* 2004). The second hypothesis suggests a runaway kinetics fire front made possible by specific terrain conditions "trench effect" (Chatelon *et al.* 2014).
In the present study, we focused on the behavior of trap causing fires in recent decades, no matter what the consequences were. From a sample of 64 events (Fig.1), we sought if the accidents were related to weather conditions or particular fuel. We also investigated the conditions in which accidents could take place in areas seemingly less risky.

Materials and methods

In Europe, there is no database of entrapments occurred during wildfires. However, the most serious accidents in recent years have been the subject of investigation reports or communications. Moreover, firefighters have left oral or sometimes written evidences of entrapments or potentially dangerous fire behaviors. For this study we analyzed 36 reports and undertook 18 face-to-face interviews with firefighters or foresters. The investigated period was 1979-2015.
For 11 of the 64 recorded events, there were no casualties or destruction. Considering the violent behavior described, it is however evident that there would have been victims in case of staff presence.
For every reported trap we first looked for: date and time of the fire start and final surface of the fire. Then we wondered what type of fire it was regarding (Lahaye *et al.* 2014) classification.
The entrapment time (H trap) was compared with fire start time (H ignit) (Promethee 2015) using a homogeneity test of mean values. We also compared the start-to-trap time (D trap) with the total duration of fire (D tot). All analysis were performed in the R environment (R Core Team 2013).

Environmental drivers

We collected air temperature (T), relative humidity (H) and windspeed (Wind) from the closest weather station from the fire (Meteo France 2016). Depending on the year and the station, the measuring time step could be from one to four hours but this data can have a significant diurnal variability. This is why we also collected Air temperature at the 850 hPa pressure level (T850) that is a representative indicator of severe fire weather (Cardil *et al.* 2014). We used reanalyzed data from the National Center for Environmental Prediction (Kalnay *et al.* 1996) to obtain daily T850 at 12:00 UTC.

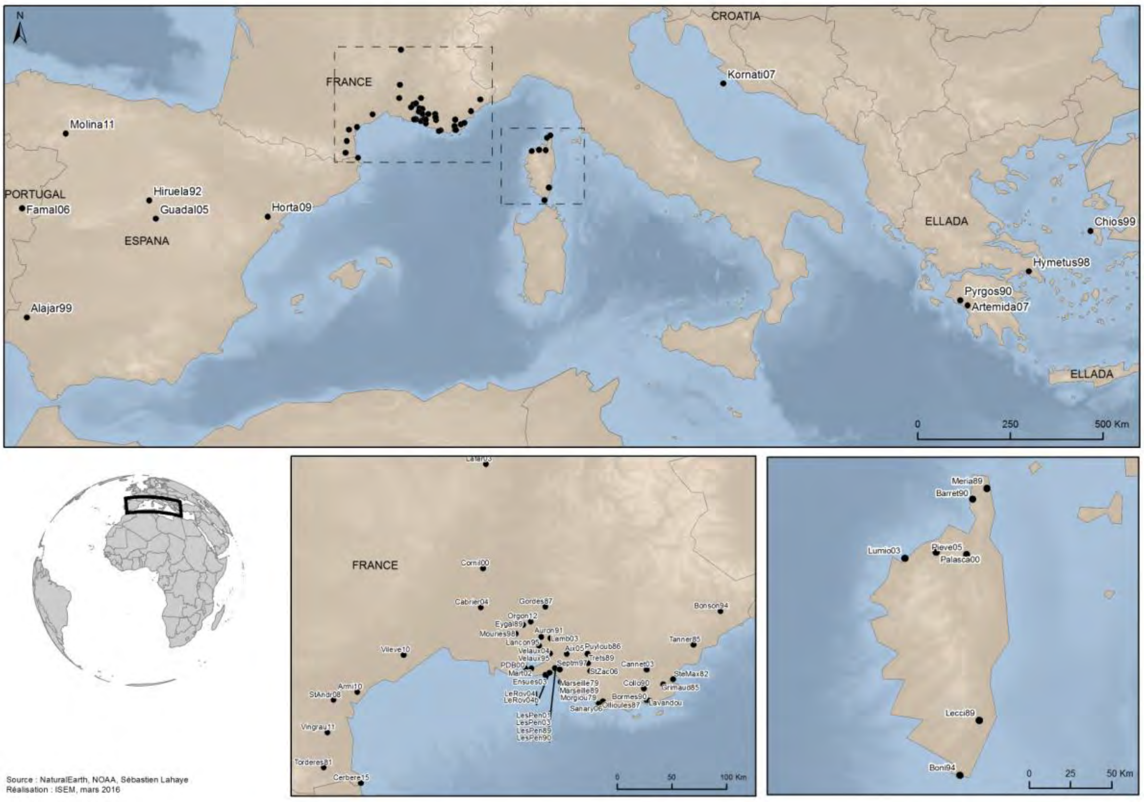


Figure 1: Entrapments location

We used the Fire Weather Index (FWI) and its sub-indices to assess the fuel sensibility (Van Wagner 1987). We compared the entrapment data with the average values collected by Météo France since 2001(Manach *et al.* 2007).

Vegetation composition within the area burned was characterized using the 1986 and 2006 French Forest Institute maps (Institut Forestier National, BDForêtV1; http://inventaire-forestier.ign.fr). We found three main fuel classes around the entrapment locations: pine forests (Pin=1), shrublands (Brush=1) or broadleaved forests (Pin=0, Brush=0).

Trap location

We first considered if the entrapment occurred in the main axis of the fire (Front=1) or due to a flanking fire. Then we looked at the topography between the fire line and the trap location (Institut Geographique National, BDAlti25; http://www.ign.fr). We noted *Slope=1* events in an upward slope or atop a ridge. We noted *ParaVal=1* traps in a parallel to the main axis of fire valley and *PerpVal=1* when the valley was perpendicular. The other cases were assumed to be *Flat*. By combining these positions according to a flowchart (Tab.1), we assigned each event a risk level (Risk).

Given the number of weather data collected, we firstly tested their autocorrelation in order to select only the most relevant using a *FactomineR* package Principal Component Analysis (Husson *et al.* 2013). We then used an *Ade4* co-inertia analysis (Dray *et al.* 2003) to find the environmental drivers associated to each Risk level.

Table1: Risk level regarding entrapment position

Front	Slope or Vall	Above	**Risk**
1	Slope=1 or ParaVal=1	1	**10**
		0	**9**
	Flat	-	**8**
	PerpVal=1	1	**7**
		0	**6**
0	Slope=1	1	**5**
		0	**4**
	Flat	-	**2**
	ParaVal=1 or PerpVal=1	1	**2**
		0	**1**

Results

About Spain, Portugal, Greece and Croatia the entrapments that have been entered here were the most serious whereas in France we obtained information on a broader sample, including minor events (Tab. 2).

Table 2: Entrapment results

	Trap number	fatalities	Seriously injured	Lightly injured	Destroyed vehicles
Sub total in France	53	27	14	34	45
Sub tot in Po Sp Cr Gr	11	75	5	0	8
Total	64	102	19	34	53
Min		0	0	0	0
Max		24	5	10	5
Mean value		1.6	0.3	0.5	0.9
Standard deviation		3.7	0.8	1.7	1

The average size of fires with entrapment was 989Ha and the first quartile was 221Ha, greater than the mean size of fires in France, 6.5Ha. The distribution of fires with entrapment did not conform to the distribution of large fire types. Trap probability was higher during *Oneway* fires and lower during *Multiway* fires.
Entrapments occurred around 16.00, ie 3 hours after the mean time of fire breakout (CI 95%, Fig. 2). Most entrapments occurred during the first two hours of fire. This period between fire start and trap followed a decreasing exponential that is not correlated with the total duration of fires (CI 95%, Fig. 3).

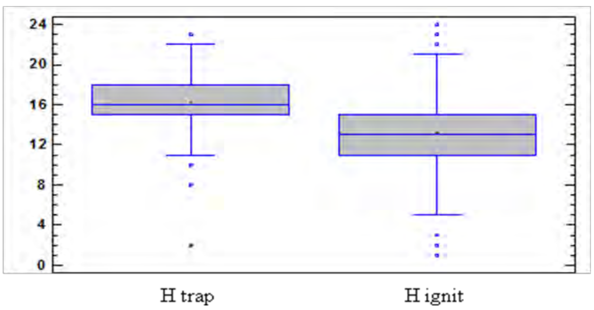
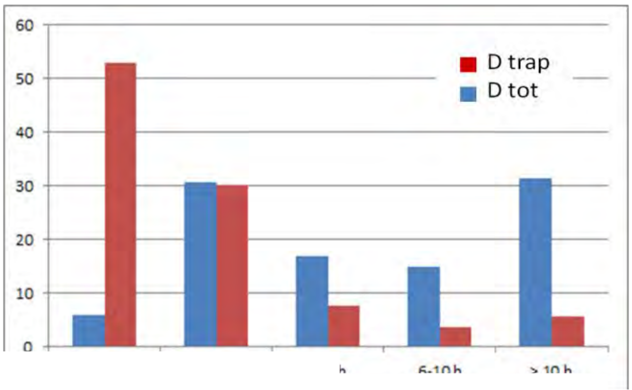


Figure 2: Comparison between entrapment hour (H trap) and fire ignition time (H ignit)

Environmental drivers

The FWI of entrapment fires was higher than the average FWI of fires (CI95%, Fig. 4/a). The DC and DMC were not significantly different (CI95%, Fig. 4/b and 4/c). The FFMC was smaller for entrapments (CI95%, Fig. 4/d). T and H were not different (CI95%, Fig. 4/e and 4/f). Wind was stronger for entrapments (CI95%, Fig. 4/g).



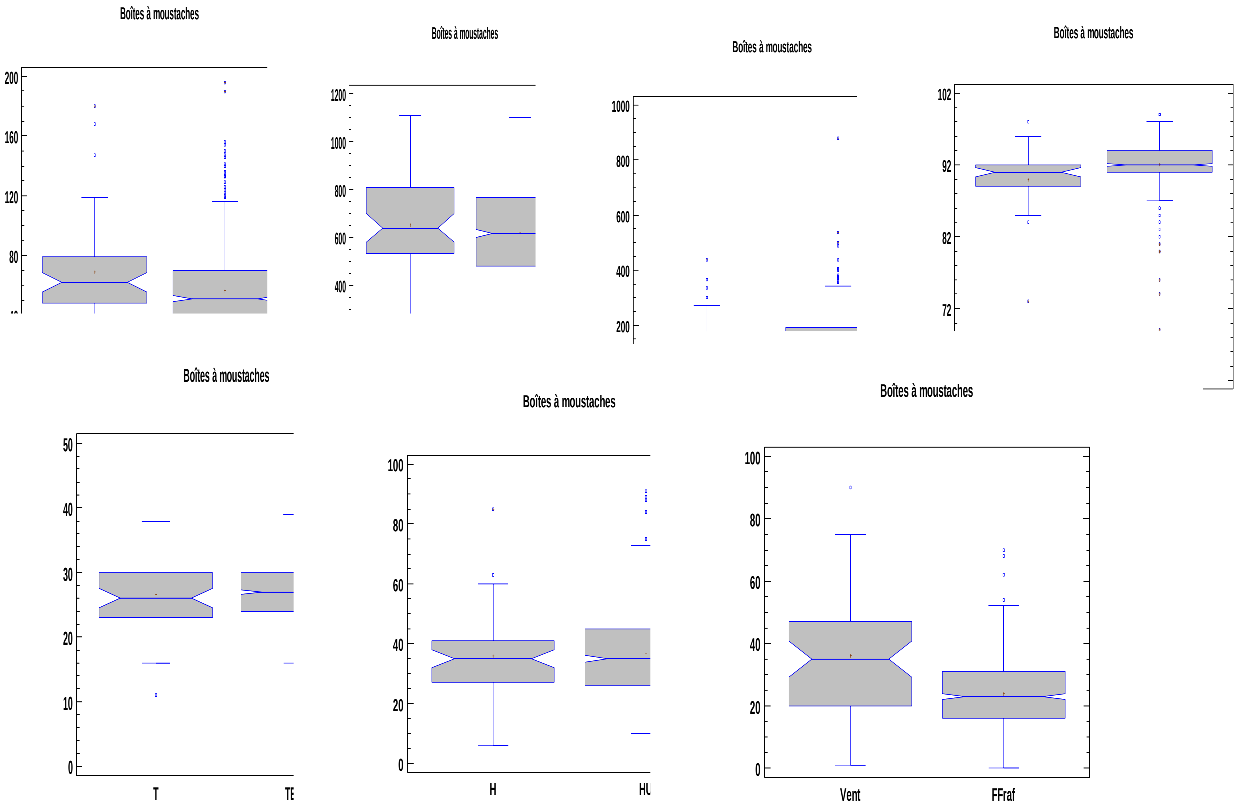


Figure 4: Comparison between traps (left boxplot) and general population of fires (right). a/ FWI; b/DC; c/DMC; d/FFMC; e/Temperature; f/Humidity; g/Windspeed

Trap location

Because of variables auto-correlation we rejected from co-inertia analysis T and H in favor of T850. We kept DMC and not DC; we also kept Wind, Pin and Brush.

The entrapments scaled on 8 Risk levels. R1 to R8 were well discriminated by environmental drivers whereas R9 and R10 were not (Fig.5). The lowest levels R1 and R2 were driven by the presence of pines and strong wind. R5, R6 and R7 were driven by DMC and Brush and R8 was driven by T850.

Discussion

We will not make any connection between environmental drivers and entrapment injuries or deaths because we didn't investigate here human factors such as training, personal experience, protective equipment, lack of communication…

Most entrapments occur during the first hours of fire. It is therefore necessary to determine in advance the days and places where the conditions are right for this type of large fire.

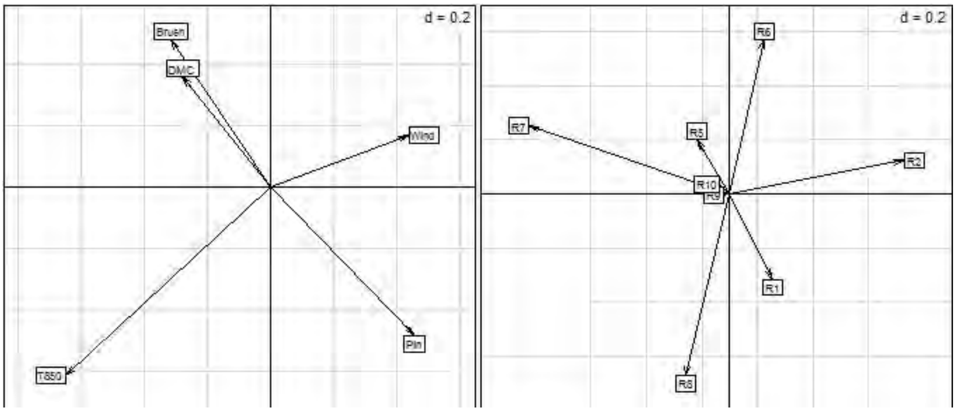


Figure 5: Co-inertia analysis between environmental data and risk level

In a previous study, we showed that the probability of an entrapment increases with the amount of vehicles involved in the fight (Lahaye *et al.* 2014). This is consistent with the fire types. *Multiways* are less urbanized mountainous inland fires. The human issues are less vulnerable than on the coast. So there are less resources assigned for fight and less entrapments.

Environmental drivers

Beyond the risk of outbreak, a high FWI also gives rise to a greater danger for stakeholders. The entrapments we studied are neither driven by fuel dryness (DC and DMC) nor by high air temperature or low relative humidity. So it is unlikely that these entrapments are flashover explosions caused by volatile organic gases accumulation. There is no intention to question the conclusions of (Carbonell *et al.* 2004); their study focused on a limited number of cases. However, it helps demystify the flashover explosions subjectively blamed for many accidents by firefighters.

Strong wind seems to be a driver of entrapments but we need to be cautious as the measure is uncertain. Local wind is often very different to the weather station registered data. More frequent use of mobile weather stations during fires, with recorded statements, could improve the results.

Trap location

Facing fire front in an upslope position or in a flow direction valley are the most risky situations. Then entrapment can occur whatever the weather and fuel environment.

In pronounced drought conditions, linked to a high temperature and low humidity, there could be entrapments for crew facing the fire on flat ground or downhill, in shrublands. This means that in these drought conditions, any frontal attack remains dangerous.

Finally, entrapments are more likely to happen on flanking fire when the wind is very strong and in dense pine forests. Crews that were supposed to be secured by low intensity fire lines and by down slopes or valleys, have nevertheless been trapped.

Acknowledgements
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References

- Carbonell G, Monet JP, Dusserre G, Sauvagnargue-Lesage S (2004) 'Embrasement généralisé éclair en feu de forêt.' Ecole des Mines d'Alès - Service Départemental d'Incendie et de Secours des Bouches du Rhône, Alès, France.
- Cardil A, Molina D, Kobziar L (2014) Extreme temperature days and potential impacts in Southern Europe. *Natural Hazards and Earth System Sciences* **2**, 3863-3886.
- Chatelon F-J, Sauvagnargue S, Dusserre G, Balbi J-H (2014) Generalized Blaze Flash, a "Flashover" Behavior for Forest Fires - Analysis from the Firefighter's Point of View. *Open Journal of Forestry* **4**, 547-557.
- Curt T, Borgniet L, Bouillon C (2013) Wildfire frequency varies with the size and shape of fuel types in southeastern France: Implications for environmental management. *Journal of Environmental Management* **117**, 150-161.
- Dray S, Chessel D, Thioulouse J (2003) Co-inertia analysis and the linking of the ecological data tables. *Ecology* **84**, 3078-3089.
- Husson F, Josse J, Le S, Mazet J (2013) FactoMineR: multivariate exploratory data analysis and data mining with R. *R package version* **1**, 102-123.
- Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woolen J, Zhu Y, Leetma A, Reynolds R (1996) The NCEP/NCAR 40-year reanalysis project. *Bulletin of American Meteorologic Society* **77**, 437-471.
- Lahaye S, Curt T, Paradis L, Hely C (2014) Classification of large wildfires in South-Eastern France to adapt suppression startegies. In '7th International Conference on Forest Fire Research'. Coimbra, Portugal. (Ed. DX Viegas) pp. 696-708. (ADAI)
- Manach J, Bertrand E, Bidet J (2007) 'Assistance météorologique à la prévention et à la lutte contre les feux de forêt en zone méditerranéenne.' Société météorologique de France, Paris, France.
- Meteo France (2016) http://www.meteofrance.com. In.
- Promethee (2015) Base de données sur les incendies de forêt en région méditerranéenne en France depuis 1973. https://www.promethee.com/. In.
- R Core Team (2013) R: A Language and Environment for Statistical Computing. In. (R Foundation for Statistical Computing: Vienna, Austria)
- Van Wagner C (1987) 'Development and structure of the Canadian Forest Fire Weather Index System.' Canadian Forestry Service, Ottawa.
- Viegas DX, Simeoni A (2011) Eruptive Behaviour of Forest Fires. *Fire Technology* **47**, 303-320.
- Viegas DX, Simeoni A, Xanthopoulos G, Rossa C, Ribeiro L, Pita L, Stipanicev D, Zinoviev A, Weber R, Dold J, Caballero D (2009) 'Recent Forest Fire Related Accidents in Europe.' European Commission, Luxembourg.

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Woody fuel consumption by fires in open eucalypt forest in south-west Western Australia

J.J. Hollis[a], W.L. McCaw[a,*], K.R. Whitford[b], M.G. Cruz[c]
[a] Department of Parks and Wildlife, Locked Bag 2, Manjimup WA 6258, Australia
[b] Previously Department of Parks and Wildlife, Dwellingup, WA 6213, Australia
[c] CSIRO, GPO Box 1700, Canberra, ACT 2601, Australia
[*] Email: Lachie.Mccaw@dpaw.wa.gov.au

Introduction

Coarse woody debris (diameter, $d > 0.6$ cm) represents the largest component of fuel available for consumption in eucalypt forest fires, and its combustion affects fire behavior, plume development, suppression difficulty and firefighter safety (Rothermel 1993; Sullivan *et al.* 2002). Combustion of woody fuel can potentially be the primary source of carbon, smoke and greenhouse gas emissions (Pyne *et al.* 1996). Coarse woody debris is also an important pool of stored carbon in forests, and provides habitat for a broad range of organisms including fungi, plants, invertebrates and terrestrial vertebrates (Lindenmayer *et al.* 2002; Woldendorp and Keenan 2005). The ability to predict woody fuel consumption under a range of burning conditions is therefore an important consideration for decision making in forest fire management.

Information relating to woody fuel consumption in Australia is limited to a relatively small range of forest types and fire environments (Hollis *et al*. 2010; Aponte *et al*. 2014; Volkova and Weston 2015). This is due partly to the time consuming nature of data collection, and to practical issues related to the characterization of fires during flaming and smouldering phases of combustion. Obtaining robust estimates of woody fuel consumption during high intensity fires poses particular challenges because of the difficulty in conducting experiments during more severe burning conditions and the uncertainty in timing and location of wildfires. In the jarrah (*Eucalyptus marginata*) forest of south-west Western Australia a network of monitoring sites has been established for the FORESTCHECK integrated biodiversity monitoring project (McCaw *et al.* 2011). This project provides baseline information about forest structure and condition and biodiversity responses to a range of management activities including silviculture and prescribed burning. The quantity and attributes of woody fuel has been measured as a routine part of the monitoring protocol. Nineteen FORESTCHECK monitoring sites were burnt between 2008 and 2015, with 11 burnt by low intensity prescribed fire and nine by unplanned (wildfires) of varying intensity. The same protocol was used to measure woody fuel quantity before and after fire. This has provided a valuable dataset for investigating consumption of woody fuels in relation to burning conditions.

In this extended abstract we describe briefly the characteristics of woody fuels present at the monitoring sites and then evaluate fuel consumption models based on the McArthur Forest Fire Danger Index (FFDI) and Byram's fireline intensity (I). These variables have been shown previously to be useful predictors of the proportion of woody fuel consumed in eucalypt forest fires in southern Australia (Hollis *et al.* 2011a; Hollis *et al.* 2011b).

Methodology

Assessment of woody fuel load and consumption
Woody fuels with *d* >2.5 cm were monitored along either 400 or 600 m of transect at each site using the line intersect method (Van Wagner 1968). Data were grouped into five diameter classes adopted by Hollis *et al.* (2011a); (2011b) (size 1: 0.6-2.5 cm, size 2: 2.5-7.5 cm, size 3: 7.5-22.5 cm, size 4: 22.5-50 cm and size 5: >50 cm). These classes approximate the time lag of fuels (Fosberg 1970) and enable comparison with other datasets. Woody fuels 0.6-2.5 cm were destructively sampled, oven dried and load calculated in t/ha. For fuels >2.5 cm fuel volume was converted to loading assuming a mean density of 0.65 kg m^{-3}.

Weather conditions and fire behavior
FFDI during the period when each site was estimated to have burnt was calculated using weather observations from representative Bureau of Meteorology automatic weather stations. Fireline intensity (Byram 1959) was inferred from crown scorch height measurements and season using the relationship of Burrows (1997).

Models tested
Five woody fuel consumption models were evaluated against the calculated consumption data:
(1) the ($FFDI^a$) model of Hollis *et al.* (2011b);
(2) the $FFDI^b$ model of Hollis *et al.* (2011b) that excludes the McCorkhill data subset;
(3) the fireline intensity model (*FI*) of Hollis *et al.* (2011a);
(4) fireline intensity model (*FIPB*) of Hollis *et al.* (2011a) which applies to prescribed fires with an upper intensity limit of 750 kW m^{-1}; and
(5) the Australian National Carbon Accounting System assumption of 50% woody fuel consumption irrespective of type, season or intensity of fire (Gould and Cheney 2007).

Model fit was evaluated using mean absolute error (*MAE*), root mean squared-error (*RMSE*), mean bias error (*MBE*) and mean absolute percentage error (*MAPE*) (Makridakis *et al.* 1998; Hollis *et al.* 2010).

Results and Discussion

Pre-fire fuel characteristics
Sites represented three timber harvest treatments: gap release, shelterwood, selective cut, and forest that had not been harvested in the previous 40 years. Total pre-fire fuel load varied between 26 and 261 t/ha (mean= 76 t/ha). Woody fuel loads were lightest in the unharvested external reference sites and heaviest in the most heavily logged gap release sites. Larger woody fuels (size classes 4 and 5) contributed the most to total fuel load comprising an average of 72%.

Fire behavior and climatic conditions
Consumption data were segregated by type of fire (prescribed or wildfire). Mount Soil Dryness Index (mm) varied from 24 to 85 for spring prescribed fires with one autumn burn at 105. Wildfires burnt in summer (December-February) with SDI of 165-185. The distribution of FFDI was similar for prescribed and wildfires (Figures 1a & b). Fireline intensity provided greater

differentiation between the datasets with prescribed fires limited to a maximum intensity of 1000 kW m^{-1} compared with a maximum intensity of 6000 kW m^{-1} for wildfires (Figs 1c and 1d).

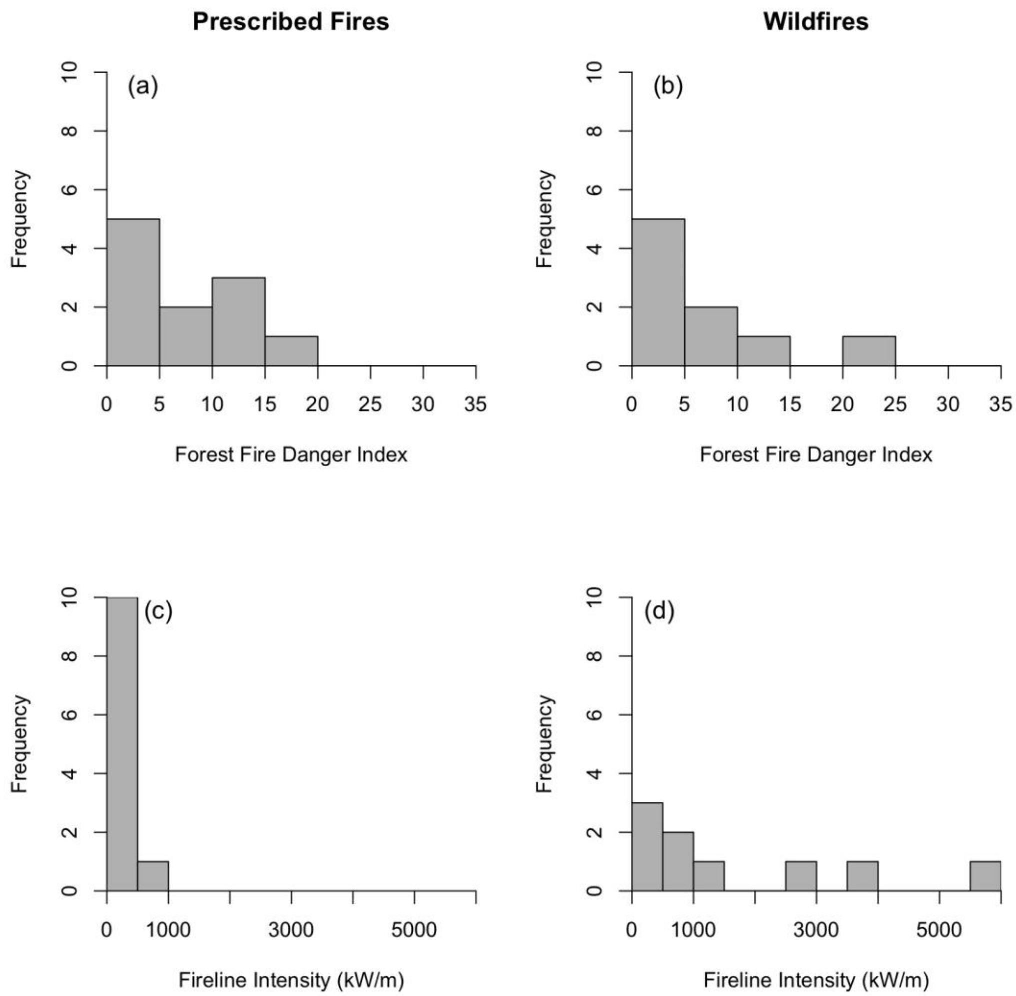

Figure 1: Distribution of Forest Fire Danger Index and fireline intensity by fire type.

Woody fuel consumption

The proportion of woody fuel consumed varied from 13 to 77% (mean=39%). Wildfires consumed a significantly greater proportion of woody fuel (mean = 51%) than prescribed fires (mean = 31%) (p = 0.009) (Fig. 2). Fuel consumption is plotted against FFDI and fireline intensity in Fig. 3 and fitted models are shown in Fig. 4. The range of consumption evident in the field data set was not represented adequately by any of the models. Models tended to over-predict the consumption of woody fuel with biases ranging from 8.4% for the fireline intensity model (*FI*) and up to 14.8% for the fireline intensity model based on prescribed fire data (*FIBP*). The *FI* model had a *MAE* of 13.9% and was superior to $FFDI^a$ and $FFDI^b$ models which had *MAE* between 15.5% and 17% and substantially over-predicted consumption (*MBE* between 10.2% and 13.6%). Predictions based on the ANCAS assumption had errors similar to the FFDI models.

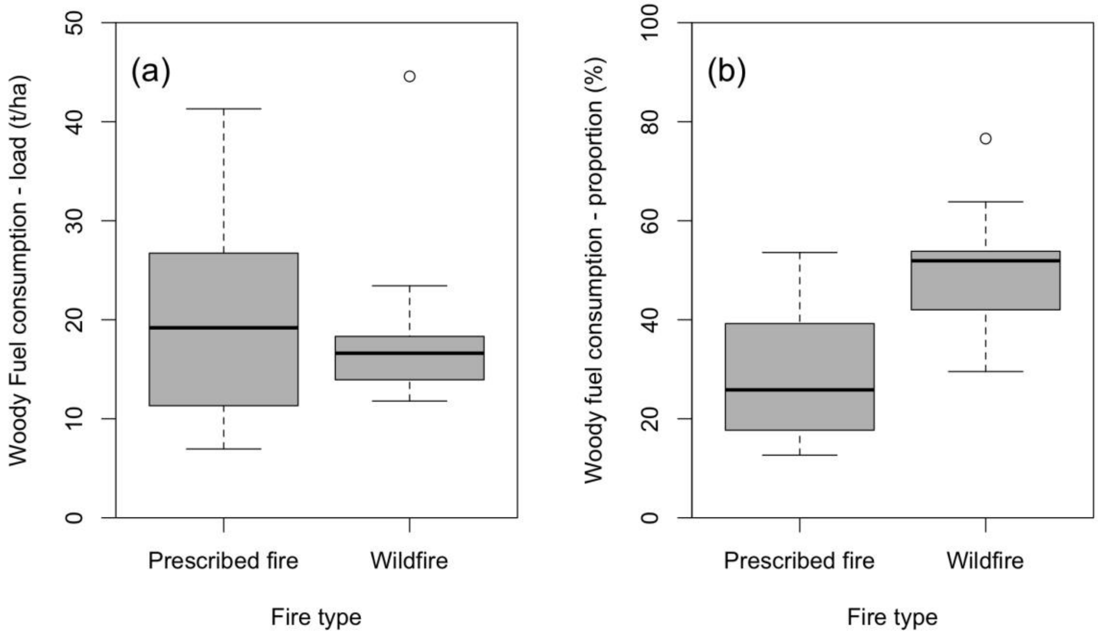

Figure 2: Distribution of woody fuel consumption by fire type as (a) load (t/ha) and (b) as proportion of pre-fire load (%).

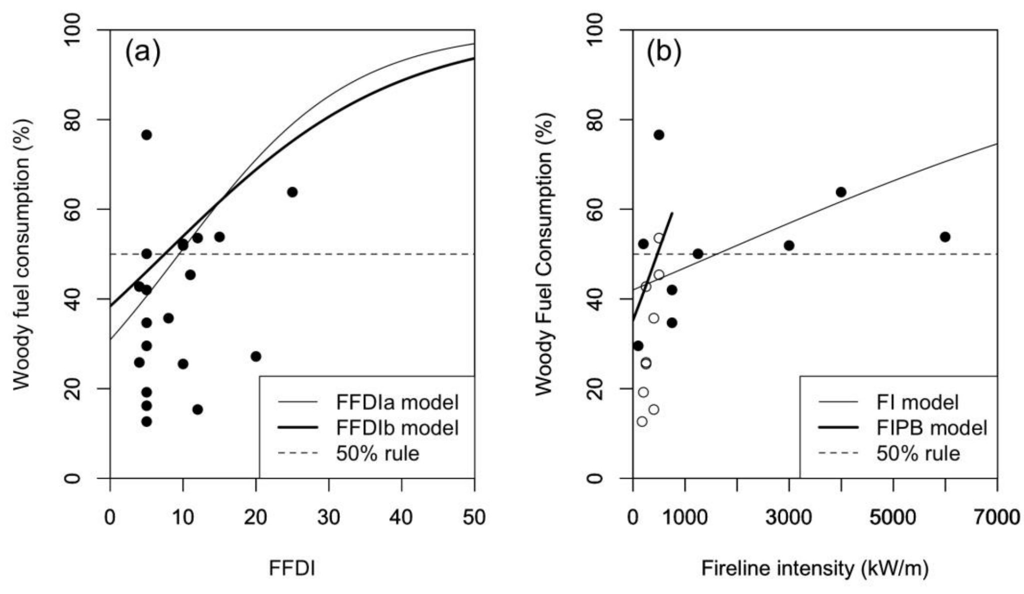

Figure 3: Woody fuel consumption (%) against (a) FFDI and (b) fireline intensity (open circles apply to prescribed fires). Hollis *et al.* (2011b) FFDI models and Hollis *et al.* (2011a) fireline intensity models are overlaid (*FI* and *FIPB (*for fires where *I* < 750 kW/m)).

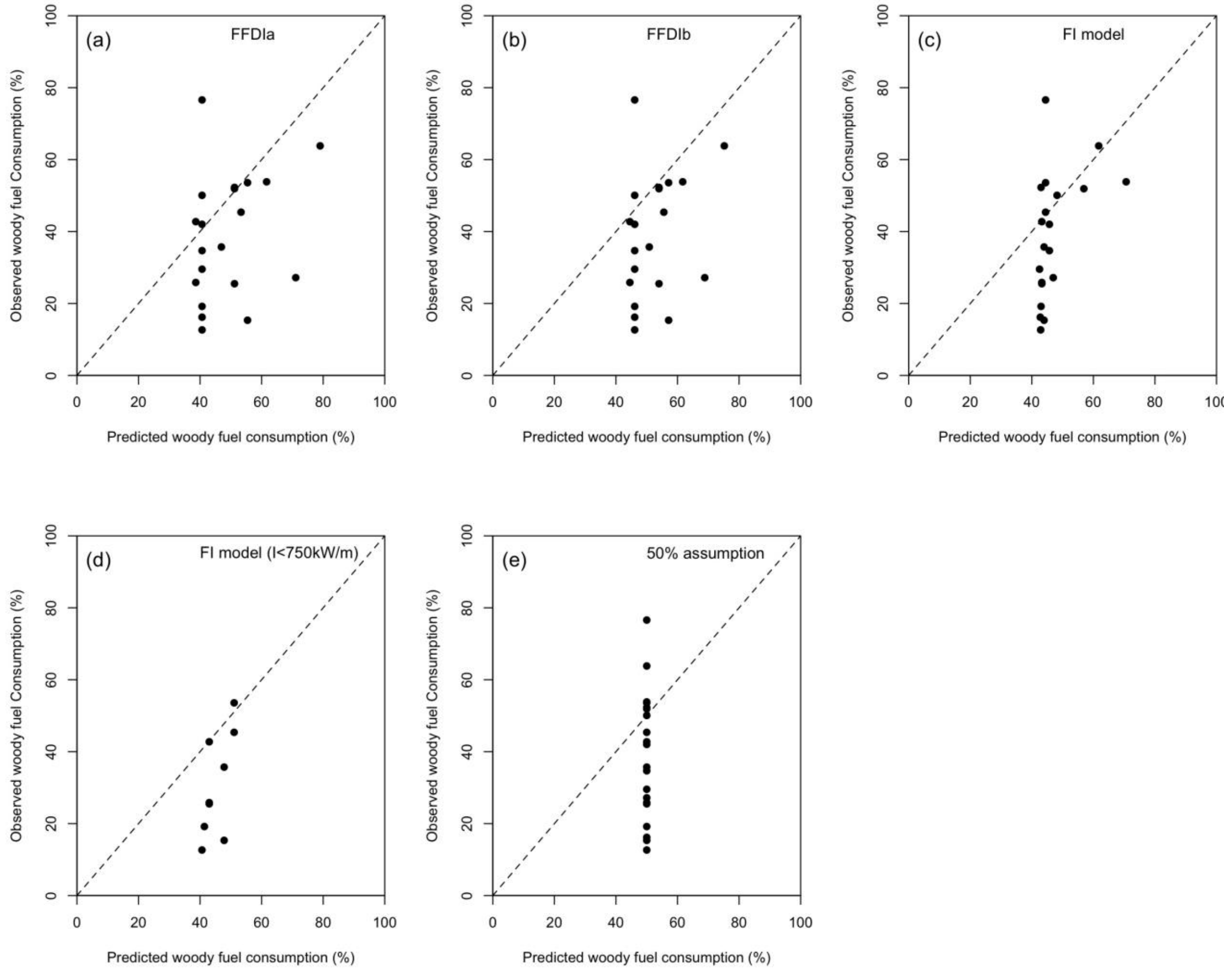

Figure 4: Predicted versus observed woody fuel consumption for (a) FFDI[a] (b) FFDI[b], (c) fireline intensity model, (d) fireline intensity model (*I* < 750 kW/m) (e) ANCAS recommendation assuming 50% woody fuel consumption.

Conclusions

This study highlights the value of opportunistic collection of post-fire data to improve the understanding of fire dynamics and to support model evaluation. Improved assessment of weather and fire behavior during prescribed fire and wildfires would increase the reliability of data for model evaluation studies. Models based on FFDI yield poorer evaluation statistics than those based on fireline intensity, which could in part reflect the difficulty determining FFDI accurately at sites burnt by wildfire due to spatial and temporal variation in weather input variables. While FFDI may be more difficult to determine in hindsight for a specific location, it is more predictable than fireline intensity and can be simulated at a range of scales. Clearly, the ANCAS assumption of 50% consumption of woody fuel is a coarse approximation. There is scope for the development of improved woody fuel consumption models by combining data from FORESTECHECK monitoring and the studies of Hollis *et al.* (2011a); (2011b). Further studies should focus on better understanding how ignition and consumption of large woody debris is influenced by seasonal dryness, and by the surface condition and decay state of individual logs.

References

Aponte C, Tolhurst KG, Bennett L (2014) Repeated prescribed fires decrease stocks and change attributes of coarse woody debris in a temperate eucalypt forest. *Ecological Applications* **24**, 976-989.

Burrows ND (1997) Predicting canopy scorch height in jarrah forest. *CALMScience* **2**, 267-274.

Byram GM (1959) Combustion of forest fuels. In 'Forest Fire: Control and Use.' (Ed. KP Davis.) pp. 61-89. (McGraw-Hill: New York)

Fosberg MA (1970) Drying rates of heartwood below fibre saturation. *Forest Science* **16**, 57-63.

Gould J, Cheney NP (2007) Fire management in Australian forests. Australian Greenhouse Office, Canberra, ACT.

Hollis JJ, Anderson WR, McCaw WL, Cruz MG, Burrows ND, Ward B, Tolhurst KG, Gould J (2011a) The effect of fireline intensity on woody fuel consumption in southern Australian eucalypt forest fires. *Australian Forestry* **74**, 81-97.

Hollis JJ, Matthews, S Anderson WR, Cruz MG, Burrows ND (2011b) Behind the flaming zone: Predicting woody fuel consumption in eucalypt forest fires in southern Australia. *Forest Ecology and Management* **261**, 2049-2067.

Hollis JJ, Matthews S, Ottmar RD, Prichard SJ, Slijepcevic A, Burrows ND, Ward B, Tolhurst KG, Anderson WR, Gould JS (2010) Testing woody fuel consumption models for application in Australian southern eucalypt forest fires. *Forest Ecology and Management* **260**, 948-964.

Lindenmayer DB, Claridge AW, Gilmore AM, Michael D, Lindenmayer BD (2002) The ecological role of logs in Australian forests and the potential impacts of harvesting intensification on log-using biota. *Pacific Conservation Biology* **8**, 121-40.

Makridakis S, Wheelwright SC, Hyndman RJ (1998) 'Forecasting: Methods and Applications.' (John Wiley and Sons).

McCaw WL, Robinson RM, Williams MR (2011) Integrated biodiversity monitoring for the jarrah (*Eucalyptus marginata*) forest in south-west Western Australia: The FORESTCHECK project. *Australian Forestry* **74**, 240-253.

Pyne SJ, Andrews PL, Laven RD (1996) 'Introduction to Wildland Fire.' (John Wiley & Sons Inc.: New York)

Rothermel RC (1993) 'Some fire behaviour modelling concepts for fire management systems, Proceedings of the 12th Conference on Fire and Forest Meteorology.' Jekyll Island, Georgia. SAF Publication 94-02. Society of American Foresters, Bethesda, Maryland.

Sullivan AL, Knight IK, Cheney NP (2002) Predicting the radiant heat flux from burning logs in a forest following a fire. *Australian Forestry* **65**, 59-67.

Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* **14**, 20-26.

Volkova L, Weston C (2015) Carbon loss from planned fires in southeastern Australian dry *Eucalyptus* forests. *Forest Ecology and Management* **336**, 91-98.

Woldendorp G, Keenan RJ (2005) Coarse woody debris in Australian forest ecosystems: A review. *Austral Ecology* **30**, 834-843.

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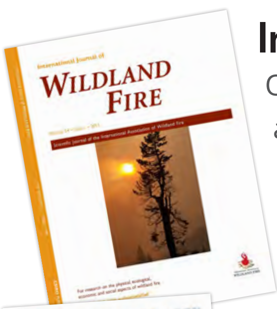
The IAWF is uniquely positioned as an independent organization whose membership includes experts in all aspects of wildland fire management. IAWF's independence and breadth of global membership expertise allows it to offer a neutral forum for the consideration of important and at times controversial, wildland fire issues. Our unique membership base and organizational structure allow the IAWF to creatively apply a full range of wildland fire knowledge to accomplishing its stated mission.

Vision: To be an acknowledged resource, from the local to global scale, of scientific and technical knowledge, education, networking and professional development that is depended on by members and partners in the international wildland fire community.



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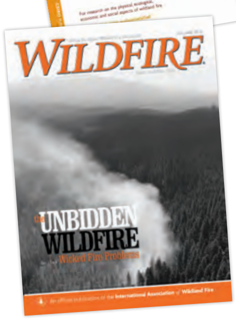

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All IAWF members receive WILDFIRE magazine, official publication of the IAWF. Our authors submit fire articles from all corners of the world and our topical editors cover a broad array of important issues in wildland fire. We encourage you to submit articles and photographs for inclusion in the magazine. www.wildfiremagazine.org.

There are so many reasons to become a member of the International Association of Wildland Fire but most importantly, the opportunity to be a member of a professional association that is committed to facilitating communication and providing leadership for the wildland fire community.

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BUSHFIRE + NATURAL HAZARDS CRC

The Bushfire and Natural Hazards Cooperative Research Centre draws together all of Australia and New Zealand's fire and emergency service authorities with the leading experts across a range of scientific fields to explore the causes, consequences and mitigation of natural disasters.

The CRC coordinates a national research effort in hazards, including bushfires flood, storm, cyclone, earthquake and tsunami.

From July 2013, $47 million over eight years in Australian Government funds under the Cooperative Research Centres Program have been matched by support from state and territory government organisations, research institutions and NGOs.

Research partners include universities, Bureau of Meteorology and Geoscience Australia, and several international research organisations.

The research program has developed under the direction of the researchers and end-user agencies. The research has three major themes covering 12 clusters of projects, most of which span the priorities of those working in a multi-hazard environment.

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WELCOME

International Association of Wildland Fire (IAWF) is extremely proud to present the 5th International Fire Behavior + Fuels Conference, co-sponsored by IAWF and Bushfire and Natural Hazards CRC of Australia and held concurrently in Portland, OR, USA, and Melbourne, Australia. This conference is being presented to bring focus to the many issues associated with fuels, fire behavior, large wildfires, and the future of fire management.

Much attention is being given to wildland fire management. It seems with each passing year we recognize escalating complexity, increasing risk, and mounting challenges. Wildland fire management cannot respond to current and future challenges without actively enlarging its body of knowledge, experience, and capabilities. Changing situations, what many would characterize as worsening situations, must be anticipated and responded to. Predictive entities continue to forecast worsening fire seasons and continued droughts leading to expectations of increasing numbers of fires, area burned, burning intensities, and duration of wildfire activity.

As all of these elements of wildland fire are manifested, we see that simply put, this is a wicked problem. How this occurred, and what can be done about it are important considerations for future strategic planning and operational management. A significant number of research reports, national leader presentations, political hearings, accountability reports, strategic plans, and forward-looking plans state the problem and actions for the future. It is commonly reported that the most extensive and serious problem related to the health of wildland areas is the over-accumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable and destructive wildfires.

Significant issues abound. New solutions are needed. Obvious targets like increased funding exist, but it is important to realize that short-term fixes are less likely to have success and long-term commitments, strategies, and actions are necessary. Management of fuel complexes; accelerated fuel treatments; preparation of communities to withstand wildfire; incorporation of learning, experience, emerging science and technology; as well as sustainable funding for wildfire suppression and fuel treatments are vital for success.

The International Association of Wildland Fire (IAWF) Bushfire and Natural Hazards CRC recognize these needs. We have an unwavering commitment to promote increased involvement, improved communication, escalated research, focused education and training, and active management support to help, promote success in wildland fire management.

This conference is designed to be innovative, revolutionary, and provocative. It will provide a forum to facilitate discussion of the latest relevant research findings, information dissemination about management treatments, stimulation of policy discussions, and inspire global fire management interaction. Both venues will provide a stage having hundreds of oral and poster presentations of new research information, practical experience lessons, and case studies; numerous knowledge and skill building workshops; on-the-ground learning field trips and tours; keynote and plenary presentations; and panel discussions by leading experts in the field. Conference participants will be able to share what is known, what needs to be learned, how to advance knowledge, and how to use this knowledge to effectively respond to increasing concerns.

On behalf of the International Association of Wildland Fire, all conference sponsors and partners, I welcome all participants and hope that this conference will meet, and even exceed your expectations of increasing awareness, knowledge, and capability in this important field in addition to networking with peers to establish future avenues of discovery. We hope that you will enjoy attending and gain significant information from what promises to be the most informative, enlightening, and powerful conference to date on fire behavior and fuels in wildland fire management.

If you were not previously a member of the IAWF, you are receiving a one-year membership in the association included in your registration. By participating as an active IAWF member you can help to improve communication between firefighting organizations, enhance firefighter and public safety, increase our understanding of wildland fire science, and improve our ability to manage fire. Your membership in the IAWF provides you with a connection to other wildland fire professionals from across the world. Our membership, which is truly international, includes professionals from the fields of fire ecology, suppression, planning, contracting, fire use, research, and prescribed fire. Our members are scientists, firefighters, mangers, contractors, and policy makers. As an association, we are unique in that we represent all areas of wildland fire management. Membership benefits include, but are not limited, to the following:

WILDFIRE magazine – All members receive Wildfire magazine, official publication of the IAWF published bi-monthly. Writers send in wildland fire articles and news from all corners of the world, and topical editors cover all the important issues in wildland fire. We encourage you to submit articles and photographs to our Wildfire Editorial Board for inclusion in the magazine.

INTERNATIONAL JOURNAL OF WILDLAND FIRE – Our other official publication of the IAWF, published by CSIRO, is dedicated to the advancement of basic and applied research covering wildland fire and is available as an additional membership option. A discounted rate of US$225 for a 1-year subscription of eight issues is offered to IAWF members; this includes a 1-year membership and a subscription to Wildfire magazine – AND free e-access to the "Journal's" abstracts and articles.

On behalf of the Board of Directors of the IAWF, thank you for your support of our association.

Thomas Zimmerman

Tom Zimmerman
IAWF President

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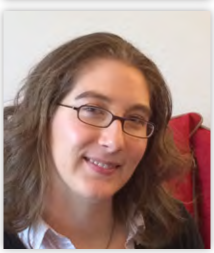

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IAWF STAFF

Mikel Robinson
Executive Director
International Association of Wildland Fire
1418 Washburn
Missoula, Montana 59801, USA
execdir@iawfonline.org
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FEATURED SPEAKERS

WELCOME + OPENING REMARKS TUESDAY, APRIL 11

Tom Zimmerman, *IAWF President & Conference Co-Chair, Retired Program Manager, Wildland Fire Management Research, Development, and Application Program, Rocky Mountain Research Station, U.S. Forest Service*

Tom has worked at multiple federal land management agencies, including the Bureau of Land Management, National Park Service, and US Forest Service. His permanent assignments include positions as Forester, Fire Control Officer, Fire Management Officer, State Fire Management Planning Specialist, Regional Fire Management Officer, Fire Technology Specialist, Fire Science and Ecological Applications Program Leader, Regional Director of Fire and Aviation Management, and Wildland Fire Management RD&A Program Manager. Tom has conducted training in the United States, China, Canada, and India, and presented papers, either in person or virtually, at conferences in the United States, Canada, Italy, South Africa, and Cyprus.

Wildland fire and emergency response constituted a major focus area and Tom has over 30 years of involvement in incident management team operations including service as an Incident Commander and Area Commander on wildland fire incidents and all hazard emergency responses across the country.

Kevin Martin, *Forest Service, Director Fire, Fuels & Aviation Management, Alaska & PNW Regions*

Kevin is the Director of Fire, Fuels and Aviation for both the Alaska and Pacific Northwest Regions of the United States Forest Service (Alaska, Oregon and Washington States). He was the Forest Supervisor on the Umatilla National Forest for 10 years and the Deputy Forest Supervisor on the Deschutes before that. Kevin was a member of the National Fire Line Officer Team for many of those years. He helped create and served as a coach for Agency Administrators at the National Fire Training Center on the Advanced Incident Management (S-520) course and has assisted Units and coached Agency Administrators across the west. He was the national lead for the Forest Service for re-working National Fire Management Leadership. He is on the Board of Directors for the Eastside Restoration Strategy, past chair of the Oregon Geographic Board and then a member of the NW Geographic Board.

The Pacific Northwest Region consists of 16 National Forests in Oregon and Washington. There are 59 District Offices, a National Scenic Area, and a National Grassland. The Alaska Region consists of two national forests, the Tongass, and the Chugach National Forest; however, they are the largest national forests in the Country. The Chugach surrounds Prince William Sound and is near Anchorage. The Tongass includes the islands and mainland of southeastern Alaska and surrounds the towns of Ketchikan, Sitka, Juneau, Petersburg, Wrangell, Yakutat and Skagway.

KEYNOTE PRESENTATION TUESDAY, APRIL 11

Ron Steffens, *Professor, Green Mountain College;*
Fire Analyst and Incident Commander, Teton National Park; FBF Conference Co-chair
Wicked (Fire) Problems, Sweet (and Messy) Solutions (Live streamed to Melbourne)

Abstract: Is my fire a wicked problem? And will it require a messy solution? The "wicked problem" concept can help us understand and manage problems which seem unsolvable — in wildland fire, these wicked fire problems are becoming too familiar and take the form of climate change, massive landscape-scale fuel transitions, land development changes (a decline in fire use coupled with houses in the fire zone), and a disconnect between politics, fire policy and the best-practices guided by fire science. In this round-the-world review of wicked fire problems (and solutions) we'll visit Africa, Australia, Canada and the United States to explore how "mess mapping" and other messy strategies may help us work our way through our fire challenges.

Bio: Ron Steffens is a professor of communications at Green Mountain College in Vermont (USA), where he teaches media, nonfiction writing, and environmental and emergency communication for two bioregionally focused graduate degrees, in Environmental Studies and in Resilient and Sustainable Communities.

For the summer fire seasons, Ron has been based out of Grand Teton National Park since 1992 where he supports Teton Interagency Fire as a fire analyst and incident commander. He began his fire career as a fire lookout in Patagonia, Arizona and continued with seasonal positions in Saguaro National Park, where he served as fire effects monitor and lead of a backcountry fire crew. He has provided fire training in Malawi and the Democratic Republic of Congo for the US Forest Service International Program and has studied fire on five continents. He is a past board member of the International Association of Wildland Fire and serves as managing editor of IAWF's Wildfire Magazine.

Dr Kevin Tolhurst AM, *Assoc. Prof., Fire Ecology and Management, Department of Forest and Ecosystem Science, University of Melbourne (Live streamed from Melbourne)*
Fire is the Problem and Fire is the Solution Fire is the Problem and Fire is the Solution

Abstract: In Australia, we have no option but to manage fire in the landscape. This management can be proactive or reactive. Reactive fire management is easier to defend publicly and politically, but this approach is costly and ineffective. Proactive fire management has been practised in Australia for tens of thousands of years by Aboriginal Australians, but in many places, aboriginal use of fire has been disrupted by European settlement. The science of proactive landscape fire management has been studied systematically since the 1950's, but being equipped with the science of fire does not guarantee sustainable fire management.The view of many Australians, including many fire scientists, is that fire is a damaging process that must be limited. Section 17(2)b of the Victorian National Parks Act (1975) specifically states that the Secretary of the National Parks shall: "ensure that proper and sufficient measures are taken to protect each national and State park from injury by fire;". The concept of fire as a damaging process is enshrined in legislation. However, planned burning is widely used in Australia as a land management tool, but there are ongoing and increasing pressures on fire use. The impacts of smoke on tourism and public health, the ecological impacts, the level of protection afforded to human and natural values and assets from wildfire by planned burning are all topics of debate. The future of fire management will need to have strong political backing. The question is how well the skills, knowledge, experience and capacity of those given the responsibility to manage fire for the population match the complexity of the task. What is clear is that there is no quick fix, but we must systematically progress along a well-defined path and do so at a rate faster than the rate of change in the climate, economy, demographics and political fashions.

Bio: Kevin Tolhurst is Associate Professor in Fire Ecology and Management in the Department of Forest and Ecosystem Science, University of Melbourne based in Creswick. Kevin has developed a professional reputation by providing expert advice on fire behavior and fire suppression strategies at major bushfires. Some examples include the Black Saturday fires in Victoria in 2009, and the Great Divide Fires in 2007. In 2015, Kevin was made a Member of the Order of Australia in recognition of his contribution to fire science and the community over a long period. Kevin has developed and taught a number of fire related subjects at undergraduate and post-graduate level as well as a national Fire Behavior Analyst course for technical specialists in the fire and land management agencies. Kevin's current research activities are centered around developing and applying a bushfire risk management decision support systems. He has established a group of fire scientists in the School of Ecosystem and Forest Sciences with a range of research, fire, land management and teaching skills.

KEYNOTE PRESENTATION WEDNESDAY, APRIL 12

Vicki Christiansen, *Associate Deputy Chief for State & Private Forestry. U.S. Forest Service*
Wildland Fire: Shared Problems, Shared Solutions

This conference addresses the "wicked" problem of wildland fire. What makes fire such a seemingly intractable, difficult problem? Part of the challenge is maneuvering in a complex wildland fire system. The wildland fire system contains the bio-physical wildland fire environment and it also includes interacting or interdependent factors that drive outcomes. These factors include different agency missions, laws and regulations; assumptions and beliefs; social/political environments; and policies, practices and protocols in how wildland fire management is approached in this nation. Many of these system factors not only display differences, but they are also not static as evidence by the changes in climate, fuels buildup, prolonged drought, invasive species, and human development. The fire problem is getting more difficult, has greater impact to people, is more costly, and we are seeing more devastating outcomes, as experienced in the Pacific Northwest in 2015. But, while wildfire may be a complex wicked problem, it is not a hopeless problem. Our path forward must be toward a shared solution as framed in the principles and goals of National Cohesive Wildland Fire Management Strategy; restore and maintain resilient landscapes, create fire-adapted communities and accomplish effective, risk-based response to wildfire. Our success depends on collective commitment and by all stakeholders at all levels to take action toward meaningful reductions in risk in the short and long-term. Significant and broad-scale reduction in wildfire risk is a difficult proposition and it will require the engagement of all stakeholders within this complex system. Collectively and at landscape scales we must assess the prioritization and resources necessary to maintain landscape resiliency and create fire adapted communities. Significantly reducing fuels across broad landscapes will require expanded use of wildland fire to achieve resilient landscapes. Using fire as a tool carries inherent risk that must be considered in the short-term to achieve the longer-term benefits. Even with greater efficiency and acceptance of short-term risk, current levels of investment may be inadequate to achieve the levels of risk reduction desired. All who have a stake in the outcome, from individual property owners to the Federal, state, territorial, tribal, and local governments, must share the costs and **level of** effort necessary to redeem responsibilities for reducing risks posed by wildfire. The National Cohesive Wildland Fire Management Strategy recognizes and accepts fire as a natural process necessary for the maintenance of many ecosystems, and strives to reduce conflicts between fire-prone landscapes and people. By simultaneously considering the role of fire in the landscape, the ability of humans to plan for and adapt to living with fire, and the need to be prepared to appropriately respond to fire when it occurs, the Cohesive Strategy takes a holistic approach to the future of wildland fire management.

Bio: Vicki Christiansen is the Associate Deputy Chief for State & Private Forestry at the U.S. Forest Service in Washington, DC. She has oversight of Fire and Aviation Management, Tribal Relations, Forest Health Protection, Cooperative Forestry and Conservation Education. She joined the Forest Service in 2010 as the Deputy Director of Fire and Aviation

Management. Vicki has worked extensively on the National Cohesive Wildland Fire Management Strategy bringing her experience as a line officer, land manager, wildland fire fighter and State Forester to the effort. Prior to joining the Forest Service she served as the Arizona State Forester and Director of the Arizona Division of Forestry. She was responsible for the protection of 22 million acres of state and private lands in Arizona, including wildland fire management. As State Forester, Vicki represented Arizona at the national and state level on forest health and wildland fire issues. She was Chair of the Wildland Fire Committee for the National Association of State Foresters. Vicki also served as the Washington State Forester where she had a 26 year career with Washington State Department of Natural Resources (DNR). She started as a wildland fire fighter while still in college and held many different positions at Washington DNR with a strong emphasis in operations managing state trust lands and regulating forest practices on state and private lands in Washington State. Her first permanent position was as a forester responsible for the reforestation of state trust lands in the Mt. Saint Helens blast zone. Vicki has been a wildland fire fighter and fire manager for 36 years. She has numerous credentials in the wildland fire program with a special expertise as a fire line-blasting advisor. Vicki has a B.S. in Forest Management from the University of Washington (1983, cum laude). She is married to a Fire Chief (retired) and has two grown sons.

PANEL PRESENTATION WEDNESDAY, APRIL 12

How Do We Make the Complex Tradeoffs Necessary to Effectively Manage Fuels for Ecosystem Health and Public Safety?

Moderator: **Tamara Wall,** *Desert Research Institute*

Panelists:

Lynn M. Decker, *North America Fire Learning Network Director, The Nature Conservancy*

Zachary Prusak, *The Nature Conservancy, Florida Fire Manager and Central Florida Conservation Program Director*

Leland W. Tarnay, *Ecologist, Air Quality, Smoke, Landscape Fire, Pacific Southwest Research Station*

Lynn Decker oversees the North America Fire Learning Network as well as the broader cooperative partnership of the USDA Forest Service, Department of the Interior agencies and The Nature Conservancy. The partnership has a fourteen-year proven track record of helping to restore the nation's forests and grasslands and to make (human) communities safer from fire. The effort serves to strengthen the ability of the partnership, its individual programs and its partners to create and demonstrate transformational change in their relationship to fire. Program elements include the Fire Learning Network (FLN), Prescribed Fire Training Exchanges (TREX), Fire Adapted Community Learning Network (FACLN) and on the ground cross-boundary implementation at scale (SPER). Lynn has extensive experience developing and executing strategy at multiple organizational levels and integrating strategic planning, science, cultural knowledge and adaptive learning to resolve key barriers to transformative resilience in fire systems. Lynn has authored several publications and served as an internal and external advisor on a variety of fire and restoration strategy planning, collaborative learning and delivery learning network topics. She also managed various teams, designed and led landscape based dynamic collaborative planning, learning events and conferences, and with core staff provides organization-wide leadership in the area of fire, people and landscapes. The Fire Learning Network has been the subject of multiple scientific publications, articles and book chapters. Previously, Lynn spent 20 years with the USDA Forest Service working at national, regional and research positions. Lynn earned a B.S. in fisheries biology from the University of California at Davis, and a M.S. in wildland resource science/freshwater ecology at the University of California at Berkeley.

Zachary Prusak has worked for The Nature Conservancy since January 2005. In his roles, Zach supports the members of the Conservancy's Florida Fire Team, which consist of the on-site fire leaders and crew at places such as the Apalachicola Bluffs and Ravines Preserve, and also supports the operations at the Disney Wilderness Preserve and Tiger Creek Preserve. Zach also works with state, federal, local and private conservation groups in order to lead and promote fire training opportunities, facilitate on-the-ground partnerships, collaborate with the Florida Governor and Cabinet on fire statutory issues while also serving as the Florida Conservancy liaison on national fire issues. The Florida Chapter recently reached their "one million acres burned since 1979" milestone on fires led or assisted by Chapter crews. Prior to joining The Nature Conservancy, Zach was the South Region Land Manager for the Brevard County Environmentally Endangered Lands Program, conducted fires and studied mosquito populations with the Reedy Creek Improvement District, and worked as a Biologist for the Florida Park Service. Zach has over 27 years' fire experience working on over 500 prescribed burns, is qualified as a RXB2, and holds both an M.S. and B.S. in Biology from the University of Central Florida. He is also serving as the current Chair of the Central Florida Prescribed Fire Council, is an active member of both the International Association of Wildland Fire and the National Center for Science Education and is available for any voice-over work that you might have!

A literal "air" head, Leland (Lee) Tarnay, has spent most of his career on understanding and managing the effects of air pollutants on forest ecology, and of forest fire emissions on air quality. Lee received his Bachelor of Science from University of California, Davis in biological sciences in 1995, and his Ph.D. from the University of Nevada, Reno in 2001, focused on the deposition of nitrogenous atmospheric pollutants to the forests and waters of the Lake Tahoe Basin. Since 2002, and up until 2015, he worked for the National Park Service as an air resource specialist, first for the National Capital Region around the Washington D.C. area, and then for the last 10 years as Yosemite National Park's first air resource specialist. For Yosemite and now as an ecologist with the U.S. Forest Service, Pacific Southwest Research Station, Lee is working across agencies on the foundational air quality and smoke-related science that will help California forest managers increase the pace and scale of fire treatments, while improving and protecting air quality

KEYNOTE PRESENTATION THURSDAY, APRIL 14

Gary Berndt, *Washington State Wildland Liaison, Commissioner of Public Lands*

We Have a "Wicked" Problem. How Did It Happen? Can It Be Fixed?

Abstract: Wildland fire management in the 21st century is pervaded with emerging trends, both good and bad; challenges; and opportunities. Wildfires of today are burning in altered vegetation and fuel complexes, exhibiting higher levels of intensity, impacting larger areas, persisting for longer durations of time, and more frequently occurring in the wildland urban interface (WUI). Increases in amounts and shifting structure of fuel complexes are promoting increases in fire intensity, severity, area burned, and magnitude of post-fire weather events. The WUI expansion shows no signs of slowing. Climate change is tending to magnify these issues and bring additional concerns.

What is happening today in wildland fire management is a "wicked " problem. It is not unique to any one country or geographic area of the world. We need to directly address how to restore and maintain resilient landscapes, how to make communities better able to withstand wildfires without loss of life and property, how to sustain proactive landscape-scale vegetation management and fuels reduction activities, and how to consider and implement the full spectrum of management activities and the full range wildfire responses. Responsibility for addressing these issues extends beyond just fire management professionals; social awareness of issues, ramifications, opportunities, and capabilities must increase. Collaborative undertakings that involve affected and interested participants must be used to set action plans.

For this talk, I would like to focus on a specific example of this situation, how it happened, and actions are underway. The State of Washington's East slopes of the Cascades, where I am from, experiences a significant threat - the potential for catastrophic wildfire followed by burned lands washing away before restoration can begin. The County I live in is "fire prone". Our County is very much a fire-adapted environment as are all the counties of this area. The rapid population growth in western cities has led to an unprecedented outmigration to the quiet lifestyle of the dry Eastern Washington environment. Commonly the dream is about having five acres and a babbling brook, and even better, bordering public land. This has resulted in a significant number of new homes on lands previously considered industrial forest. These lands are directly adjacent to federal USFS lands. This migration and lifestyle shift has made my county the fifth fastest growing county in Washington State.

In our county, we have now suffered four major wildfires in the last five years with large-scale negative impacts. Large, damaging wildfires are not just a product of wildland vegetation. The WUI growth, lack of forest management, changing weather patterns, fire suppression budget reductions, expectations that 911 solves all problems, and general resistance for developments that can survive the passage of a wildfire have all interacted to create this problem. This scenario came upon us with little resistance socially or politically until it reached the scale of continuous catastrophic impact to everyone across the landscape.

Now what? Can this be fixed? More of the same will not help. Proactive measures are necessary. Increasingly frequent and damaging wildfires cannot simply be accepted as unavoidable events. Industrial forests are being lost to subdivisions, citizens see the forest as static and unchanging, economies are built on growth models, demand increases, suppression costs escalate. It's time to consider the past, examine where we are, and develop strategies for solutions because there can be solutions that make a difference. It's up to us. The problem is complex, the solutions will not be simple.

Bio: Gary Berndt is actively involved in his community and served as City Council member and later Mayor (1988-2004). He formerly served as a County Hospital District Commissioner and the Vice President of the local Chamber of Commerce. He is also an active Rotary member and past president of the local chapter. Gary served as a Kittitas County Commissioner from 2013 until April 1, 2016 when he resigned to take a position as "Washington State Wildland Liaison" reporting to the Commissioner of Public Lands. He was formerly employed by Washington State Department of Natural Resources (1973-2011), he retired in May 2011 as Assistant Region Manager for Resource Protection in S.E. Washington. He was responsible for wildland fire management program on State and private lands and directed prevention, preparedness, training and suppression activities. He also served as Agency Administrator and as Line Officer (agency representative) on many Type 1,2, and 3 incidents.

Gary was involved with curriculum development and course delivery nationally of the National Association of State Foresters "Complex Incident Management Course" from 2000-2010. He served as an instructor and as team coach. This course is currently S-520 equivalent for Type 1 National rating.

He was on the National Steering Committee for the development and delivery of the "Leadership of Organizations Course" known as L-480 from 2003-2006. He was recruited and assisted in the development and delivery of an Australian Course known as the "Advanced Incident Leadership Program" which was a national course delivered once per year to 20 selected managers from across Australia, New Zealand, and Tasmania. The course was developed in 2001 and was been presented annually from 2002 –2012.

Gary has lived in Cle Elum, Washington with his wife, he has 2 daughters and 3 grandchildren.

LIGHTNING INFORMATION SESSION

CAMPFIRE SESSION

WORLD CAFE

SESSION KEY

TUESDAY, APRIL 12 9:35-9:55 EXHIBIT HALL E

LIGHTNING INFO SESSION ONE

NASA FIRE SCIENCE AND APPLICATIONS: TECHNOLOGY, SATELLITES, AIRBORNE DATA AND MODELS

Presented by Amber Soja, NIA / NASA

NASA supports fire research and the application of fire data, models and technology in many cross-cutting Earth Science programs to include Terrestrial Ecology, Carbon Cycle and Ecosystems, Climate Variability and Change, Atmospheric Composition, Interdisciplinary Science and Applied Science. In this presentation we will discuss NASA Missions that have data that could support fire research, land management, fire recovery and active firefighting. We will also provide several examples of the successful use of NASA satellite and model data in fire science research and the application of those data.

Bio: Amber's research interests focus on connections between fire regimes, the atmosphere and biosphere, and feedbacks to and from the climate system. She has two decades of research experience, where she has taken part in and led numerous national and international teams of research scientists. Specifically, she uses Geographic Information Systems (GIS) and satellite-derived data as tools to explore these dynamic relationships. Dr. Soja is currently an Associate Research Fellow at the National Institute of Aerospace, resident in Climate Sciences at NASA LaRC. She has recently taken a part-time Associate Program Manager position in the NASA Applied Sciences Program, Wildland Fire.

APRIL 12 9:35-9:55

CAMPFIRE SESSION ONE

SMOKE IS A GLOBAL PROBLEM

Led by Int'l Smoke Symposium Committee

Join the planning committee for the 2nd International Smoke Symposium to discuss how we can raise awareness of the global diversity of approaches, issues and ideas in fire behavior and smoke management.

LIGHTNING INFO SESSION TWO

PUTTING THE "I" IN WILDFIRE PREPAREDNESS: INSURANCE & NFPA WORKING TOGETHER TO ENSURE WILDFIRE SAFETY IN THE WUI

Presented by Michele Steinberg and Lucian Deaton, NFPA

Communities at risk to wildfire across the United States share the common challenges of risk reduction, resident understanding, and motivation. The insurance industry can and does play an active role in the shared responsibility with residents on homeowner engagement and recognition for their preparedness.

Hear from NFPA about successful partnerships that have been forged with insurance companies to motivate homeowners in the wildland urban interface through the Firewise Communities/USA® Recognition Program and other local efforts. The session will also explore social behavioral change and decision making influenced by risk considerations in the wildland urban interface.

Bio: Michele Steinberg is the Division Manager for Wildland Fire Operations at the National Fire Protection Association (NFPA), where she leads a team dedicated to wildfire safety education, advocacy and outreach. NFPA is a global nonprofit organization established in 1896 and devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. Michele has worked in the disaster safety arena for more than 25 years. Current NFPA wildfire safety initiatives include the Firewise Communities/USA® Recognition Program, home wildfire risk evaluation seminars, Wildfire Community Preparedness Day, and TakeAction, focused on preparedness for youth and families.

Bio: Lucian Deaton manages international partnership development for NFPA's Wildland Fire Operations Division with its Firewise and wildfire standards focus in Africa, Latin America, Canada, Europe, and Australasia. Lucian previously managed the national Firewise Communities Program. Former to NFPA, Lucian worked with the International Association of Fire Chiefs (IAFC) managing the National Ready, Set, Go! Program and was a lobbyist in DC starting in 2001 on public safety issues before Congress and the Federal agencies. He has an MS in Urban Planning and an MS in Natural Resources from Virginia Tech and lives in Denver, CO.

TUESDAY, APRIL 12 3:35–3:55 EXHIBIT HALL E

LIGHTNING INFO SESSION THREE

INNOVATIONS IN EARLY WILDFIRE DETECTION: INTERNATIONAL CASE STUDIES

Presented by Brendan Kramp, Director of Business Development, North America, Insight Robotics

INSIGHT ROBOTICS

Recent technological innovations in wildfire detection have developed the ability to detect fires at very early stages with precise location, enabling more effective risk avoidance and response. In this presentation, Brendan Kramp will give a brief overview of how thermal detection has been developed to detect fires as small as one tree several miles away in both daytime and nighttime conditions. International case studies will show how the technology is being used to save lives, property and forests while significantly reducing costs associated with suppression.

Bio: Brendan Kramp is Director of Business Development, US and Canada, at Insight Robotics. With a strong commitment to social innovation and environmental conservation, Brendan is responsible for building strategic partnerships and helping customers in agriculture and forestry safeguard natural resources and infrastructure with intelligent threat detection. Prior to Insight Robotics, Brendan held several roles in fundraising, partnership development and business development for international institutions in the US, UK and Europe, including academic institutions, international conservation organizations, and an international media organization. Brendan holds an undergraduate degree from Brown University and an MBA from HEC Paris.

LIGHTNING INFO
SESSION FOUR

COME LEARN MORE ABOUT COLUMBIA HELICOPTERS!

Presented by Jim Rankin, CEO of Columbia Helicopters

CAMPFIRE SESSION
SESSION TWO

STUDENTS OF FIRE

led by Kelsy Gibos

Connect with us and we'll use technology to make a connection with conference participants in Melbourne, Victoria, Australia. Join us for some heated discussion about hot wildfire community topics that apply in both hemispheres.

Kelsy Gibos is a Wildfire Management Specialist at Edson Wildfire Management Area, Canada. Kelsy has been instrumental in implementing the Students of Fire initiative!

WEDNESDAY, APRIL 13 3:35-3:55 EXHIBIT HALL E

LIGHTNING INFO
SESSION FIVE

NATIONAL FIRE DANGER RATING SYSTEM

Presented by Matt Jolly

The National Fire Danger Rating System has been used by many agencies in the United States since 1972. A few updates were introduced in 1988, but the system has remained relatively static form more than 40 years. Based on recent science, three updates to improve and simplify NFDRS are being implemented: 1) Growing Season Index (GSI) will compute live fuel moistures; 2) The Nelson Model will compute fine dead fuel moisture; and 3) Fuel models will be reduced to five fuel types. This presentation will discuss how these updates affect NFDRS outputs and the user experience.

Bio: Dr. Matt Jolly is a Research Ecologist in the Fire, Fuel and Smoke Science Program of the US Forest Service, Fire Sciences Laboratory in Missoula, MT. His main research interest is to improve our understanding of the roles that live and dead fuels play in wildland fires and to use this improved understanding to develop or improve predictive tools that can help support fire management decisions.

LIGHTNING INFO
SESSION SIX

FIRE BEHAVIOR FUEL MODEL (FBFM) GUIDEBOOK-DATABASE

Demo by ; Wendel J. Hann, PhD, Landscape Fire Ecologist, University of Idaho, Wildland Fire RD&A and Linda Tedrow, MS, Research Fire Scientist, University of Idaho, Wildland Fire RD&A (photos in folder)

This session demonstrates development of a Fire Behavior Fuel Model (FBFMP) Guidebook-Database for the US. The demonstration will illustrate interactive engagement in reviewing vegetation and fuels information, making mapping rule changes, and recording rationale for changes. The LANDFIRE Program experienced first-hand the value of guidebooks during the Alaska FBFM calibration workshop. The FBFM guidebook-database will improve LANDFIRE ReMap and enhance future updates to data products. The Guidebook may also be useful for other purposes such as site-specific project planning. The primary focus will be on the conterminous United States with possible additional work in other areas of the U.S. LANDFIRE is hosting a workshop on the guidebook-database at the International Association of Wildland Fire conference in Portland, on Monday April 11, 2016. Following the conference, there will be interactive webinars organized by geographic areas. Watch the LANDFIRE website, our bulletins, and our post cards for webinar announcements. To be included on the invitation list for the workshops, please contact us at http://www.landfire.gov/contactus.php.

Bio: Wendel is an accomplished landscape fire ecologist with over 40 year's experience. Current work with the Wildland Fire RD&A involves LANDFIRE fire regime, fuel, and fire behavior mapping and development of associated technology transfer. Wendel retired from the U.S. Forest Service in 2009 with more than 30 years experience ranging from early years fighting fires, packing mules, and clearing trails to work in land, wildland fire, and prescribed fire management to landscape ecology research to his last assignment as National Landscape Fire Ecologist. Wendel has a PhD from the University of Idaho, and MS and BS from Washington State University.

Bio: Linda is an accomplished Research Fire Scientist. Her current work with the Wildland Fire RD&A involves LANDFIRE fire regime, fuel, and fire behavior mapping and development of associated technology transfer. Linda started her work with the University of Idaho as a Remote Sensing Specialist. Prior work involved development of geospatial algorithms to identify radioactive landfills for the Idaho National Laboratory as a Visualization Engineer. Linda is currently working on a PhD from the University of Idaho and has an MS in Geographic Information Sciences from Idaho State University and a BS in geology from the University of California at Berkeley.

campfire SESSION CAMPFIRE SESSION
SESSION THREE

WOMEN IN FIRE SCIENCE

led by Kara Yedinak

This campfire session is aimed at gathering information regarding who may be interested in forming a Women in Fire Sciences group. Groups supporting women in a particular field have been around for quite some time now. However, these groups tend to focus on the traditional academic STEM disciplines, thus often missing interdisciplinary fields such as fire science. In exploring the interest and ideas participants may have, we hope to identify key areas where grass roots support and communication may be beneficial. We encourage ideas and support from any and all interested conference attendees.

Bio: Kara Yedinak is a postdoctoral research fellow in the Department of Forests, Rangelands, and Fire Sciences at the University of Idaho. Kara received her BS in Physics from Pacific University (2002) where she studied low dimensional chaos and fluid flow. She worked as a fire behavior science research technician at the Fire Sciences Laboratory in Missoula, Montana (2004 to 2007). In 2013, Kara completed her PhD at the Laboratory for Atmospheric Research at Washington State University studying coupled atmosphere-fire behavior interactions using simulations and field observations. Currently Kara is focused on investigating concepts surrounding wildland fire propagation theory and acoustics.

THURSDAY, APRIL 14 10:35–10:55

LIGHTNING INFO SESSION SEVEN
NATIONAL FIRE DANGER RATING SYSTEM

info SESSION LIGHTNING INFO
SESSION SEVEN

MONITORING THE FIRE EDGE AND TRACKING PERSONNEL WITH MODERN TECHNOLOGY

presented by Josh Hintze

Exploring how the modern technologies of RFID and radar can improve the safety of fire fighters and increase the effectiveness of firefighting strategies.
Our website is www.tagsmyth.com

LANDFIRE

led by Henry Bastian and Frank Fay,
LANDFIRE Business Leads, DOI and US USDA Forest Service

LANDFIRE is a program that provides over 20 national geo-spatial layers (e.g. vegetation, fuel, disturbance, etc.), databases, and ecological models that are available to the public for the US and insular areas. Henry Bastian and Frank Fay are the project business leads. Come and visit with them about LANDFIRE current and future status, updates, remap, and new developments. LANDFIRE, Landscape Fire and Resource Management Planning Tools, is a shared program between the wildland fire management programs of the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior, providing landscape scale geo-spatial products to support cross-boundary planning, management, and operations. LANDFIRE is a cornerstone of a fully integrated national data information framework for developing and improving vegetation and fuels data products based on the best available authoritative data and science. LANDFIRE's mission is to provide agency leaders and managers with a common "all-lands" data set of vegetation and wildland fire/fuels information for strategic fire and resource management planning and analysis.

Bio: Henry is a Fire Manager with DOI, currently located in Boise, ID. He oversees and coordinates enterprise systems for the National Fire Plan and Operations System (NFPORS), Interagency Fuels Treatment Decision Support System (IFTDSS), and LANDFIRE. Prior, he was in Washington, D.C. as the business lead for LANDFIRE. Henry worked for the National Park Service as a fire ecologist where he led the fire ecology and fire effects monitoring program. Prior to this, he worked in the State of Utah in vegetation management. He graduated from Snow College and Utah State University, with a degree in fish and wildlife biology.

Bio: Frank is an Applied Fire Ecologist with US Forest Service in Washington DC where he oversees LANDFIRE and the Hazardous Fuels Programs. Prior to this work Frank was in Utah, Oregon, and California working in forest planning, silviculture, environmental coordination, project planning, and hotshot firefighter. Temporary assignments have included: Senior Assistant to the Climate Change Advisors Office in Washington DC, Assistant Director of Fuels and Fire Ecology Washington DC, and District Ranger. Frank is a certified Fire Ecologist and a certified Silviculturist. Frank has a BS in forestry from Humboldt State University and graduate work from the University of Washington.

LOOKING BACK & MOVING FORWARD WITH COLLECTIVE WISDOM

The fire season of 2015 was yet another monumental season. Such seasons with severe, intense fire behaviour; lost values; records for acres burned and expenditures are becoming commonplace. What do we learn from these seasons that helps us move forward with research and management to ensure the trajectory of our fire management programs and their outcomes benefit land management and societal objectives? During these two World Café's we will hear the experiences of two land managers: what they have learned from recent fire seasons and how that leads to changing direction. Following their experiences the attendees will share their experiences and learn from others as they meet in smaller groups led by subject experts to discuss critical management issues.

WEDNESDAY MORNING

8:00-9:00 AM EXHIBIT HALL E

Fire Behaviour and Fire Management – Does Normal Exist?

Denise Blankenship,
Deputy Fire Director,
US Forest Service

Denise will share her observations across several seasons; providing examples of well-known fire 'rules' that have been broken as fires, fire seasons, and climate have been changing. What do we know?What should we expect in this ever changing world? And how do we adapt?

DISCUSSION TOPICS:

Fire Behaviour – What is the new normal?

Modeling Fire Behaviour – Nuances and challenges

Fuel Treatments – When do they work best?

Air quality – To breathe or not to breathe? - is not the only question.

THURSDAY MORNING

7:30-8:30 AM EXHIBIT HALL E

Protecting Values While Managing Fire

Jack Oelfke, Chief of Natural and Cultural Resources, North Cascades National Park, National Park Service

Managing diverse values on a landscape poses significant challenge especially when considering the threats they may face from fire and fire management. Jack will share his experiences with the National Park Service working to incorporate direct and indirect impacts from fire suppression and fire and its effects on cultural and natural resources as well as other values. He will share interesting insights into values and potential impacts that may be overlooked as well as incorporating those considerations into fire planning and wildfire management.

DISCUSSION TOPICS:

Cultural Artifacts – Arrowheads to ghost towns

Natural Resources – From the species to the ecosystem

Act Now While the Fire is Hot - Communicating and integrating in an emerging incident

After the Fire is Over – Managing fire effects

GENERAL INFORMATION

BANKING

ATM machines are located in the MLK Lobby next to Stir, in Exhibit Hall A Lobby at the bottom of the escalator, and in the South Gingkoberry Lane Lobby across from Portland Roasting. There is a transaction fee of $3.

CONFERENCE PROCEEDINGS

All authors are invited to submit an Extended Abstract to the Conference Proceedings. To properly prepare your extended abstract, please adhere to the provided instruc¬tions. You can use the Word soft copy of this instruc¬tions file as a formatting template. Please remember that your abstract must be in final form when you submit it to us; it will not be reviewed or edited. Copies of the extended abstracts will be posted on the conference web site. There will be no distinction between oral and poster presentations in the proceedings. The deadline for submissions is
June 1, 2016. For more information, templates and submission system visit:
http://portland.firebehaviorandfuelsconference.com/presenters/conference-proceedings

CONTINUING EDUCATION

The program has been approved for Continuing Education from the Society of American Foresters. Please ask for tracking sheet at the registration desk.

DINING

A light continental breakfast will be provided each morning in the Exhibit Hall E.
Light refreshments will be provided each day during the morning and afternoon networking breaks, also in Exhibit Hall E. All conference guests are invited to attend the Award Luncheon on Wednesday where we will have a plated lunch. There are several eating establishments in the Oregon Convention Center including two in Exhibit Hall E, as well as many within walking distance.

EXHIBITORS

The exhibitors will be set up on Monday afternoon, April 11. Monday evening from 6-8 pm there will be Social Reception with the exhibitors featuring a Pacific Northwest Menu and no-host bar. The Exhibitors are located on the1st level of the Oregon Convention Center in Exhibit Hall E. We encourage you to visit our sponsors and exhibitors each morning and during lunch and breaks.

EXHIBIT HALL HOURS

Monday . . . . . .6:00-8:00 pm
Tuesday . . . . . .7:30 am – 7:30 pm
Wednesday . . .8:00 am – 4:00 pm
Thursday . . . . .7:30 am – 1:00 pm

GREAT INITIATIVE/SUSTAINABILITY/ RECYCLING

The International Association of Wildland Fire (IAWF) is committed to minimizing the environmental impact of its conferences and meeting through:

- Reducing the amount of solid waste produced by the event;
- Reducing energy and water consumption at the event;
- Minimizing or off-setting harmful emissions resulting from vehicular transportation and energy consumption associated with the event;
- Disposing of solid and liquid waste in an environmentally responsible manner;
- Selecting facilities who have developed a sustainability policy;
- Buying environmentally aware products; and
- Educating participants and exhibitors.

We invite our conference participants and vendors to join us in this goal of incorporating environmentally responsible procedures and practices and in the use of environmentally responsible products while participating in this conference. Working together, we can make this a successful 'Green' event. Please remind yourself and help others to remember to reduce, reuse, and recycle!

The Oregon Convention Center is committed to recycling and provides recycling areas within the exhibit halls for exhibitor use. In addition, there are specialized recycling containers with designated labels throughout the facility to meet your event waste needs.

INTERNET/CHARGING STATIONS

Complimentary Wireless Internet is available throughout the Exhibit Hall and the meeting rooms. We have provided charging stations near the entrance of the Exhibit Hall.

MOBILE APPLICATION

Sponsored by PHOS-CHEK

To download the mobile app:

- iPhone and iPad users--search "EventBoard" on the Apple App Store.
- Android users--search " EventBoard " on the Google Play Store.
- Our Conference will be listed under All Conferences
- Click on our conference to enter the mobile app site.

Thanks! We hope you enjoy the mobile app!

PARKING

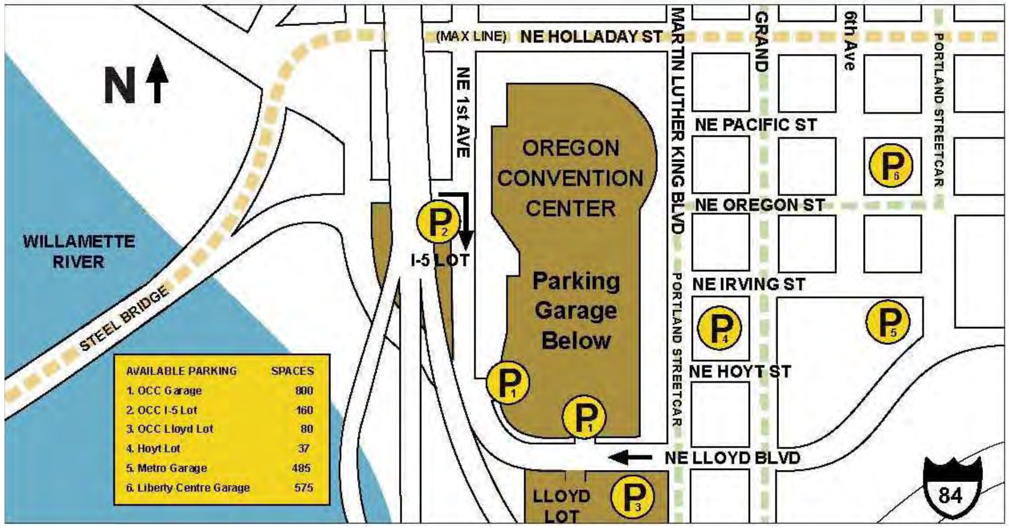
In addition to street and bus parking in the surrounding area, the OCC provides on-site parking in its clean and secure underground parking garage. Eight hundred spaces are available on the garage's two levels. Disabled parking is available in the garage and all OCC lots on a first-come, first-served basis. In addition, there is public parking in the Lloyd Lot (corner of Northeast MLK Boulevard and Northeast Lloyd Boulevard) via a credit card only pay box. In/out privileges are not available. The maximum daily rate to park is $10. Overnight parking in the garage is prohibited.
The parking garage offers four electric vehicle charging stations, two on each level. Spaces are indicated by brightly-lit green murals and are available on a first-come, first-served basis.
Enter the garage via its First Avenue or Lloyd Boulevard entrances. Clearance on the P1 level is seven feet; clearance on the P2 level is nine feet.

POSTERS

Posters will be on display in the Exhibit Hall E. The formal poster presentation will be Tuesday Evening from 5:30-7:30 pm. Light hors d' oeuvres and no-host bar will be available.

Please see the detailed program for the list of posters. All posters will be left up the entire three days, and will be staffed by the authors during the formal presentation on Tuesday.

Poster presenters may place their posters anytime between 7:30 am -4:00 pm on Tuesday. All posters must be removed before 1:00 pm on Thursday, April 14th.



We will provide you with the means to attach your poster (pushpin, Velcro, clips).

PRESENTERS

Please note that all presenters will be required to use the computers we are supplying; this will ensure smooth transitions between presentations.

We have provided an on-line submission system to upload your presentations. All oral presenters are required to turn in their presentations the day prior to their session. This is very important so we can load your presentations and make any adjustments that may be needed before your presentation. Please do your very best to help us out with this!
You can either use the online system or you can upload your presentation at the speaker table in the registration area onsite.

Online Submission System: https://iawf.submittable.com/submit/53904

SIDE MEETINGS

We have a room available for impromptu side meetings throughout the week; Room E148. There is a schedule on the door, sign up at your desired time, please respect others by staying to your schedule time.

SPEAKER READY ROOM – A Speaker Ready Room is available for all conference presenters to preview their material prior to presentation. The Speaker Ready Room is Room E147.

TRANSPORTATION

Portland's MAX light rail stops 300 times a day at our front door, connecting riders to downtown, surrounding neighborhoods, the Oregon zoo, and Portland International Airport. The Streetcar's Central Loop stops at our MLK lobby entrance every 15 minutes. Also, at the MLK lobby entrance, TriMet's Bus Line No. 6 provides access to downtown stops and outlining areas.

Compliments of Travel Portland each conference attendee will receive a pass that is good for the week of the conference for all busses and trains in Portland.

WELLNESS

Take care of yourself at the Fire Behavior and Fuels Conference. We all know that our health and wellness should take top priority, but sometime we need a reminder. Take advantage of the group led physical activity session that we will be providing. Please check at the registration desk for a list of activities.

Also, take advantage of the hotels fitness and recreation offerings.

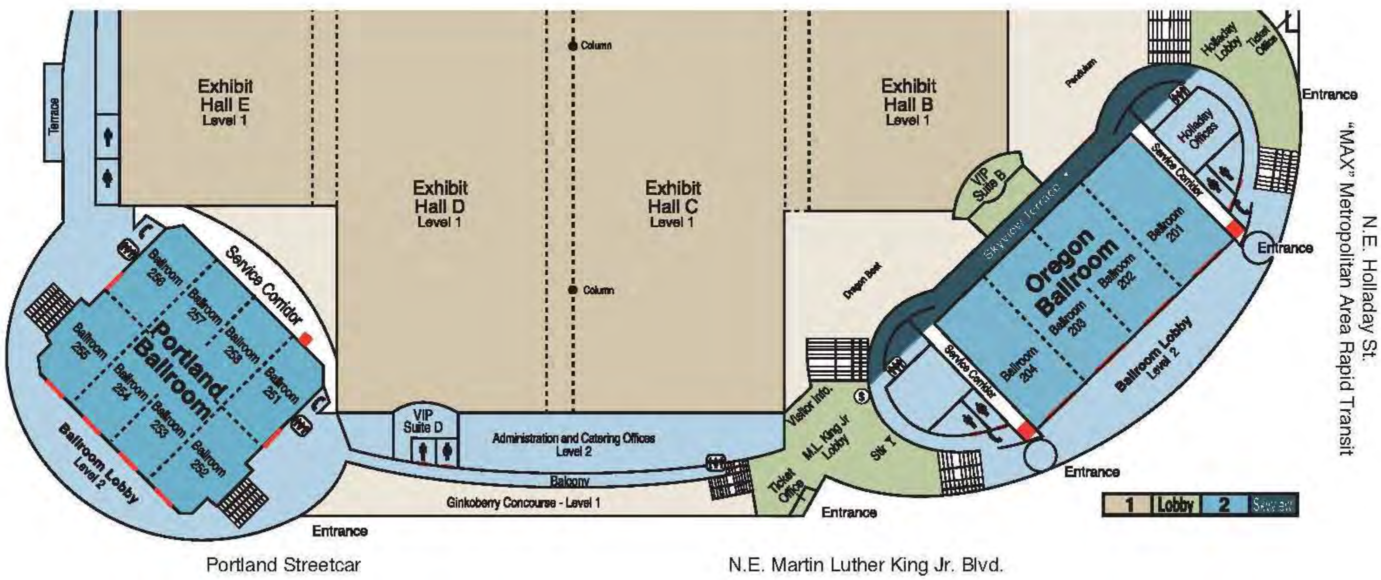
DoubleTree by Hilton Portland
- Bicycle Rental
- Fitness Room
- Stationary bikes
- Treadmills

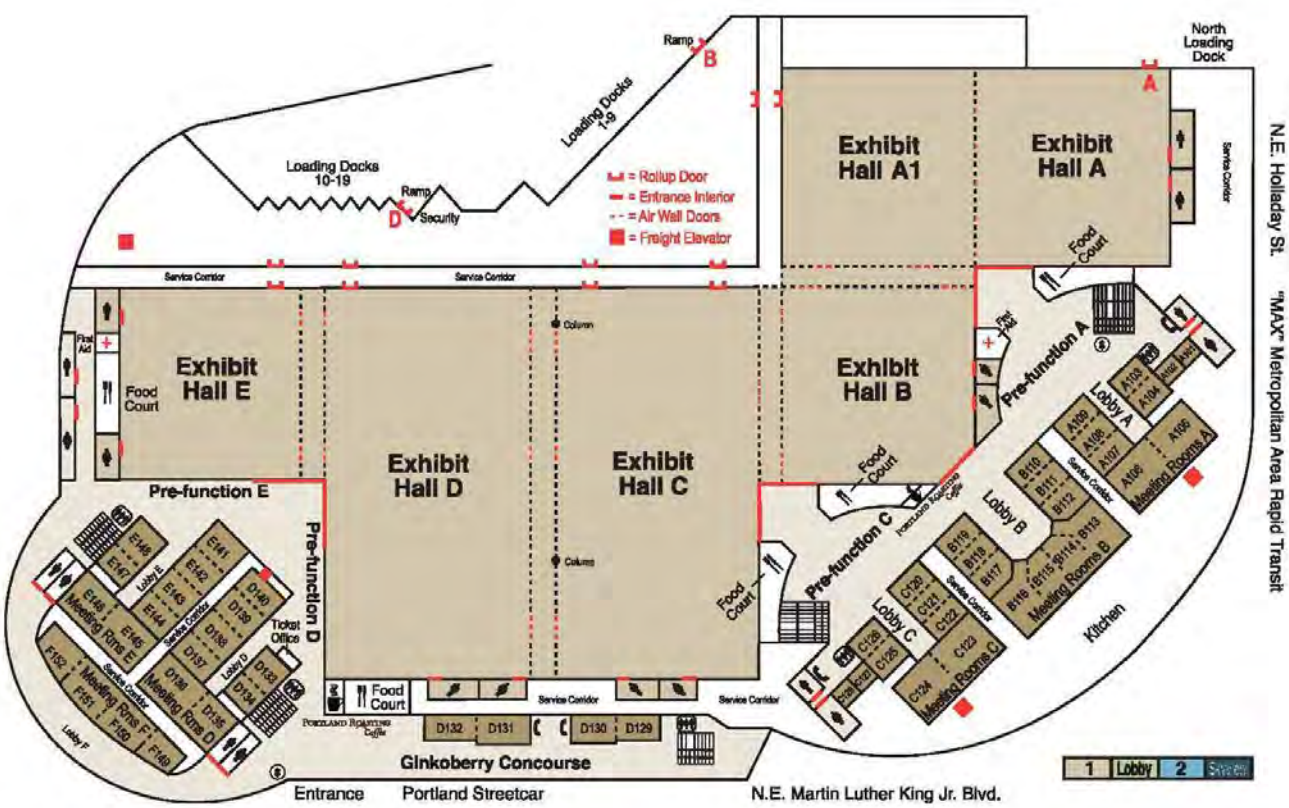
Courtyard Marriott-Portland Downtown/ Convention Center
- Hotel Fitness Center
- Cardiovascular equipment
- Free weights
- Treadmill, elliptical, universal gym, free weights
- Indoor Pool

QUESTIONS/INFORMATION

If you have any questions or need any assistance please visit the registration desk which will be located in the foyer area outside of the Exhibit Hall E.

convention CENTER maps





Monday, April 11, 2016					
7:00 am-6:00 pm	**Conference Registration/Information Desk Open** *(Pre-Function E)*				
WORKSHOPS					
	Room E141	**Room E143**	**Room E144**	**Room E146**	**Room E147**
8:30 - 12:30	**#1** - Fuel and Fire Tools (FFT)—An application for Wildland Fuel and Fire Management Planning	**#11** -The Future of Fire and Fuels Management: Adapting Fuels Treatments in a Changing Climate	**#5** - Introduction to the BehavePlus fire modeling system	**#2 -** Fire Behavior Fuel Model Guidebook – LANDFIRE: Invest your knowledge in FBFM calibration rules for the conterminous US	**#3 -** Accessing Fire Weather Information: A Tutorial on Using the MesoWest/Synoptic API Web Services
12:30-1:30 pm	**Lunch - on your own**				
WORKSHOPS (cont.)					
	Room E141	**Room E143**	**Room E144**	**Room E146**	**Room E147**
1:30 - 5:30 pm	**#7** – How to generate, interpret and apply landscape-scale hazard and risk assessment results	**#11** - Cont.. The Future of Fire and Fuels Management: Adapting Fuels Treatments in a Changing Climate	**#10** - Linking Fire Behavior, Fire Effects, and Weather Systems in Prescribed Fire Planning	**#12** -Fuels Treatment Effectiveness: Joint Fire Science Workshop for Current Research, Preliminary Results and Implications (by invitation for JFSP PI's)	**#9** - Getting more "Good Fire" on the Ground Across North America
12:00-6:00 pm	**Exhibitor Set-up** *(Exhibit Hall E)*				
6:00-8:00 pm	**Social Reception with Exhibitors** *(Exhibit Hall E)*				
8:00 pm	**Afterhours Networking** - Spirit of '77, 500 NE Martin Luther King Jr Blvd, Portland				

Tuesday, April 12, 2016			
7:30 am-5:00 pm	**Conference Registration/Information Desk Open** *(Pre-Function E)*		
7:30-8:15	**Greet-the-Day Gentle Yoga - Led by Johnny Stowe** *(Wellness Lounge Room E142)*		
8:30-9:30	**Welcome and Opening Session** *(Portland Ballroom 254/255)* **Tom Zimmerman,** *IAWF President and Conference Co-chair* **Ron Steffens,** *Professor, Green Mountain College & Conference Co-chair* **Kevin Martin,** *Director Fire, Fuels & Aviation Management, Alaska and PNW Regions, US Forest Service*		
9:30-10:00	**NETWORKING BREAK with Exhibitors** *(Exhibit Hall E)*		
9:35-9:55	**Lightning Info Session One:** NASA Fire Science and Applications: Technology, Satellites, Airborne Data and Models *Presented by Amber Soja, NASA*	**Lightning Info Session Two:** Putting the "I" in Wildfire Preparedness: Insurance & NFPA Working Together to ensure Wildfire safety in the WUI *Presented by Michele Steinberg and Lucian Deaton, NFPA*	**Campfire Session One:** Smoke is a Global Problem *Led by Int'l Smoke Symposium Committee*

	CONCURRENT SESSIONS *(Tuesday, April 12)*				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
	SPECIAL SESSION ONE: Towards Efficient Large Fire Management: Monitoring, Modeling, and Accountability *Moderator: Matt Thompson*	**Rx Fire** *Moderator: Johnny Stowe*	**Fire and Smoke Modeling** *Moderator: Casey Teske*	**Risk Assessment** *Moderator: Elizabeth Reinhardt*	***Fire Behavior*** *Moderator: LaWen Hollingsworth*
10:00-10:20	SS1.1 A framework for optimal incident management: safe and effective response in a new fire management paradigm *Christopher Dunn*	1. Is It Time To Say Goodbye to Fire Rotations? *Cecil Frost*	6. Multiphase CFD Model of Wildland Fire Initiation and Spread *(remote)* *Vladimir Agranat*	12. A National Wildfire Risk Assessment for U.S. Forest Service Lands *Greg Dillon*	17. Trends and thresholds in fire behavior across Yellowstone's young lodgepole pine forests *Kellen Nelson*
10:20-10:40	SS1.2 Large airtankers in US fire management: describing historical use and discussing implications related to efficiency *Crystal Stonesifer*	2. Restoration of xeric oak forests in south-central United State with prescribed fire *Stephen Hallgren*	7. Data-driven Forecasting Paradigms for Wildland Fires using the CAWFE modeling system and Fire Detection Data *Janice Coen*	13. Perception and Management of Sociopolitical Risks on Large Fires *Armando Gonzalez-Caban*	18. Fuels and Fire Behaviour in New Zealand Wilding Conifers *Tara Strand*
10:40-11:00	SS1.3 Meaningful translation of aerial firefighting objectives, context and outcomes into effectiveness across the range of fire sizes for the Aerial Firefighting Use and Effectiveness Study *Keith Stockmann*	3. Post-fire tree mortality model assessment following prescribed burning treatments in National Park units of the western U.S. *Jeffrey Kane*	8. GridFire: A Fast Raster-Based Fire Spread and Severity Model *Gary Johnson*	14. Investigating temporal trends in wildfire hazard *Jessica Haas*	19. Using McArthur Model To Predict Bushfire Prone Areas In New South Wales *Liran Sun*
11:00-11:20	SS1.4 Firefighting Resource Use and Movement in the United States *Erin Belval*	4. 2015 National Prescribed Fire Use Survey *Pete Lahm*	9. Towards an integrated fire-atmosphere prediction system with data assimilation *Sher Shranz*	15. Wildfire threat to residential structures in the Island Park Sustainable Fire Community *Joe Scott*	20. An experimental study of the stochastic nature of firebrand flight *Ali Tohidi*
11:20-11:40	SS1.5 Develop a simulation/optimization procedure to study the daily suppression resource movement in Colorado *Yu Wei*	5. The Smoke-wise Community and the Path to More Fire *Peter Lahm*	10. High Fidelity Reduced Order Models for Wildland Fires *Alan Lattimer*	16. Impact Oriented Fire Paths *Joaquin Ramirez*	21. The Frequency in the Flames: Acoustic Impulse Events Generated by Wildland Fire Fuels *Kara Yedinak*
11:40-12:00	SS1.6 Summary: Infusing Risk Management Principles into the Fire Management System *Matthew Thompson & David Calkin*	Discussion	11. Field-scale testing of detailed physics-based fire behavior models *Eric Mueller*	Discussion	22. Exploratory analysis of interactions of patchy/clumpy fuel configurations on fire behavior with a physics-based fire model *Francois Pimont*
12:00-1:45	**Lunch - on your own**				
1:30-1:45	**Work-the-Kinks-Out Gentle Yoga - Led by Johnny Stowe** *(Wellness Lounge Room E142)*				

	CONCURRENT SESSIONS *(Tuesday, April 12)*				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
	Smoke Management *Moderator: Tamara Wall*	**Community Protection and Adaptation** *Moderator: Jerry McAdams*	**Fire and Smoke Modeling** *Moderator: Kurtis Nelson*	**Fire and Climate** *Moderator: Tim Brown*	**Fire Behavior** *Moderator: Kara Yedinak*
1:45-2:05	23. Managing Fire in the Only EPA Declared Public Health Emergency in America *Nikia Hernandez*	28. Landscaping with Ornamental Trees and Exterior Structure Features using EcoSmart Fire Model *Mark Dietenberger*	32. The effect of static stability on the atmospheric response to a wildland fire *Joseph Charney*	37. Fire weather drives the population collapse of obligate-seeder forests *David Bowman*	42. ForestFireFOAM: A Numerical Tool For Investigating The Burning Dynamics Of Wildland Fuels *Mohamad El Houssami*
2:05-2:25	24. When there's Fire there's Smoke: Linking Wildfire to Distant Urban Airsheds. A 5 Year Health Economic Assessment of the Western US, 2010-2014 *Benjamin Jones*	29. Setting Wildfire Evacuation Triggers by Coupling Fire and Traffic Simulation Models *Dapeng Li*	33. A Study of the Influence of Vertical Canopy Structure on Fire-Atmosphere Interactions *Michael Kiefer*	38. Contributions to a megafire: Fire-induced winds, drought, and fuel buildup due to fire suppression *Janice Coen*	43. A Fundamental Exploration of Flame Structure in Wildland Fires *Colin Miller*
2:25-2:45	25. Smoke in the City: How Often and Where Does Smoke Impact Summertime Ozone in the United States? *Steven Brey*	30. Coupling the human and biophysical dimensions of wildfire to better understand wildfire risk and risk mitigation *Max Nielsen-Pincus*	34. Ignition from fire perimeter and assimilation into a coupled fire-atmosphere model *Adam Kochanski*	39. Climate-induced variations in global wildfire danger from 1979 to 2013 *W. Matt Jolly*	44. Forward Heating in Wind-Driven Fire Spread *Wei Tang*
2:45-3:05	26. Impact of wildfires on regional air pollution *Alexandra Larsen*	31. Wildland/Urban Interface: U.S. Fire Department Wildfire Preparedness and Readiness Capabilities *Michele Steinberg*	35. Developments in the BlueSky smoke modeling framework and related smoke tools *Sim Larkin*	40. Exploring interactions among multiple disturbance agents and future climates in forest landscapes *Robert Keane*	45. Laboratory Studies on the Generation of Firebrands and Ignition of Structural Components *Raquel Hakes*
3:05-3:25	27. Sensor Messaging: Guidance for Interpretation of Short-Term Concentration Readings *Susan Stone*	Discussion	36. The Effect of Forest Gaps on the Transport and Dispersion of Smoke Plumes from Low-Intensity Wildland Fires *Jovanka Nikolic*	41. Projected impacts of climate change on vegetation and fire in the Huachuca Mountains of Arizona *Christopher O'Connor*	46. Experimental Study on the Surface Spread of Smouldering Peat Fires *Xinyan Huang*
3:25-4:00	**NETWORKING BREAK with Exhibitors** *(Exhibit Hall E)*				
3:35-3:55	**Lightning Info Session Three:** Innovations in Early Wildfire Detection: International Case Studies *Presented by Brendan Kramp, Insight Robotics*	**Lightning Info Session Four:** Come learn more about Columbia Helicopters! *Presented by Jim Rankin, Columbia Helicopters*	**Campfire Session Two:** Students of Fire *Led by Kelsy Gibos*		
4:00- 4:45	**GENERAL SESSION** *(Portland Ballroom 254/255) - Live streamed to Melbourne* **Wicked (Fire) Problems, Sweet (and Messy) Solutions** **Ron Steffens,** *Professor, Green Mountain College & Conference Co-chair*				
4:45-5:30	**GENERAL SESSION** *(Portland Ballroom 254/255) - Live streamed from Melbourne* **Fire is the Problem and Fire is the Solution** **Dr Kevin Tolhurst AM,** *Assoc. Prof., Fire Ecology and Management, Department of Forest and Ecosystem Science, University of Melbourne*				
5:30-7:30	**Poster Session** *(Exhibit Hall E) List of Poster Presentations listed at the end of the program*				
7:30 pm	**After Hours Networking** - Altabira City Tavern (located on the top floor of the Hotel Eastland) - 1021 NE Grand Ave.				

Wednesday, April 13, 2016					
7:30 am-5:00 pm	**Conference Registration/Information Desk Open** *(Pre-Function E)*				
7:00 am	**Group Led Run/Walk - Led by Amanda Stamper** - *(meet in the lobby at the DoubleTree Hotel)*				
8:00-8:45	**Greet-the-Day Gentle Yoga - Led by Johnny Stowe** *(Wellness Lounge Room E142)*				
8:00-9:00	*Exhibit Hall E* ~ **Breakfast with the Exhibitors** ~ **World Café - Fire Season 2015 – Looking Back and Moving Forward with Collective Wisdom** ***Fire Behavior and Fire Management – Does Normal Exist?*** Denise Blankenship, Deputy Fire Director, US Forest Service				
9:00-9:45	**GENERAL SESSION** *(Portland Ballroom 254/255)* **Wildland Fire: Shared Problems, Shared Solutions** ***Vicki Christiansen,*** *Associate Deputy Chief for State & Private Forestry, U.S. Forest Service*				
9:45-10:00	**Transition to Concurrent Sessions**				
	CONCURRENT SESSIONS				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
	SPECIAL SESSION TWO: Wildland Fire Emission Factors – Latest research and implications for management and policy *Moderator: Shawn Urbanski*	**Smoke Management** *Moderator: Steve Miller*	**Case Studies** *Moderator: Norman Arendt*	**Wildfire Response** *Moderator: Tim Sexton*	**Fire Weather** *Moderator: Faith Ann Heinsch*
10:00-10:20	SS2.1 Emission Factors and Wildland Fire: Policy Implications and Applications *Pete Lahm*	47. Differential respiratory health effects from the 2008 northern California wildfires: a spatiotemporal approach *Colleen Reid*	53. Lessons Learned from an Unexpected Spread Event on a Large Fire in a Remote Mountain Park *Kelsy Gibos/Dave Finn*	57. The effectiveness of large air tankers for containing wildfire ignitions *Hari Katuwal*	63. Introducing and Validating a New Fire Weather Index: The Hot-Dry-Windy (HDW) Index *Alan Srock*
10:20-10:40	SS2.2 Background to Emission Factor Development *Shawn Urbanski*	48. Montana Idaho Airshed Group Smoke Management Decision Support *Erin Law*	54. Developing and Implementing Geospatial Data Collection of Fuel Treatments, Lessons Learned *Justin Shedd*	58. Providing Information about Uncertainty Using Probability Distributions: USDA Forest Service Wildfire Suppression Expenditure Forecasting *Charlotte Ham*	64. Testing the Hot-Dry-Windy Index for the 2015 Fire Season in the Pacific Northwest *Brian Potter*
10:40-11:00	SS2.3 Emission Factors – Latest Research *Shawn Urbanski*	49. A Flexible Decision Support Framework for Smoke Management: 3 Case Studies *Matthew Mavko*	55. A 72-day Probabilistic Fire Growth Simulation as a Decision Support Tool on a Large Mountain Fire in Alberta, Canada *Kelsy Gibos/Neal McLoughlin*	59. What Does It Mean to Have a High Initial Attack Success Rate in Wildland Firefighting? *Karen Short*	65. Daily Relationships Between Fire Danger and Satellite-Derived Metrics of Fire Activity Across CONUS *Patrick Freeborn*
11:00-11:20	SS2.4 Assessing the limits of large diameter live and dead fuel consumption and their potential influence on emissions *Matt Jolly*	50. Understanding Smoke Transport from Prescribed Burning in the Wildland Urban Interface of Bend, Oregon *Susan O'Neill*	56. Something Wicked This Way Burns: A Wicked Fire Problem in a Coastal Oregon Town *Ron Steffens*	60. Beyond ICS: Propositions on Managing Complex Fire Events *Branda Nowell*	66. Alaska Fire and Fuels System *Joe Young*

	CONCURRENT SESSIONS *(Wednesday, April 13)*				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
11:20-11:40	SS2.5 Will fire average emission factors provide the ability to evaluate the effectiveness of emission reduction techniques? *Roger Ottmar*	51. Wildland Fire Smoke: A Hazard for Health Disaster Management *Darlene Oshanski*	Discussion	61. Writing Incident Objectives in WFDSS: What we Know, How we can do Better *Tim Sexton*	67. Comparison of temperature and relative humidity values from Sling Psychrometers and Electronic Weather Meters in an Controlled Environment *Charles McHugh*
11:40-12:00	SS2.6 Assessing New Emissions Factors for Estimating Emissions from Wildland Fires *Duncan Lutes*	52. Smoke Monitoring in the Field: Understanding Equipment and the Value of Particulate Matter Data in Making Smoke Management Decisions *Don Schweizer*	Discussion	62. What is the Strategy? A Comparison of WFDSS and ICS 209 *Tim Sexton*	Discussion
12:00-1:30	**Awards Luncheon** *(Portland Ballroom 256/257)*				

	CONCURRENT SESSIONS				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
	Continued... SPECIAL SESSION TWO: Wildland Fire Emission Factors – Latest research and implications for management and policy *Moderator: Shawn Urbanski*	**Fire Economics** *Moderator: Joe Scott*	**Fire and Smoke Modeling** *Moderator: Nancy French*	**Fire Effects** *Moderator: Kelsey Gibos*	**Fire Weather** *Moderator: Brian Potter*
1:30-1:50	SS2. 7 Smoke Emission Modeling Inter-comparison Project (SEMIP) *Susan O'Neill*	68. Benefits and Incentives for Fuels Treatment in the Mokelumne Basin *Mark Buckley*	73. Assimilation of satellite active fires detection into a coupled weather-fire model *Jan Mandel*	78. Black Carbon Production and Storage as a Result of Differing Fire Frequencies in Longleaf Pine Forests *Adam Coates*	84. The MesoWest/Synoptic Web Service: A Tool for Accessing Fire Weather Data *Joshua Clark*
1:50-2:10	Panel Discussion	69. Minority Households Willingness-to-Pay for Public and Private Wildfire Risk Reduction in Florida: A Latent Class Analysis *Jose J. Sanchez*	74. Evaluation and improvement of an advanced regional modeling framework, addressing effects of wildfire emissions on modeled air quality for the Pacific Northwest *Vikram Ravi*	79. Recovering Lost Ground: Effects of Soil Burn Intensity on Nutrients and Ectomycorrhiza Communities of Ponderosa Pine Seedlings *Ariel Cowan*	85. A Novel Wildfire Prediction Tool Utilizing Fire Weather and Machine Learning Methods *Leo Deng*
2:10-2:30		70. Hedonic Models for Homes Vulnerable to Wildfire *David Rossi*	75. The importance of biomass burning feedbacks: Focus on CALIOP-based estimates of smoke plume injection height *Amber Soja*	80. Basal duff smoldering beneath old pines: a distinctive pattern of ground combustion *Jesse Kreye*	86. Modeling of Thunderstorm-Induced Wind Shifts *Scott Goodrick*

	CONCURRENT SESSIONS *(Wednesday, April 13)*				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
2:30-2:50	Panel Discussion	71. Systematic Investigation of Wildfire Damage and Risks on Property Values *Qiuhua Ma*	76. Field-Scale Validation of Data-Driven Wildland Fire Spread Simulations *Cong Zhang*	81. Quantifying Emission Factors from Smouldering Peat Fires: a Laboratory Study *Rory Hadden*	87. How Do Very Large Fires Get to be Very Large Fires? *Harry Podschwit*
2:50-3:10		72. The Effect of Wildfires on Recreation Visitation: A Historical Analysis of the National Park Service's Intermountain Region *Kara Walter*	77. Effects of Forest Canopy on Atmospheric Turbulence During Wildland Fires *Warren Heilman*	82. Flammability of North America Pines *Morgan Varner*	88. Defining fire season length using daily climatic, satellite, and documentary fire records *Karin Riley*
3:10-3:30		Discussion	Discussion	83. Can Wildfire Restore Conifer-encroached California Black Oak Woodlands? *Deborah Nemens*	Discussion

3:30-4:00	**NETWORKING BREAK with Exhibitors** *(Exhibit Hall E)*
3:35-3:55	**Lightning Info Session Five:** National Fire Danger Rating System (NFDRS) – Update 2016 *Presented by Matt Jolly*
	Lightning Info Session Six: Fire Behavior Fuel Model (FBFM) Guidebook-Database *by Wendel Hann and Linda Tedrow*
	Campfire Session Three: Women in Fire Science *Led by Kara Yedinak*
4:00-6:00	**JOINT PANEL SESSION WITH MELBOURNE** *(Portland Ballroom 254/255) - Live streamed* **How Do We Make the Complex Tradeoffs Necessary to Effectively Manage Fuels for Ecosystem Health and Public Safety?** **PANEL MODERATOR:** **Tamara Wall,** *Desert Research Institute* **PANELISTS:** **Lynn M. Decker**, North America Fire Learning Network Director, The Nature Conservancy **Zachary Prusak,** The Nature Conservancy, Florida Fire Manager and Central Florida Conservation Program Director **Leland W. Tarnay,** Interagency Ecologist, Air Quality, Smoke, Landscape Fire, Pacific Southwest Research Station
6:00-7:00 pm	**Sahyinidra Yoga and Meditation - Led by Johnny Stowe** *(Wellness Lounge Room E142)*
7:00 pm	**After Hours Networking** - Doug Fir Restaurant and Lounge, 830 E Burnside Street, Portland
	Thursday, April 14, 2016
7:30 am-5:00 pm	**Conference Registration/Information Desk Open** *(Pre-Function E)*
7:30-8:30	*Exhibit Hall E* ~ **Breakfast with the Exhibitors** ~ **World Café - Fire Season 2015 – Looking Back and Moving Forward with Collective Wisdom** **Protecting Values While Managing Fire** *Jack Oelfke, Chief of Natural and Cultural Resources, North Cascades National Park, National Park Service*
7:30-8:15	**Greet-the-Day Gentle Yoga - Led by Johnny Stowe** *(Wellness Lounge Room E142)*

	CONCURRENT SESSIONS (*Thursday, April 14*)				
	Room E141	Room E143	Room E144	Room E145	Room E146
	SPECIAL SESSION THREE: Joint Fire Science Program and Smoke Science Research: Status of Progress Towards Meaningful Solutions *Moderator: Al Riebau*	**Fire Use/Restoration** *Moderator: Gene Rogers*	**Technology** *Moderator: Robert Ziel*	**Fire Effects** *Moderator: Eric Miller*	**Education, etc** *Moderator: Amanda Stamper*
8:30-8:50	SS3.1 Critical Assessment of Wildland Fire Emissions Inventories: Methodology, Uncertainty and Effectiveness *Wei Min Hao*	89. Modeling alternative fire response policies: proof-of-concept and preliminary results *Karin Riley*	94. Emerging Communication Technologies for Wildland Firefighting *Ed Mills*	100. Impacts of Post-fire Salvage Harvesting on Early-seral Ecosystems in Western Oregon *John Bailey*	106. Automating Fuel Model Assignment and Spatial Alignment for Fire Spread Modeling in Roaded Areas *Casey Teske*
8:50-9:10	SS3.2 Overview of the SC Regional Emissions and Aging Measurements (SCREAM) study *Sonia Kreidenweis*	90. Analyzing tradeoffs among socioeconomic and ecological restoration goals on the national forests of the Pacific Northwest *Kevin Vogler*	95. Synergistic Use of New NASA Technologies for Pre-, Active, and Post-Fire Applications *E. Natasha Stavros*	101. Mapping Severe Fire Potential in the Contiguous United States *Brett Davis*	107. Educating the Future Fire Workforce to Respond to Increasingly Complex Challenges *Leda Kobzair*
9:10-9:30	SS3.3 Emissions and properties of light absorbing particles emitted from fire *Gavin McMeeking*	91. Using Natural Ignitions to Accomplish Land Management Objectives *Kelly Martin*	96/97. Efforts to Enhance the Emergency Fire Shelter: A Collaboration between the U. S. Forest Service and NASA *Tony Petrilli and Josh Fody*	102. Spatial Analysis of the Influence of Fire Severity on Forest Structure on the North Rim of Grand Canyon National Park *Valentijn Hoff*	108. Burning for Blooms, Birds, and Butterflies: Partnerships and Pyrodiversity in the Willamette Valley *Amanda Stamper*
9:30-9:50	SS3.4 Investigation of particle and vapor wall-loss effects on controlled wood smoke smog chamber experiments *Jeffrey Pierce*	92. Restoring Fire to North American Wildlands - A Call to Action *Tim Sexton*		103. Fire Moss as a Tool for Post-Wildfire Ecosystem Restoration *Chris Ives*	109. Aerial Firefighting with Helicopters *Jim Rankin*
9:50-10:10	SS3.5 Data and Tools for Analysis of Smoke Impacts on Ozone and PM *Matt Mavko*	93. Planning for a future of more fire, safer fire, and better fire *Christopher O'Connor*	98. Evaluating the Quality of a Wildfire Defensible Space with Airborne LiDAR and GIS *Jason Harshman*	104. Disentangling the Drivers of Wildfire Severity in a Multi-Owner Forest Landscape *Harold Zald*	110. UWSP Fire Crew Approaching Tomorrow's Problems With Today's Education and Training *Jacob Livingston*
10:10-10:30	Discussion	Discussion	99. Detection of Forest Fires Impact with Remote Sensing Data, ALSAT, In Semi-arid Zones, Algeria *Zegrar Ahmed*	105. Estimating Fire Induced Basal Area Mortality with Multi-temporal LiDAR *Michael Hoe*	Discussion

10:30-11:00	**NETWORKING BREAK with Exhibitors** *(Exhibit Hall E)*
10:35-10:55	**Lightning Info Session Seven:** Monitoring the Fire Edge and Tracking Personnel with Modern Technology *Presented by Josh Hintze* — **Campfire Session Four:** LANDFIRE *Led by Henry Bastian and Frank Fay*
11:00-11:40	**GENERAL SESSION** *(Portland Ballroom 254/255)* **We Have a "Wicked" Problem. How Did It Happen? Can It Be Fixed?** ***Gary Berndt,*** *Washington State Wildland Liaison, Commissioner of Public Lands*
11:40-1:00	**Lunch - on your own**
12:40-12:55	**Work-the-Kinks-Out Gentle Yoga - Led by Johnny Stowe** *(Wellness Lounge Room E142)*

CONCURRENT SESSIONS

	Room E141	Room E143	Room E144	Room E145	Room E146
	Continued... SPECIAL SESSION THREE: JFSP and Smoke Science Research: Status of Progress Towards Meaningful Solutions *Moderator: Doug Fox*	**SPECIAL SESSION FOUR: Managing Wildfire for Resource Benefit: Increasing Opportunities, Improving Ecosystems** *Moderator: Laurie Kurth*	**Fuels** *Moderator: John Bailey*	**Fire Effects (landscape)** *Moderator: Lily Konantz*	**Shared Responsibility** *Moderator: Michael Gollner*
1:00-1:20	SS3.6 A casual inference analysis of the effect of fire smoke on ambient air pollution levels *Alexandra Larsen*	SS4.1 Where are we and where can we go with managing fire and what do we need to get there? *Jim Hubbard*	111. New frontiers in fuel sampling: new techniques for measuring fuels for fire management in the US *Robert Keane*	117. Simulating the Joint Impacts of Wildfires and Fuel Management on Landscape Resiliency in Central Oregon USA *Ana Barros*	123. Successful Stewardship Begins with Trust: The Southern Blues Restoration Coalition *Dana Skelly*
1:20-1:40	SS3.7 Comparative study of emission factors and mutagenicity of red oak and peat smoke from smoldering and flaming combustion *Yong Ho Kim*	SS4.2 Where have we been with managing fire for resource benefits? *Laurie Kurth, Frankie Romero, Henry Bastian*	112. Modeling fuels and fire effects in 3D with FuelManager and STANDFIRE *Francois Pimont*	118. Forest fuels and potential fire behavior twelve years after variable-retention harvest in lodgepole pine *Justin Crotteau*	124. A Framework for Collaborative Learning: Forest Fuels and Vegetation Monitoring in the Southern Blue Mountains *Becky Miller*
1:40-2:00	SS3.8 Fire and Smoke Model Evaluation Experiment (FASMEE) *Roger Ottmar*	SS4.3 Do We Need Wildland Fire Use Back? *Frankie Romero*	113. Next-Generation Fuels Mapping at Regional Scales: accounting for uncertainty and spatial variability *Susan Prichard*	119. Multi-dimensional cost-effectiveness of fuel treatments in dry mixed conifer forests: an inventory originated analysis *Jeremy Fried*	125. Fire Adapted Communities - Networking on a Local & National Scale *Jerry McAdams and Forest Shafer*
2:00-2:20	SS3.9 Airborne based smoke marker ratios from prescribed burning *Amy Sullivan*	SS4.4 Managing Fire – Working with partners to protect communities and other values, reduce risk, and improve ecosystems *Panel Members: Forest Schafer – Lake Tahoe Fire Districts Darren Borgias – The Nature Conservancy Judy Reese – State of Alaska Judy Knobel – Washington Department of Natural Resources Dave Baker – Livestock rancher*	114. Changes of masticated fuelbed properties over time in the western US *Pamela Sikkink*	120. The effects of a long-term, landscape-scale, fuel management program on three-dimensional fuel loading and distribution *Nicholas Skowronski*	126. Think bigger: statewide wildfire risk perceptions in Idaho *Thomas Wuerzer*
2:20-2:40	SS3.10 How wild is your model fire? Constraining WRF-Chem wildfire smoke simulations with satellite observations *Jeffrey Pierce*		115. Estimating Litterfall Rates Following Stand-replacement Disturbance in Northern Rocky Mountain Ecosystems *Christine Stalling*	121. Driving fire behaviour models with forest inventory data in Canada *Dan Thompson*	127. How Wildland Fire Leaders are Co-Managing Risk *Michael Zupko*
2:40-3:00	Panel Discussion		116. Post Treatment Fuel Loading Differential in Two Logged Areas of Banff National Park *Erin Tassell*	122. Utilizing drought science and information in wildfire management decision context *Timothy Brown*	128. New Approaches for Mapping the Wicked Problem of Wildfire *Cody Evers*

PROGRAM SCHEDULE

3:00-3:15	**NETWORKING BREAK** *(Pre-Function E)*				
	CONCURRENT SESSIONS				
	Room E141	**Room E143**	**Room E144**	**Room E145**	**Room E146**
	Continued... **SPECIAL SESSION THREE: JFSP and Smoke Science Research: Status of Progress Towards Meaningful Solutions** *Moderator: Cindy Huber*	**Continued...** **SPECIAL SESSION FOUR: Managing Wildfire for Resource Benefit: Increasing Opp., Improving Ecosystems** *Moderator: Laurie Kurth*	**Fire and Carbon** *Moderator: Ron Steffens*	**Fire Management Planning** *Moderator: Tom Zimmerman*	**Fire Weather/Fuel Moisture** *Moderator: Mary Taber*
3:15-3:35	SS3.11 Megafire, Fuel Loading, and Emissions in the Continental United States under Changing Climate *Yong Liu*	SS4.5 Risk Assessment in the Southern Sierras *Matt Thompson, Phil Bowden*	129. Quantifying avoided wildfire emissions from significant wildfires in California *Thomas Buchholz*	135. A Legacy of Fire Use: Fire Management and Fire Use in Eastern Province of Zambia *LaWen Hollingsworth*	141. Moisture Exchange Models for Standing Dead Grass in Alaska *Eric Miller*
3:35-3:55	SS3.12 Future Mega-fires and smoke impacts *Sim Larkin*	SS4.6 Rogue Basin – Risk Assessment across land ownership boundaries *Kerry Metlen*	130. Estimates of biomass consumption based on MODIS Fire Radative Power overestimate global biomass consumption and carbon release *Bryce Kellogg*	136. Living with Fire – Lessons Learned from Central Africa Grass Savannas and how it relates to Fire Management in the United States *Jim Menakis*	142. Examination of pyrophytic plant combustion and the relationship between fuel moisture, energy released, and emissions *Evan Ellicott*
3:55-4:15	SS3.13 Modeling evaluation of the contribution of wildland fire emissions of BC deposition rates in the Western US *Serena Chung*	SS4.7 Application of landscape-scale wildfire risk assessment results to incident management *Joe Scott*	131. A new top-down method for estimating aerosol emissions applied to large wildfires in North America *Tadas Nikonovas*	137. Introduction to STARFire: wildland fire spatial planning and budgeting *Douglas Rideout*	143. Climatic and eco-hydrological drivers of fuel moisture dynamics in complex terrain *Petter Nyman*
4:15-4:35	SS3. 14 Estimating climate impacts on future wildfires and SE US Air Quality *Uma Shankar*	SS4.8 Case Study - Bald Knob Fire, Pisgah NF *Riva Duncan*	132. Snag Dynamics and Fuel Succession Following Wildfires in the Eastern Cascade Mountains *David Peterson*	138. A Survey of Fire Managers: Characterization of Resource Importance, Scarcity, and Substitutability by Resource Type *Crystal Stonesifer*	144. Flammability of Live Vegetation: Combustibility and Ignitability Assessment *Jan Christian Thomas*
4:35-4:55	Panel Discussion	SS4. 9 The High Meadow Wildfire - A Natural Ignition Managed for Multiple Objectives In a Complex Social Environment *Mark Rosenthal*	133. Estimating canopy bulk density distribution using calibrated t-LiDAR indices *Francois Pimont*	139. Water Quality Above All Else: Fire Management in the Greater Victoria (British Columbia) Water Supply Area *Robert Walker*	145. Critical Examination of the Haines Index and its Use *Brian Potter*
4:55-5:15		SS4.10 Case Study - Paradise Fire, Olympic NP *Todd Rankin*	134. Effects of Stand Thinning in Modifying Crown Fire Behavior in a Black Spruce Stand in Interior Alaska *Eric Miller*	140. NASA Fire Science and Applications: Technology, Satellites, Airborne Data and Models *Amber Soja*	146. Developing new references for fine dead fuel moisture in the Southeastern United States *Matt Jolly*
5:15-5:20	**Transition to Closing Session**				
5:20-5:40	**Closing Session** *(Portland Ballroom 254/255)*				
7:00	**After Hours Networking** - Punchbowl Social, 340 SW Morrison Street, Portland				
	Friday, April 15, 2016				
8:00 - 5:00	**Field Trip #1 – Burning for Blooms, Butterflies, Birds (and Bouquets): Prescribed Fire in the Willamette Valley**				
8:30 - 12:30	**Field Trip #2 Columbia Helicopters**				

P1. A Novel Application of Wildfire Risk Assessments in Land Management Plans- ***Jennifer Anderson***

P2. Oregon's Prescribed Fire Council: working in the future with prescribed burning and managed wildfire **- *John Bailey and Amanda Stamper***

P3. Experimental Research of Grass Ignition by the Heated up to High Temperatures Carbon Particle- ***Nikolay Baranovskiy***

P4. Mathematical Simulation of Heat Transfer in Coniferous Tree at the Forest Fire Influence- ***Nikolay Baranovskiy***

P5. Geomonitoring of Forest Fire Danger Using GIS and Remote Sensing: Case Study for Typical Area of Tomsk Region- ***Nikolay Baranovskiy***

P6. Characterizing biogeographical variation in encounter rates between fire and fuel treatments in the conterminous United States- ***Kevin Barnett***

P7. Tools for Improving Fire Behavior Fuel Model Spatial Data- ***Kori Blankenship***

P8. Relationships between Firing Technique, Fuel Consumption, and Turbulence and Energy Exchange during Prescribed Fires- ***Kenneth Clark***

P9. Back to the Fire and Fire Surrogate Study for Wisdom on Fuels Treatment Longevity- ***Justin Crotteau***

P10. Blueprint For Survival, New Options, Skills, Procedure, For Extreme, Fast Fires -***Troop Emonds***

P11. Reluctant to Simplify: Examining Assumptions about Wildland Firefighting Communication- ***Rebekah Fox***

P12. Two Frameworks for Post-fire Prediction of Tree Mortality Across Pyrogenic Landscapes- ***Michael Gallagher***

P13. The Available Science Assessment Project: Evaluating the Supporting Science Behind Climate Adaptation Actions for Fire and Fuels Management - ***Rachel M. Gregg & Whitney Reynier***

P14. A GIS tool and framework for integrating White-headed woodpecker habitat models into Fire and Land Management Planning Scenarios- ***Jessica Haas***

P15. Development of a high-resolution (5-m) fuel model map based on LiDAR and NAIP and its application to Marin County, CA -***Hilary Hafner***

P16. Conterminous United States LANDFIRE Analysis and Remap of the Fire Regime Group Layer -***Wendel Hann***

P17. Conterminous United States FIRE BEHAVIOR of FUELS for VEGETATION: Invest Your Knowledge in the LANDFIRE Guidebook – ***Wendel Hann & Lindaw Tedrow***

P18. A Fire History of the White Cap Creek Watershed in the Selway-Bitterroot Wilderness in Idaho -***Valentijn Hoff***

P19. Inexpensive Smoke Sensors and Aerial Platforms for Smoke Monitoring and Model Validation -***John Hom***

P20. The Effect of Post-Mountain Pine Beetle Salvage Treatments on Fuel loads and Fuel Moisture in Colorado Lodgepole Pine Forests -***Paul Hood***

P21. Smoke Management Information Resources on the FRAMES Emissions and Smoke Portal -***Josh Hyde***

P22. The Southwest Fire Science Consortium: An Opportunity in Fire Science and Management - ***Chris Ives***

P23. Effectiveness and Longevity of Ponderosa Pine Fuels Reduction Treatments: A Legacy of Research at Lick Creek Demonstration/Research Forest in Montana, USA -***Katelynn Jenkins***

P24. Simulation of a Prescribed Fire Event in the Jones Ecological Research Center -***Michael Kiefer***

P25. Comparative Study of Emission Factors and Mutagenicity of Red Oak and Peat Smoke from Smoldering and Flaming Combustion -***Yong Ho Kim***

P26. Operational Maps Created from LiDAR Technology Identifying Landscape Firebreaks - ***Vesa Leppänen***

P27. Dependence of Daysmoke modeling of smoke plume vertical profiles on updraft core number -***Yongqiang Liu***

P28. Emissions Estimations and Smoke Plume Transport Analysis of the King Fire - ***Marlin Martinez***

P29. Does pre-spruce beetle outbreak history affect how outbreaks alter fuels? - ***Nathan Mietkiewicz***

P30. Fire Emissions Inventory Systems' Organization and Costs -***Helen Naughton & Kendall A. Houghton***

P31. Evaluating shortwave radiation models for fuel moisture prediction -***Petter Nyman***

P32. Planning for fire use and containment using a predictive spatial model of landscape-driven barriers to fire spread -***Kit O'Connor***

P33. Assessing Impacts of Climate Change and Human Population Growth on Forest Fire Potential in the Tropics - A Case Study of the Tain II Forest Reserve in Ghana - ***Eric Osei-Kwarteng***

P34. FIRESEV East: Mapping higher severity fire potential for the Eastern U.S. -***Matthew Panunto***

P35. Post-fire Logging Produces No Lasting Impacts on Understory Vegetation in Northeastern Oregon -***David Peterson***

P36. Evaluating CMAQ's Ability to Simulate Ozone and PM2.5 from Wildland Fire Emissions -***Thomas Pierce***

P37. Summarizing wildfire development with growth statistics -***Harry Podschwit***

P38. Synoptic Meteorology Associated with Large Fire Growth Episodes -***Brian Potter***

P39. Effects of a British Columbia Wildfire on Soil Water Repellency -***Aaren Ritchie-Bonar***

P40. Fire and Smoke Model Evaluation Experiment (FASMEE) -***Roger Ottmar***

P41. Innovations in Post Fire Assessment and Recovery, Malheur National Forest, Canyon Creek Complex -***Dana Skelly***

P42. Multi-scale analyses of wildland fire combustion processes in open-canopied forests using coupled and iteratively informed laboratory-, field-, and model-based approaches -***Nicholas Skowronski***

P43. Real-Time Smoke Monitoring Using Rapid Deploy Equipment to Aid in Fire Management and Ensure Public Safety -***Mike Slate and Ricardo Cisneros***

P44. Putting the "I" in Wildfire Preparedness: Insurance & NFPA Working Together on Social Change Understanding -***Michele Steinberg***

P45. Development of Real-Time Particulate and Toxic-Gas Sensors for Firefighters -***Fumiaki Takahashi***

P46. Communities Using Early Wildfire Detection Technology to Successfully Reduce Risk, Damage, and Losses -***Brendan Kramp***

P47. Do Fuels Treatments Promote Drought Resistance in Lassen National Park? -***Mike Vernon***

P48. Understory Vegetation Changes with Different Seasons and Intervals of Prescribed Burning -***Harold Zald***

P49. Facilitating Fire Potential Depictions in Preparation and Response Decisions: Integrating Tools Online -***Robert Ziel***

P50. National Wildfire Coordinating Group's Smoke Committee and Recent Air Quality Regulatory Updates – ***Peter Lahm et al.***

SOCIAL ACTIVITIES

AWARDS LUNCHEON

APRIL 13, 12:00 -1:30 PORTLAND BALLROOM 256/257

On Wednesday we will have our awards luncheon. The luncheon is included in your registration so everyone is welcome to attend. We will be presenting our newest award "Excellence in Wildland Fire Management". We will also be announcing the recipients of the " Vallette Early Career Award" and the " Ember Award for Excellence in Wildland Fire Science". We will also be announcing the recipients of the best Student Poster Awards. We have some special guests we will be recognizing for their service and support of the IAWF. It will be a great time so we hope you will join us!

AFTERHOURS NETWORKING

We have selected a location each evening for afterhours networking.
Please join your fellow conference participants at the following locations:

MONDAY

Spirit of 77
2 minute walk from the convention center.
500 NE Martin Luther King Jr Blvd
Portland, OR 97232
503-232-9977
http://www.spiritof77bar.com

TUESDAY

Altabira City Tavern (located on the top floor of the Hotel Eastland)
4 minute walk from the convention center
1021 NE Grand Ave. Suite 600
Portland, OR 97232
503-963-3600
http://www.altabira.com/

WEDNESDAY

Doug Fir Restaurant and Lounge
(13 minute walk from the convention center,
streetcar also available)
830 E Burnside St,
Portland, OR 97214
503.231.9663
http://www.dougfirlounge.com

THURSDAY

Punchbowl Social
(Max Blue Line or Uber)
340 SW Morrison St
Portland, OR 97204
503-334-0360
http://punchbowlsocial.com/portland

PORTLAND BLAZERS

Wednesday Evening, we've been extended an offer from Travel Portland and Portland's professional basketball team the Trail Blazers for discounted tickets to the game against the Denver Nuggets.

International Association of Wildland Fire

2015-16 | PORTLAND TRAIL BLAZERS

The Portland Trail Blazers look forward to welcoming the International Association of Wildland Fire to Portland! We are pleased to offer your attendees discounted ticket prices for our game against the Denver Nuggets on Wednesday, April 13th! To book, your attendees just use the online link and promo code provided. If you'd like to take advantage of this offer or have questions please contact Alec Botts. We look forward to welcoming your group to the Moda Center!

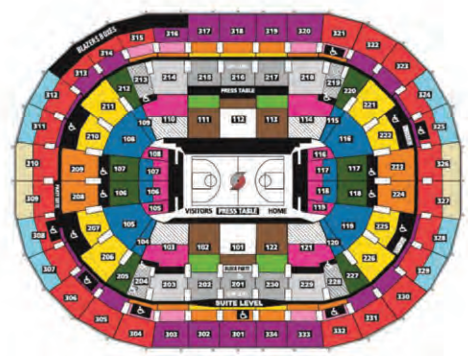
Portland Trail Blazers
vs.
Denver Nuggets

Wednesday, April 13th @ 7:00PM

300-Level starting @ $13 per ticket

200-Level starting @ $39 per ticket

100-Level starting @ $67 per ticket



Website:
http://www.rosequarter.com/travelportland

Promo Code: **travelportland**

We can offer your group a variety of options, including:

- Special ticket savings available for individuals through online link and promo code, which can be easily placed on your conference website or in emails for pre-conference purchases.
- Blocks of tickets available for larger orders in advance to ensure group seating, plus the ability to gain access to group leader incentives which can include free tickets to the game!
- Hospitality Packages (meeting space/dinner/luxury suites/networking opportunities)
- Exclusive Fan Experience opportunities with private access to the court before or after the game!

Order deadline: TBD
After deadline, please call for availability

For more information contact:
Alec Botts
503.963.3926
alec.botts@trailblazers.com

Orders are filled on a first-come first-served basis and are subject to availability. No refunds or exchanges.

WORKSHOPS

Workshop #1 - Fuel and Fire Tools (FFT)—An application for Wildland Fuel and Fire Management Planning

Instructors: *Susan Prichard, Research Scientist, School of Environmental and Forest Sciences, University of Washington and Roger Ottmar, Research Forester, Pacific Wildland Fire Sciences Laboratory, US Forest Service*

The Fire and Environmental Research Applications team (FERA) of the Pacific Wildland Fire Sciences Laboratory has developed the Fuel and Fire Tools (FFT) application. FFT has integrated a suite of five fuel and fire management products that will be demonstrated at this workshop. The suite of tools includes the Fuel Characteristics Classification System (FCCS), Digital Photo Series, Consume, piled fuel biomass and emissions calculator, and the Fire Emissions Production Simulator (FEPS).

The FFT allow users to build and characterize fuel beds, assess potential fire hazard and surface fire behavior, and estimate the amount of fuel consumed and emissions produced if burned during a wildland fire. The workshop will provide background information on the individual tools and demonstrate how to use FFT through several exercises.

Workshop #2 - Fire Behavior Fuel Model Guidebook - LANDFIRE: Invest your knowledge in FBFM calibration rules for the conterminous US

Instructors: *Wendel J. Hann, PhD, Landscape Fire Ecologist, University of Idaho, Wildland Fire RD&A; Linda Tedrow, MS, Research Fire Scientist, University of Idaho, Wildland Fire RD&A; Henry Bastian and/or Frank Fay, LANDFIRE Business Leads, DOI and US USDA Forest Service*

Participants enhance LANDFIRE's rules for mapping fuel models resulting in improved fire behavior predictions for vegetation of the Conterminous United States. Instructors and participants interactively evaluate and improve content of a draft guidebook. Guidebook content blends the maps and descriptions of vegetation and fuel characteristics with fuel model rules and expected fire behavior. Participants integrate their knowledge of the diversity of relationships between fire behavior, fuel model rules, and vegetation and fuel characteristics to assist instructors in enhancing local to national confidence in fuel model and fire behavior mapping.

Workshop #3 - Accessing Fire Weather Information: A Tutorial on Using the MesoWest/Synoptic API Web Services

Instructors: *Joshua Clark, Developer, University of Utah and Joe Young, Developer, University of Utah*

MesoWest software to access, archive, and disseminate environmental information relevant to fire professionals in the United States and Canada has been extensively updated recently (see http://mesowest.org). MesoWest has been providing access to weather information for fire weather applications for nearly two decades. Over 40 million observations are added and archived each day from over 40,000 locations, including observations from permanent and temporary deployments of Remote Automated Weather Stations (RAWS). While the legacy map, graphical, and tabular interface software (MesoWest, http://mesowest.utah.edu , and ROMAN, http://raws.wrh.noaa.gov) continue to be used extensively by fire weather professionals, these were designed by necessity as "one size fits all" tools to meet common needs of operational, commercial, academic, and public users.

The MesoWest development team at the University of Utah is now collaborating with software developers at Synoptic Data to expand access to environmental information around the world. To simplify access to both recent and archived data, the MesoWest/Synoptic Application Programming Interface (API) is now available to allow users to develop their own customized queries to obtain the environmental information of interest to them. Fire professionals can access observations in the vicinity of specific wildfires, obtain alerts when conditions change in selected areas, or design their own fire weather monitoring tools.

Workshop #5 - Introduction to the BehavePlus fire modeling system

Instructors: *Faith Ann Heinsch, Physical Scientist, USDA Forest Service; LaWen Hollingsworth, Fire Behavior Specialist, USDA Forest Service; and Greg Dillon, Spatial Fire Analyst, USDA Forest Service*

The BehavePlus fire modeling system is the successor to BEHAVE, which was first available for field application in 1984. It is an appropriate tool for many fire management applications including prescribed fire planning, fuel model testing, assessing fuel hazard, and projecting the behavior of an ongoing fire. BehavePlus can be effectively used to learn about specific fire models (such as transition to crown fire) that are included in spatial modeling systems where relationships are not as readily apparent.

BehavePlus includes models for surface and crown fire spread and intensity, crown fire type, safety zone size, size and shape of a point source fire, containment requirements, spotting distance, scorch height, tree mortality, probability of ignition, and fine dead fuel moisture. The program help system includes a description of the many input and output variables. That information is also available in a single reference document with many internal links. This interactive workshop provides an introduction to BehavePlus for new users, helping them determine if it meets their needs. Workshop attendees will learn how to use the program through interactive, hands-on exercises that will allow them to explore many basic features of BehavePlus. Attendees bringing their own computers will benefit the most from this workshop.

Workshop #7 - How to generate, interpret and apply landscape-scale hazard and risk assessment results

Instructors: *Joe H. Scott, Wildfire Science Consultant, Pyrologix LLC; Julie Gilbertson-Day, Wildfire GIS Analyst, Pyrologix LLC and James Menakis, Fire Ecologist, USDA Forest Service*

The wildland fire risk assessment process has been utilized at multiple scales to address different land management questions by USDA Forest Service, Department of Interior land management agencies, and state agencies. While most land managers consider the wildland fire risk assessment a product that is used strictly by fire and fuel specialists, the actual use of the assessment has much greater application for land and resource planning and implementation. This workshop is targeted for resource managers to develop a better understanding of the wildland fire risk assessment processes and how it can be used in resource management decisions and planning.

This workshop will first introduce managers to the wildland fire risk assessment concept and methodology for developing an assessment. Second, it will demonstrate the application of the wildland fire risk assessment at multiple scales (national to local) focusing on resource management issues. And third, it will show the benefits of incorporating the wildland fire risk assessment into land management plans and forest plan revisions. By the end of the workshop resource managers will have a solid understanding of how to accomplish a wildland fire risk assessment and why it's directly important to their land management planning and implementation.

A landscape-level wildfire hazard assessment entails four main steps. First, we identify the study area, fire occurrence areas (FOAs) and fire modeling landscape area required to assess hazard for the specific land management unit under assessment. Next we summarize historical wildfire occurrence within the FOAs to ensure that sufficient fire occurrence data exist within each FOA, and then summarize historical fire weather within each FOA. Armed with knowledge of historical weather, we can now acquire, critique, update and edit fuel and vegetation data (from the LANDFIRE program, for example). This step produces an up-to-date fuelscape for use in simulation models that generate detailed spatial information on wildfire likelihood and intensity, as well as other fire behavior variables such as type of fire, crown fraction burned, flame length, etc.

Workshop #9 - Getting more "Good Fire" on the Ground Across North America

Instructors: *Johnny Stowe, Heritage Preserve Manager, SC Department of Natural Resources USA; Steve Miller, Land Management Bureau Chief, St. John's Water Management District (FL, USA); and Morgan Varner, Professor, Virginia Tech USA; Chair, Coalition of Prescribed Fire Councils, Amanda Stamper, Fire Management Officer, The Nature Conservancy*

Southeastern North America (SErn) has made huge strides in restoring the culture of Rxd burning in the last two decades, including not only (1) gathering buy-in from a broad array of supporters (including the public and practitioners, as well as in the policy-arena) and (2) getting more good fire "on-the-ground" — but efforts to implement the SErn model to other parts of the continent — in particular the western U.S. — have been relatively unproductive. This lack-of-success appears to center in part on the diametric pattern of land ownership in these areas (mostly private in the SE and mostly public in the West) and associated policy and landscape features, as well as cultural and other human dimension factors. So the SErn model, while helpful to continental (and global) efforts to get more land burned under prescription, is not the key to success. We will provide an interactive forum to discuss the socio-ecological differences and concomitant challenges of these regions with the aim of developing region-specific yet parallel paradigms for the SErn and western regions of the continent. The North American Coalition of Prescribed Fire Councils provides a overarching umbrella to connect ideas emanating from this workshop with the key people who can develop them further and carry them forward. We envision this workshop stimulating discussion that would informally carry through the conference, culminating in a gathering toward the end of the week to weave together ideas.

Workshop #10 - Linking Fire Behavior, Fire Effects, and Weather Systems in Prescribed Fire Planning

Instructors: *LaWen Hollingsworth, Fire Behavior Specialist, USDA Forest Service; Matt Jolly, Research Ecologist, USDA Forest Service; Duncan Lutes, Fire Ecologist, USDA Forest Service; Faith Ann Heinsch, Physical Scientist, USDA Forest Service and LaWen Hollingsworth, Fire Behavior Specialist, USDA Forest Service.*

The Missoula Fire Sciences Lab has developed several computer programs that can be used in prescribed fire planning to evaluate fire behavior, fire effects, and suitable weather scenarios for burning. The BehavePlus fire modeling system is often used to develop fire behavior scenarios for prescribed fire. FireFamilyPlus can be used to evaluate historical weather to determine the potential for burn windows. The First Order Fire Effects Model (FOFEM) can be used to evaluate potential fire effects, such as fuel consumption smoke production and tree mortality. Integrating results from multiple systems allows managers to develop burn plans will accomplish the objectives and identify the associated parameters for potential burn windows.

Interactive, hands-on exercises will allow attendees to explore the features of these systems using a sample prescribed burn plan. Time will be allowed for questions regarding the use of these systems in prescribed fire planning. Attendees bringing their own computers will benefit the most from this workshop.

Workshop #11 - The Future of Fire and Fuels Management: Adapting Fuels Treatments in a Changing Climate

Partners: *USDOI The Northwest Climate Science Center, EcoAdapt, OSU Institute for Natural Resources, in coordination with the NW Fire Science Consortium and Northern Rockies Fire Science Network.*

This workshop culminates the Available Science Assessment Project (ASAP), sponsored by the Dept. of Interior's Northwest Climate Science Center (NWCSC), through which we are evaluating the science behind fire and fuels management actions under climate change, with a focus on prescribed fire. This project focused on WA, OR, ID and western MT forests, but findings may be more broadly applicable.

The upcoming workshop will build on interviews with fire managers who manage resources under shifting fire regimes, a systematic mapping of relevant literature, and an earlier science review panel discussion of the state of science behind prescribed fire use under changing climate conditions. We are now bringing managers and scientists together for broader discussions regarding fuels management in the context of climate change in order to:

- Document and synthesize social and expert knowledge of how fuels management is being adapted in response to shifts in climate and fire regimes;
- Explore opportunities for further integration of scientific research and climate-informed management;
- Discuss agency plans and priorities for managing fire (with specific reference to the role of prescribed fire) under future climate conditions;
- Describe the intended management application of desired future research and products on fire and fuels management;
- Develop partnerships between fire experts and forest/fire managers to ensure future research is addressing specific management needs; and
- Help refine the NW CSC Science Agenda in the area of fire regimes and climate change.

The workshop will consist of a mix of formal presentations by scientists and managers and small and/or large group discussion sessions. Information gathered from this meeting will help focus the NWCSC's future calls for fire-related research, and stimulate the possibility of drafting an OpEd piece for peer-reviewed journals, such as Fire Ecology.

Workshop #12 - Fuels Treatment Effectiveness: Joint Fire Science Workshop for Current Research, Preliminary Results and Implications

(For JFSP PI's, by invitation)

Sponsored by Joint Fire Science Program

From 2012 – 2015 JFSP has, through five funding opportunity notices, funded 27 research projects focused on multiple aspects of fuels treatment effectiveness. In 2014 OWF partnered with JFSP to fund 5 research projects. The majority of these projects are currently in progress. This workshop is targeted towards these researchers and is intended to provide a forum to share interim results, identify opportunities for continued or future collaboration and to identify future research needs. This will be a "working workshop" for researchers with active research. Participants will be invited to participate by JFSP and OWF.

Workshop Objectives:

- Share interim results on fuels treatment effectiveness research with funding organizations and between researchers
- Identify opportunities for collaboration on on-going research projects
- Identify future fuels treatment effectiveness research needs
- Facilitate coordination between researchers and fire science exchange network principal investigators and coordinators in preparation for dissemination of research results.

FIRESCIENCE.GOV

Research Supporting Sound Decisions

Funding wildland fire research and distributing results to support sound policy and management decisions

Your Program at work: recently completed research includes—

- Determination of the Effects of Heating Mechanisms and Moisture Content on Ignition of Live Fuels
- A New Time Series Remote Sensing Approach to Mapping Fine Fuels in Sonoran Desert Ecosystems
- Quantifying the Effectiveness and Longevity of Wildland Fire as a Fuel Treatment
- Fuel Loads, Invasive Species, and Post-Fire and Post-Mastication Succession in Chaparral Shrublands
- American Fire History, 1960-2010

Fire Science Exchange Network — Accelerating awareness, understanding, and adoption of wildland fire science information

Connect and learn through

Field Tours
Workshops
Conferences
Webinars
Syntheses
Fact Sheets
Newsletters
Social Media

FIELD TRIPS

Field Trip #1

BURNING FOR BLOOMS, BUTTERFLIES, BIRDS (AND BOUQUETS): PRESCRIBED FIRE IN THE WILLAMETTE VALLEY

Friday, April 15 - 8:00 am - 5:00 pm

Meet the bus in front of the Oregon Convention Center on MLK Ave.

This field trip will leave from the Oregon Convention Center (OCC) at 8:00 am and travel to the following stops throughout the day; Nature Conservancy's Kingston Prairie and Baskett Butte Preserves; Baskett Slough National Wildlife Refuge; private lands; and will end with a visit to a local winery to sample some of the north Willamette Valley's finest bouquets. The bus will return to OCC around 5:00 pm.

Restoring fire's important role in the ecology of Willamette Valley prairies, savanna, and woodlands has become a focus of restoration and conservation in recent years with the listings of species such as Fender's blue butterfly, Streaked horned lark, and Kincaid's lupine as threatened or endangered under the Endangered Species Act. Over 1000 acres are being burned annually to restore and maintain habitat and other ecological conditions necessary for the conservation of these and other culturally important, rare and native, threatened and endangered, plants and animals. On this field trip, we will be looking at fire effects from Fall 2015 prescribed burning in prairie and oak savanna managed by The Nature Conservancy, US Fish and Wildlife Service, and private lands enrolled in the Partners for Fish and Wildlife and Natural Resource Conservation Service Wetland Reserve Programs.

The cost of the field trip is $55/person and includes transportation, lunch, snacks, water and wine tasting at Firesteed Winery.

Field Trip #2

COLUMBIA HELICOPTERS

Friday, April 15 - 8:30 am - 12:30 pm

Meet the bus in front of the Oregon Convention Center on MLK Ave.

SPONSORED BY

COLUMBIA HELICOPTERS

Tour the facilities of Columbia Helicopters to get an up close and personal look at the nations fleet of heavy helicopters that are used in aerial firefighting.
Participants will be able to get valuable knowledge on accessories (buckets, tanks, etc.) that are currently used by helicopters on fires and get up close with many of the helicopters that could be on a fire and is using a helicopter resource.

Columbia Helicopters will invite other operators who currently work on fires to participate as well as Simplex, a local vendor who builds fire tanks for most helicopters and SEI, a vendor who provides the Bambi Bucket.

Industry experts will be available to answer any questions.

The tour will leave the Oregon Convention Center at 8:30 am and return around 12:30 pm. Columbia Helicopters is located at the Aurora Airport, 10 miles South of Portland, Oregon.

The cost of the field trip is $10 and includes transportation.

EXHIBITORS

Association for Fire Ecology
www.fireecology.org

The Association for Fire Ecology is an organization of professionals dedicated to improving the knowledge and use of fire in land management through science and education.

Our vision for the Association for Fire Ecology is that its membership of respected professionals from around the world together play a key role in wildland fire and fire ecology research, education, management, and policy, to enhance our knowledge and management of fire as a fundamental ecological process.

The Association for Fire Ecology and its members share the following common beliefs:

- Fire is a critical ecological process in many ecosystems throughout the world.
- Land management goals often reflect plant communities with a past history of repeated fire events, however, fire regimes have been significantly altered on many landscapes, which may threaten native plant and animal assemblages, resulting in uncharacteristic ecological consequences.
- Plant communities, species composition, and soils have been significantly altered on many landscapes, causing change in the fire regime.
- Cultural burning has historically been part of the fire regime in many areas of the world.
- Restoring and maintaining native plant and animal assemblages and appropriate fire regimes is desired, although it is recognized that this may not always be possible.
- Science and education are critical in helping us understand ecological patterns and processes, how land management has affected fire regimes, and how vegetation and fire regimes can be restored.
- Science should inform both policy and land management decisions that affect fire regimes.

Bushfire & Natural Hazards CRC
http://www.bnhcrc.com.au

The Bushfire and Natural Hazards Cooperative Research Centre draws together all of Australia and New Zealand's fire and emergency service authorities, land management agencies, as well as non-government organisations and leading experts across a range of scientific fields to explore the causes, consequences and mitigation of natural disasters.

The CRC was launched at Parliament House Canberra by the Minister for Justice, the Hon Michael Keenan, MP, on 10 December 2013. The Minister said the Bushfire and Natural Hazards CRC acknowledged the ongoing impacts of natural hazards upon communities, emergency service providers, governments, agriculture and other industries.

In announcing the Australian Government commitment to the CRC in February 2013, then Prime Minister Julia Gillard said the new centre would build on the work of the Bushfire CRC and expand the research into natural hazards.

The Bushfire and Natural Hazards CRC is funded for eight years with $47 million from the Australian Government's Cooperative Research Centres Program. The remainder funds - cash and in-kind - comes from partner agencies, government organisations and research institutions from all states and territories and New Zealand.

The Bushfire and Natural Hazards CRC is an incorporated not-for-profit public company limited by guarantee. It is managed through a small central office co-located with the Australasian Fire and Emergency Service Authorities Council in East Melbourne, with staff also based in Adelaide, Darwin and Canberra. It has a skills-based Board of Directors elected by its Members. The Board is chaired by an independent Director.

Columbia Helicopters
www.colheli.com

Columbia Helicopters began using helicopters to fight fire in the later 1960s, using a Sikorsky S-61 and bucket to support fire fighters on the ground. Over the years, the company has moved to larger, heavier-lifting helicopters, and has modernized their firefighting technology as well.

For decades, Columbia Helicopters fought wildland fire successfully with buckets slung below the company's fleet of red and white helicopters. Most recently, the company has deployed to fires using SEI Torrentula Bambi Buckets equipped with the PowerFill system. These buckets contain four high volume pumps that allow the pilot to fill the bucket in sources as shallow as 18-inches. Because the buckets are slung approximately 200-feet below the helicopter, pilots can fill from tree-lined streams or ponds, or other water sources with limited access. The system includes a foam reservoir tank in the back of the aircraft for deployment of short-term retardant, and the pilots can also fill the buckets from long-term retardant stations.

Most recently, Columbia Helicopters worked with Simplex Aerospace of Oregon to develop internal tanks for Columbia's fleet of CH-47D Chinook helicopters. The use of internal tanks will now permit the company to fight fires in the urban interface. These 2,800-gallon tanks slip in and out of the Chinook with relative ease, providing versatility on the fire lines. The tanks are filled from a 12-foot snorkel pump that the pilot lowers into a water source or into a long-term retardant batch plant. The tank system also includes a foam reservoir, allowing the pilots to inject short-term retardant into the tank as it flies to the fire.

Commonwealth Scientific and Industrial Research Organisation (CSIRO)
http://www.csiro.au/en

Australia's leading multidisciplinary research organisation, with more than 5000 talented people working out of 55 centres in Australia and internationally. We play a vital role in enhancing collaboration within the Australian national innovation system, and as a trusted advisor to government, industry and the community.
The Science and Industry Research Act 1949 defines our purpose and the functions we undertake for the benefit of Australia:

- To carry out scientific research for any of the following purposes:
- Assisting Australian industry;
- Furthering the interests of the Australian community;
- Contributing to the achievement of Australian national objectives or the performance of the national and international responsibilities of the Commonwealth; and
- Any other purpose determined by the Minister;
- To encourage or facilitate the application or utilisation of the results of such research.

Our secondary functions include international scientific liaison, training of research workers, publication of research results, technology transfer of other research, provision of scientific services and dissemination of information about science and technology.

We're committed to building connections with the best partners in Australia and the world to complement our science capability and accelerate the delivery of the benefits of our research. We are a trusted scientific advisor and collaborate extensively with government, universities and industry.

Dragonslayers
www.dragonslayers.com

Dragonslayers.com does two specific things:
First we consolidated and advanced the traditional wildfire hand tools. They are stronger, wider, longer, more versatile, safer and by far much more effective. These were engineered so that each fire fighter can have their own tool that breaks down and lays flat for mobilization to an incident with their own personal gear. One Universal handle and a Magnum Pulaski, and a Troop Tool weighs 7 lbs. So versatile and responsive is this simple set of tools is that it allows each fire fighter to have a stand upright better angled McLeod scraping tool, an angled shovel for digging and throwing dirt, a better mop-up stand erect tool, a safety staff for negotiating

Envirovision Solutions
www.evsusa.biz

ForestWatch® is a wildfire detection and monitoring system integrating real world data into a powerful decision support and emergency management system that can significantly reduce the time between fire ignition, discovery and dispatch. ForestWatch® software enables an interface with highly programmable "off the shelf" cameras capable of pan, tilt, and up to 36X optical zoom, in automatic and fully manual modes, providing panoramic color images, geo-referencing, and smoke detection yielding real time fire intelligence. Night time detection, utilizing near-infrared, provides for 24/7 protection. Camera footage is date and time stamped and archived for investigations and after action reviews. Integrated geo-referencing pinpoints fire start locations and displays latitude, longitude, distance and bearing on the image, utilizing standard ESRI GIS compatibility. ForestWatch® Online provides web access to near real time and stored images allowing fire mangers to view new fire starts or ongoing incidents.

FRAMES – Fire Research and Management Exchange System
www.frames.gov

FRAMES strives to provide a convenient, systematic exchange of information and technology within the wildland fire research and management community. Developed by the University of Idaho in collaboration with the USFS Rocky Mountain Research Station, FRAMES includes a searchable online database of wildland fire-related documents, tools, videos, projects, and data; Collaboration Space for user groups; Online Training and Certifications developed by NWCG, NAFRI, WFMRDA, LANDFIRE, and the University of Idaho; the FRAMES Emissions & Smoke Portal with educational materials on air quality and smoke management developed by the NWCG Smoke Committee (SmoC) and the University of Idaho; and Archived Webinars from JFSP Regional Consortia, IAWF, and the Wildland Fire Lessons Learned Center. FRAMES is located in the Department of Forest, Rangeland, and Fire Sciences in the University of Idaho College of Natural Resources in Moscow, Idaho.

Heli-Fire Support
www.helifiresupport.com

Heli-Fire Support is an industry leader in services that provide experience with Tanks, Gels, Trucks. Heli-Fire Support services include:

- Mobile Self supporting Dip Sites 2x 11,000 gallon tanks
- Mobile Heil Gel Plants for Helicopter and SEATS
- Ground Application Service
- Heli - Engine Minimal Impaxt Suppression Pumps
- Thermal Gel Distributor

Our Goal is to provide very safe and effective dip sites with quality personnel and equipment in a timely manner that is cost effective and with minimal impact to the environment.

Insight Robotics
www.insightrobotics.com

Insight Robotics is the leading solutions provider for managing risks to natural resources and critical infrastructure. Our innovations include the first automated wildfire detection system capable of spotting a single tree on fire up to 5 km away and an aerial survey solution for precise mapping and pinpointing of risk areas across large land areas.

The Insight Robotics Wildfire Detection System arms operations teams with real-time alerts complete with critical data, pinpoint coordinates, 3D maps and images of emerging wildfires so that they have the insights they need to effectively allocate firefighting resources and quickly plan a targeted first attack. The system is capable of detecting fires 24 hours a day, without the need for human monitoring, and is equally effective at night and in all visibility conditions. By tackling wildfire risk head on, forestry and firefighting staff can reduce costs and save lives and property.

Insight Robotics solutions have detected 100% of wildfires within line of sight in their respective coverage zones to date in projects across Asia, North America and Africa. The company was voted IBM Global Entrepreneur of the Year and Best for the Environment by B Corp in 2015. The company also was ranked #4 for robotics in Fast Company's "Most Innovative Companies of 2016".

International Association of Wildland Fire
www.iawfonline.org

The International Association of Wildland Fire (IAWF) was formed in 1990 as an international professional membership association focusing on all aspects of wildland fire. For 25 years IAWF has grown from its fledgling early years to being the foremost global member focused association spanning 30+ countries.

IAWF is uniquely positioned as an independent organization whose membership includes experts in all aspects of wildland fire. IAWF independence and breadth of global membership expertise allows it to offer a neutral forum for the consideration of important, at times contentious, wildland fire issues.

International Fire Relief Mission
www.ifrm2007.com

The International Fire Relief Mission is a 501(c)(3) nonprofit corporation that provides humanitarian aid to fire and EMS first responders in developing countries by recycling serviceable fire fighting and EMS equipment. IFRM dispatches teams to the receiving countries to demonstrate and provide the necessary information to safely and effectively use the donated gear. Founded by retired firefighters and medics in 2007, IFRM is propelled by monetary, equipment and in-kind donations from corporate partners and individuals; its field staff is all-volunteer. IFRM maximizes its donors' gifts by operating with a 98% efficiency rating, as measured by the Charity Navigators and the Better Business Bureau. The International Fire Relief Mission is firefighters helping firefighters.

Joint Fire Science Program
http://www.firescience.gov/

The Joint Fire Science Program funds scientific research on wildland fire and distributes results to help policymakers, fire managers, and practitioners make sound decisions, by:

- providing credible research tailored to the needs of fire and fuel managers
- engaging and listening to clients and then developing focused, strategic lines of new research responsive to those needs
- soliciting proposals from scientists who compete for funding through a rigorous peer-review process designed to ensure the best projects are funded
- focusing on science delivery when research is completed with a suite of communication tools to ensure that managers are aware of, understand, and can use the information to make sound decisions and implement projects

The Joint Fire Science Program is uniquely positioned to tailor wildland fire research in response to the emerging needs of policymakers and fire managers. An annual cycle of proposal solicitation, review, and funding ensures timely response to evolving conditions. Research projects complement and build on other federal research programs, such as those in the Forest Service Forest and Rangeland Research Stations, U.S. Geological Survey, and National Fire Plan. Synthesis of research findings and targeted delivery to managers are essential components of the Program.

More than 90 colleges and universities have collaborated on and partnered with JFSP sponsored research projects. By engaging master's and doctoral candidates in these projects, we are training the next generation of resource managers and scientists. This collaboration extends to private, non-profit organizations and tribal, state, county, and local governments as well. In all, nearly 200 organizations have become partners in JFSP-sponsored research.

Kestrel Weather & Environmental Meters
www.kestrelinstruments.com

At Nielsen-Kellerman, we've been researching, designing, manufacturing and distributing our Kestrel Weather & Environmental Meters for 15 years. NK's team of experts and engineers are determined to make the most accurate and reliable handheld weather devices available. We are continuously dedicated to researching ways to improve the Kestrel line and create new products to meet our customers' needs. Every Kestrel meter offers patented features, certified accuracy and are Rugged (drop tested to MIL-STD-810G standards) and waterproof (sealed to IP67 standards). They are designed, built and tested entirely in the USA, and backed by an industry-leading 5 year warranty.

NFPA

www.firewise.org • www.fireadapted.org

To save lives and property from wildfire, the National Fire Protection Association's (NFPA) Firewise® Program teaches people how to adapt to living with wildfire, encourages neighbors to work together and take action to prevent losses. We all have a role to play in protecting ourselves and each other from the risk of wildfire. Firewise is a key component of the Fire Adapted Communities initiative – a collaborative approach that connects all those who play a role in wildfire education, planning and action with comprehensive resources to help reduce risk. The program provides access to training resources, online learning center, print and audiovisual materials.

National Cohesive Strategy

http://www.forestsandrangelands.gov/strategy@US_Wildfire

The National Cohesive Wildland Fire Management Strategy is a strategic push to work collaboratively among all stakeholders and across all landscapes, using best science, to make meaningful progress towards Resilient Landscapes, Fire Adapted Communities, Safe & Effective Wildfire Response. The result of larger and more destructive fires that have led to increasing costs to lives, natural resources, communities, economies, and fighting fires, Congress called for a Cohesive Strategy in the 2009 FLAME Act. No one agency or organization can act alone to resolve these issues. It is only through "working better together" that we can achieve real change on the landscape level. Through an "all hands, all lands" approach, the Cohesive Strategy is providing the framework for collaborative success towards each of the three tenets above. The vision of the Cohesive Strategy is to safely and effectively extinguish fire when needed; use fire where allowable; manage our natural resources; and as a nation, to live with wildland fire.

National Fallen Firefighters Foundation

www.firehero.org

The United States Congress created the NFFF to lead a nationwide effort to remember America's fallen firefighters. Since 1992, the non-profit foundation has developed and expanded programs to honor fallen fire heroes and assist their families and coworkers. The NFFF offers assistance through the Survivors Network, conferences and workshops. The Foundation also provides college scholarships for spouses, partners, children and step children to help them fulfill dreams that may otherwise need to be abandoned.

The NFFF also works closely with the fire service to help prevent and reduce line-of- duty deaths and injuries. For more information on the Foundation and its programs contact us at 301-447-1365 or visit www.firehero.org.

Northern Rockies Fire Science Network

http://nrfirescience.org

Effective science communication is critical to science-informed management. Because a long and rich history of fire research exists and contemporary fire research continues, fire and fuels managers are overwhelmed by the available scientific information. Sponsored by the Joint Fire Science Program (JFSP), the Northern Rockies Fire Science Network (NRFSN) is part of a national knowledge exchange network that focuses on fire science delivery and application between research and management. Now in its fourth year, the NRFSN has become a go-to resource for reliable, relevant, and timely information to meet the needs of managers and scientists involved in fire and fuels management in Rocky Mountain forests of Idaho, Montana, eastern Washington, and northwestern Wyoming.

The NRFSN conducts a variety of activities to enhance communication, strengthen collaborations, synthesize science, and increase science application to critical fire management challenges. These activities include fieldtrips, workshops, science reviews, science briefs, e-newsletters, and online databases with publications and webinar and video recordings. The NRFSN also identifies and communicates regional research priorities to scientists and the JFSP. Our goal is that these activities increase scientist-manager interactions and result in greater mutual understanding and application of wildland fire science to management.

You can learn more at our website http://nrfirescience.org and by visiting our both in the exhibitor hall. We are always interested in feedback and welcome the chance to discuss your ideas for future NRFSN activities and products.

Oregon State University
www.nwfirescience.org

The Northwest Fire Science Consortium is part of a national network of consortia established by the Joint Fire Science Program to accelerate the awareness, understanding, and adoption of wildland fire science information by federal, tribal, state, local, and private stakeholders in Oregon and Washington. Our mission is to build bridges and collaboration between fire and land managers and scientists in the region.

PHOS-Chek (Mobile App Sponsor)
www.phos-chek.com

For over 50 years PHOS-CHeK has provided the world's leading chemical solutions for management of wildland and structural fires. PHOS-CHeK Long-Term Fire Retardants, Class A & B Foams, Gels, and Fuel Gelling Agents are the safest, most effective and environmentally friendly fire chemicals available and are fully qualified by the USDA Forest Service. PHOS-CHeK Fire Retardants are available in powder and liquid form.

MVP-Fx is the "flagship" all-phosphate retardant. This new formulation is highly visible on the fuel and in the air when dropped and is widely used in the airtanker industry. Our 259F is another formulation which is the only fire retardant that is helicopter fixed-tank qualified by the USFS.

PHOS-CHeK has several Class A foam formulations with WD 881 being the premier product. It is highly concentrated providing superior foaming capability for all applications and is the most cost effective product on the market.

We offer two Gels: PHOS-CHeK INSUL-8 and PHOS-CHeK Aquagel-K, These use super absorbant polymer technology to thicken water. Thickened water stays where you put it, even on vertical surfaces, making nearly all of the water used available to stop fire. Phos-Chek INSUL-8 is a liquid concentrate that can be deployed from ground equipment or aircraft. It can be mixed on demand and makes superior gel at low use rates.

Phos-Chek Aquagel-K is a dry powder that is ideal for batch mixing and is targeted toward aerial application.

Flash 21 is the premier fuel gelling agent used for prescribed burning. Flash 21 is now the product of choice to be used with aerial ignition devices such as Helitorchs, flame throwers, terra-torches and blivet applications.

For our new Home Defense Program, the same long-term fire retardant, without the red dye, is now available in ¾ gallon jugs of concentrate and 5 gallon buckets of ready to use retardant, giving individuals the power to protect their own property and belongings long before a wildfire threat is imminent.

Scotty FIREFIGHTER
www.scottyfire.com

Manufacturer of Forestry Hand Pumps & Backpacks, Foam Eductors, "Through-the-Pump" Foam Proportioners, "Foam-Fast" Cartridge Applicators, Portable Foam Systems, Air-Aspirating Foam Nozzles, Fog Nozzles, Spanner Wrenches, Shut-Offs, 3-Way Valves, Connectors. A Division of Scott Plastics Ltd., British Columbia, CANADA.

SimTable
www.simtable.com

Simtable provides digital sandtables to the wildfire and emergency management communities. Combining existing GIS data with next generation agent-based modeling and ambient computing SimTable provides a straightforward easy to use approach in incident response and training. Interactive simulations and realtime maps can be distributed across the web and mobile devices.

Simtable is based in Santa Fe, New Mexico. Current research and development includes LiveTexture which coordinates mobile, aerial and social media videos and photos into one 3D texture of an ongoing incident.

SweatHawg
www.sweathawg.com

Hard Hat Sweatbands stop dripping sweat.

Durable and easily washable, each has a cushy double layer of ultra-absorbent fabric that absorbs ten times its weight in water! Revolutionary absorbency is sewn into aggressively wicking fabrics that disperse, evaporate and cool. Our hard hat sweatband is a major addition to hard hat comfort and safety.

Known best by construction workers and wildland firefighters, these are made for all who wear hard hats, bump hats, welding helmets and face shields, who need to keep sweat from dripping in their eyes for comfort and safety. Easily folds around the brow band in most hard hats to manage excess perspiration. Very comfortable. Machine washable. OSHA Compliant. Made in USA. Bulk discounts available.

TAGSMYTH LLC
www.tagsmyth.com

TAGSMYTH, a wholly owned subsidiary of IMSAR LLC, was initially founded to solve a problem in the livestock industry where cattle would get lost or go missing. Since its inception, TAGSMYTH has developed solutions for tracking and monitoring assets and personnel. TAGSMYTH believes that knowing where something is, and where something has been is the foundation of successfully fulfilling most responsibilities. Together with it's parent company IMSAR, they have developed a system which utilizes radio frequency and radar for wildland fire fighting that allows emergency service personnel to know the location of the fire edge and team members. TAGSMYTH is a team of technology experts with the dedication and the know-how to solve complex and challenging responsibilities.

Technosylva
http://technosylva.com/

Solutions for Wildfire Protection Planning & Operational Response from San Diego (CA). Technosylva has developed the only specific wildfire management tools in the market, used in agencies since 1997.

FIRESPONSE: Unique Decision Support System for Wildland firefighting from the dispatching to the incident management, available in desktop, web and mobile platforms.

WILDFIRE ANALYST: the ultimate tool for analyzing real-time Wildfire Behaviour.

Our team has a rich legacy in conducting fuels mapping, fire behaviour analysis and wildfire risk assessments, focused on integrating analysis results into usable applications to support fire professionals for protection and mitigation planning, as well as response and suppression.

US Forest Service Fire Science Research
http://www.fs.fed.us/rmrs/science-program-areas/fire-fuel-and-smoke
http://www.firelab.org
http://www.fs.fed.us/pnw/fera
http://www.airfire.org

The U.S. Forest Service conducts fundamental and applied research in wildland fire. The U.S. Forest Service Fire Science Research booth showcases wildland fire research conducted by the U.S. Forest Service, with contributions primarily from the Pacific Northwest Research Station's Pacific Wildland Fire Sciences Lab, the Rocky Mountain Research Station's Fire, Fuel, and Smoke Science Program, and the Washington Office's Research and Development. Materials on active fire science research as well as historical documents are available. The U.S. Forest Service educates and mentors future fire science managers and provides tours, curriculum, teacher workshops, and presentations to increase the public's understanding of the science of wildland fire. Educational materials are also available at the booth.

5TH INTERNATIONAL
FIRE BEHAVIOUR + FUELS
CONFERENCE

MELBOURNE, AUSTRALIA, 2016

Presented by

International Association of Wildland Fire

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5TH INTERNATIONAL

FIRE BEHAVIOUR + FUELS

CONFERENCE

MELBOURNE, AUSTRALIA, 2016

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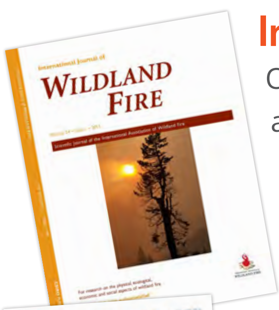
INTERNATIONAL ASSOCIATION OF WILDLAND FIRE

The International Association of Wildland Fire (IAWF) is a non-profit, professional association representing members of the global wildland fire community. The purpose of the association is to facilitate communication and provide leadership for the wildland fire community.

The IAWF is uniquely positioned as an independent organization whose membership includes experts in all aspects of wildland fire management. IAWF's independence and breadth of global membership expertise allows it to offer a neutral forum for the consideration of important and at times controversial, wildland fire issues. Our unique membership base and organizational structure allow the IAWF to creatively apply a full range of wildland fire knowledge to accomplishing its stated mission.

Vision: To be an acknowledged resource, from the local to global scale, of scientific and technical knowledge, education, networking and professional development that is depended on by members and partners in the international wildland fire community.



International Journal of Wildland Fire

Our official fire science journal, published on our behalf by CSIRO, is dedicated to the advancement of basic and applied research covering wildland fire. IAWF members have access to this leading scientific journal online, as a members benefit. For those members who want to receive the hard copy version of the journal, they may receive it at the IAWF discounted rate of US $225, which includes your IAWF membership and a 1-year subscription to WILDFIRE.

WILDFIRE Magazine

All IAWF members receive WILDFIRE magazine, official publication of the IAWF. Our authors submit fire articles from all corners of the world and our topical editors cover a broad array of important issues in wildland fire. We encourage you to submit articles and photographs for inclusion in the magazine. www.wildfiremagazine.org.

There are so many reasons to become a member of the International Association of Wildland Fire but most importantly, the opportunity to be a member of a professional association that is committed to facilitating communication and providing leadership for the wildland fire community.

1418 Washburn
Missoula, Montana, USA
(01) (406) 531-8264
Toll Free from US & Canada: (888) 440-IAWF (4293)
www.iawfonline.org

International Association of Wildland Fire

BUSHFIRE + NATURAL HAZARDS CRC

The Bushfire and Natural Hazards Cooperative Research Centre draws together all of Australia and New Zealand's fire and emergency service authorities with the leading experts across a range of scientific fields to explore the causes, consequences and mitigation of natural disasters.

The CRC coordinates a national research effort in hazards, including bushfires flood, storm, cyclone, earthquake and tsunami.

From July 2013, $47 million over eight years in Australian Government funds under the Cooperative Research Centres Program have been matched by support from state and territory government organisations, research institutions and NGOs.

Research partners include universities, Bureau of Meteorology and Geoscience Australia, and several international research organisations.

The research program has developed under the direction of the researchers and end-user agencies. The research has three major themes covering 12 clusters of projects, most of which span the priorities of those working in a multi-hazard environment.

www.bnhcrc.com.au

WELCOME

International Association of Wildland Fire (IAWF) is extremely proud to present the 5th International Fire Behavior + Fuels Conference, co-sponsored by IAWF and Bushfire and Natural Hazards CRC of Australia and held concurrently in Portland, OR, USA, and Melbourne, Australia. This conference is being presented to bring focus to the many issues associated with fuels, fire behavior, large wildfires, and the future of fire management.

Much attention is being given to wildland fire management. It seems with each passing year we recognize escalating complexity, increasing risk, and mounting challenges. Wildland fire management cannot respond to current and future challenges without actively enlarging its body of knowledge, experience, and capabilities. Changing situations, what many would characterize as worsening situations, must be anticipated and responded to. Predictive entities continue to forecast worsening fire seasons and continued droughts leading to expectations of increasing numbers of fires, area burned, burning intensities, and duration of wildfire activity.

As all of these elements of wildland fire are manifested, we see that simply put, this is a wicked problem. How this occurred, and what can be done about it are important considerations for future strategic planning and operational management. A significant number of research reports, national leader presentations, political hearings, accountability reports, strategic plans, and forward-looking plans state the problem and actions for the future. It is commonly reported that the most extensive and serious problem related to the health of wildland areas is the over-accumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable and destructive wildfires.

Significant issues abound. New solutions are needed. Obvious targets like increased funding exist, but it is important to realize that short-term fixes are less likely to have success and long-term commitments, strategies, and actions are necessary. Management of fuel complexes; accelerated fuel treatments; preparation of communities to withstand wildfire; incorporation of learning, experience, emerging science and technology; as well as sustainable funding for wildfire suppression and fuel treatments are vital for success.

The International Association of Wildland Fire (IAWF) Bushfire and Natural Hazards CRC recognize these needs. We have an unwavering commitment to promote increased involvement, improved communication, escalated research, focused education and training, and active management support to help, promote success in wildland fire management.

This conference is designed to be innovative, revolutionary, and provocative. It will provide a forum to facilitate discussion of the latest relevant research findings, information dissemination about management treatments, stimulation of policy discussions, and inspire global fire management interaction. Both venues will provide a stage having hundreds of oral and poster presentations of new research information, practical experience lessons, and case studies; numerous knowledge and skill building workshops; on-the-ground learning field trips and tours; keynote and plenary presentations; and panel discussions by leading experts in the field. Conference participants will be able to share what is known, what needs to be learned, how to advance knowledge, and how to use this knowledge to effectively respond to increasing concerns.

On behalf of the International Association of Wildland Fire, all conference sponsors and partners, I welcome all participants and hope that this conference will meet, and even exceed your expectations of increasing awareness, knowledge, and capability in this important field in addition to networking with peers to establish future avenues of discovery. We hope that you will enjoy attending and gain significant information from what promises to be the most informative, enlightening, and powerful conference to date on fire behavior and fuels in wildland fire management.

If you were not previously a member of the IAWF, you are receiving a one-year membership in the association included in your registration. By participating as an active IAWF member you can help to improve communication between firefighting organizations, enhance firefighter and public safety, increase our understanding of wildland fire science, and improve our ability to manage fire. Your membership in the IAWF provides you with a connection to other wildland fire professionals from across the world. Our membership, which is truly international, includes professionals from the fields of fire ecology, suppression, planning, contracting, fire use, research, and prescribed fire. Our members are scientists, firefighters, mangers, contractors, and policy makers. As an association, we are unique in that we represent all areas of wildland fire management. Membership benefits include, but are not limited, to the following:

WILDFIRE magazine – All members receive Wildfire magazine, official publication of the IAWF published bi-monthly. Writers send in wildland fire articles and news from all corners of the world, and topical editors cover all the important issues in wildland fire. We encourage you to submit articles and photographs to our Wildfire Editorial Board for inclusion in the magazine.

INTERNATIONAL JOURNAL OF WILDLAND FIRE – Our other official publication of the IAWF, published by CSIRO, is dedicated to the advancement of basic and applied research covering wildland fire and is available as an additional membership option. A discounted rate of US$225 for a 1-year subscription of eight issues is offered to IAWF members; this includes a 1-year membership and a subscription to Wildfire magazine – AND free e-access to the "Journal's" abstracts and articles.

On behalf of the Board of Directors of the IAWF, thank you for your support of our association.

Thomas Zimmerman

Tom Zimmerman
IAWF President

5TH INTERNATIONAL

FIRE BEHAVIOUR + FUELS

CONFERENCE

Welcome to the 5th International Fire Behaviour and Fuels Conference.

The five day program is packed with features: two workshops, more than 70 speakers, an international panel session, three PhD Three Minute Thesis, two field trips, and plenty of opportunities for networking.

The conference is in both Melbourne, Australia and Portland, Oregon, with the Bushfire and Natural Hazards CRC supporting the event in both locations. This is the first time that the conference is occurring concurrently in two locations and the two conference committees have worked together on the programs and joint promotion.

The conference theme of Wicked Problems, New Solutions: our fire, our problem is an acknowledgment that we need to share information globally about bushfire behaviour and fuels, how we engage with communities and other stakeholders so that we can act locally to protect our communities and our natural environment.

In any given year we are reminded of the relevance of innovation and research in the emergency management and land management sectors. The research, case studies and personal reflections on show this week demonstrate the significant work and the benefits that will be delivered over coming years, both in Australia and internationally.

I invite all conference delegates to attend the sessions with questions prepared, look at the posters and network with colleagues. Such interactions can be the first steps towards partnerships and new learning, which are important measures of the success of this conference.

ALEN SLIJEPCEVIC
Chair, Conference Steering Committee, Melbourne
Vice-President, International Association of Wildland Fire

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Director,
Knowledge & Engagement
Department of Environment, Land, Water and Planning
Melbourne, Victoria, Australia

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Operational Services/ Community Planning
NSW Rural Fire Service
Sydney, New South Wales, Australia

Michael Rumsewicz PhD
Research Director
Bushfire and Natural Hazards CRC
Melbourne, Victoria, Australia

Mike Wouters
Senior Fire Ecologist
Manager Fire Knowledge & Engagement
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Sustainable Resource Development
Brooklyn, New York, USA

IAWF STAFF

Mikel Robinson
Executive Director
International Association of Wildland Fire
1418 Washburn
Missoula, Montana 59801, USA
execdir@iawfonline.org
406-531-8264

EUAN FERGUSON AFSM

Euan Ferguson Pty Ltd, VIC, Australia

Euan Ferguson is a forester and fire emergency manager with 39 years' experience in fire and fuels risk management, community engagement and emergency management leadership. In 2015 Euan retired after 5 years as Chief Officer with the Victorian Country Fire Authority (CFA). Previously, Euan held the role of Chief Officer and CEO of the South Australian Country Fire Service for 9 years. Prior to that, Euan held a range of field fire and forestry roles with CFA and with the public land management authority in Victoria. In the 1980's, Euan was a member of the Army Reserve, was commissioned in 1985, and served with 91 Forestry Squadron. Euan has held a number of key appointments including past Chair and inaugural member of the Board of the National Aerial Firefighting Centre (NAFC); past Chair and member of the Board of the Australasian Fire and Emergency Services Authorities Council (AFAC). Euan is currently a member of the Board of Directors of the International Association of Wildland Fire (IAWF). Euan is an advocate for firefighter safety through better decision making and promotes the philosophy of intent based leadership.

Abstract #2: When Your Burn Becomes Front Page News

The pressures to achieve burn targets put burn bosses into an unenviable situation. In an increasingly prescriptive environment, you will be damned if you fail to achieve public and political expectations on your burn targets. But burning in narrowing windows of opportunity increases the risk of losing control of your burn. Your critics will use hindsight and a wide range of expectations to criticise your good intentions. You gamble your authority, your reputation, your job and perhaps lengthy and costly litigation. Even the best intentioned experienced and capable burn bosses, working on well planned and resourced burns can find things go awry very quickly. All of a sudden, your burn has become an organisational crisis. How do you deal with this? How do you prepare? Can you prepare? The author bases this presentation on his own personal experiences and recent case studies. The presentation deals with ways to improve the resilience of your organisation, your team and yourself. It offers some hints to manage your organisation through a crisis, whilst still managing the incident and your people. It focusses on approaching tasks from a systems point of view, enabling a just culture and an ethos of continuous improvement. The concepts of "co-production" of planned burns with neighbours, of decentralised decision making and the value of having a "Devil's Advocate" on your team are discussed. It proposes that sticking to clear values and behaviours, can enable model behaviours in times of challenge.

DR SARAH MCCAFFREY

Research Forester, United States Department of Agriculture Forest Service

Sarah McCaffrey, Ph.D. is a Research Forester for the USDA Forest Service, Northern Research Station. Her research focuses on the social aspects of fire management. This work has included projects examining wildfire risk perception, social acceptability of prescribed fire and thinning, characteristics of effective communication programs, and incentives for creation and maintenance of defensible space. She has also initiated work examining social issues that occur during and after fires including evacuation decision making, agency-community interaction during fires, and community health impacts of experiencing a fire. This has included work interviewing emergency responders and residents after wildfires in the U.S. as well as work in Australia where she assisted the Bushfire Cooperative Research Centre with their post-fire data collection following the February 7th 2009 bushfires and was named a USDA liaison to the Victorian Bushfires Royal Commission. She received her PhD in Wildland Resource Science in 2002 from the University of California at Berkeley.

Abstract #1: Public response to fire management across countries: more similarities than differences

The growing social impact of bushfires around the world highlights the need to better understand the range of public response to wildfire management. However, such understanding needs to be based on empirical evidence rather than anecdotal narratives. This presentation will review findings from fire social science research published from 2000 to 2014. Initially, the majority of studies were North American based, however, recent years have seen a growing number of studies from Australia. Of note is the comparability in findings across studies and across countries. This presentation will first discuss common findings where it may be more profitable for fire educators and managers to focus as they work to improve the social outcomes of wildfires. It will also discuss where there are points of difference, in research and management focus, and what these differences may mean for considering future research questions and management decisions.

DR KEVIN TOLHURST AM

Assoc. Prof., Fire Ecology and Management,
Department of Forest and Ecosystem Science, University of Melbourne

Kevin Tolhurst is Associate Professor in Fire Ecology and Management in the Department of Forest and Ecosystem Science, University of Melbourne based in Creswick. Kevin has developed a professional reputation by providing expert advice on fire behaviour and fire suppression strategies at major bushfires. Some examples include the Black Saturday fires in Victoria in 2009, and the Great Divide Fires in 2007. In 2015, Kevin was made a Member of the Order of Australia in recognition of his contribution to fire science and the community over a long period. Kevin has developed and taught a number of fire related subjects at undergraduate and post-graduate level as well as a national Fire Behaviour Analyst course for technical specialists in the fire and land management agencies. Kevin's current research activities are centred around developing and applying a bushfire risk management decision support systems. He has established a group of fire scientists in the School of Ecosystem and Forest Sciences with a range of research, fire, land management and teaching skills.

His research and consulting interests include:

- Wildfire behaviour prediction
- Development of prescribed burning techniques and guidelines
- Landscape-scale fire ecology management
- Fire risk management
- Ecological impacts of repeated fires

Abstract #12: Fire is the Problem and Fire is the Solution

In Australia, we have no option but to manage fire in the landscape. This management can be proactive or reactive. Reactive fire management is easier to defend publicly and politically, but this approach is costly and ineffective. Proactive fire management has been practised in Australia for tens of thousands of years by Aboriginal Australians, but in many places, aboriginal use of fire has been disrupted by European settlement. The science of proactive landscape fire management has been studied systematically since the 1950's, but being equipped with the science of fire does not guarantee sustainable fire management.

The view of many Australians, including many fire scientists, is that fire is a damaging process that must be limited. Section 17(2)b of the Victorian National Parks Act (1975) specifically states that the Secretary of the National Parks shall: "ensure that proper and sufficient measures are taken to protect each national and State park from injury by fire;". The concept of fire as a damaging process is enshrined in legislation. However, planned burning is widely used in Australia as a land management tool, but there are ongoing and increasing pressures on fire use. The impacts of smoke on tourism and public health, the ecological impacts, the level of protection afforded to human and natural values and assets from wildfire by planned burning are all topics of debate.

The future of fire management will need to have strong political backing. The question is how well the skills, knowledge, experience and capacity of those given the responsibility to manage fire for the population match the complexity of the task. What is clear is that there is no quick fix, but we must systematically progress along a well-defined path and do so at a rate faster than the rate of change in the climate, economy, demographics and political fashions.

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Melbourne Convention and Exhibition Centre (MCEC) is located on the banks of the iconic Yarra River in South Wharf. Within the Convention Centre lies the centrepiece – The Plenary. MCEC and Plenary are easily found via Convention Centre Place next to DFO and Hilton Melbourne South Wharf. You can also walk down the Exhibition Centre Concourse from the Clarendon Street entrance.

Melbourne Convention and Exhibition Centre (MCEC)
1 Convention Centre Place
South Wharf Victoria 3006
Phone: +61 3 9235 8000
www.mcec.com.au

GETTING THERE

TRAVELLING BY PUBLIC TRANSPORT

BY TRAM

Catch any of the following trams and get off at the stop opposite the Clarendon Street entrance of MCEC:

Route 96 – St Kilda to East Brunswick
Route 109 – Port Melbourne to Box Hill
Route 12 – Victoria Gardens to St Kilda

Alternatively catch tram number 48 or 70 and get off at the Flinders Street stop. Then take a short walk towards the Yarra River, across the Seafarers Bridge. For further tram timetable information and trip planning, visit the Victorian Public Transport website here.

BY TRAIN

Take any train that goes to Southern Cross Station. Get off at Southern Cross Station and catch tram number 96, 109 or 12 as above. For further train timetable information and trip planning, visit the Victorian Public Transport website here.

BY BUS

The SkyBus transports visitors directly from Melbourne Airport to Southern Cross train station.
Bus route 237 operates from Queen Victoria Market, via Southern Cross Station to Lorimer Street South Wharf from Monday to Friday. Lormier Street is approximately a five minute walk to MCEC. There is also a coach pick up/drop off point at Bay 1, Convention Centre Place (closest to DFO South Wharf).

For further bus timetable information and trip planning, visit the Victorian Public Transport website. (ptv.vic.gov.au)

TRAVELLING BY CAR

DRIVING YOURSELF

If you're driving to Melbourne Convention and Exhibition Centre, there are five car parks available for use.

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1060 undercover parking spaces available, managed by Wilson Parking. Entrance and exit off Normanby Road. Open 24 hours, seven days a week.

Fees *(weekdays including public holidays):*
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2.0 - 3.0 hour $39.00
3.0 - 4.0 hour $49.00
4.0 + hours. . . . .$49.00 max
Lost ticket. $50.00

Evening rate

Monday to Thursday: $15.00, entry from 6.00pm and exit before 6.00am the next day. Casual rates will otherwise apply. Friday: $19.00, entry from 6.00pm and exit before 6.00am the next day. Casual rates will otherwise apply.

Weekend rate

$19.00, per day, per exit. Casual rates will otherwise apply.

Earlybird rate

Monday to Friday: $16.00 entry between 6.00 – 9.00am and exit between 3.00pm - midnight. Casual rates will otherwise apply.

Please note - All MCEC car park patrons will be directed to car park Door 1 during overnight closure (8.00pm – 6.00am), to access the external areas of South Wharf Promenade.

CATCH A TAXI

Travelling to the Exhibition Centre?

Ask the taxi driver to drop you off at the Clarendon Street entrance of MCEC.

Travelling to the Convention Centre?

Ask the taxi driver to drop you off at Convention Centre Place,
next to the Hilton Melbourne South Wharf and DFO South Wharf.

CAR HIRE

You can pick up a rental car from Melbourne Airport or within Melbourne. For more information contact the companies below for current rates and pick-up/drop off points.

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Outside Australia: +61 3 9338 1800
www.avis.com.au/car-rental/

Budget

Within Australia: 13 27 27
Outside Australia: +61 3 9241 6366
www.budget.com.au

Europcar

Within Australia: 1300 13 13 90
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www.europcar.com.au/places/australia/melbourne

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Redspot

Within Australia: 1300 66 88 10
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DELEGATE INFORMATION

FULL REGISTRATION INCLUSIONS

The following is included in full conference registration;

- Access to all program sessions across the duration of the conference for full registrations or on your nominated day of attendance for 1 day registrations
- Conference catering including; morning and afternoon tea and lunches and poster session drinks
- Full registrations include one ticket to the welcome reception and conference dinner
- Complimentary wireless internet access in the conference area
- Delegate handbook

ASN EVENTS REGISTRATION / INFORMATION DESK

The conference office hours are;
Tuesday open from 10:30am – 6:30pm
Wednesday open at 8:00 am – 6:00pm
Thursday open at 8:30 am – 5:30pm

SESSION LOCATIONS

Plenary Room/ Breakout 1 – Room 105 and 106
Breakout 2 – Room 104
Breakout 3 – Room 103

SPEAKER PREPERATION INSTRUCTIONS

The audio-visual equipment is being supplied and manned by operations staff from The Melbourne Convention Centre. Please visit the speaker preparation room 101 to load your presentation at least a full session in advance of your session. You should bring your talk on a USB, saved in a format for display on a PC within the room. A technician will be on hand to assist with any transfer / loading issues and to help you check your presentation. PCs will be available in the speaker preparation room and presentation rooms.

CONFERENCE APP

The official 5th International Fire Behaviour and Fuels Conference 2016 web app will keep you organised during the meeting.
You can view:

- An up-to-date daily program
- Speaker abstracts
- Speaker bios (where supplied)
- Venue maps
- Conference sponsors
- Update your profile information

Downloading the Fire Behaviour and Fuels 2016 Conference Mobile App is easy!

INSTRUCTIONS FOR APPLE DEVICES

Step 1: Copy 5th-fire-behaviour-and-fuels-conference.m.asnevents.com.au to your browser or use the above QR code.
Step 2: You will be asked to install this web app onto your iPhone – tap the screen and the icon will appear on your home screen for future use.

For further benefits and instructions for Android devices please see staff at the registration desk.

DISPLAYING YOUR POSTER

Presenters need to display their poster within the exhibition area from Wednesday 13 April.
The official poster session is to be held Wednesday evening between 5:15-6:15pm.

The maximum size provided is 1m wide by 1.2m high.
Please visit the registration desk for additional adhesive supplies.

INTERNET

Internet will be provided for all delegates. Please connect via Melbourne Convention and Exhibition Centre free WiFi.

CERTIFICATE OF ATTENDANCE

At the conclusion of the conference you will be able to download your certificate of attendance. Please login to your Currinda profile (https://members.asnevents.com.au/register/event/1417) by entering as a returning delegate and using your email address and password to login. Then move to the bottom section of your event dashboard till you reach the section on downloads. From here you will be able to download your certificate of attendance.
Please note you will only be able to download your certificate of attendance if full registration payment has been received.

NAME TAGS

Delegates are required to wear their name tags to all conference and catered sessions.

HOTEL CHECK OUTS

You are required to check out of your room by 10:00am. Should any person fail to do so, a $50.00 late departure fee will apply.

Your hotel receptions have facilities to store your luggage. ASN have forwarded your advance room payment to your chosen hotel. You will need to settle additional private expenses yourselves on departure.

Please note hotel rooms are not guaranteed available until 2.00pm on each day though can be made available earlier in the day at the discretion of the hotel itself.

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PRE-CONFERENCE WORKSHOPS | MONDAY 11 APRIL

9:00 - 12:30	**Workshop 1 - Grassland Fuels and Fire Behaviour,** Bureau of Meteorology
12:30 -13:30	**LUNCH BREAK** - participants to make their own arrangements
13:30 -17:30	**Workshop 2 - Fire Weather and Risk,** Bureau of Meteorology
17:30 - 19:00	**WORKSHOP NETWORKING FUNCTION** - for participants in Workshop 2

Workshops sponsored by Australian Government Bureau of Meteorology

PRE-CONFERENCE WORKSHOP (CONTINUED) & DAY 1 | TUESDAY 12 APRIL

9:00 - 12:00	**Workshop 2 - Fire Weather and Risk continued…,** Bureau of Meteorology		
10:30 - 18:30	Conference Registration / Information Desk Open		
	STREAM 1 sponsored by SCION forests products innovation	**STREAM 2**	**STREAM 3**
	Room 105 / 106	**Room 104**	**Room 103**
	Chair Richard Thornton, CEO (Bushfire and Natural Hazards CRC)		
13:00 -13:30	**OPENING CEREMONY**		
13:30 - 14:15	**KEYNOTE: Public response to fire management across countries: more similarities than differences** ***Dr Sarah McCaffrey***, *Research Forester, United States Department of Agriculture Forest Service*		
14:15 - 15:00	**KEYNOTE: When Your Burn Becomes Front Page News** ***Euan Ferguson AFSM***, *Euan Ferguson Pty Ltd / Retired CFA Chief Officer*		
15:00 - 15:30	Questions, Answers, Discussion		
15:30 - 16:00	**AFTERNOON TEA**		
	Fire Behaviour and Fire Behaviour Predictions *Chair Lachlan McCaw (Dept. of Parks & Wildlife, WA)*	**Contemporary Bushfire Policies and Frameworks / Risk Modelling and Decision Support Systems** *Chair Tony Blanks*	**Fire Weather and Climate** *Chair Elizabeth Ebert (Bureau of Meteorology)*
16:00 - 16:05	*Announcements and Introductions*	*Announcements and Introductions*	*Announcements and Introductions*
16:05 - 16:30	Fuels and Fire Behaviour in New Zealand Wilding Conifers. ***Grant Pearce*** *(Scion Research)*	Trials, Tribulations and Triumph: Lessons Learnt from Tenure-blind Fuel Reduction in Tasmania. ***Sandra Whight*** *(Tasmania Fire Service)*	Climate Change and Wildland Fire Intensity. ***Mike Flannigan*** *(University of Alberta, United States)*
16:30 -16:55	Investigation of Firebrand Generation in a Pine Forest. ***Alexander Filkov*** *(University of Melbourne, VIC)*	Bush Fire Protection Standards for Existing Development. ***Jon Gaibor*** *(NSW Rural Fire Service)*	Long-range spotting by bushfire plumes: The effects of plume dynamics and turbulence on firebrand trajectory. ***Will Thurston (*** *Bureau of Meteorology)*
16:55 - 17:20	What effect does coarse woody debris have on rate of spread of a bushfire? ***Andrew Sullivan*** *(CSIRO)*	Simulation Analysis-based Risk Evaluation (SABRE) Fire. Operational Stochastic Fire Spread Decision Support Capability in the Queensland Fire and Emergency Services. ***Ben Twomey*** *(Queensland Fire and Emergency Services)*	A Tasmanian case study of fire weather behaviour using Visual Weather. ***Paul Fox-Hughes*** *(Bureau of Meteorology)*
17:30 -19:00	**WELCOME RECEPTION**		

DAY 2 | WEDNESDAY 13 APRIL

8:00 - 18:00	Conference Registration / Information Desk Open		
	STREAM 1	**STREAM 2**	**STREAM 3**
	Room 105 / 106	**Room 104**	**Room 103**
8:00 - 9:00			**Publishing in *International Journal of Wildland Fire* (Workshop)** Susan G. Conard, *George Mason University, Editor-in-Chief* Stefan Doerr, *Swansea University, Editor-in-Chief* Jenny Foster, *CSIRO Publishing, Journals Publisher*
	Chair Stuart Ellis, CEO (Australasian Fire and Emergency Service Authorities Council)		
9:00 - 9:45	**KEYNOTE: Wicked Fire, Sweet Solutions** ***(by video link from Portland)*** ***Ron Steffens***, *Green Mountain College & Conference Co-chair*		
9:45 - 10:30	**KEYNOTE: Fire is the Problem and Fire is the Solution** ***Dr Kevin Tolhurst***, *Assoc. Prof., Fire Ecology and Management, Department of Forest and Ecosystem Science, University of Melbourne, VIC*		
10:30 - 11:00	Questions, Answers, Discussion		
11:00 - 11:20	**MORNING TEA**		

	Fire Behaviour and Fire Behaviour Predictions *Chair Stuart Matthews (NSW Rural Fire Service)*	**Risk Modelling and Decision Support Systems** *Chair Mark Chladil (Tasmania Fire Service)*	**Fire Weather and Climate** *Chair Grant Pearce(Scion Research)*
11:20 -11:45	User oriented verification of fire spread models. ***Paul Fox-Hughes*** *(Bureau of Meteorology)*	Using Maps to Successfully Display Complex Bushfire Behaviour Attributes in Victoria. ***Frazer Wilson*** *(Forest Fire Management Victoria)*	Modelling the fire weather of the Blue Mountains fires of 17 October 2013. ***Simon E. Ching*** *(Bureau of Meteorology)*
11:45 -12:10	Characterising Fire Weather for Victorian Fire Risk Landscapes. ***Sarah Harris*** *(Monash University, VIC)*	Changes to WUI Fire Risk in Disparate Communities of Southern California, USA. ***Christopher Dicus*** *(California Polytechnic State University, United States)*	Large-eddy simulations of pyro-convection and its sensitivity to moisture. ***Will Thurston*** *(Bureau of Meteorology)*
12:10 -12:35	Modified fire behaviour in a coupled fire-atmosphere model. ***David Kinniburgh*** *(Monash University, VIC)*	Playing With Models: How Risk Analysis Tools Have Been Applied in Tasmania to Evaluate the Most Effective Approach to Fuel Reduction. ***Rochelle Richards*** *(Tasmania Fire Service)*	Analysing the Impacts of Vegetation and Topography on Wind Fields over Complex Terrain. ***Rachael Quill*** *(University of New South Wales, ACT)*
12:35 - 13:00	Sensitivity of Atypical Lateral Fire Spread on Lee Slopes to the Fire Environment and Fire-Atmosphere Coupling. ***Jason Sharples*** *(University of New South Wales, ACT)*	Developing a New Model for Quantifying Bush Fire Risk and Effective Treatment. ***Melissa O'Halloran*** *(NSW Rural Fire Service)*	Enhanced Weather Situational Awareness - Filling the Gaps Between the Modelled World and Reality. ***David Field*** *(NSW Rural Fire Service)*
13:00 -13:40	**LUNCH**		
	Fire Behaviour and Fire Behaviour Predictions *Chair Matt Plucinski (CSIRO)*	**Risk Modelling and Decision Support Systems / Fire Impacts** *Chair Nic Gellie (Ecofuego)*	**Smoke Management / Fuels and Fuels Modification (inc Prescribed Burning)** *Chair David Bruce (Bushfire and Natural Hazards CRC)*
13:40 - 13:45	*Announcements and Introductions*	*Announcements and Introductions*	*Announcements and Introductions*
13:45 - 13:50	**Student Presentation - "Three Minute Thesis"** Refinement of the submodels of pyrolysis and firebrand transport and undertaking experiments to validate those for a physics-based bushfire prediction model. ***Rahul Wadwhani*** *(Victoria University, VIC)*	**Student Presentation - "Three Minute Thesis"** Empirical analysis of spot-fire and ember behaviour during extreme fire weather conditions. ***Michael Storey*** *(Wollongong University, NSW)*	**Student Presentation - "Three Minute Thesis"** The Hydro-Geomorphic Sensitivity of Forested Water Catchments to Wildfire. ***Rene van der Sant*** *(Melbourne University, VIC)*
13:50 - 14:15	The Effect of Curing on Fire Behaviour in Grasslands. ***Susan Kidnie*** *(Country Fire Authority, VIC)*	A Spatial DSS for the Understanding and Reduction of Long-Term Wildfire Risk. ***Graeme Riddell*** *(The University of Adelaide, SA)*	Evaluation of Smoke Plume Models. ***Laurence McCoy*** *(NSW Rural Fire Service)*
14:15 - 14:40	A new fire behaviour prediction model for spinifex grasslands. ***Neil Burrows*** *(Dept. of Parks and Wildlife, WA)*	An Integrated Bushfire Risk Decision Support Tool for Land Use Planning. ***Laura Gannon*** *(Hawksley Consulting)*	Surface fuel load modelling with LiDAR data: a case study of Upper Yarra Reservoir area, Victoria, Australia. ***Yang Chen*** *(Monash University, VIC)*
14:40 - 3:05	Too wet to burn? Predicting Forest Soil Moisture in Complex Terrain. ***Sean F. Walsh*** *(Universty of Melbourne, VIC)*	Evaluating Prescribed Burn Effectiveness Using Phoenix RapidFire Gridded Ignition Case Studies. ***Jessica Wells*** *(NSW Rural Fire Service)*	Developing Fuel Maps for Predicting Smoke Dispersion for Forests of Victoria, Australia. ***Luba Volkova*** *(University of Melbourne, VIC)*
15:05 - 15:30	Opening the treasure trove: Re-examining A.G. McArthur's experimental fire data. ***James S. Gould*** *(CSIRO)*	Predictions, Sensors and Collective Awareness. ***Anthony Griffiths*** *(Dept. of Environment, Land, Water and Planning, VIC)*	Building a Comprehensive Fuel Map. From Research to Operational Use. ***Belinda Kenny*** *(NSW Rural Fire Service)*
15:30 - 15:50	**AFTERNOON TEA**		
	Chair Simon Heemstra (NSW Rural Fire Service)	*Chair Murray Carter (Dept. of Fire & Emergency Services, WA)*	*Chair Miguel Cruz (CSIRO)*
15:50 - 16:15	Evaluation of Operational Wind Field Models over Complex Terrain. ***Rachael Quill*** *(University of New South Wales, ACT)*	Carbon Accounting for Fires: Emissions versus Sequestration Potential from Charcoal Production. ***Stefan H.Doerr (*** *Swansea University, Wales, United Kingdom)*	An alternative to forest type: modelling fuel directly with using biophysical models. ***Thomas J. Duff*** *(University of Melbourne, VIC)*
16:15 - 16:50	Using fire line geometry to model dynamic fire spread. ***Jason Sharples*** *(University of New South Wales, ACT)*	Radar Burn Ratio: A novel index for automatic fire impact assessment. ***Cristina Aponte*** *(University of Melbourne, VIC)*	New approaches to predicting surface fuel moisture in south east Australian forests. ***Gary Sheridan*** *(University of Melbourne, VIC)*
16:50 - 17:15	Quantifying uncertainty in data and predictions for fire behaviour models. ***Trent Penman*** *(University of Melbourne, VIC)*	Quantification of fuel moisture content and identification of critical thresholds for escalation of fire activity in SE Australia's forest regions. ***Rachael Nolan*** *(University of Technology Sydney)*	Effective prescribed burning strategies for eucalypt forests in southern Australia. ***Owen F. Price*** *(University of Wollongong, NSW)*
17:15 - 18:15	**POSTER SESSION & EXHIBITION**		
19:00 - 22:00	**CONFERENCE DINNER - Showtime Events Centre**		

DAY 3 | THURSDAY 14 APRIL

8:30 - 17:30	Conference Registration / Information Desk Open		
	STREAM 1	**STREAM 2**	**STREAM 3**
	Room 105 / 106	**Room 104**	**Room 103**
	Chair/ Panel Co-Moderators: ***Alan Goodwin*** *, CFO, Dept. of Environment, Land, Water & Planning, VIC and* ***Tamara Wall*** *, Desert Research Institute (Portland)*		
09:00 - 11:00	**PLENARY SESSION: How do we make the complex tradeoffs necessary to effectively manage fuels for ecosystem health and public safety?** **(by video link between Melbourne & Portland)** *1.* ***Liam Fogarty*** *, Director Knowledge and Community Engagement, Depart. of Environment, Land, Water and Planning* *2.* ***Murray Carter*** *, Director Office of Bushfire Risk, Depart. of Fire and Emergency Services* *3.* ***Sandra Whight,*** *Manager Fuel Reduction Unit Tasmania Fire Service* *4.* ***Sarah McCaffrey*** *, Research Forester, United States Department of Agriculture Forest Service* *5.* ***Lynn M. Decker*** *, North America Fire Learning Network Director, The Nature Conservancy* *6.* ***Zachary Prusak*** *, The Nature Conservancy, Florida Fire Manager and Central Florida Conservation Program Director* *7.* ***Leland Tarnay*** *, USFS/NPS*		
11:00 - 11:20	**MORNING TEA**		
	Fire Behaviour and Fire Behaviour Predictions *Chair Cuong Tran (Ten Rivers)*	**Fire Impacts** *Chair David Bruce (Bushfire and Natural Hazards CRC)*	**Fuels and Fuels Modification (inc Prescribed Burning)** *Chair Rochelle Richards (Tasmania Fire Service)*
11:20 - 11:25	*Announcements and Introductions*	*Announcements and Introductions*	*Announcements and Introductions*
11:25 - 11:50	How fire propagates from the dead surface fuel to the first branch in ornamental vegetation of WUI. ***Anne Ganteaume*** *(National Research Institute of Science and Technology for Environment and Agriculture, France)*	Fire and Water: New tools for evaluating water supply impacts of fire. ***Joanna Wand*** *(Dept. of Environment, Land, Water & Planning, VIC)*	Monitoring and forecasting fuel moisture content for Australia using a combination of remote sensing and modelling. ***Marta Yebra*** *(Australian National University, ACT)*
11:50 - 12:15	Review of 20 years of progress in wildfire modelling using a fully physical approach. ***Dominique Morvan*** *(Aix-Marseille University, France)*	Burnt down to ashes: modelling wildfire ash distribution and composition after the Black Saturday Fires (Melbourne, 2009). ***Cristina Santin*** *(Swansea University, Wales, United Kingdom)*	The effect of commercial thinning operations on Overall Fuel Hazard in foothills mixed species forest in the Wombat State Forest, Victoria. ***Michael A. Hansby*** *(Terramatrix)*
12:15 - 12:50	The Best of Both Worlds: Fire Spread Predictions From The Head And The Heart. ***Matt Plucinski*** *(CSIRO)*	Measuring What Didn't Happen: Trying to Objectively Assess Fire Service Bushfire Protection. ***Tim Wells*** *(Country Fire Authority, VIC)*	Modeling the moisture content of dead grass fuels for fire danger and behaviour forecasting. ***Susan Kidnie*** *(Country Fire Authority, VIC)*

12:50 -13:30	**LUNCH**		
	Fire Behaviour and Fire Behaviour Predictions / Shared Responsibility, Community Partnerships etc *Chair Greg Esnouf (Bushfire Consulting)*	**Fire Suppression and Incident Management / Fire Danger** *Chair Neil Cooper (ACT Parks and Conservation Service)*	**Fuels and Fuels Modification (inc Prescribed Burning)** *Chair Jim Gould (CSIRO)*
13:30 - 13:35	*Announcements and Introductions*	*Announcements and Introductions*	*Announcements and Introductions*
13:35 - 14:00	Fire behaviour prediction, improvement in model accuracy and opportunities for future research. ***Miguel G. Cruz*** *(CSIRO)*	Which Configurations Cause Entrapment Risk? ***Sébastien Lahaye*** *(Service departemental d'Incendie et de Secours des Bouches-du-Rhone, France)*	Woody Fuel Dynamics after Fire in Open Eucalypt Forest in south-western Australia. ***Lachlan McCaw*** *(Dept. of Parks & Wildlife, WA)*
14:00 - 14:25	Evolution of Fire Behaviour Analysis into Operational Business as Usual - The New South Wales Experience. ***Simon Heemstra*** *(NSW Rural Fire Service)*	Knowing Fire: Understanding and managing the tacit knowledge of fire held by Agency Staff Members. ***Tony English*** *(Parks Victoria)*	Improving estimates of fuel consumption and fire-related carbon emissions in Siberia with ecosystem specific field data. ***Elena Kukavskaya*** *(V.N. Sukachev Institute of Forest SB RAS, Russia)*
14:25 - 14:50	Indigenous Fire Knowledge and Best Practice Science in the Gulf of Carpentaria. ***Terrence Taylor*** *(Carpentaria Land Council Aboriginal Corporation, QLD)*	Lessons from the operational application of Himawari-8 products. ***Rick McRae*** *(ACT Emergency Service Agency)*	Rural New Zealand Perceptions of Risk Associated with Wildfires and Escape Burns. ***Veronica R. Clifford*** *(Scion Research)*
14:50 - 15:15	Sharing Responsibility: who is ready for a more meaningful partnership? ***Delene Weber*** *(University Of South Australia, SA)*	The National Fire Danger Rating System. ***Joe Buffone*** *(Country Fire Authority, VIC)*	Eight Case studies: effectiveness of prescribed burning in Mallee, heathy, and forest fuel types during the 2013 and 2014 fire seasons in Victoria. ***Nicholas J. Gellie*** *(Ecofuego)*
15:15 - 15:35	**AFTERNOON TEA**		
	Chair Tamara Beckett (DELWP, VIC)	*Chair Lyndsey Wright (Bushfire and Natural Hazards CRC)*	*Chair Andrew Sullivan (CSIRO)*
15:35 - 16:00	Using bushfire characterisation to foster shared responsibility in a high risk community. ***Suriya Vij*** *(Dept. of Environment, Land, Water & Planning, VIC)*	Exploring physical measures of fire for calculating fire danger. ***Stuart Matthews*** *(NSW Rural Fire Service)*	Understanding flammability in the mountainous forests of South Eastern Australia. ***Jane Cawson*** *(University of Melbourne, VIC)*
16:00 - 16:25	Community Protection Planning in NSW Tailoring Bush Fire Risk Management to Individual Communities. ***Patrick Schell*** *(NSW Rural Fire Service)*	Investigating Inconsistencies of Grassland Curing Assessment between Multiple Jurisdictions across Australia. ***Danielle Wright*** *(Country Fire Authority, VIC)*	Post-tropical cyclone fuel assessment and bushfire risk. ***Matthew Geiger*** *(Queensland Fire and Emergency Services)*
16:25 - 17:00	There are No Boundaries: the South Para Collaborative Fire Management Plan. ***Aidan Galpin*** *(Dept. of Environment, Water and Natural Resources, SA)*	Leveraging smart phone technology for assessing fuel hazard in fire prone landscapes. ***Luke Wallace*** *(RMIT University, VIC)*	National Burning Project - National Guidelines for Prescribed Burning. ***Paul de Mar*** *(GHD Australia)*
17:00 - 17:30	**CLOSING CEREMONY**		

FIELD TRIPS | FRIDAY 15 APRIL

8:00 -16:00	**East Central Bushfire Risk Landscape** *Field Trip sponsored by* VICTORIA State Government – Environment, Land, Water and Planning	**Forest Fire and Fuels** *Field Trip sponsored by* CFA	Buses depart & return to Melbourne Convention and Exhibition Centre. Lunch provided

POSTER LISTING

SOCIAL ACTIVITIES

WORKSHOP NETWORKING FUNCTION

This function is for participants in Workshop 2.
The venue is the foyer of the Bureau of Meteorology
and will include light food and beverages.

MONDAY 11 APRIL • 5:30 PM - 7:00 PM

WELCOME FUNCTION

The Welcome Function will be held in the trade exhibition.

TUESDAY 12 APRIL • 5:30 PM - 7:00 PM

This event will include food and beverages.

CONFERENCE DINNER

Showtime Events, South Wharf

(A 2-minute walk from Melbourne Convention Centre)

WEDNESDAY 13 APRIL • 7:00 PM - 10:00 PM

This casual function will include dinner and beverages.
The stand-up format will allow for plenty of mingling
and networking with superb views across
the Yarra River to the city skyline.

WORKSHOPS

WORKSHOP 1 – GRASSLAND FUELS AND FIRE BEHAVIOUR

MONDAY 11 APRIL, 9.00AM TO 12.30PM

Venue - Bureau of Meteorology, 700 Collins St, Docklands

The aim of this workshop is to set out the current state of knowledge of grassland fuels and fire behaviour and to discuss areas of future research.

The workshop will be divided into four main sections; (1) the current state of knowledge of grassfire behaviour, (2) advancements made as part of the CFA Grassland Curing and Fire Danger Ratings Project, (3) grass fuel structure and fire behaviour and (4) grass fire danger rating and future work. Topics covered will include a historical perspective of McArthur's work in grasslands, best methods for assessing grassland curing and fuel load, results from a national grassland curing experimental burn program and end user perspectives. Following discussions at a fuel load workshop in Melbourne (2015), we will discuss fuel load and fuel structure; the effects on fire behaviour and how we might capture these variables in future. This workshop is targeted at anyone with an interest in grassland fire behaviour (fire managers, fire researchers, students, etc.).

Speakers will include Miguel Cruz (CSIRO), Andrew Sullivan (CSIRO), Joe Buffone (Chief Officer, CFA), Alen Slijepcevic (Deputy Chief Officer, CFA) and Susan Kidnie (CFA).

The pre-conference workshop is on the morning of Monday 11 April at the Bureau of Meteorology, which is a 15 minute walk from the Melbourne Convention and Exhibition Centre. This will allow participants to also register for the Fire Weather and Risk Workshop, which is at the same venue in the afternoon.

WORKSHOP 2 – FIRE WEATHER AND RISK

MONDAY 11 APRIL - 1.30PM TO 5.30PM, followed by networking drinks.
TUESDAY 12 APRIL - 9:00AM TO 12:00PM.

Venue - Bureau of Meteorology, 700 Collins St, Docklands

This workshop will focus on two main topics – smoke management; and ensemble and probability forecasting – within the overall theme of transitioning science to services.

Each topic will feature keynote addresses from experts in the field, addressing current operational practice, research trends and what best practice might be. The talks will be followed by plenary discussions led by knowledgeable and provocative facilitators. Speakers will be drawn from both the operational and research sectors, and we aim to also help the fire community learn from successes in other areas.

This workshop builds on previous similar fire weather and risk workshops in Busselton (2013) and Bowral (2011) and will appeal to fire and land managers and operational staff, policy makers and researchers.

This pre-conference workshop follows Workshop 1, and is on the afternoon of Monday 11 April and the morning of Tuesday 12 April, at the Bureau of Meteorology, a 15 minute walk from the Melbourne Convention and Exhibition Centre. An icebreaker function on the Monday night is included.

Australian Government
Bureau of Meteorology

BREAKFAST WORKSHOP

Published in INTERNATIONAL JOURNAL OF WILDLAND FIRE

WEDNESDAY 13 APRIL – 8.00AM TO 9.00AM, *light breakfast provided*

Venue - Level 1, Melbourne Convention Centre, Room 103

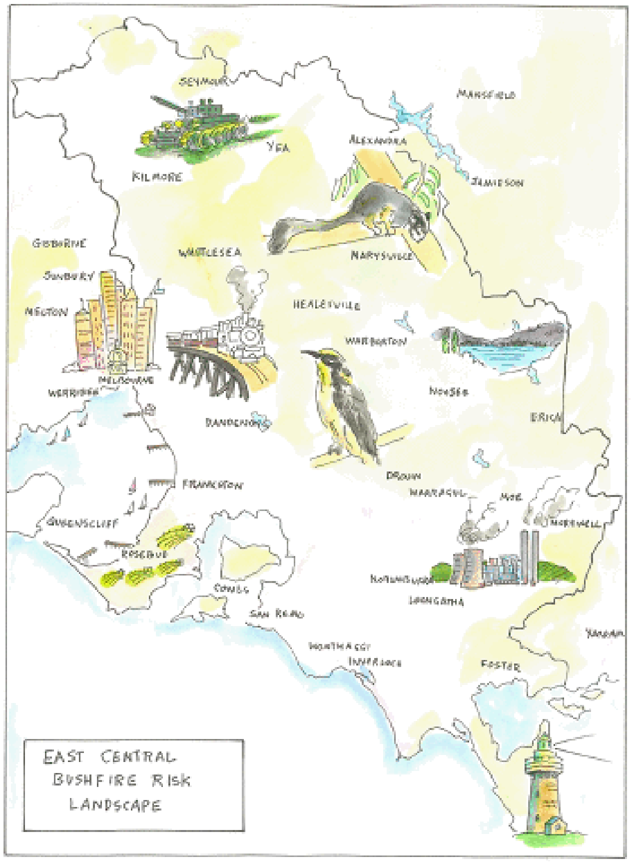
This workshop is aimed at assisting authors and potential authors to get their best work published in IJWF. The presenters will provide helpful guidelines, as well as some information on the journal, followed by an informal feedback session.

PRESENTERS INCLUDE;

Susan G. Conard, George Mason University, Editor-in-Chief
Stefan Doerr, Swansea University, Editor-in-Chief
Jenny Foster, CSIRO Publishing, Journals Publisher

FIELD TRIPS

The Field Trips will take place on FRIDAY 15 APRIL. Buses will depart MCEC at 8am and return at 4pm.



FOREST FIRE AND FUELS FIELD TRIP

South east Australia's tall Eucalyptus forests are the scene of some of the most catastrophic fires on earth, including the 2009 Black Saturday fire, Australia's worst ever natural disaster which resulted in the loss of 173 lives and cost the community in excess of $4.5B. These forests are the home to numerous rural populations, but at the same time are highly valued for recreation, timber and ecological values, and include the catchments that supply the city of Melbourne's 4.5 million residents with drinking water. As a result, fire management in these forests must reconcile a complex interplay of objectives, maximising human safety, while maintaining ecological values and protecting critical ecosystem services such as water supply. On this 1 day field trip we will visit the majestic Mountain Ash (Eucalyptus regnans) forests to the north of Melbourne. Via a series of site visits and guest speakers from universities and agencies, we will explore the regions fire history, discuss fire management issues with key stakeholders, and visit current fire and fuel research sites. The bus journey will take in the beautiful Yarra Valley to the north of Melbourne, a renowned wine region. Lunch will be provided.

Field Trip sponsored by

CFA

EAST CENTRAL BUSHFIRE RISK LANDSCAPE FIELD TRIP

The Victorian Government has adopted a risk based approach to bushfire management which combines strong community partnerships with the latest science and information to more effectively target actions to reduce bushfire risk. The Department of Environment, Land, Water and Planning, which is responsible for the management of public Forests and Parks in Victoria and has adopted this approach at a bushfire risk landscape level. This field trip will investigate how this is happening within what is known as the East Central Bushfire risk landscape.

3.3 million people live in the East Central landscape , as do many rare and threatened plants and animals and significant community assets including most of Melbourne's water supply and nearly all of Victoria's energy supply. Managing risk means managing risk to all these values.

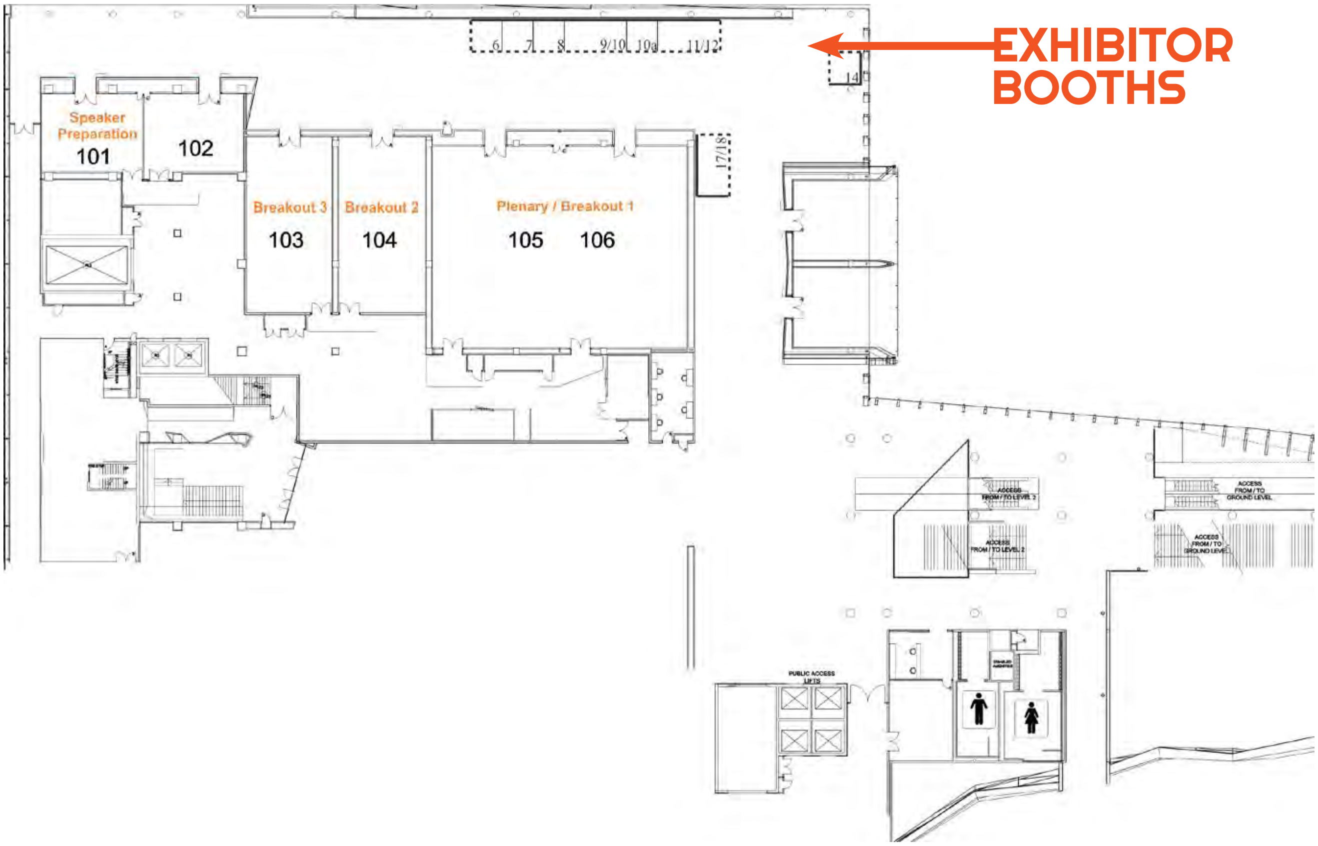
This field trip will provide an overview of DELWPs approach, the complexity of the landscape, how DELWP works with partners and communities to get good results and how science drives this approach and continued improvement.

During this field trip we will travel into the Dandenong ranges and meet with community members, water authorities, local fire staff and ecologists and discuss how we make this vision, a strategy and how we implement this on the ground and measure our effectiveness.

Field Trip sponsored by

VICTORIA State Government | Environment, Land, Water and Planning

TRADE DIRECTORY



AUSTRALIAN FIRE AND EMERGENCY SERVICE AUTHORITIES COUNCIL (AFAC)

BOOTH 9 & 10

Web: www.afac.com.au

AFAC is the National Council for Australian and New Zealand emergency services agencies -creating synergies across the emergency management sector. Through a collaboration network, development of industry doctrine, events and conferences AFAC delivers knowledge and innovation to its members and the broader emergency management sector.

Australian Government
Bureau of Meteorology

BUREAU OF METEOROLOGY

GOLD SPONSOR

BOOTH 14

Web: www.bom.gov.au

The Bureau of Meteorology is Australia's national provider of weather, climate, water, ocean and space weather information. We have been the nation's definitive source of environmental intelligence for more than 100 years, and since the 1940s have provided alerts and Fire Weather Warnings to the public.

The Bureau collaborates closely with fire agencies across Australia, assisting them to prepare for fire and severe weather events and providing specialised weather services in support of response and recovery operations. Through the Bushfire and Natural Hazards CRC and other partnerships the Bureau is investigating and modelling the relationship between weather, climate, and fire behaviour.

BUSHFIRE AND NATURAL HAZARDS CRC

BOOTH 9 & 10

Web: www.bnhcrc.com.au

The Bushfire and Natural Hazards CRC draws together all of Australia and New Zealand's fire and emergency service authorities, land management agencies, as well as non-government organisations and leading experts across a range of scientific fields to explore the causes, consequences and mitigation of natural disasters.

The purpose of the Bushfire and Natural Hazards CRC is to conduct end-user inspired applied research to:

- Reduce the risks from bushfire and natural hazards
- Reduce the social, economic and environmental costs of disasters
- Contribute to the national disaster resilience agenda
- Build internationally renowned Australian research capacity and capability
- Enable Australian small to medium enterprises to be innovative in natural hazard products and services.

COUNTRY FIRE AUTHORITY

FIELD TRIP SPONSOR & BOOTH 8

Web: www.cfa.vic.gov.au

CFA (Country Fire Authority) is a volunteer and community based fire and emergency services organisation. You can find CFA brigades all across regional Victoria, as well as outer metropolitan Melbourne with an urban/rural interface. We help protect 3.3 million Victorians and more than one million homes and properties across the state. We have over 57,000 volunteers who are supported by more than 680 career firefighters. CFA also employs over 1,500 support staff who work in areas such as community education, media, communications, training, health and safety, finance, human resources and emergency management.

CSIRO – BUSHFIRE DYNAMICS

BOOTH 17 &18

Web: www.csiro.au/en/Research/Environment/Extreme-Events/Bushfire

CSIRO's research is used to respond to bushfires in many ways, from weather warnings to fire-fighter training to predicting fire behaviour.

CSIRO PUBLISHING

BOOTH 17 & 18

Web: www.publish.csiro.au | Phone: +61 3 9545 8400

CSIRO PUBLISHING is a science and technology publisher with a global reputation for quality products and services. Our international publishing programme covers a range of scientific disciplines, including agriculture, the plant and animal sciences, planning and building, health and environmental management. Our product range includes journals, books and magazines, in print and online.

DEPARTMENT OF ENVIRONMENT, LAND, WATER AND PLANNING

FIELD TRIP SPONSOR

Web: www.delwp.vic.gov.au

The Department of Environment, Land, Water and Planning is tasked with ensuring that Victoria has the right conditions to enable economic growth, while delivering liveable, inclusive and sustainable communities. We bring together planning, local government and infrastructure, environment, climate change and water functions, to ensure an integrated approach to the development of long-term State and regional strategies that build on social, environmental and economic opportunities to provide for future population growth and change. We build community resilience by adopting an all-hazards, all-agencies approach across our built and natural environments to improve protection against natural disasters and other emergencies.

FIELD AIR

BOOTH 11 & 12

Web: www.fieldair.com.au

The Air Tractor AT-802F single engine Air Tanker combines speed, performance and absolute reliability to accurately deliver its 3,200 litre suppressant load to the fire. Capable of operations nearby the fire, from remote air strips or with optional amphibious scooping capability, Air Tractor is relied upon by fire authorities worldwide.

INTERNATIONAL ASSOCIATION OF WILDLAND FIRE

BOOTH 6

Web: www.iawfonline.org

The International Association of Wildland Fire (IAWF) was formed in 1990 as an international professional membership association dealing with all aspects of wildland fire. For 25 years IAWF has grown from its fledgling early years to being a global leader focused association spanning 30 countries. The IAWF's independence and breadth of global membership expertise allows it to offer a neutral forum for the consideration of important, at times contentious, wildland fire issues. IAWF's membership and organization allow the group to creatively apply a full range of wildland fire knowledge to perform its stated mission of Uniting the Global Wildland Fire Community.

KENELEC

BOOTH 7

Web: www.kenelec.com.au

Established in 1962, Kenelec Scientific is one of Australia's leading and longest serving scientific & environmental technology companies. With offices in Sydney and Melbourne and key distributors located throughout Australasia, we are recognized as innovative industry leaders in the supply of latest generation technologies at competitive prices.

Kenelec Scientific provides a wide range of scientific and environmental solutions to companies throughout Australasia. We employ highly trained and experienced sales and technical support staff, maintain state-of-the-art NATA accredited calibration laboratories, offer a range of popular laboratory services, provide validation services to industry and have an established rental department servicing the needs of our rental clients.

Kenelec Scientific operates a Quality Management System that fully complies to ISO 9001:2008 and is committed to providing the highest level of service and technical support on an extensive range of innovative products.

SCHOOL OF ECOSYSTEM AND FOREST SCIENCE, UNIVERSITY OF MELBOURNE

BOOTH 10A

Web: www.ecosystemforest.unimelb.edu.au

The University of Melbourne is home to Australia's largest bushfire research and teaching effort. The University offers graduate courses in Bushfire Planning and Management that combine bushfire science with urban planning, design and construction and fire management subjects, to equip professionals for managing fire risk across built and natural environments.

SCION RURAL FIRE RESEARCH GROUP

LECTURE THEATRE SPONSOR

Web: www.scionresearch.com/fire

Scion is the NZ Crown Research Institute (CRI) that specialises in research, science and technology development for forestry. Scion's Rural Fire Research Group is NZ's only provider of specialist fire research expertise in forest and rural landscapes. We develop science and technology to protect life and property, and to manage fire in the landscape. Understanding how fires are likely to behave in different weather conditions, terrain and fuel types, and the factors affecting community and firefighter safety, are essential to rural fire management and prevention. The Group has developed a range of tools and guidelines now widely used by NZ fire managers to support fire management decision-making.