Fourth Fire Behavior and Fuels Conference Proceedings

AT THE CROSSROADS:

Looking Toward the Future in a Changing Environment

Raleigh, North Carolina, USA • February 18 -22, 2013

St. Petersburg, Russia • July 1-4, 2013

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INTRODUCTION TO THE PROCEEDINGS OF THE FOURTH FIRE BEHAVIOR AND FUELS CONFERENCE

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The Fourth Fire Behavior and Fuels Conference was held in Raleigh, North Carolina, USA, February 18-22, 2013. The theme for this conference was *At The Crossroads: Looking Toward the Future in a Changing Environment.* Joint sponsorship of the conference was by the International Association of Wildland Fire (IAWF) and the International Association for Fire Safety Science (IAFSS). A second session of the conference was held in St. Petersburg, Russia, July 1-4, 2013 in conjunction with National Research Tomsk State University and Worchester Polytechnic Institute. The joint conferences proceedings contain 71 written contributions.

This conference was the fourth in a series that include: The First Fire Behavior and Fuels Conference held in Portland, Oregon, USA, March 27-30, 2006. The Second Fire Behavior and Fuels Conference was held in Destin, Florida, USA, March 26-30, 2007. The Third Fire Behavior and Fuels Conference was in Spokane, Washington, USA, October 25-29, 2010. The 2013 conference was unique as it featured two conferences in the same year, one in the United States and a second in Russia five months later.

The Raleigh session included fourteen all or part-day workshops and a fire science quiz bowl that preceded the conference on Monday, February 18th. The conference opened on the morning of February 19th and included seven plenary speakers, one hundred thirteen oral presentations, two moderated panel discussions, sixty-seven poster presenters and a mid-week banquet. Attendance was lower than anticipated due to economic constraints, however 350 were present and evaluations of the conference were quite positive.

Session topics included: Smoke, Prescribed Fire, Fire Modeling, Fire Weather, Management Implications, Fire Effects - History and Monitoring, Fuel Classification, Fuels Treatment and Decision Support Information. Special Sessions included: Behavior and Ecological Consequences of Smoldering Fires, Fire Culture – Using the Humanities to Revive the Ancient Link of People and Prescribed Fire, A Tribute to George W. Byram, The RxCADRE project and Fuels and Fire Behavior in Mountain Pine Beetle Affected Forests.

The St. Petersburg edition was developed in order to extend the international outreach of the conference and create more opportunities for international collaborations around fire behavior and fuel research. This first attempt outside of the USA was a success, with around 150 attendees from all around the world with a large participation from Russia, 7 keynote presentations, plus 75 oral presentations and over 40 posters representing the last research developments in fire behavior and fuel modeling from 21 countries. The first day was dedicated to workshops with 5 workshops about new applications developed in research and now available to end-users. Among those, a half-day workshop was organized by IJWF (International Journal of Wildland Fires, the official journal of IAWF) to train non-native speakers to publish in scientific Journals in English. During 3 days of conference all presentations were made on most actual topics: Fuel, Management, Fire Behavior, Remote Sensing, Fire Research and Impact, Simulations, Smoke, Extreme Fires and Wildland-Urban Interface.

In addition to the technical part, a boat trip was organized along the Neva River, the conference dinner was held in a nice restaurant along the Baltic Sea, and a field trip was proposed at the end of the conference in a forest that was damaged by a recent wildfire.

IAFSS, as co-organizer of the conference delivered several awards for the two editions that included $500 prizes. The awards were: Best paper, best student paper and best applied paper:

Raleigh:

- Best paper. "First Look at Smoke Emissions from Prescribed Burns in Long-unburned Longleaf Pine Forests" *by Timothy Johnson, Sheryl Akagi, Robert Yokelson, Ian Burling, David Weise, James Reardon and Shawn Urbanski.*
- Best applied paper: "Fire behaviour prediction tools for fire managers - lessons learned from tools development in New Zealand" *by H. Grant Perce and Veronica R. Clifford.*
- Best student paper: "Observations of fire behavior on a grass slope during a wind reversal" *by Diane Hall, Allison Charland, Craig Clements, Daisuke Seto, Jon Contezac and Braniff Davis.*

St. Petersburg:

- Best paper: “Mathematical Modeling of Crown Forest Fires with Fire breaks” *by Valeriy Perminov.*
- Best student paper: “Relating Vertical Wind Profiles to Vegetation Structure for Fire Behaviour Prediction” *by Kangmin Moon, Thomas Duff and Kevin Tolhurst.*
- Best applied paper: “Multi-scale Simulation of a Very Large Fire Incident. Computation from the Combustion to the Atmospheric Meso-Scale” *by Jean-Baptiste Filippi, Celine Mari C. and Frédéric Bosseur.*

Two special issues are in preparation in International Journal of Wildland Fire (IJWF) and Fire Safety Journal that will present a selection of the best contributions presented during the two editions.

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The conference organizers gratefully acknowledge the support of the following organizations and individuals who have contributed to this event:

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A special thank you to the conference planning committees who worked hard to pull together two very successful events:

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CITATION
Wade DD & Fox RL (Eds), Robinson ML (Comp) (2014) 'Proceedings of 4th Fire Behavior and Fuels Conference', 18-22 February 2013, Raleigh, NC and 1-4 July 2013, St. Petersburg, Russia. (CD-ROM) (International Association of Wildland Fire: Missoula, MT)

Edited by Dale Wade and Rebekah Fox

Compiled by Mikel Robinson

Cover design by Shauna Murphy

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Framing our fire story to promote sustainable policies and practices

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Abstract: For the 2012 fire season, a USFS 'Fire Ban' directive raised concerns that a return to a 'suppression' only response to fire would undermine long-term fire management strategies and policies. I discuss the ramifications of this directive in my Conference Keynote with a 40-year perspective and a call for communicating our fire expertise.

Introduction

'*If Americans had a National Register of Historic Places for fire, the Selway-Bitterroot region would rank among the early entries*.' (Pyne 2012). Steve Pyne penned these words following a July 2, 2012, flight over the Selway-Bitterroot Wilderness (SBW) hosted by West Fork Ranger Dave Campbell. The flight celebrated 40 years of free-burning fires in the Selway Country following approval of the White Cap Plan in 1972 by Forest Service Chief John McGuire. Steve was referring to the trajectory of fires in the SBW from the 1910 'big blow-up', to the massive Pete King Fire of 1934, to the recent four decades of free-burning fires.

Despite the historical significance of this 'fire place', the Forest Service's Washington Office chose to commemorate the auspicious occasion of the 40th Anniversary with a Fire Ban disseminated to Regional Foresters in a letter dated May 25, 2012. Due to budget issues, suppression costs, and firefighter exposure, the May 25 letter emphasized initial attack as the standard operational procedure. Accompanying the Fire Ban was the statement that: '*We acknowledge, and emphasize, that such an approach is not sustainable over the long-run.* ***It would contribute to deterioration of ecosystem health and the vulnerability of communities to catastrophic wildfire.*'**

So why even go there? The Ban was an attempt to extinguish the very spark that keeps the momentum of Selway Country ecosystems alive, well, and healthy, while reducing firefighter exposure and reducing costs. It actually contradicted the state of fire ecology knowledge and over 50 years of fire science research, leaving agency personnel with the feeling that they had been returned to a known flawed historic '10 am' policy of suppressing all fires, at any cost. Adding to this confusion, after hearing of the content of the May 25 letter, members of the public asked, 'if this is not sustainable over the long run, why are we doing it?' The irony of the Fire Ban is that it actually increased suppression costs and increased firefighter exposure in large western wildernesses like the Bob Marshall and the SBW where past fires regulate the size and severity of new fires.

Prior to the July 2 over flight of the Selway-Bitterroot Wilderness, Dave Campbell briefed the two passengers (Fig. 1) from a map that looked as though it had freckles. The freckles were the extensive distribution of past fire perimeters that had accumulated over 40 years of positive wilderness fire decisions. Dave Campbell, himself, has made 260 decisions to allow lightning fires to burn freely in the SBW during his tenure on the West Fork Ranger District. All of those fires produced meaningful wilderness benefits while reducing costs and firefighter risks.

Fig 1. Bob Mutch, Dave Campbell, and Steve Pyne following their July 2012 over flight of the SBW

The historical fires witnessed during the July flight were represented by every size, shape, and description as they burned under a multitude of fire weather and fire behavior conditions. What we saw unfolding below us on this flight back through time was the repeated scenario of a recent fire being regulated in terms of size, spread, and intensity by earlier fires. In other words, so many fires have been allowed to burn in the Selway Country over the years that a self-regulating system has emerged—a system whereby the health of these ecosystems is more within the range of historical variability rather than far outside it (Fig 2). Allowing the continuance of such fires substantially reduces firefighter exposure and costs, both now and in the future.

Fig. 2 The eastward spread of the 2011 Hell's Half Fire is halted by the 1999 Devil's Storm Fire on the right.

The Selway-Bitterroot Wilderness natural fire program received a helpful boost from a similar program in Sequoia and Kings Canyon National Parks that preceded the Selway effort by four years. Operational information was shared with the Forest Service about protocols established in the Park Service's free fire zone established in 1968. Sierra Nevada Parks in California have enjoyed a very successful natural fire program ever since. In Yosemite National Park, for example, lightning fires have been allowed to burn under specific prescriptions since 1972 (vanWagtendonk and Lutz 2007). These fires burn in the upper montane and subalpine vegetation zones, comprising approximately 83 percent of the park.

A thesis for enhanced future communications

Let there be no mistake about the intent of the May 25 letter to all Forest Service Regions. It was perceived by people in the field as a Fire Ban and its direction was implemented in a manner that emphasized aggressive initial attack. For example, then Intermountain Regional Forester Harv Forsgren issued a letter one week later to his National Forest Supervisors underscoring the fact that '*Our default response will be to aggressively initial attack all wildfires where safe to do so, including those in Wilderness areas*.' In an AP article (8-18-12), Susan Montoya Bryan reported that: '*This season is different. Now firefighters are trekking deep into the Gila National Forest with trains of equipment-carrying horses and one overriding goal: snuffing out all fires, no matter how small or remote.*' She went on to say '*Across the West, only one fire — deep in the Teton Wilderness in Wyoming — is being allowed to burn* (for resource benefit).'

Countering the Fire Ban could easily fall into the trap of pointing fingers at high level officials and asking 'How could you?' But a far more productive response places each of us in fire science, fire management, and resource management squarely in the limelight as those who have responsibility to ensure more sustainable fire policies in the future. Consider how the following thesis might place us in a more proactive communication role in the future:

> *We, the fire community, have failed to tell our story in a manner that policy makers get it, resulting in the recent enactment of unsustainable fire policies that produce catastrophic outcomes in fire-adapted ecosystems*.

If we want to avoid a repeat of the 2012 Fire Ban in the future, we need to step forward, individually and collectively, to better frame our story so that policy makers, politicians, and the public develop, implement, and support sustainable fire management policies and programs. Steve Pyne framed our story many years ago when he said that we have too much of the wrong kind of fire and not enough of the right kind of fire. In other words, too much wildfire and not enough prescribed fire. Professor Emeritus Harold Biswell of UC-Berkeley weighed in on this same topic years ago when he chided agencies for not having a balanced fire management program. He had a 'rule of thirds' that suggested agencies invest a third of their fire budget in fire prevention, a third in prescribed fire, and a third in fire suppression. One could debate his proportions based on local conditions, but one cannot argue with the importance of a balanced fire management program.

In the September-October 2012 issue of Wildfire, Ron Steffens provided some useful insights on how we might better 'frame' our story for improved understanding by the public. In addition to the public audience, we need to add the policy makers and politicians who also have a key role to play. Ron cited principles to better framing that included the need to engage in public dialogue; to act openly, ethically, and apolitically; and to use terms that resonate to frame the discussion. He went on to explain the basic tenets of framing: first, how do we get people to think about our issues: and, secondly, how do we get people to think in such a way they want to solve our issues through public policies?

How can we frame the earlier thesis in a manner that provides a positive incentive for all of us to communicate more productively in the future? Such framing might look like this:

> *We, the fire community, need to tell our story so convincingly that policy makers, politicians, and the public develop and support fire management policies that produce a balanced program, sustaining the health of fire-adapted ecosystems while reducing suppression costs and risks to firefighters***.**

The need to fulfill our responsibility in framing a more clearly understood, compelling, and receptive story that will build and maintain trust in our land management is an urgent one. In the same September-October issue of Wildfire, IAWF President Dan Bailey sounded the alarm; an alarm that is emphasized by the onslaught of megafires almost every fire season. '*It is time to make wildland fire policies work...*' Dan Bailey said, or see the status quo *'…continue to result in larger, more deadly, and more costly wildfires.*'

In the need to better frame our story, it is important to remember that at times we can be our own worst enemy. For example, a workshop at the Lubrecht Forest in Montana, May 2007, presented the message that wildland fire use is the riskiest type of fire you will ever manage. As true as that statement is at the outset of a program allowing long duration fires to burn freely amidst uncertain future weather conditions, the message becomes less and less relevant as the program matures. The agency's current emphasis on risk management is conditioning decision makers that risk implies a negative situation. We must approach risk from wildland fires correctly. It should not automatically project a negative perception, but should be a welcome addition to the information that aids decision making. New tools and technologies now afford managers greater risk assessment and long-term management planning capability than ever before, placing us in a favorable situation to better manage fires. Finally, as in the case of the SBW, 40 years of free-burning fires have produced the positive situation where fires become self-regulating and low risk events. That outcome needs to be better communicated to policy makers to allay fears that we may have helped instill in them by our static framing of an *emerging* wildland fire use program as inherently risky.

Fire behavior experience and science help frame our story

Phil Omi (2005) reported that scientists had speculated for years that natural fires might become self-regulating as burned areas created buffers that would regulate the size and severity of future fires. Also, close observers of the SBW fire program experienced a similar gut reaction for years that past fires were accruing positive interest in the future's fire ledger. Simply stated: Past fires were regulating the size and intensity of future fires without human intervention. Teske *et al.* (2012) gave scientific credence to this gut reaction in their analysis of fire-on-fire interactions in the Bob Marshall Wilderness, Selway-Bitterroot Wilderness, and the Frank Church-River of No Return Wilderness. They reported evidence from remote sensing that large fires generally inhibit the spread of subsequent fires, while small fires appear to have little impact on the spread of other fires (Fig. 3).

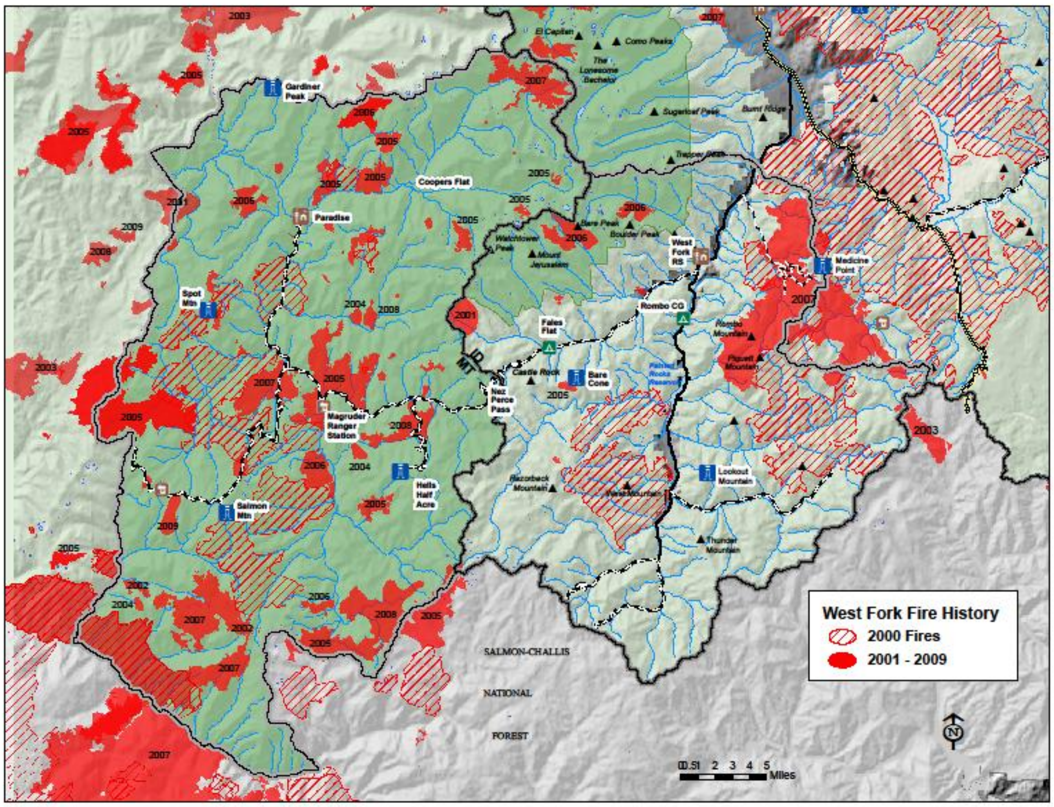

Fig 3. Wildland fires on the West Fork District, Bitterroot NF, 2000-2009, including many in the Selway-Bitterroot Wilderness (dark green)

Byron Bonney (2012) framed a SBW Success Story for the Western Region of the National Cohesive Strategy. He indicated that the most important contributions to the success of the SBW program are threefold: 1) allowing fire to return to the wilderness ecosystem to accomplish the restoration and maintenance of resilient landscapes on a much larger scale, 2) contributing to and increasing the safety of firefighting resources by reducing exposure, and 3) reducing, over the past 40 years, the size and intensity of future fires, producing a self-regulating ecosystem where new fires burn into older fire areas.

Forest lands outside wilderness are being restored by such forest management practices as silvicultural prescriptions, thinning, and prescribed burning. But there were reports that the 2012 Fire Ban even interfered with traditional prescribed burning projects in some regions. Such programs should be encouraged, not hindered, when you consider that silvicultural prescriptions and prescribed fire over many years turned the massive Rodeo-Chediski Fire in Arizona into just another low intensity prescribed burn on the Ft. Apache Reservation. Supporting such programs is essential when you consider that the management of natural resources and ecosystems is often fraught today with contentious issues that are debated heatedly among polarized groups. We know that silvicultural projects can be delayed for extended periods by appeals, court actions, and litigation. It is the resources that ultimately suffer when people agree to disagree over a course of action. Declining ecosystem health in many areas has led to an unnatural accumulation of fuels, widespread high intensity fire behavior, and direct threats to people, property, and natural resources. This area, too, is ripe for framing our successes in ecosystem restoration.

The numerous fire behavior and fuel workshops at the 4th Fire Behavior and Fuel Conference in Raleigh NC in February 2013 attested to the fact that we know a lot about the fire environment of the ecosystems we manage. We have a depth of science to draw upon as we frame our fire story. I am reminded of one Forest Service intern from Florida who attended the Raleigh conference. He clearly understood his responsibility to tell his prescribed fire 'success story' and promised to make it available in the near future. He did that and his story is at the publishers. The rest of us need to follow his good example.

Conclusion—How to frame a better fire future

The Forest Service Washington Office needs to conduct a detailed After Action Review of the Fire Ban and share the Lessons Learned widely with all partners. Secondly, management practitioners and fire researchers must become more active in framing the fire story so that policy makers allow enough fires of the 'right kind.' Thirdly, heed the call by IAWF President Dan Bailey for an outside review of sustainable fire policy issues (similar to the review that followed the Yellowstone fires of 1988). Finally, we must return to the strength of interagency partnerships as we frame our story and implement balanced fire management policies.

If we do not rise to the challenge of telling our story more clearly, others will tell our story for us—and we will deserve what we get. For example, author Michael Kodas said in an ***onearth*** website essay (August 30, 2012):

> '*…the agency is quickly responding to almost every blaze in an attempt to keep small fires from raging out of control. That's despite the long-term harm to forest ecosystems and the likelihood that the new policy could prime forests for even more destructive fires in the future.*'

We find ourselves in the enviable position to contribute our own stories—to document our fire experiences and science in a manner that produces credible fire policies and sound practices for a more sustainable resource management legacy.

Editor's Note: With 60 years of experience in fire research and management, Bob Mutch offered his insights on fire history and policy in his Keynote presentation at IAWF's 4th Fire Behavior and Fuels Conference in Raleigh, NC. At the close of the conference, US Forest Service Chief Tom Tidwell announced that the 2012 'fire ban' letter was rescinded and a new directive affirming a range of fire responses was issued for the 2013 fire season.

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Burning in their backyards and having them say 'thank you'

Steven R. Miller

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Abstract: Planning and executing any prescribed burn can be considered a complex process. The complexities can grow exponentially, both in size and in number, if the burn is in the wildland urban interface (WUI). One of the variables that makes burning in the WUI so challenging, is the neighbors themselves. Rightfully or not, the neighbors are nervous about fire managers lighting fires in what they consider to be 'their backyard'. The St. Johns River Water Management District (SJRWMD) has been burning in their neighbors backyards to restore ecosystems and reduce hazardous fuel loads since 1992. Along the way, staff from the SJRWMD have developed effective tools for communicating with their neighbors and garnering their support. Since the inception of the District's fire program, I have had the pleasure of serving as the leader of the program. SJRWMD manages approximately 400,000 acres, much of it interspersed with high-end homes and condominiums; we typically burn approximately 30,000 acres each year. I will share some of the lessons we have learned and the strategies and techniques used by District staff to get our neighbors in the WUI to say 'thank you' for burning their backyards.

Additional keywords: Prescribed fire, controlled burn, WUI, urban interface.

Introduction

Prescribed fire managers feel pressure when they are planning and managing prescribed fires. In the urban interface, that pressure goes up exponentially, because of the risks involved. I have focused on prescribed fire in the urban interface because when I am working fires in the west and talk about the need for more burning and more fuels management, westerners tell me that prescribed fire is easy in Florida so I do not really know about the challenges they face. In Florida, we may not have terrain, and we do get fresh air everyday so smoke management is easier, but I am going to focus on some complex burns in the urban interface to prove that we 'walk the walk' in order that people may be more likely to listen when we 'talk the talk'.

At the recent Association of Fire Ecology Congress in Portland, the closing panel discussion was entitled *'The Future of Federal Wildland Fire Management Policy'* and the abstract included the following statement:

> *'This new guidance addresses a growing recognition that our use of prescribed fire and fuels management to reduce the impacts of wildfires on local communities and increase forest health* ***has largely failed***.' (AFE 2012).

That statement causes me great concern, because we are fire's faithful. If fire were a church, fire managers would be the deacons, or the College of Cardinals, depending on your faith. If we as fire's faithful begin to say that we have failed, our detractors will only be too ready to capitalize on our admission of failure.. To be successful we need to believe in what we are doing and we need to talk about our successes.

Why focus on prescribed fire?

Why am I such an advocate for prescribed fire? Because it works! My employer, the St Johns River Water Management District has a Conservation Area called Heart Island. In February of 1995, we did a prescribed burn on 80 acres. In July of 1995, a lightning ignited wildfire burned 150 acres. A portion of the wildfire burned in flatwoods where no fuel management had occurred in decades and a portion of the wildfire burned through the area burned in February. In the areas where no fuels treatment had occurred the trees succumbed to bark beetles and had to be salvaged, but the trees in the portion that was prescribed burned previously survived. Some people might say that the prescribed fire did not work because the area reburned in the wildfire. I say it did its job because the fire intensity was so much less in the previously burned area that the trees survived.

Earlier this week, I participated in a workshop on crown fires. One of the participants, Morris Johnson, told the participants about a fuel treatment outside of Alpine Arizona. The fuel treatment thinned the canopy to about one quarter of the original tree density. In June of 2011, the Wallow Fire was raging as a running crown fire toward Alpine. When the fire hit the edge of the fuel treatment, the fire changed from a running crown fire to a surface fire. The pine litter and grasses on the ground still burned, but the fire was drastically different. The change in fire behavior allowed firefighters to stop the flames before they entered the town itself. Some of the trees in the fuel treatment died as a result of the fire, so some critics would say the treatment failed. I say that the change in fire behavior that resulted when the fire entered the fuel treatment saved the town. Had the fire entered town as a running crown fire, it is unlikely that much of the town of Alpine would remain. I call that a success.

This past fall I was in Texas to participate in the Complex Incident Management Course. During that course, Paul Hanneman shared the story of the Bastrop Fire that burned in September of 2011. The fire started near Bastrop State Park from a powerline. A portion of the park had recently been prescribed burned. When fire burned through the park, the fire behavior in the area previously prescribe burned was dramatically different, and the trees within the old burn survived, while those outside the recent prescribe burn were killed by the fire. Paul went on to mention how bad the situation really was; on September 4, 2011, there were 65 large fires burning across the state and resources were stretched so thin that strike teams were being assembled where individual engines were spaced 800 miles apart. On a day when resources were scarce, that prescribed burn was still on duty, it was not called away to respond elsewhere. When the wildfire came through, the prescribed burn still did its job of altering the fire behavior to protect resources.

I work for a water management district, but what in the world is one? Florida has five water management districts that were established in 1977 to protect water resources. Protection is achieved through permitting groundwater use, improving water quality by cleaning up areas impacted by pollution, protecting water quality and quantity by protecting wetlands, and providing flood protection for Floridians in flood prone areas. The flood control projects and the wetlands protection efforts include land acquisition and management. I lead the group that is responsible for managing those lands. The land base includes 420,000 acres where we serve as the lead manager and another 200,000 acres, which we jointly own with another agency with whom we cooperate in the management. We work closely with our partners and with our neighboring agencies. Most of the ecosystems we manage are dependent upon fire for their ecological health and perpetuation. The biological demand for fire means that we should be burning approximately 67,000 acres each year. The biological demand is represented by the yellow polygon in Fig. 1. We began managing fire in 1993. Over time, we have gotten better at burning and we got more acres burned, our ten-year average acres burned stands at just under 31,000 acres/year. We have not hit our biological demand in any single year but we are making strides toward it. Looking at Fig. 1, you can see that as the prescribed fire acres increase the wildfire acres decrease. I would like to think that that is a cause and effect relationship.

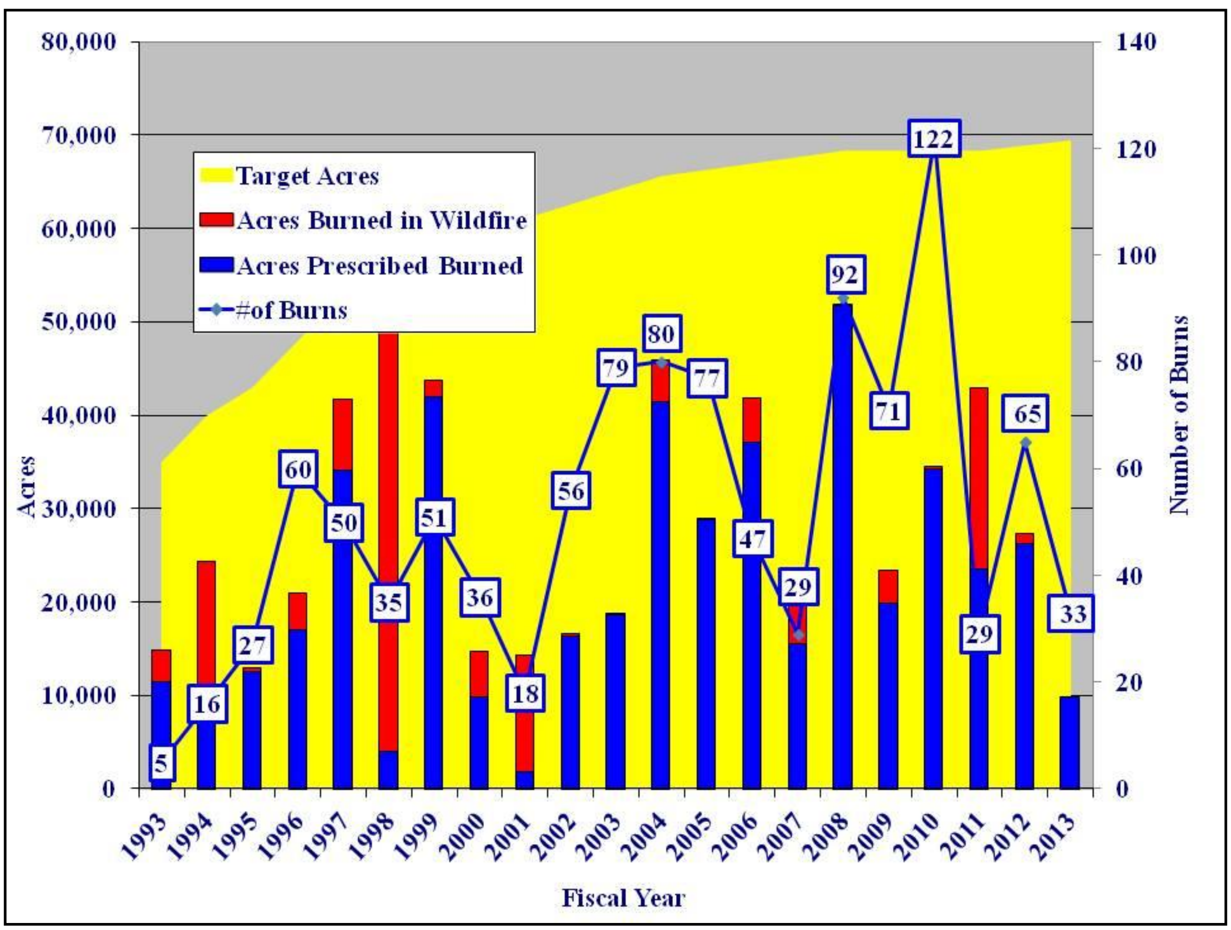

Fig. 1. Fire management history at St. Johns River Water Management District.

Success stories that prove we walk the walk

Julington Durbin Preserve

The Julington Durbin preserve is located within the city limits of Jacksonville, FL and portions are adjacent to I-95. The preserve is jointly managed with the City of Jacksonville. It shares a common boundary with hundreds of individual condominium each with a picture window looking right out at the lands we manage. Fig. 2 shows we are literally managing in their backyard. Our management of Julington Durbin is not just a fire management story; it is a forest health story. The property is about 2100 acres. Twelve hundred of those acres are wetlands and swamps along miles of two creeks, but down the middle of the peninsula, there is 900 acres of sandhill. Sandhill is a rare community that is dependent upon very frequent fire; one fire every two-five years. In this case, nearly half of the sandhill had been planted to sand pine by the previous owner. The tremendous ecological treasure of a sandhill is the diversity of the groundcover. Hundreds of species are found in the groundcover of healthy sandhills. Sand pine though forms dense canopies that shade out the groundcover. Sand pine also is a species that has a stand replacement fire regime on a 20-60 year return interval. These sand pine needed to go from an ecological standpoint to give the rare groundcover a chance to live and to protect the neighboring homeowners from a stand replacement wildfire, should one start.

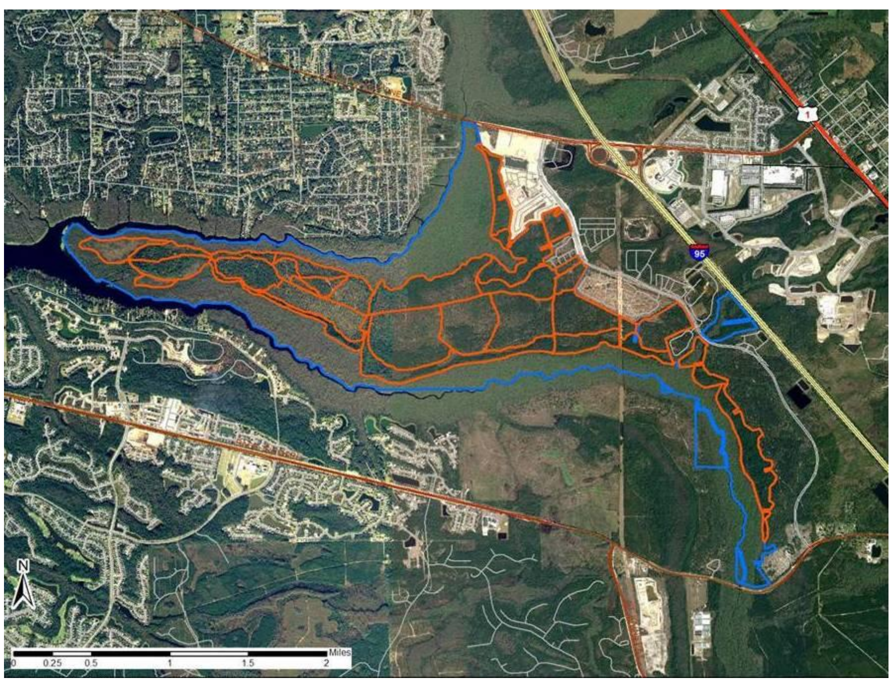

Fig. 2. Aerial of Julington Durbin

In 2004, we harvested the sand pine. In May 2005, we began burning the cutover sandhills. During that timeframe, the condos were under construction and we were trying to get a lot done before they were occupied. The burns triggered a response from the groundcover that had been suppressed under the sand pines. As if by magic, wiregrass and wildflowers appeared. We followed up with additional burns and mechanical sand pine control in 2008 and 2009 and 2012. Because the area is so close to a large human population, the area is used for recreation by hikers, bikers and horseback riders. Three public schools use the area to train their cross-country teams. During a burn in May of 2012, fifteen separate people came up to our fire staff and thanked us for burning the area. In fact, during one recent burn, one of the neighbors approached the Incident Commander and said they were glad we were there and that they were beginning to feel neglected because we were burning an adjacent unit more often than we were burning the one in his backyard.

We have established a reputation and an effective relationship with our neighbors. We protect that relationship like it was gold. During one burn the wind direction began to clock to the point where if we continued we would have smoke blowing on one of the condos, so we plowed a very shallow fireline through some luxuriant groundcover to cut off the burn. We rehabbed the line and came back and finished the burn on a day when the smoke would not blow toward the homes. Our relationship with the neighbors is too important to tarnish it by burning more acres when the smoke would impact them.

Because the more you burn the easier it gets, we are trying to burn this area on a two-year rotation. A two-year rotation produces less smoke, has reduced fire behavior, which makes the fire easier to control, and produces a very positive ecological effect. Fig. 3 shows how we have been able to repetitively burn units near our neighbors.

Fig. 3. Aerial showing proximity of burns to condominiums

At Julington Durbin, we have only 900 acres of fire maintained ecosystems and very complex smoke management, so we burn very small burn zones using hand ignition.

Hal Scott Regional Park and Preserve

Hal Scott is a 9,515 acre tract on the southeast side of Orlando. The southern boundary is SR 528, which is a divided highway with a 65 mile per hour speed limit. The Orlando International Airport is a few miles to the west. The east side abuts the community of Wedgefield. Wedgefield is a 6,500-acre housing development with significant acreage of unmanaged native vegetation within its bounds. Also present at Hal Scott, are red cockaded woodpeckers (RCW's). RCW's are a federally listed T&E species dependent upon very frequently burned sandhills and flatwoods. Ideal habitat is perpetuated with a two or three year burning rotation. Hal Scott differs from Julington Durbin because Hal Scott has 7,500 acres that need to be burned on a short rotation. The area has very few days when smoke management objectives can be met so we burn large zones using aerial ignition, right in people's backyards. The highway, subdivisions and RCW clusters can be seen in Fig. 4.

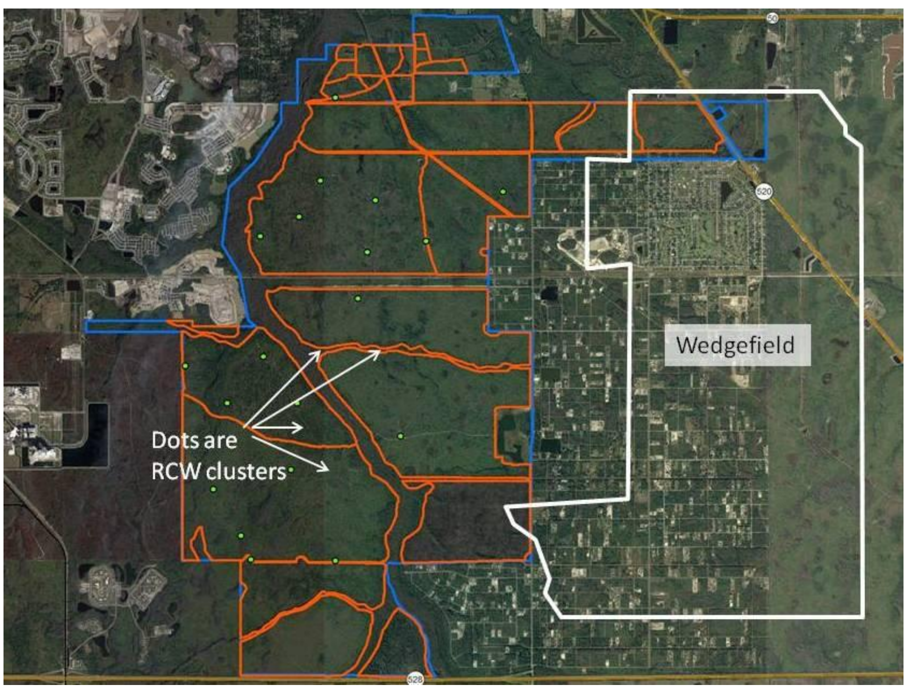

Fig. 4. Hal Scott and surrounding WUI

Fortunately, Wedgefield recognized that they had a need to provide some level of their own fire protection so they became a Firewise community in 2000. They have a very active Firewise committee and we interact with them frequently and effectively. Their Firewise activities make our fire management significantly easier.

However, the Land Manager at Hal Scott is not just about easy; he is also about delivering a quality fire management program. He recognized that the scorch on the longleaf was significantly greater when he did mass ignition, so he changed to flanking strips. While flank strips reduce the scorch, they also prolong his exposure to risk, because it takes longer to burn the zones using flank strips than it did to use mass ignition. But proper fire management is not just about quantity, it is also about quality. The flank strips shown in Fig. 5, demonstrates the Land Managers commitment to quality.

Fig. 5. Flank strips burning adjacent to Hwy 528

Canaveral Marshes

Canaveral Marshes Conservation Area is 6,741 Acres of fuel model three marsh grass wedged between three highways, a retirement community and the St. Johns River (Fig. 6). The retirement community is called Great Outdoors and started as a seasonal resort where the residents lived primarily in their RV, but would hook their RV up to a small structure that included a real bathroom, living room and laundry. It has morphed into half million-dollar homes that still have space to attach an RV. The neighborhood is filled with people from other parts of the county where fire is not as important as here. The neighborhood was more focused on maintaining the golf course than they were on reducing fuels in their conservation areas that are adjacent to our fuel model three marshes. If a fire started in the marsh and ran toward the Great Outdoors, the fire that met the homes would have 20-30 foot flame lengths and the only effective suppression tactic would be evacuation. Fire management on the Canaveral Marsh Conservation Area is critical not only to maintain the ecology of this herbaceous marsh, but also to protect Great Outdoors from wildfire.

In the early days, we received some push back from the residents. The pushback changed dramatically to support following a 2006 wildfire named the Areca Palm Fire. That fire jumped across a four-lane highway and was burning toward the Great Outdoors and required the residents to evacuate. Fortunately, the fire was stopped before it got to the Great Outdoors. Following that experience, the residents began to work with Brevard County Fire Rescue, the Florida Forest Service and us to qualify as a Firewise Community. Suddenly our efforts to establish firebreaks and to manage fuels were warmly received. In 2010, Great Outdoors qualified as a Firewise Community. Now our fire management efforts are supported by our neighbors. When we burn the zones adjacent to the Great Outdoors, dozens of residents follow along in their golf carts on the community streets adjacent to our firelines while our ignition and holding personnel perform their duties, (Fig. 7). On the days we burn we are more interesting than their golf game.

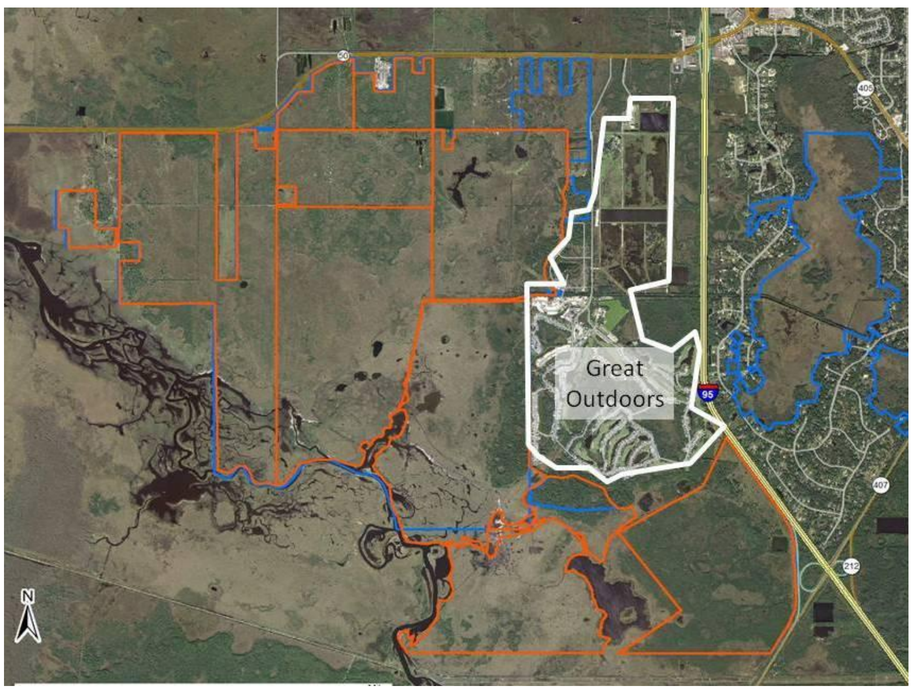

Fig. 6. Canaveral Marshes and surrounding WUI

Fig. 7. Recent burn with residents watching from golf carts.

River Lakes Conservation Area

River Lakes is a 36,156-acre conservation area near Melbourne. One burn zone, River Lakes 8 is nearly 5,000 acres immediately adjacent to I-95 for several miles. It too is dominated by fuel model three. In the 1980's there were 17 wildfires that burned 6,617 acres in River Lakes 8. They typically occurred when the area was dry and frequently resulted in organic soil fires. These smoldering fires produced smoke for weeks and frequently resulted in accidents on I-95. In 1989, the District Forester for the Florida Forest Service approached the District about developing a cooperative fire management plan that would burn River Lakes 8 so frequently that wildfires would be unlikely. That burn zone is nearly 5,000 acres and there is no way to make it smaller, so when we ignite it, we have to burn the whole zone unless the fire gets rained out. Since 1993, we have tried to keep the zone on a three-year rotation. Even with a three-year rotation, the flame lengths are dramatic and the real problem is not smoke on the highway; the real problem is drivers stopping to take pictures and video of the fire while other people drive past at 70 mph. We have developed a close relationship with the Florida Highway Patrol and they manage the traffic. Fig. 8 and Fig. 9 show why this close coordination is so import.

Fig. 8. Proximity of fire and smoke to I-95.

Fig. 9. Post fire image of RL-8 and I-95.

Does all this burning work?

In River Lakes 8, we have prescribed burned the area seven times since 1993. From the time we began managing the zone on a three-year rotation, it has had zero wildfires and there have been no smoke impacts to I-95 and thus no smoke related accidents.

In Canaveral Marshes, we burned the zone immediately to the west of Great Outdoors on, February 5, 2012. On February 20, 2012, there was a wildfire two units to the west. The wildfire was not able to burn into either the zone that was burned in February 2011 or the one burned in 2012. Great Outdoors was protected by over two miles of recently burned marsh grass.

Julington Durbin had a longleaf pine that was hit by lightning. The bole of the tree caught fire and burning bark flakes rained down. That longleaf however was in a zone that had been prescribe-burned three months previously, so when we discovered it the next day, only the bole of the tree was burning. We have had one wildfire at Julington Durbin in the fourteen years we have owned it. Yes, prescribed fire is working.

What are our tools for success?

In order to be successful we use the following seven tools, we: 1) Communicate; 2) Cooperate with other fire managers and with the neighborhoods; 3) Build confidence; 4) Manage our SMOKE; 5) Prepare; 6) Train; and 7) Empower fire managers to make on-the-ground decisions without consulting higher authority.

Communicate

We use every tool available to communicate our fire message. We have general messages on our website about land management that mention fire, we have specific pages about fire management, and we have messages about restoration projects and include segments on how important fire is to restoration. We announce individual burns on our website on the day of the burn. We send out annual fire plans to our neighboring homeowner associations, and we inform them of individual burns through email and phone trees. Great Outdoors has their own closed circuit television; they put our fire messages on their television system including planned burn dates and times.. In some communities, we have used the reverse 911 system to announce our burns. Fig. 10 shows one of the signs we put on our boundary line to inform new neighbors of our activity even if they have not yet watched us burn. We have kiosks at the entrance of the property and adjacent to the restoration project that inform visitors about the importance of fire management and the role it plays in our restoration project.

We work with the media during Florida's annual 'Prescribed Fire Awareness Week'. We have even held a mini fire academy for members of the media. Fig. 11 shows a reporter carrying a drip torch during that event. Once a reporter has had the chance to carry a drip torch and participate in a prescribed fire, they have a whole new perspective on the prescribed fire message.

Fig. 10. Prescribed fire sign on SJRWMD boundary.

Fig. 11. News media participating in prescribed burn during prescribed fire awareness week.

Cooperate

In an upcoming book, Steve Pyne writes ‘*They (Floridians) know that in the public eye, if one of them fails, they have all failed. Elsewhere, fire divides. In Florida, it joins’* (Pyne in process). We partner with all the federal, state, and local agencies who work with fire. We have partnerships with The Nature Conservancy. We regularly ‘horse trade’ personnel and equipment to complete prescribed burns. We don’t worry about reimbursement because we know that we may loan another agency an engine and two people today, but next week we will borrow a tractor plow and an operator.

We also cooperate with our agency partners and our neighboring communities when a community wants to become Fire Wise. Our time and energy to help a neighborhood become Fire Wise is a sound investment.

Build confidence

When we are determining the resource needs for an individual burn, the number of suppression resources is determined by two things; what do we need to catch a potential escape, and what do we need so every neighbor who looks out their window and sees fire, also sees someone managing it. We often include big red structural engines, not because we will actually use one to attack fire, but because our neighbors feel safer when they see one. Most neighbors don’t think of our type 6 brush trucks as a fire truck, they are conditioned to look for big red trucks and they are more confident of our fire management when they see one. The big red fire trucks are one of the reasons our efforts to cooperate are so important.

Manage smoke

Proper smoke management is so important. We do not compromise on dispersion or wind forecasts. Skimping a few points on the dispersion or a few miles per hour on the wind, may let you burn on an extra day or two, but the potential problems outweigh the benefits. We also mop up aggressively when necessary in the urban interface as a demonstration of our commitment to minimizing impacts to our neighbors. Smoke related complaints or accidents erode that public confidence that we try so hard to build.

Prepare

We prepare our perimeter fire boundaries. If our neighbors have heavy fuels we will mow, or drum chop a 30-60 foot wide firebreak on our side to reduce the risk of escape. We always have a hard fire line next to a boundary, and in the urban interface, we modify the adjacent fuels to convert the fuel from a shrub fuel model to a litter or grass fuel model in order to reduce the fire behavior at the edge.

Train

A great football coach once said, '*We practice like we play*'. We train like we work, cooperatively. If we are going to pool agencies on the fireline, we need to pool agencies in training so we have commonality before we reach critical points. We are blessed with very little turnover so the energy we would have spent on initial training we are able to spend on more advanced training. We encourage each of our staff to get some kind of fire training each year in addition to the required refresher training.

Empower Fire Managers

Because we have so little turnover, our fire managers are pretty experienced and we empower them to make decisions. A person managing a fire next to a subdivision or an interstate highway should not have to call someone in an office fifty miles distant in order to implement a decision during a fire.

Conclusion

It helps that when we burn in Florida, the burned area greens up in weeks, and frequently has abundant wildflowers. The public, and our neighbors, like how our burns look soon after they are completed. But, the tools we are using can be employed elsewhere in the country to garner public support for fire management and forest ecosystem restoration. Once we have earned that support, we need to protect the relationships we have built. As Bob Mutch stated in his opening keynote to this conference: '*the more you burn the easier it gets'*. We cannot surrender, we won't retreat, we are at a crossroads in fire management and we must move forward. It is incumbent upon us to leave the fire-adapted ecosystems we manage in better condition than when we started by applying appropriate fire regimes, while at the same time safeguarding public health and safety.

I teach at the Southern Area Wildland Fire Engine Academy. The instructor pool refer to one another as the cadre. During one academy, a student asked me what cadre was. I told him it is the group of people who serve as instructors and leadership; but the question got me thinking, so I looked up the word cadre. One definition was 'A nucleus of trained personnel around which a larger organization can be built and trained.' That is what we meant, but I also saw another definition 'A tightly knit group of zealots who are active in advancing the interests of a revolutionary party' (the free dictionary 2012). This is what we fire managers need to be; a tightly knit group of zealots who are active in advancing prescribed fire and fuel management.

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First look at smoke emissions from prescribed burns in long-unburned longleaf pine forests

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Abstract: While fire has long played a role in the longleaf pine ecosystem, there are still some stands in the southeastern United States where fire has not been reintroduced and fuels have accumulated for 50 years or more. As part of a larger study examining fuel loading and smoke emissions on Department of Defense installations in the southeastern U.S., fuels and trace emissions were measured during three prescribed burns at Ft. Jackson Army Base near Columbia, South Carolina in November 2011. These pine-forest understory fires provided valuable emissions data for fires that burned in stands that had little or no exposure to fire for decades. Smoke emissions were measured on the ground and from an aircraft by scientists from a large team of atmospheric researchers. (Akagi *et al*. 2013) To characterize initial emissions in the lofted plume and in point sources of residual smoldering combustion, trace-gas species were measured using an airborne FTIR and a ground-based FTIR, respectively. Whole-air sampling canisters were also collected from both ground- and airborne-based platforms. A total of 97 trace gases were quantified in this work, largely via infrared spectroscopy. Selected emissions data were compared with similar data collected from prescribed burns sampled in coastal North Carolina in 2010 in younger fuels beds of loblolly/longleaf stands near Camp Lejeune (Burling *et al*. 2011). The emission factors measured in this work differ by ~13-195% to EF measured from the managed stands at Camp Lejeune for organic and N-containing species, suggesting that fire emissions in similar ecosystems can exhibit large variability. Part of the differences, however, may be ascribed to burn conditions as well, since the NC burns were during the wet season whereas the SC stands were burned after an extended drought. We also report the first detailed FTIR emissions data for a suite of monoterpenes. Fig. 1 displays the emission factors (g/kg fuel) for several monoterpenes and isoprene as measured by the ground-based FTIR system. Due to their unsaturated structure, terpenes are highly reactive compounds emitted from plants thought to contribute to secondary organic aerosol formation (SOA) (Saathoff *et al*. 2009; Hennigan *et al*. 2011) and the formation of small oxygenated volatile organic compounds (OVOCs) (Jacob *et al*. 2002) in fire plumes. The known chemistry and measured abundance of monoterpenes suggests that these species impacted secondary plume processes including ozone, OVOC, and SOA formation in sampled plumes within the first few hours after emission.

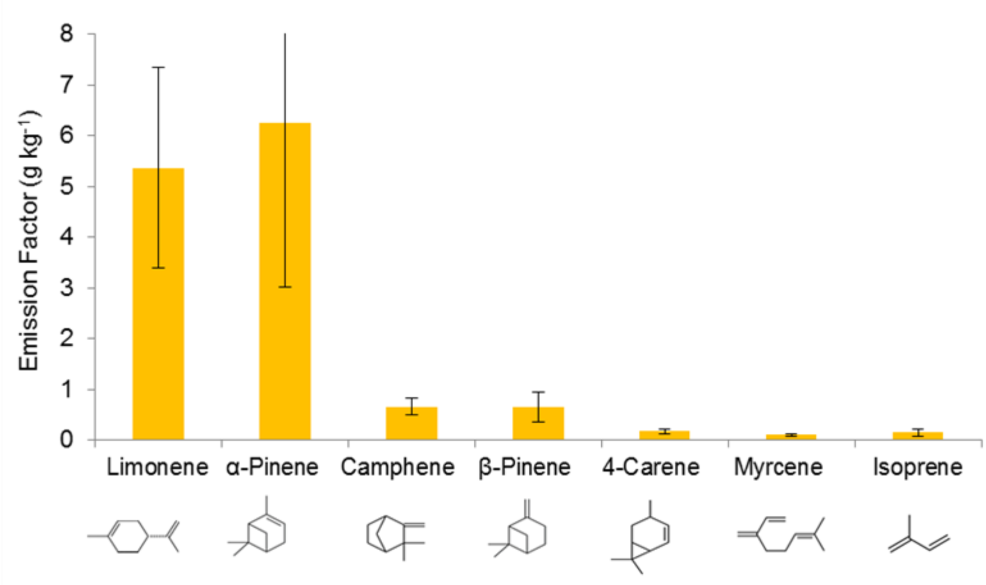

Fig. 1. Ground-based terpene emission factors (EF, measured in g analyte per kg fuel) of several monoterpenes and isoprene as measured during the 2 November 2011 prescribed burn at Fort Jackson, SC. The error bars in this graph show the variability all ground-based fires as a 1-σ standard deviation.

Additional keywords: Biomass burning, prescribed fire, monoterpenes, longleaf pine, residual smoldering combustion

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The influence of prescribed fire and burn interval on fuel loads in four North Carolina forest ecosystems

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Abstract: Prescribed fire is an important management tool in southern US forests, with more acres burned in the South than any other region of the US. Research from prescribed fire studies shows high temporal and spatial variability in available fuel loads due to physiographic, edaphic, meteorological and biological factors. In an effort to account for parts of this variation and contribute to the expanding southern fuels database, we measured forest fuels on sites in North Carolina's Croatan and Uwharrie National Forests prior to and following prescribed burns. Results confirm previous findings that well-executed prescribed fires are an effective tool to reduce litter and live shrub fuel loads, especially on sites with high understory biomass; however, the increase in dead shrub biomass may contribute to future fireline intensity. Prescribed fire on these sites had almost no detectable influence on dead woody fuels. The use of site-specific shrub biomass equations had a significant impact on estimates of understory fuels.

Introduction

The area burned by wildfire in the US is expected to double by the middle of the 21st century primarily due to projections of future climate change and the buildup of forest fuels following the longstanding 20th century policy of wildfire suppression (Vose *et al*. 2012). Prescribed fire is an ecologically sensitive and economically practical method to reduce fuel loads and mitigate the potential for catastrophic wildfires (Saveland 1987). More acres are burned in the south with prescribed fire than any other region of the US, with over 6.4 million acres burned in 2011 (Andreu and Hermansen-Baez 2008; Waldrop and Goodrick 2012). Despite its prevalent use in the south, prescribed fire and fuels research in the southeastern piedmont, central hardwoods and southern Appalachian Mountains has lagged behind western states and the southeastern coastal plain (Waldrop *et al*. 2006). While the southeastern coastal plain has a long history of studying and employing prescribed fire, research has shown high spatial and temporal variability in available fuel loads (Andreu *et al*. 2012). Estimates of understory biomass, a strong driver of fire behavior, are often included in published research; however, equations to calculate biomass based on measured variables are limited to few studies and sites.

Understory composition and density strongly influence fire behavior and post-fire fuel loads in forest ecosystems. Understory woody stem density has been shown to decrease immediately following prescribed fire, but this reduction is short-lived in fire adapted ecosystems where prolific sprouting typically leads to increased abundance, frequency and density within a year or two (Langdon 1981; Waldrop *et al*. 1987; Arthur *et al*. 1998; Phillips and Waldrop 2008). For example, live shrubs such as inkberry (*Ilex glabra* L.*)* in the coastal plain and mountain laurel (*kalmia latifolia* L.) in the southern Appalachians are highly flammable, yet decreases in coverage following a burn are often followed by prolific sprouting that can result in greater coverage than was present before the fire (Hughes and Knox 1964; Lewis and Harshbarger 1976; Elliott *et al*. 1999). In southeastern pine stands, Sackett (1975) found that gallberry (*Ilex glabra* L.) and saw-palmetto (*Serenoa repens* Bartr.) heights and weights increased steadily for six to twelve years following prescribed fire before tapering off. A chronic fire regime will, however, reduce the abundance and size of sprouts (Lewis and Harshbarger 1976; Langdon 1981; Waldrop *et al*. 1987). Rapid regrowth of understory species following prescribed burning is an important consideration for fuel managers when determining appropriate burn frequencies.

The forest floor, consisting of dead and decaying plant parts, is an important driver of forest fires due to its quick drying time and contribution to fire ignition and spread. Estimates of forest floor consumption vary widely due to forest type, fire intensity, pre-burn loading and timing of burn. It is well understood that fire reduces litter biomass, and annual burns generally result in a greater reduction than periodic burns (Scowcroft 1965; Kodama and Van Lear 1980; McKee 1982; Brockway and Lewis 1997). Scholl and Waldrop (1999) reported litter mass losses of 47 to 80% following prescribed fire in coastal plain pine stands. Little research has been done on the long-term recovery of forest floor litter following prescribed fire. Stambaugh *et al.* (2006) calculated maximum litter recovery rates of 32, 85 and 97%, one, five and ten years, respectively, following prescribed fire in Ozark oak-hickory forests, but these were theoretical estimates. Parresol *et al*. (2006) found that litter-duff loadings can recover in as little as two to three years on upper coastal plain sites, and Loucks *et al*. (2008) found that litter mass following leaf fall was similar to pre-burn estimates in an Appalachian hardwood forest.

Down deadwood (DDW), dead woody material visible above the litter layer, is another important component of forest fuels that influences fire behavior; however, the high variability in published DDW data from fire studies makes only general observations possible at this time. Both Scholl and Waldrop (1999) and Hartman (2004) reported that DDW fuels ≥0.64 cm but <2.54 cm diameter increased following prescribed fire in coastal plain pine and Ozark hardwood forests, respectively. In the Scholl and Waldrop study increases ranged from 7 to 71% across different fire complexes. Other size classes of DDW responded differently in the two studies. Waldrop *et al*. (2004) reported non-significant decreases in DDW <2.54 cm diameter and a non-significant increase in DDW ≥2.54 cm but <7.62 cm diameter in pine dominated piedmont forests following prescribed fire. In one of the few studies that followed changes in DDW after prescribed fire, Loucks *et al*. (2008) found that all size classes of DDW <7.62 cm diameter decreased following prescribed fire, but returned to pre-burn levels following leaf-off.

CWM (DDW ≥7.62 cm in diameter) is less of a concern to southeastern fire managers since these fuels generally don't contribute to fire ignition and spread, and aren't consumed during prescribed fires (Scholl and Waldrop 1999; Goodrick *et al.* 2010). Waldrop *et al*. (2004) reported non-significant decreases and increases in CWM biomass among different slope positions following prescribed fire in pine-dominated southern piedmont forests. In a study of eight fuel complexes in pine plantations of the upper Atlantic Coastal Plain, Scholl and Waldrop (1999) found no change in CWM biomass in seven of the eight complexes, and a decrease of 8% in the other. Loucks *et al*. (2008) reported a trend toward decreasing CWM biomass following prescribed fire in Appalachian hardwood forests. Following dormant season prescribed burns in the longleaf pine flatwoods of Florida, Hanula *et al.* (2012) reported no significant differences in

CWM volume between sites with different burn frequencies, but found that CWM decayed significantly slower on annually burned sites than unburned sites.

To quantify the impact of prescribed fire on fuel loading and contribute to the southern fuels database, we estimated pre and post fire fuel loading in four North Carolina forest ecosystems with different cover types and burn frequencies. Due to staffing limitation, fuel loads were measured in the summer and not immediately prior to and after the prescribed burns. We hypothesized several post-prescribed fire ecosystem changes including; 1) a reduction in litter and duff; 2) biomass changes in FWM (DDW<7.52 cm diameter) would be difficult to detect and variable among classes; 3) CWM biomass would be unchanged; 4) a reduction in live understory biomass would be offset by an increase in dead understory biomass.

Materials and methods

Study area

This research was conducted in North Carolina's Croatan and Uwharrie National Forests. Croatan National Forest (CNF) is located on the coastal plain in Jones County and is composed primarily of loblolly pine (*Pinus taeda* L.) and longleaf pine (*Pinus palustis* Mill.) stands with a pine-hardwood mix found between the managed pine and unmanaged bottomland hardwoods. The US Forest Service began using prescribed fire on the CNF in the early 1960s. Two longleaf pine stands (i.e., CNF-1 and CNF-3), each with different burn cycles, were selected for this study. Both sites were planted with longleaf pine in the 1930s and managed for sawtimber. Dormant season prescribed fire is employed on these sites to reduce fuel loads and improve habitat. Both these mesic sites have minimal slope, are open-canopied and contain a large volunteer loblolly pine component that likely established before the current fire cycles were introduced. Plots were established on each site (CNF-1 n=20 and CNF-3 n=19) to cover the entire management area.

CNF-1 is an annually burned 6 ha stand with an understory dominated by gallberry (*Ilex coriacea* Pursh), fetterbush (*Lyonia lucida* lam.), waxmyrtle (*Myrica cerifera* L.) and year-old hardwood spouts. Fuel load data was measured in June 2004, approximately four months after the previous annual burn (Fig. 1a). The site was burned again on February 19, 2005 and post-burn fuel loads were measured in June 2005 (Fig. 1b). Fuel moistures prior to the 2005 burn were 4-5% for 1-hr fuels, 11% for 10-hr fuels, 16% for 100-hr fuels, and 70% for live woody fuels. Fire intensity was low to moderate.

CNF-3 is a 27 ha stand burned every three years with an understory dominated by *Vaccinium* species, swamp pepperbush (*Clethra alnifolia* L.), giant cane (*Arundinaria gigantean* Walt.), gallberry, waxmyrtle, and hardwood saplings. Fuel load data was measured in June 2004 (Fig. 2a), approximately three years after the previous burn. The site was burned on January 5, 2005, and post-burn fuel loads were measured in June 2005 (Fig. 2b, c and d). Dead fuel moisture prior to the burn ranged from 11 to 15%, and live fuel moisture was 70%. Fire intensity was moderate and coverage was mosaic (J. Cherry, personal communication, August 8, 2013).

Fig. 1. CNF-1 (i.e. Annual burn site) June 2004 (a), approximately four months following prescribed fire, and June 2005 (b), approximately five month following prescribed fire.

a.

b.

c.

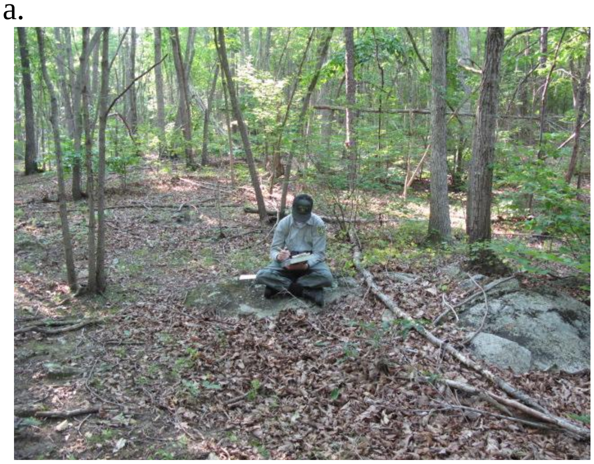
d.

Fig. 2. CNF-3 June 2004 (a), approximately three years following prescribed fire, June 2005 (b), approximately six months following prescribed fire, and one day following prescribed fire (c and d).

Uwharrie National Forest (UNF) is located on the piedmont in Montgomery and Randolph counties. UNF is a highly fragmented forest with numerous privately owned land holdings surrounded by public forestland. This presents unique management challenges, especially when dealing with fire at the wildland-urban interface. The US Forest Service began using prescribed fire on the UNF in the 1980s to reduce fuel loads. Two research sites (i.e., UNF-O and UNF-P) were established in UNF that are representative of typical piedmont forests. Both sites are predominantly mesic with slopes ranging from 0 to 30%. Scattered rock outcroppings are present throughout the sites. Each stand has been treated with prescribed fire on a three to five year cycle to reduce fuel loads. Plots were established on each site (UNF-O n=30 and UNF-P n=30) to cover the entire management area.

UNF-O is a 21 ha oak-hickory stand that grew naturally following clearing in 1916. The sparse understory is composed primarily of hardwood saplings with ferns and giant cane growing in the bottomlands. Fuel load data was measured in July 2004 and the site was burned on March 10, 2005 (Fig.3). Pre-burn fuel moistures were 7-8% for 1-hr fuels and 11-12% for 10-hr fuels. Fire intensity was low to medium, with average flame lengths between 2 and 3 ft and less than 25% crown scorch (Fig 4). Post-burn fuel loads were measured in July 2005.

a.



b.

Fig. 3. UNF-O July 2004 (a) and July 2005 (b), approximately four months following prescribed fire.

UNF-P is a 77 ha loblolly pine stand planted in 1964. While classified as a loblolly pine stand, the overstory is codominant with hardwoods that make up approximately 34% of the total stand basal area calculated from trees $\geq$12.7 cm dbh. The understory is dominated by hardwood saplings, *Vaccinium* species and *Vitis* species. Fuel load data was measured in July 2004 and the site was burned on April 6, 2005 (Fig. 5). Only the southern half of the stand was burned due to rain, resulting in a final sample size of 15 plots. Pre-burn fuel moisture was 5-6% for 1-hr fuels and 9% for 10-hr fuels. Flame length averaged 3-4 ft with spotting up to 6 ft. Most of the area had 25% crown scorch with some pockets larger than 50% (K. Cagle, personal communication, August 10, 2013). Post-burn fuel loads were measured in July 2005.

a.

b.

Fig. 4. UNF-O site. Litter was completely consumed in some areas while only partially consumed in others (a and b).

a.

b.

Fig. 5. UNF-P July 2004 (a) and July 2005 (b), approximately three months following prescribed fire.

Methods

Field plots were established to measure fuel loading on each site and included fuelbed height, coarse woody material (CWM), fine woody material (FWM), litter, duff, and understory biomass. Protocols for measuring fuel loading followed those used by the USDA Forest Inventory and Analysis Program to measure down woody debris and fuels (FIA 2004). Under this protocol, plots consisted of four 7.3 m radius subplots with three subplots located 35.6 m and 0, 150 and 270 degrees from the center subplot. Three transects were established in each subplot to measure CWM and FWM. CWM was measured when it intersected a transect and FWM was tallied along the transects in each subplot. Litter and duff depth and fuelbed height were measured at the end of each transect, and a 2.1 m radius microplot was established in each subplot to estimate live and dead shrub and herbaceous biomass. Research plots at CNF-3 and UNF-P consisted of four subplots, but only CWM was measured outside of the central subplot at UNF-P because it was determined through field testing that an acceptable estimate of FWM and microplot data could be calculated from the central subplot when measuring FWM on all three transects (Gavazzi *et al*. *'in press'*). A single plot design, without subplots, was employed at CNF-1 and UNF-O to avoid overlapping subplots in these narrow stands.

FWM and CWM biomass were calculated based on line intercept theory whereby values can be summed across transects to estimate per-unit area biomass (Van Wagner 1968; de Vries 1973; Brown 1974). FWM was classified as 1-, 10- and 100-hour fuels equating to less than 0.6 cm, 0.6 to 2.5 cm, and 2.5 to 7.6 cm in diameter at the line intersect, respectively, and tallied by size class when a piece intersected one of the transects. 1- and 10-hour fuels were measured along a 1.8 m length of each transect, and 100-hour fuels were measured along a 3.1 m length of each transect. FWM diameter was measured along one random transect in each plot to determine the mean size class diameter. FWM biomass (Eq. 1) was calculated in tons ac^{-1} as;

$$\textbf{FWM} = \sum_{i=1}^{n} \frac{u\,\mathrm{dia}_i^{\angle}\,\rho\,d\,a\,c}{L} \qquad (1)$$

where n is the total number of pieces of FWM tallied per size class, u is the units conversion factor (11.64); dia is the mean diameter for each class of FWM (in); ρ is the average green specific gravity of species know to exist in each forest type; d is a decay class reduction factor that accounts for biomass loss through decay (assumed to be 0.9 across all samples); a is the correction factor for orientation (assumed to be 1.13); c is a slope correction factor = $\sqrt{1 + (\mathrm{slope}\,\% / 100)^2}$; and L is the transect length (ft). Slope and orientation correction factors from Brown (1974).

CWM was measured when a piece intersected any point along one of the transects. Species, decay class, length, and small and large end diameters were recorded for each piece of CWM. Decay class was categorized on a one to five scale as defined in the FIA protocols, where a decay class of 1 was assigned to recently dead pieces and decay class 5 was assigned to highly decayed pieces. CWM (Eq. 2) was calculated in tons acre^{-1} as:

$$\textbf{CWM} = \sum_{i=1}^{n} \frac{u\,(\mathrm{d}_s^{\angle} + \mathrm{d}_l^{\angle})\,\rho\,d\,c}{L} \qquad (2)$$

where *n* is the total pieces of CWM sampled along each transect; *u* is the units conversion factor (5.8); d_s and d_l are the small and large end diameters (in) of each piece of CWM measured, respectively; ρ is the green specific gravity of each piece of CWM measured; *d* is a decay class reduction factor for conifers (class 1=1.0, class 2=0.84, class 3=0.71, class 4=0.45, class 5=0.35) and hardwoods (class 1=1.0, class 2=0.78, class 3=0.45, class 4=0.42, class 5=0.35) (Waddell 2002); *c* and *L* are the same as for FWM above.

Litter depth was measured at the end of each transect furthest from plot center and included undecomposed forest floor in the A_e soil horizon. Duff (defined as partially decomposed litter between the A_e horizon and mineral soil surface) was measured separately. Litter and duff depth were also combined into forest floor depth because differentiating between the two classes can be difficult followed prescribed fire. Litter and duff bulk density were estimated by collecting 0.04 m^2 samples from ten random plots in each site prior to prescribed burning. Samples were brought back to the lab, dried at 65°C for two weeks, or until there was no change in mass, and weighed. Litter and duff biomass were calculated by multiplying mean depth measurements from each plot by the mean bulk density estimates for each site. Litter biomass was multiplied by percent litter cover, estimated in each microplot, to better estimate site-level biomass.

Site-specific parameters included litter and duff bulk density, green wood specific gravity (table 1) and mean FWM size class diameter (table 2). Green wood specific gravity values were taken from Markwardt and Wilson (1935) and Jenkins *et al*. (2003). If a piece of CWM was not identifiable to species, it was classified as either hardwood or softwood and assigned a specific gravity value based on the average for species found on the site.

Table 1. Site-specific litter and duff bulk density and green wood specific gravity

Site	Litter bulk density (lb ft^{-3})	Duff bulk density (lb ft^{-3})	FWM specific gravity	CWM specific gravity	
				hardwoods	Softwoods
CNF-1	1.7	4.3	0.53	0.54	0.53
CNF-3	1.4	3.5	0.53	0.54	0.53
UNF-O	0.9	4.6	0.56	0.53	0.47
UNF-P	2.2	3.6	0.50	0.53	0.47

CNF-Croatan National Forest 1- and 3-year burn cycle; *UNF*-Uwharrie National Forest oak (O) and pine (P) sites

Table 2. Pre- and post-burn site-specific fine woody material size class diameter

Site	Treatment	FWM diameter (in)		
		1-hour fuel	10-hour fuel	100-hour fuel
CNF-1	Pre-burn	0.14	0.47	1.68

	Post-burn	0.13	0.51	1.40
CNF-3	Pre-burn	0.13	0.46	1.67
	Post-burn	0.13	0.49	1.47
UNF-O	Pre-burn	0.14	0.44	1.77
	Post-burn	0.14	0.46	1.66
UNF-P	Pre-burn	0.15	0.48	1.55
	Post-burn	0.15	0.46	1.59

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites

Live and dead understory biomass of woody and herbaceous stems less than 2.54 cm diameter were calculated from measurements of height and ocular estimates of percent cover in each microplot. Site-specific biomass equations were developed for the CNF sites by destructively harvesting samples from seven 1 m^2 plots on each site after recording height and percent cover. Only seven plots were established due to time constraints; however, an effort was made to position plots across a wide range of cover percents. Samples were separated into woody and herbaceous components, dried at 65°C for two weeks, or until there was no change in mass, and weighed. Regression equations based on height and/or percent cover were developed using the stepwise modeling function in JMP (Version 9.0) (SAS Institute, Cary, NC). Independent variables with single (e.g., height or percent cover) or paired (e.g., height times percent cover) probability less than 0.05 were included in the regression equations. Prolific sprouting of shrubs and herbs after fire is a typical response in fire adapted ecosystems such as these so site-specific equations with height and percent cover as independent variables were selected for comparison of means to better capture changes in biomass following the prescribed fires.

Live and dead understory shrub and herbaceous biomass at the UNF sites were calculated using equations developed by Brown and Marsden (1976) and Gilliam and Turrill (1993), respectively, since site specific equations were not developed or found in the literature. These shrub equations were also compared to those developed on the CNF sites to assess the difference between using site- and non site-specific equations when estimating understory fuels.

Biomass estimates were calculated using SAS statistical software (Version 9.2) (SAS Institute, Cary, NC). Analysis of means was tested using the Tukey HSD function in JMP to test for statistical differences between pre- and post-burn fuel loads. Results are reported in inches, ft, and t ac^{-1} since these are the standard units used by fire managers to estimate fuel loads.

Results

Croatan National Forest shrub and herbaceous biomass equation comparison

Live shrub biomass equations using only percent cover as the independent variable had higher R^2 and lower P values than equations that used both height and percent cover as independent variables (table 3). There wasn't a significant relationship between the independent variables and dead shrub biomass at CNF-3 and dead herbaceous biomass at CNF-1 so data were combined from both sites to develop best fit equations. Dead shrub and live herbaceous biomass at CNF-1 and live and dead herbaceous biomass at CNF-3 were best modeled with height and percent cover as independent variables.

Table 3. Best fit models for CNF shrub and herbaceous biomass

Site	Fuel Load	*A*	*b*	*P*	R^2	n
CNF-1	Live Shrub[1]	84.20	0.51	0.043	0.59	7
	Live Shrub[2]	-9.44	3.57	0.002	0.89	7
	Dead Shrub[1]	25.96	1.46	0.019	0.70	7
	Live Herb[1]	-3.78	0.84	0.010	0.84	6
	Dead Herb[1*]	-2.17	1.13	<0.001	0.99	6
CNF-3	Live Shrub[1]	-133.86	0.96	0.033	0.61	7
	Live Shrub[2]	-108.04	7.62	<0.001	0.95	7
	Dead Shrub[1*]	8.76	1.81	<0.001	0.80	10
	Live Herb[1]	-11.31	0.67	0.008	0.93	5
	Dead Herb[1]	-11.90	1.25	0.027	1.00	3

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites
[1]Equation form: biomass (t ac^{-1}) = *a* + (% cover x height (ft) x *b*)
[2]Equation form: biomass (t ac^{-1}) = *a* + (% cover x *b*)
*Site parameters not significant at $P<0.05$ so data combined from both sites

Shrub and herbaceous biomass estimates were influenced by the equations used. Brown and Marsden (1976) equations, using only percent cover as the independent variable, resulted in the highest estimates of live shrub biomass at both sites (table 4). While estimates were not significantly different between the site-specific equations at CNF-1 ($P\geq0.25$), the site-specific equation at CNF-3 using percent cover as the independent variable was significantly larger pre- and post-burn by 0.7 and 0.9 t ac^{-1} ($P<0.01$), respectively, than the equation using percent cover and height. Biomass estimates from the live shrub site-specific equations using only percent cover as the independent variable were significantly smaller ($P<0.01$) than the non-site-specific equation at all sites and treatments except for CNF-3 following the burn ($P=0.52$). There was no significant difference between the two site-specific equations at CNF-1 ($P\geq0.25$). Mean biomass estimates from the two dead shrub equations were significantly different both pre- and post-burn at CNF-3 but not CNF-1 ($P<0.01$ and ≥0.07). The dead shrub biomass estimate from the site-specific equation at CNF-3 was 0.3 t ac^{-1} smaller than the non site-specific equation before the prescribed burn, but 1.0 t ac^{-1} larger after it ($P<0.01$).

Table 4. Live and dead shrub biomass estimates before and after prescribed fire using site- and non site-specific equations

Site	Treatment	Biomass (t ac^{-1})				
		Live shrub[1]	Live shrub[2]	Live shrub[3]	Dead shrub[1]	Dead shrub[3]
CNF-1	Pre-burn	0.7 (0.1)^{AB}	0.4 (0.1)^{B}	0.9 (0.2)^{A}	1.1 (0.2)^{A}	0.7 (0.1)^{A}
	Post-burn	0.8 (0.1)^{AB}	0.6 (0.1)^{B}	1.1 (0.2)^{A}	0.8 (0.2)^{A}	0.5 (0.0)^{A}
CNF-3	Pre-burn	1.6 (0.1)^{A}	2.3 (0.1)^{B}	2.9 (0.1)^{C}	0.2 (0.0)^{A}	0.5 (0.0)^{B}
	Post-burn	0.4 (0.1)^{B}	1.3 (0.1)^{A}	1.5 (0.2)^{A}	1.7 (0.2)^{A}	0.7 (0.1)^{B}
UNF-O	Pre-burn			0.8 (0.1)		0.3 (0.0)
	Post-burn			0.7 (0.1)		0.4 (0.0)
UNF-P	Pre-burn			1.6 (0.3)		0.3 (0.0)
	Post-burn			1.3 (0.2)		0.4 (0.0)

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites
Numbers in parentheses are the standard error of the mean
[1]Equation form: biomass (t ac^{-1}) = a + (% cover x height (ft) x b)
[2]Equation form: biomass (t ac^{-1}) = a + (% cover x b)
[3]Equation from Brown and Marsden (1976)
[ABC]Within site, biomass component and treatment means with the same letter not significantly different, P<0.05

Live herbaceous biomass estimates from the two equations were significantly different at CNF-1, but only significantly different at CNF-3 before the burn (table 5). Pre- and post-burn live herbaceous biomass estimates at CNF-1 were 0.4 t ac^{-1} larger using the site-specific equation

Table 5. Live and dead herbaceous biomass estimates before and after prescribed fire using site- and non site-specific equations

Site	Treatment	Biomass (t ac^{-1})			
		Live herb[1]	Live herb[2]	Dead herb[1]	Dead herb[2]
CNF-1	Pre-burn	0.78 (0.10)^{A}	0.40 (0.03)^{B}	0.03 (0.01)^{A}	0.04 (0.01)^{A}
	Post-burn	0.79 (0.08)^{A}	0.40 (0.03)^{B}	0.01 (0.01)^{A}	0.02 (0.01)^{A}
CNF-3	Pre-burn	0.31 (0.03)^{A}	0.21 (0.02)^{B}	0.13 (0.03)^{A}	0.06 (0.01)^{A}
	Post-burn	0.33 (0.03)^{A}	0.27 (0.02)^{A}	0.05 (0.02)^{A}	0.01 (0.01)^{B}
UNF-O	Pre-burn		0.07 (0.03)		0.01 (0.01)
	Post-burn		0.11 (0.03)		0.01 (0.01)
UNF-P	Pre-burn		0.05 (0.04)		0.00 (0.00)
	Post-burn		0.05 (0.03)		0.01 (0.01)

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites

Numbers in parentheses are the standard error of the mean
[1]Equation form: biomass (t ac^{-1}) = *a* + (% cover x height (ft) x *b*)
[2]Equation from Gilliam and Turrill (1993)
[AB]Within site, biomass component and treatment means with the same letter not significantly different, $P<0.05$

compared to the non site-specific equation ($P<0.01$). There was no significant difference between the two equations at CNF-3 post-burn ($P=0.11$), and pre-burn biomass using the site-specific equation was only 0.1 t ac^{-1} larger compared to the non site-specific equation ($P<0.01$). Dead herbaceous biomass was $\leq$0.1 t ac^{-1} across all sites, treatments and equations. While there was a significant difference between the two equations at CNF-3 post-burn ($P<0.05$), biomass from the site-specific equation was <0.1 t ac^{-1} ($P<0.05$) larger compared to the non site-specific equation.

Croatan National Forest fuel loads

Litter coverage was the only fuel estimate significantly impacted by prescribed fire at the annually burned site (i.e., CNF-1) with a decrease of 28% ($P<0.01$, table 6). Mean 100-hour fuel and dead shrub biomass decreased 0.4 and 0.3 t ac^{-1} ($P\geq0.23$, tables 7 and 8), respectively, and 10-hour fuel biomass increased 0.1 t ac^{-1}($P=0.36$). Litter biomass decreased 0.4 t ac^{-1} ($P=0.11$), and duff biomass increased 0.5 t ac^{-1} ($P=0.50$) after the burn. Combining litter and duff resulted in no change in forest floor biomass or depth following prescribed fire ($P\geq0.93$). Live shrub cover increased 10% ($P=0.19$) while height decreased 0.5 ft ($P=0.56$) resulting in a nearly undetectable 0.1 t ac^{-1} increase in biomass ($P=0.75$, table 8). Dead shrub cover and height decreased 5% and 0.1 ft ($P\geq0.29$), respectively, resulting in a decrease of 0.3 t ac^{-1} ($P=0.27$, table 8). Mean live herbaceous cover, height and biomass were relatively unchanged as a result of prescribed fire, and a 0.4 ft and 2% decrease ($P=0.21$ and 0.09) in dead herbaceous height and cover, respectively, only reduced biomass <0.1 t ac^{-1} ($P=0.18$, tables 9). Mean CWM biomass increased 1.4 t ac^{-1} ($P=0.33$), and mean live and dead fuelbed height decreased 0.2 and 0.4 ft, respectively, following the prescribed burn ($P\geq0.35$, table 7).

Table 6. Litter depth, percent cover, and biomass, and duff and forest floor depth and biomass before and after prescribed fire

Site	Treatment	Litter depth	Litter cover	Litter biomass	Duff depth	Duff biomass	Forest Floor depth[1]	Forest floor biomass[1]
		(in)	(%)	(t ac^{-1})	(in)	(t ac^{-1})	(ft)	(t ac^{-1})
CNF-1	Pre-burn	0.5 (0.1)	79 (4)[a]	1.2 (0.3)	0.3 (0.1)	2.1 (0.4)	0.7 (0.1)	3.3 (0.6)
	Post-burn	0.4 (0.1)	51 (5)[a]	0.8 (0.2)	0.3 (0.1)	2.6 (0.5)	0.7 (0.1)	3.3 (0.6)

CNF-3	Pre-burn	2.0 (0.1)[a]	99 (0)[a]	5.2 (0.3)[a]	0.8 (0.1)[a]	5.1 (0.4)[a]	2.8 (0.1)[a]	10.2 (0.6)[a]
	Post-burn	0.6 (0.0)[a]	75 (3)[a]	1.1 (0.1)[a]	0.5 (0.0)[a]	3.4 (0.2)[a]	1.1 (0.1)[a]	4.5 (0.3)[a]
UNF-O	Pre-burn	1.4 (0.1)[a]	92 (1)[a]	2.0 (0.1)[a]	0.6 (0.0)[a]	5.2 (0.3)[a]	2.0 (0.1)[a]	7.2 (0.4)[a]
	Post-burn	0.4 (0.0)[a]	44 (5)[a]	0.3 (0.1)[a]	0.4 (0.0)[a]	3.2 (0.3)[a]	0.7 (0.1)[a]	3.4 (0.3)[a]
UNF-P	Pre-burn	1.3 (0.1)[a]	96 (1)[a]	5.2 (0.5)[a]	0.6 (0.1)[a]	3.8 (0.7)[a]	1.9 (0.2)[a]	8.9 (1.0)[a]
	Post-burn	0.6 (0.1)[a]	77 (4)[a]	1.8 (0.3)[a]	0.3 (0.0)[a]	2.2 (0.3)[a]	0.9 (0.1)[a]	4.0 (0.5)[a]

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites
Numbers in parentheses are the standard error of the mean
[a]Within site and fuel class treatment means significantly different, *P*<0.05
[1]Sums may differ from reported means due to rounding

There were significant biomass changes at the site that was burned every three years (i.e., CNF-3). Only dead shrub biomass was significantly larger after the burn with an increase of 1.5 t ac^{-1} (*P*<0.01, table 8). Litter cover and depth were both significantly smaller following the burn with decreases of 24% and 1.4 in, respectively (*P*<0.01, table 6). This resulted in a significant

Table 7. Fine and coarse woody material biomass, and live and dead fuelbed height before and after prescribed fire

Site	Treatment	Fine woody material			Coarse woody material	Live fuelbed height	Dead fuelbed height
		1-hour fuel	10-hour fuel	100-hour fuel			
		(t ac^{-1})	(t ac^{-1})	(t ac^{-1})	(t ac^{-1})	(ft)	(ft)
CNF-1	Pre-burn	0.07 (0.02)	0.6 (0.1)	1.1 (0.3)	2.2 (0.9)	2.4 (0.2)	2.0 (0.4)
	Post-burn	0.07 (0.01)	0.7 (0.1)	0.7 (0.2)	3.6 (1.3)	2.2 (0.1)	1.6 (0.3)
CNF-3	Pre-burn	0.11 (0.01)[a]	0.5 (0.1)	0.6 (0.1)	1.6 (0.4)	2.9 (0.1)[a]	1.4 (0.1)[a]
	Post-burn	0.09 (0.01)[a]	0.6 (0.0)	0.6 (0.1)	1.5 (0.4)	2.0 (0.1)[a]	2.2 (0.2)[a]
UNF-O	Pre-burn	0.16 (0.01)[a]	0.7 (0.1)[a]	2.2 (0.3)	4.9 (1.2)	1.0 (0.2)	0.5 (0.1)
	Post-	0.25	1.0 (0.1)[a]	2.0 (0.2)	5.3	0.8 (0.2)	0.8

	burn	(0.02)[a]			(1.3)		(0.2)
UNF-P	Pre-burn	0.11 (0.01)	0.7 (0.1)	2.3 (0.3)	2.6 (0.9)	1.0 (0.2)	0.5 (0.1)[a]
	Post-burn	0.11 (0.01)	0.6 (0.1)	2.6 (0.4)	3.5 (0.5)	0.7 (0.1)	0.1 (0.0) [a]

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites
Numbers in parentheses are the standard error of the mean
[a]Within site and fuel class treatment means significantly different, *P*<0.05

Table 8. Live and dead shrub height, percent cover and biomass before and after prescribed fire

Site	Treatment	Live shrub ht	Live shrub coverage	Live shrub biomass	Dead shrub ht	Dead shrub coverage	Dead shrub biomass
		(ft)	(%)	(t ac^{-1})	(ft)	(%)	(t ac^{-1})
CNF-1	Pre-burn	4.4 (0.6)	30 (5)	0.7 (0.1)	5.2 (0.4)	23 (5)	1.1 (0.2)
	Post-burn	3.9 (0.5)	40 (5)	0.8 (0.1)	5.1 (0.6)	18 (3)	0.8 (0.1)
CNF-3	Pre-burn	6.4 (0.4)[a]	80 (2)[a]	1.6 (0.1)[a]	3.0 (0.3)[a]	6 (1)[a]	0.2 (0.0)[a]
	Post-burn	4.1 (0.4)[a]	52 (4)[a]	0.4 (0.1)[a]	6.4 (0.4)[a]	29 (2)[a]	1.7 (0.2)[a]
UNF-O	Pre-burn	5.3 (0.9)[a]	27 (4)	0.8 (0.1)	2.7 (0.5)[a]	5 (1)	0.3 (0.0)
	Post-burn	2.7 (0.5)[a]	27 (4)	0.7 (0.1)	4.6 (0.8)[a]	9 (2)	0.4 (0.0)
UNF-P	Pre-burn	5.7 (1.0)	52 (7)	1.6 (0.3)	3.9 (1.1)	6 (1)[a]	0.3 (0.0)
	Post-burn	4.9 (1.0)	45 (6)	1.3 (0.2)	5.2 (1.3)	11 (2)[a]	0.4 (0.0)

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites
Numbers in parentheses are the standard error of the mean
[a]Within site and fuel class treatment means significantly different, *P*<0.05

decrease in litter biomass of 4.1 t ac^{-1} (*P*<0.01). Duff biomass was reduced 1.7 t ac^{-1} due to a 0.3 in decrease in depth (*P*<0.01, table 6). 1-hour fuel biomass increased less than 0.1 t ac^{-1} (*P*=0.09), 10-hour fuel biomass increased 0.1 t ac^{-1} (*P*=0.18), and 100-hour fuel biomass was unchanged following the burn (table 7). The increase in dead shrub biomass was due to a 23% increase in percent cover and a 3.4 ft increase in height (*P*<0.01, table 8). Live shrub biomass decreased 1.2 t ac^{-1} as both height and cover decreased 2.3 ft and 28%, respectively (*P*<0.01, table 8). There was very little change in live and dead herbaceous biomass (table 9). Live herbaceous cover increased 9% (*P*=0.02), but height decreased by 0.4 ft (*P*<0.01) resulting in a 0.02 t ac^{-1} decrease in biomass (*P*=0.72). Both dead herbaceous cover and height significantly decreased 8% and 1.7 ft (*P*<0.01), respectively, resulting in a 0.04 t ac^{-1} reduction in biomass (*P*<0.05). The live fuelbed significantly decreased 0.9 ft and the dead fuelbed significantly increased 0.8 ft (*P*<0.01, table 7). CWM biomass was not significantly different after the controlled burn (*P*=0.90, table 7).

Table 9. Live and dead herbaceous height, percent cover and biomass before and after prescribed fire

Site	Treatment	Live herb ht	Live herb coverage	Live herb biomass	Dead herb ht	Dead herb coverage	Dead herb biomass
		(ft)	(%)	(t ac^{-1})	(ft)	(%)	(t ac^{-1})
CNF-1	Pre-burn	3.1 (0.2)	66 (6)	0.78 (0.10)	1.0 (0.2)	4 (1)	0.03 (0.01)
	Post-burn	3.2 (0.2)	65 (5)	0.79 (0.08)	0.6 (0.2)	2 (1)	0.01 (0.01)
CNF-3	Pre-burn	3.1 (0.1)[a]	37 (3)[a]	0.31 (0.03)	2.8 (0.2)[a]	11 (2)[a]	0.13 (0.03)[a]
	Post-burn	2.7 (0.1)[a]	46 (3)[a]	0.33 (0.03)	1.1 (0.3)[a]	3 (1)[a]	0.05 (0.02)[a]
UNF-O	Pre-burn	1.2 (0.4)	12 (4)	0.07 (0.03	0.5 (0.2)	2 (1)	0.01 (0.01)
	Post-burn	1.0 (0.2)	17 (5)	0.11 (0.03)	0.3 (0.2)	2 (2)	0.01 (0.01)
UNF-P	Pre-burn	0.5 (0.2)	8 (6)	0.05 (0.04)	0.2 (0.1)	1 (1)	0.00 (0.00)
	Post-burn	0.5 (0.2)	8 (5)	0.05 (0.03)	0.1 (0.1)	1 (1)	0.01 (0.01)

CNF-Croatan National Forest 1- and 3-year burn cycle, *UNF*-Uwharrie National Forest oak (O) and pine (P) sites
Numbers in parentheses are the standard error of the mean
[a]Within site and fuel class treatment means significantly different, *P*<0.05

Uwharrie National Forest fuel loads

Duff and litter fuel loads were significantly reduced and 1- and 10-hour fuel biomass were significantly increased after prescribed fire on the UNF-O site (tables 6 and 7). Duff depth decreased 0.2 in resulting in a 2.0 t ac^{-1} decrease in duff biomass (*P*<0.01). Litter depth and percent cover decreased 1 in and 48%, respectively, resulting in a 1.7 t ac^{-1} decrease in litter biomass (*P*<0.01). 1- and 10-hour fuel biomass increased 0.1 t ac^{-1} and 0.3 t ac^{-1} (*P*<0.01), respectively, but 100-hour fuel was not significantly different after the burn (P=0.53). Live and dead shrub height were the only understory components to be significantly impacted by prescribed fire at UNF-O with decreases of 2.6 ft and 1.9 ft, respectively ($P \leq 0.01$, table 8). Live shrub percent cover was unchanged and mean biomass was 0.1 t ac^{-1} smaller after the burn (P=0.74). Dead shrub percent cover increased 4% (P=0.05), resulting in a 0.1 t ac^{-1} increase in mean biomass (P=0.43). Live and dead herbaceous biomass were relatively unchanged by fire (table 9). Live herbaceous height decreased 0.2 ft, and percent cover increased 5% ($P \geq 0.48$), resulting in a 0.04 t ac^{-1} decrease in biomass (P=0.38). Dead herbaceous height decreased 0.2 ft (P=0.64) and percent cover and biomass were unchanged. Live fuelbed height decreased 0.2 ft, and dead fuelbed height increased 0.3 ft as a result of prescribed fire ($P \geq 0.21$, table 7). There was no significant change in CWM, but mean biomass increased 0.4 t ac^{-1} (P=0.83, table 7).

Duff, litter and dead shrub cover were the only fuels impacted by prescribed fire at UNF-P (tables 6 and 9). Duff depth decreased 0.3 in (P=0.02), resulting in a 1.6 t ac^{-1} decrease (P=0.03) in duff biomass. Litter depth and percent cover decreased 0.7 in and 19%, respectively, resulting in a 3.4 t ac^{-1} decrease in litter biomass (P<0.01). 100-hour fuel biomass increased 0.3 t $ac\text{-}^{-1}$ and 10-hr fuel biomass decreased 0.1 t ac^{-1} ($P \geq 0.37$, table 7). Mean live shrub height decreased 0.8 ft and cover decreased 7% resulting in a 0.3 t ac^{-1} decrease in biomass ($P \geq 0.39$, table 8). Dead shrub height increased 1.3 ft and cover increased 5% resulting in a 0.1 t ac^{-1} increase in dead shrub biomass ($P \geq 0.30$, table 8). Live and dead herbaceous biomass were unchanged by prescribed fire, with almost no detectable change in height or percent cover (table 9). Dead herbaceous biomass decreased less than 0.1 t ac^{-1} (P=0.52). Both live and dead fuelbed heights decreased 0.3 ft (P=0.09) and 0.4 ft (P<0.01), respectively, but only the change in dead fuelbed height was significant (table 7). Mean CWM biomass increased 0.9 t ac^{-1} following prescribed fire (P=0.43, table 7).

Forest floor consumption following prescribed fire

Litter and duff (i.e., forest floor) fuel loadings were reduced by prescribed fire on all sites except for the annually burned site (i.e., CNF-1) where there was no change. CNF-3 had the highest reduction in forest floor fuel load following prescribed fire (5.7 t ac^{-1}), and was also the site with the highest pre-burn forest floor biomass. There was a strong relationship across sites between pre-burn forest floor biomass and the loss of forest floor due to prescribed fire (R^2= 0.99, P<0.01, Fig. 6). Approximately 53% of the forest floor was consumed by prescribed fire on all sites except for CNF-1.

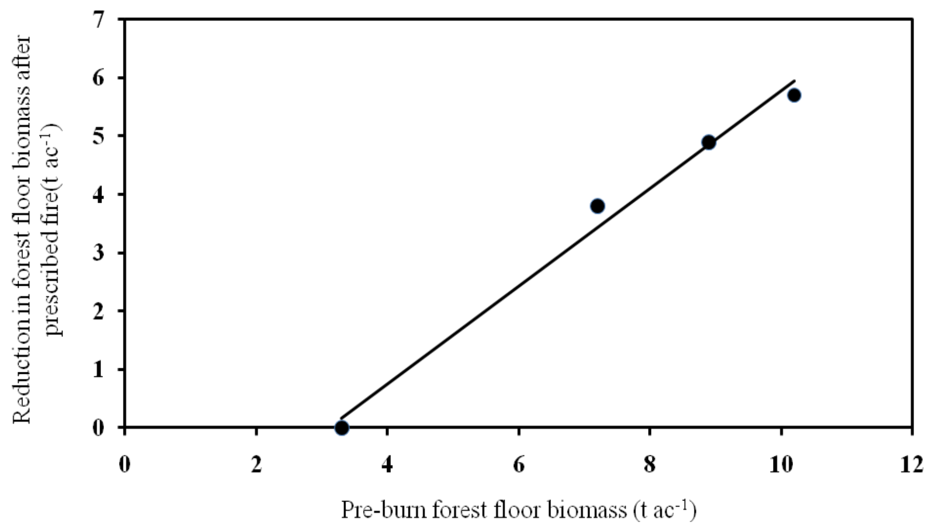


Fig. 6. Change in forest floor biomass following prescribed burning at four research sites in North Carolina's piedmont and coastal plain. (R^2=0.99, P<0.01)

Discussion

Litter and duff biomass were significantly reduced by over 50% and 33%, respectively, on all sites except for the annually burned site at CNF (i.e., CNF-1). This is consistent with findings in the literature, and the expected result that prescribed fire reduces forest floor fuels (Scowcroft 1965; Kodama and Van Lear 1980; Waldrop *et al*. 2004). The use of pre-burn site-specific bulk density values may have resulted in an over- or under-estimation of post-burn litter and duff estimates. Our assumption that weight loss decreases in proportion to volume may be incorrect, but no data was found in the literature to confirm this either way. Sampling post-burn litter and duff may have provided a more accurate estimate of post-burn bulk density. Ottmar and Andreau (2007) estimated litter and duff bulk density across southeastern US forests and found high variability within and between forest types. Our estimates compare favorably with theirs, and the significant reduction in litter depth and cover in this study indicates that our post-burn biomass estimates are reasonable. The strong relationship across sites between pre-burn forest floor biomass and the amount of forest floor consumed by prescribed fire is an interesting finding, although more data points are necessary to test the robustness of this trend.

That forest floor was not impacted by prescribed fire at CNF-1 is not surprising. Although nothing was found in the literature comparing pre- and post-burn fuel loads on annually burned sites, this burn frequency results in the maintenance of low fuel levels. Fuel loads would not be expected to increase significantly in this open canopied ecosystem under an annually burned management regime. Litter coverage was reduced 28%, but litter depth was only reduced 0.1 in from an already low 0.5 in. Waldrop *et al*. (1987) compared southeastern coastal plain loblolly pine sites and found that forest floor biomass was lowest on annually burned sites compared to sites with longer burn intervals. Duff depth increased less than 0.1 in, but this resulted in a 0.5 t ac^{-1} increase in biomass. The increase in duff biomass is likely due to the difficulties encountered when categorizing blackened litter and duff following prescribed fire. Charred litter as well as inputs from burned foliage and woody material can easily be mistaken for unrecognizable litter and misclassified as duff. When litter and duff were combined into forest floor depth and biomass, there was no change in fuel loading. Given that one year of litter fall had occurred between the pre- and post-burn estimates it is likely that most, if not all, of the new litter accumulation was consumed by the burn.

The lack of significant change in FWM, and both live and dead understory fuel loads at CNF-1 suggests that the site either did not burn adequately or that new fuel inputs were equal to those consumed by the fire. The decrease in mean litter, dead shrub and total FWM biomass, and live and dead fuelbed heights, as well as visual observations following the burn, indicate that the site did burn adequately, and that inputs have not kept up with consumed fuels. Since fuel loads were measured in early June, one could expect the live understory biomass to continue increasing, and mean fuel loads to approach pre-burn levels following leaf fall.

Changes in FWM biomass were variable across the sites, and differences that were significant were less than 0.3 t ac^{-1}. This is consistent with other studies across the southeastern US. Scholl and Waldrop (1999) found that 10-hour fuels tended to increase while 1- and 100-hour fuels tended to decrease across different fuel complexes in southeastern coastal plain loblolly pine sites. However, differences were small and the authors did not report levels of significance. Loucks *et al*. (2008) reported non-significant decreases in 1- and 100-hour fuels and a significant decrease in 10-hour fuel immediately following prescribed fire in Appalachian hardwood sites, but differences were small and not significant post-leaf fall the following year. This study found a significant increase in 10-hour fuel at UNF-O, but the increase was only 0.3 t ac^{-1}. Waldrop *et al*. (2004) reported no significant changes in woody fuels following prescribed fire across different landscape ecosystem classification units in southeastern piedmont pine sites.

There were no significant changes in CWM biomass following prescribed fire on our sites, but mean CWM values increased at CNF-1 and both UNF sites. The non-significant increase in CWM following the prescribed fire at CNF-1 can be explained by four large dead stems that fell into the plots and became new CWM following the pre-burn measurements. The increase in CWM biomass at the UNF sites is mostly due to the exposure of pieces that were buried under the forest floor before the burn. These pieces were covered by litter along the measurement transect and, by protocol not counted in the pre-burn inventory. This uncovering of previously buried pieces of CWM also occurred at CNF-3, but the intensity of this fire was such that CWM pieces were observed burning the day after the prescribed fire (Fig. 7). Any additions of new or previously buried pieces of CWM on this site were likely offset by the burning of CWM that resulted in less measureable biomass, either through smaller diameters or shorter lengths. Scholl and Waldrop (1999), Waldrop *et al*. (2004) and Loucks *et al*. (2008) all reported no significant changes in CWM biomass following prescribed fire. These results are not surprising as prescribed fire in the south isn't expected to consume CWM biomass except under very high fire intensity, fuel load and drought conditions.

Fig. 7. CWM still burning one day after prescribed fire was completed on CNF-3.

Prescribed fire had the biggest impact on fuel loads at CNF-3 with more significant differences and the largest reduction in fuel loading compared to the other sites. It was also the only site with significant changes in live and dead fuelbed heights and live and dead shrub biomass. Reductions in live fuelbed height and live shrub biomass were more than offset by increases in dead fuelbed height and dead shrub biomass, with a net decrease of 0.1 ft and a net increase of 0.3 t ac^{-1}, respectively. While the 5.7 t ac^{-1} reduction in forest floor biomass will reduce the wildfire risk in this stand, the significant increase in dead fuelbed and dead shrub biomass may result in a higher than expected post-burn risk; especially if the forest floor recovers quickly, as has been reported in other forest types by Loucks *et al*. (2008) and Parresol *et al*. (2006).

Live and dead understory biomass was not impacted by prescribed fire on CNF-1 and the UNF sites. While there was a significant decrease in live shrub height and a significant increase in dead shrub height at UNF-O, there was no detectable change in biomass for either fuel load. This result at UNF-O is the result of using only percent cover in the biomass equations used, and stresses the importance of including height in shrub biomass equations. Shrub cover has been shown to sprout prolifically following prescribed fire (Lewis and Harshbarger 1976; Arthur *et al* 1998; Waldrop *et al.* 1987). Although live shrub cover was unchanged after prescribed fire at UNF-O, the reduction in height was not included in the regression equation and likely resulted in an overestimation of live shrub biomass.

Including height in site-specific equations had a significant impact on shrub biomass at CNF-3, a site with a dense shrub understory. The non site-specific equation significantly over-estimated both pre- and post-burn live shrub biomass, but more importantly, significantly underestimated post-burn dead biomass by 59%. This difference would result in fuel managers underestimating the biomass of this quickly ignitable fuel by 1.0 t ac^{-1} and could confound efforts to predict fire behavior and intensity. Live herbaceous biomass estimates using site-specific equations were twice as high as estimates from non site-specific equations at CNF-1, but differences were only 0.4 t ac^{-1}. This difference, as well as the low overall biomass of herbaceous shrubs, may not be of concern to fuel managers when planning prescribed fires. Live and dead herbaceous biomass at the UNF sites was less than 0.1 t ac^{-1} due to the nearly closed canopy conditions in the overstory.

This research confirms previous findings that prescribed fire can significantly reduce fuel loads in southeastern US forests. Our hypothesis that forest floor fuels (i.e., litter and duff) would be reduced by prescribed fire was correct for all sites except the annually burned site. It appears that the low intensity annual burns are keeping fuel loads at a steady state, whereby new inputs are being consumed before they can accumulate. There was no consistent trend in the response of FWM to prescribed burning. Few changes were significant, and those that were significant only changed by 0.3 t ac^{-1}. CWM was not impacted by prescribed fire at any of the sites, except that pieces of CWM buried by litter and not measured pre-burn were exposed and included in the post-burn inventory. The increase in dead shrub biomass that was hypothesized to offset reductions in live shrub biomass was not as pronounced as expected, except on the site with the largest pre-burn live shrub biomass. In this case, increased dead shrub biomass more than offset the decrease in live shrub biomass following prescribed fire. This research, while conducted on a limited geographic scale, contributes to our understanding of the impact that prescribed fire has on fuel loads in the southeastern US, and provides valuable site-specific data to the southern fire dataset.

Acknowledgements

The authors would like to acknowledge the support of Sara Strickland for her contribution toward data collection and understory biomass sample processing, Johnny Boggs and Emrys Treasure for their contribution toward data collection, Dave Chojnacky for assistance with initial SAS programming, and the many summer interns that assisted during data collection. This work was supported through funding from the National Fire Program, Southern Global Change Program, and Eastern Forest Environmental Threat Assessment Center.

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Influence of homogenously applied fire prescriptions on the distribution of hardwoods and mast in the longleaf pine ecosystem

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Abstract: Land managers often use fire prescriptions to mimic intensity, season, completeness, and return interval of historical fire regimes (Fill et al. 2012). However, fire prescriptions based on average historical fire regimes do not consider natural stochastic variability. Hiers et al. (2000) reported heterogeneity in the season of fire applications was likely the most important factor affecting legume plant diversity in fire-maintained systems. Furthermore, management activities applied with spatial and temporal variability are more likely to create and maintain a heterogeneous forest structure and plant composition (Bond and Archibald 2003). Therefore, applying prescribed fire based on averages coupled with consistent firing techniques could result in a homogeneous landscape, with little variation in relative abundance of important plant species and stand structure.

We hypothesized an average fire-return interval coupled with a single firing technique would result in an unnatural distribution of some plants. We tested this hypothesis by evaluating the abundance and distribution of oak (*Quercus* sp.) and persimmon (*Diospyros virginiana*) stems and mast after 22 years of a homogeneously applied, historical-based growing-season fire prescription in the longleaf pine (*Pinus palustris*) – wiregrass (*Aristida beyrichiana*) complex. We assigned 5 cover types using a GIS overlay map of land cover and firebreaks provided by the U.S Department of Defense: Upland Hardwood (UH), Bottomland Hardwood (BH), Upland Pine (UP), managed opening (Open) and Low Intensity Fire Transition Zone (LIFTZ). We characterized UH as any upland forest stand dominated by hardwood species (primarily oak), BH as hardwood-dominated forest stands (primarily blackgum) associated with drainages, UP as upland longleaf pine-dominated forest, and Open as unforested areas maintained as grasslands. We defined LIFTZ as UP ≤ 25 m from a firebreak. We sampled UH as a baseline for comparison among other forest types and to extrapolate mast availability to the landscape scale.

During September 2011, we randomly established 30 25-m transects in each of the five treatments. Three observers conducted mast abundance surveys on 10 transects in each treatment (n=120). The observers used 8×42-mm binoculars to count fruits on reproductively mature oak and persimmon for 60 seconds on each stem that overlapped the transect. Trees were deemed reproductively mature if they were dominant or co-dominant in the canopy, ≥4.5 cm diameter breast height, or were producing fruit (Greenberg and Simons 1999). Upland hardwood and BH make up a relatively small portion of the land area within 25m of firebreaks. Mean fruit abundance was greatest in LIFTZ (mean fruits/transect 51 ±15, $P < 0.001$) and UH (mean fruits/transect 49 ±11, $P < 0.001$). However, all detected persimmon fruits were in LIFTZ (mean

fruits/transect 4 ±3). When extrapolated to the landscape scale, a disproportionate percentage of mast available at Fort Bragg Military Installation falls within LIFTZ (80% of mast, 17% of land area). Also, UH provided a disproportionate amount of mast at the landscape scale with 8% of mast produced in 2% of the area. Mast availability was disproportionately low in all other cover types. Oak stem density was greatest in LIFTZ (mean stems/transect 19 ±5, $P < 0.001$) and UH (mean stems/transect 17 ±2, $P < 0.001$). However, all detected persimmon stems were in LIFTZ (mean stems/transect 3 ±2). When extrapolated to landscape scale, a disproportionate percentage of stems (oak and persimmon) were within LIFTZ (66% of stems, 17% of land area). Also, UH provided a disproportionate number of stems at the landscape scale with 6% of stems produced in 2% of the area. Stem density was disproportionately low in all other treatments.

In upland longleaf stands, this fire regime killed young hardwood trees, thereby decreasing compositional and structural heterogeneity within the upland pine forest type. Often, this result is viewed as a success because hardwood encroachment is considered degrading to the structural requirements of the endangered red-cockaded woodpecker (*Picoides borealis*; RCW), which is a focal wildlife species in the longleaf pine ecosystem. Interestingly, Kilgo and Vukovich (2012) suggested red-headed woodpeckers (*Melanerpes erythrocephalus*), another species of concern, may benefit from hardwood species as cover. Thus, managers should strive to include variability in fire regimes to allow some hardwoods to persist. Further, many wildlife species native to this ecosystem are dependent on mast production and hardwood structure for survival. Therefore, dispersion of some overstory hardwoods across the landscape is necessary for proper ecosystem function and should not be viewed as deleterious to longleaf pine systems. Our data indicate local management activities must mimic spatial distribution, frequency, and intensity of historical disturbances to maximize structural heterogeneity and conserve key ecosystem functionality. We recommend a multi-tiered management approach focusing on maintaining heterogeneity at the stand-, landscape-, and ecosystem-scales.

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Global sensitivity analysis for the rothermel model based on high dimensional model representation

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Abstract: Rothermel's wildland surface fire spread model is widely used in North America. The model outputs depend on a number of input parameters, which can be broadly categorized as fuel model, fuel moisture, terrain and wind parameters. Due to the inevitable presence of uncertainty in the input parameters, the sensitivity of the model output to a given input parameter can be very useful for understanding and controlling the sources of parametric uncertainty. Instead of obtaining the local sensitivity indices, we perform a global sensitivity analysis that considers the synchronous changes of parameters in their respective ranges. The global sensitivity indices corresponding to different parameter groups are computed by constructing the truncated ANOVA-high dimensional model representation for the model outputs with a polynomial expansion approach. We apply global sensitivity analysis to six standard fuel models, namely, short grass, tall grass, chaparral, hardwood litter, timber and light logging slash. The sensitivity results are systematically compared.

Introduction

Wildland fire management requires an understanding of fire behaviors. Predicting fire behavior can be based solely on experience, which requires the predictor to have a profound comprehension of the interrelation of fire, topography, fuel and weather, which are collectively referred to as the fire environment (Pyne *et al*. 1996). Fire can present a variety of behaviors and can be affected by a wide range of environment factors whose variations can lead to both drastic changes of fire behaviors that easily draw predictors' attention, and moderate ones that are hard to notice but may be crucial to the growth of the fire. Alternatively, fire modeling attempts to simulate fire behavior in a repeatable way have been playing an increasingly vital role in aiding fire management activities, especially with the development of rapid computing facilities and algorithms.

Fire models are in general classified as statistical models (McMaster 1973), empirical models (Rothermel 1972), physical models (Albini 1986), and atmosphere-fire models (Linn *et al.* 2002; Clark 2004). On account of the varying computational complexities, one model may be more suitable for one task than for the others. For example, empirical models are often used for prediction, while physical and atmosphere-fire models are used in post-processing. To facilitate the fulfillment of various fire management needs, various fire models have been incorporated in software systems such as FARSITE (Finney 2004) and BehavePlus (Andrews 2007).

Rothermel's surface fire spread model (Rothermel 1972) is the most widely used wildland fire model in North America. The model is categorized as "semi-empirical" since it was developed using the principle of conservation of energy, as well as experiments. There have been several variants of the Rothermel model in the literature that modify the modeling of certain terms (see Albini 1976; Wilson1990; Catchpole and Catchpole 1991). Also, Sandberg *et al*. (2007) extends the original model so that it can predict fire behaviors for more complex fuelbeds.

The Rothermel model depends on a wide range of input parameters, such as fuel type, fuel moisture contents, terrain and wind related variables. These parameters are subject to uncertainties, due to model error, modeling error, and data error. As a result, the model outputs are also uncertain. Jimenez *et al*. (2007, 2008) addressed the uncertainty quantification of the Rothermel model with efficient Monte Carlo sampling methods. Another important question is the sensitivity analysis of the model. Sensitivity analysis quantifies the amount of uncertainty in the output contributed by an input parameter (or, group of parameters). Sensitivity information is of critical importance in wildfire management since it allows for allocation of resources to control the factors that are more important for fire behavior than others. Sensitivity analysis can be local, in the sense that the rate of change of the model output with respect to a certain parameter at some given point is taken as the measure for sensitivity. On the other hand, global sensitivity analysis (GSA) completely explores the parameter space, considering interactions among parameters.

The variance-based Sobol' GSA (Sobol' 1993, 2001) is a popular method for computing the sensitivities of a model. The variance of each ANOVA-high dimensional model representation (HDMR) component is used as the measure of its importance. Salvador *et al*. (2001) studied Sobol' sensitivity analysis of the Rothermel model for Mediterranean shrublands. The Sobol' indices were computed by estimating high dimensional conditional expectations. In most physical systems, noticeable high orders of parameter interaction are rarely seen (Rabitz *et al*. 1999), which means considering only low order parameter interactions can sufficiently represent a model. Based on this observation, we propose using an orthogonal polynomial expansion for the truncated ANOVA-HDMR of the Rothermel model. The Sobol' indices can be obtained directly from the expansion coefficients. We perform Sobol' sensitivity analysis for six fuel models selected from the 13 standard fuel models (Anderson 1982; Albini 1976), namely short grass, tall grass, chaparral, hardwood litter, timber, and light logging slash. We observe significant differences in the sensitivity patterns for different types of fuel, underlying the importance of sensitivity analysis to determine the significant parameters of the model.

Formulation of the Rothermel model

The Rothermel model consists of more than 80 highly nonlinear algebraic equations. The main outputs include but are not limited to *the rate of fire spread* (*ros* in *m/s*), *the direction of maximum spread* (*sdr* in º) and *reaction intensity* (*ri* in kW/m^2). In accordance with Bachmann (2001), the rate of spread, for example, is formulated as:

$$\mathrm{ros} = \frac{ri \cdot \xi \cdot (1 + \Phi_c)}{\rho_b \cdot \varepsilon \cdot Q_{ig}}$$

where ξ is the propagating flux ratio, Φ_c is a combination of the slope and wind factors, ρ_b is the ovendry bulk density, ε is the effective heating number, and Q_{ig} is the heat of pre-ignition.

The inputs for the model can generally be identified as 12 parameters, which are the ovendry fuel loading w_o, fuel depth d, surface-area-to-volume ratio sv, fuel heat content $heat$, fuel particle density ρ_p, fuel moisture content M, fuel total mineral content S_t, fuel effective mineral S_e, wind speed at midflame height *wsp*, slope (vertical rise/horizontal run) slp, wind direction θ, and fuel moisture of extinction m_x. The three parameters w_o, sv and M can be further subdivided into five size classes that categorize the different fuel moisture time-lag classes: dead fuel, 0-0.6cm (*d1*); dead fuel 0.6-2.5cm (*d2*); dead fuel, 2.5-7.5cm (*d3*); live herbaceous fuel (*lh*); and live woody fuel (*lw*). Hence, the total number of input parameters for the Rothermel model reaches 24.

Assuming parametric uncertainty exists in all input parameters, we are interested in detecting which parameters cause larger variations in the model output. The methodology we will use is described in the following section.

Sobol' global sensitivity analysis

Sensitivity analysis (SA) attributes the uncertainty in the output to different sources of input variables, and uses the amount of contribution of an input to characterize its importance. An input parameter whose variation leads to large uncertainty in the model output is tagged as sensitive or important. Therefore it is of practical importance to identify the sensitive parameters and minimize their uncertainty so that more robust models in support of fire management can be developed.

Variance decomposition based on ANOVA-HDMR

Sobol' Global Sensitivity Analysis (GSA) is based on the ANOVA-high dimensional model representation (ANOVA-HDMR) that decomposes the model as a series of component functions that hierarchically increase in the number of parameters. Suppose we denote the model function by $\mathrm{f}(\mathbf{x})$, where $\mathbf{x}$ represents the d input parameters: $\mathrm{x}_1, \mathrm{x}_2, \dots, \mathrm{x}_d$. Then the ANOVA-HDMR of $\mathrm{f}(\mathbf{x})$is given by

$$\mathrm{f}(\mathbf{x}) = \mathrm{f}_\emptyset + \sum_{i_1} f_{\{i_1\}}(x_{i_1}) + \sum_{i_1<i_2} f_{\{i_1,i_2\}}(x_{i_1}, x_{i_2}) + \cdots + \sum_{i_1<\cdots<i_r} f_{\{i_1,\cdots,i_r\}}(x_{i_1}, \cdots, x_{i_r}) + \cdots + f_{\{1,2,\dots,d\}}(x_1, \cdots, x_d). \quad (1)$$

The constant term $\mathrm{f}_\emptyset$ is the mean (expectation) of the model, $f_{\{i_1\}}(x_{i_1})$ represents the main effect of the parameter $\mathrm{x}_{\mathrm{i}_1}$, $f_{\{i_1,i_2\}}(x_{i_1}, x_{i_2})$ represents the second order interactions due to $\mathrm{x}_{\mathrm{i}_1}$ and $\mathrm{x}_{\mathrm{i}_2}$, and so on. Each non-zero component function, f_u, $\mathrm{u} \subseteq \{1,2,\dots,\mathrm{d}\}$, has a partial variance σ_u^2. The ANOVA-HDMR is an orthogonal decomposition of the model function in the sense that the total variance of the model is decomposed as the sum of the variances of the component functions, i.e., $\sigma^2 = \sum_{\mathrm{u}\subseteq\{1,2,\dots,d\}} \sigma_\mathrm{u}^2$. The normalized quantity $\sigma_\mathrm{u}^2/\sigma^2$ is used to measure the importance of the parameters related to the index set u.

There is a total of $2^d - 1$ partial variances and to compute all of them can be impractical. Sobol' (1993) introduces two types of sensitivity measures for a certain parameter x_i:

$$S_{\{i\}} = \frac{1}{\sigma^2}\sigma^2_{\{i\}}, \quad \bar{S}_{\{i\}} = \frac{1}{\sigma^2}\sum\nolimits_{i\in v}\sigma^2_v.$$

S and $\bar{S}$ are called the main effect and total effect respectively. The main effect only considers the impact of a parameter to the function output by itself, whereas the total effect incorporates the interactions of the parameter with other parameters. The above definitions can be easily extended to define sensitivity measures for groups of parameters. A Monte Carlo based algorithm to compute the main and total effects has been designed by Sobol'(1993), and improved by Saltelli(2002).

Truncated ANOVA-HDMR and orthogonal polynomial expansion

In the presence of a large number of input parameters, computing Sobol' sensitivity indices can be time consuming. However, it is often observed that in physical problems the higher order interactions are negligible (Rabitz *et al*. 1999), and therefore it is sufficient to capture a few lower order interactions and consider a truncated version of ANOVA-HDMR (1). Li *et al*. (2001) suggested expanding the component functions of (1) in terms of series of orthogonal polynomials:

$$f_{\{i_1\}}(x_{i_1}) = \sum_{r_1=1}^{R_1^1} \alpha_{r_1}^{i_1}\phi_{r_1}^{i_1}(x_{i_1}) \quad (2)$$

$$f_{\{i_1,i_2\}}(x_{i_1}, x_{i_2}) = \sum_{r_1=1}^{R_1^2}\sum_{r_2=1}^{R_2^2} \beta_{r_1 r_2}^{i_1 i_2}\phi_{r_1}^{i_1}(x_{i_1})\phi_{r_2}^{i_2}(x_{i_2}) \quad (3)$$

as $i_1 < i_2 < \cdots < i_{d'}$ take values in the index set $\{1,2,\ldots,d\}$ and $1 \le d' \le d$. Here $\phi_{r_1}^{i_1}(x_{i_1}), r_1 = 1,2,\ldots$, are orthogonal polynomials of degree r_1 associated with the parameter x_{i_1}, and $\alpha_{r_1}^{i_1}$, $\beta_{r_1 r_2}^{i_1 i_2}$, … are the coefficients of expansion.

It is noteworthy that the polynomial expansions for the first and second order components (2) and (3), as well as for the omitted higher order components, conform to the well-known polynomial chaos expansion (PCE) (Xiu and Karniadakis 2002). The clear distinction lies in the fact that PCE in general sets a unified maximum expansion order and no expansion term exceeds the specified order, while for the approximation (2) and (3) each component function can have its own maximum expansion degree, i.e., R_1^1 and $R_1^2 + R_2^2$ can be different.

Due to the orthogonality of the polynomial basis, the expansion coefficients can be computed by orthogonal projections:

$$\alpha_{r_1}^{i_1} = \frac{\int_{\boldsymbol{\Omega}} f(\mathbf{x})\phi_{r_1}^{i_1}(x_{i_1})p(\boldsymbol{x})d\boldsymbol{x}}{\int \left(\phi_{r_1}^{i_1}(x_{i_1})\right)^2 p_{i_1}(x_{i_1})dx_{i_1}} \quad (4)$$

$$\beta_{r_1 r_2}^{i_1 i_2} = \frac{\int_{\boldsymbol{\Omega}} \mathrm{f}(\mathbf{x}) \phi_{r_1}^{i_1}(x_{i_1}) \phi_{r_2}^{i_2}(x_{i_2}) p(\boldsymbol{x}) d\boldsymbol{x}}{\iint \left(\phi_{r_1}^{i_1}(x_{i_1}) \phi_{r_2}^{i_2}(x_{i_2})\right)^2 p_{i_1}(x_{i_1}) p_{i_2}(x_{i_2}) dx_{i_1} dx_{i_2}} \qquad (5)$$

as $\mathrm{i}_1 < \mathrm{i}_2 < \cdots < \mathrm{i}_{\mathrm{d}'}$ take values in the index set $\{1,2,\ldots,\mathrm{d}\}$ and $1 \le \mathrm{d}' \le \mathrm{d}$. Here $\boldsymbol{\Omega}$ is the domain of the input parameters and $p(\boldsymbol{x}) = \prod_{i=1}^{d} p_i(x_i)$ is the joint probability density function (pdf). If orthonormal polynomials are used as the basis in the expansions (2) and (3), then the denominators will be 1. The numerators involve high dimensional integrals, which can be approximated by Monte Carlo or quasi-Monte Carlo methods (Niederreiter 1992; Caflisch 1998). Only one sequence of random numbers is adequate to compute all the expansion coefficients, as well as the model output variance σ^2. For orthonormal polynomial expansions, the main effects and total effects can consequently be approximated by

$$\mathrm{S}_{\{\mathrm{i}\}} = \frac{1}{\sigma^2} \sum_{\mathrm{r}_1} (\alpha_{\mathrm{r}_1}^{\mathrm{i}})^2 \ , \quad \bar{\mathrm{S}}_{\{\mathrm{i}\}} = \frac{1}{\sigma^2} \left(\sum_{\mathrm{r}_1} (\alpha_{\mathrm{r}_1}^{\mathrm{i}})^2 + \sum_{\mathrm{r}_1} \sum_{\mathrm{r}_2} \sum_{j} (\beta_{r_1 r_2}^{ij})^2 + \cdots \right), \quad (6)$$

since the inner products (the denominators shown in (4) and (5)) of the polynomial basis are all 1. For general orthogonal polynomials, each term in (6) has to be multiplied by the inner product of its corresponding basis. Extension of (6) for a group of parameters can be made by including the coefficient terms related to the group in the summations.

Results and discussion

We apply Sobol' GSA to the Rothermel model for different types of fuel. Six fuel models, namely, short grass (SG), tall grass (TG), chaparral (CH), hardwood litter (HL), timber (TI) and light logging slash (LLS), are considered in our numerical results. These fuel models are selected from the 13 standard fuel models (Anderson 1982; Albini 1976), which extend the original 11 standard fuel models specified by Rothermel (1972).

Of the 24 input parameters of the Rothermel model, 14 parameters are common to all six fuel models. The common parameters are listed in Table 1. Values of the remaining 10 parameters are unique to the fuel models, and they are shown in Table 2. The symbols that denote the parameters are consistent with those introduced in the second section.

Table 1—Common fuel model parameters.

Parameter	Symbol	Value	Unit
low heat content	*heat*	18622.0	kJ/kg
1-h fuel moisture	m_{d1}	8.0	%
10-h fuel moisture	m_{d2}	8.0	%
100-h fuel moisture	m_{d3}	8.0	%
live herbaceous fuel moisture	m_{lh}	150.0	%
live woody fuel moisture	m_{lw}	150.0	%

Particle density	ρ_p	512.5	$\mathrm{kg/m^3}$
effective mineral content	S_e	1.0	%
Slope	slp	14.04	º
total mineral content	S_t	5.55	%
10-h surface area/vol ratio	sv_{d2}	358.0	$\mathrm{m^2/m^3}$
100-h surface area/vol ratio	sv_{d3}	98.0	$\mathrm{m^2/m^3}$
direction of wind	θ	45	º
midflame wind speed	wsp	2.3	m/s

Table 2—Input parameter values unique to fuel models.

Parameter	SG	TG	CH	HL	TI	LLS	Unit
D	0.3	0.76	1.83	0.06	0.3	0.3	M
m_x	12	25	20	25	25	15	%
sv_{d1}	11483.0	4921.3	6562.0	8202.0	6562.0	4921.0	$\mathrm{m^2/m^3}$
sv_{lh}	4921.0	4921.0	4921.0	4921.0	4921.0	4921.0	$\mathrm{m^2/m^3}$
sv_{lw}	4921.0	4921.0	4921.0	4921.0	4921.0	4921.0	$\mathrm{m^2/m^3}$
$w0_{d1}$	0.17	0.67	1.12	0.65	0.67	0.34	$\mathrm{kg/m^2}$
$w0_{d2}$	0	0	0.90	0.09	0.45	1.01	$\mathrm{kg/m^2}$
$w0_{d3}$	0	0	0.45	0.03	1.12	1.23	$\mathrm{kg/m^2}$
$w0_{lh}$	0	0	0	0	0	0	$\mathrm{kg/m^2}$
$w0_{lw}$	0	0	1.12	0	0.45	0	$\mathrm{kg/m^2}$

Due to the measurement error in experiments and other factors, uncertainties are assumed to exist in all input parameters. We model the uncertainty in each parameter using the uniform distribution $U(a,b)$, where the constants a and b are determined so that the mean of the distribution is as given in Table 1 and Table 2, and the standard deviation is 5% of the mean. The purpose of setting the coefficient of variation (defined as the ratio of the standard deviation to the mean) to be 5% is to ensure that both dead and living fuel damping moistures do not exceed their extinction moistures. In this case, fire propagates on both categories of fuels, which is the case of most interest to fire departments.

Note that fuels of certain size classes can be absent for a fuel model. Consequently the model outputs have zero sensitivity to the corresponding surface-area-to-volume ratio and fuel moisture content parameters, since they are only related to the fuel loading parameters in the model formulation. As a result, it makes more sense to consider sensitivity to groups of parameters. The entire set of parameters can be easily categorized into 10 groups as shown in Table 3.

Table 3—Grouping of input parameters.

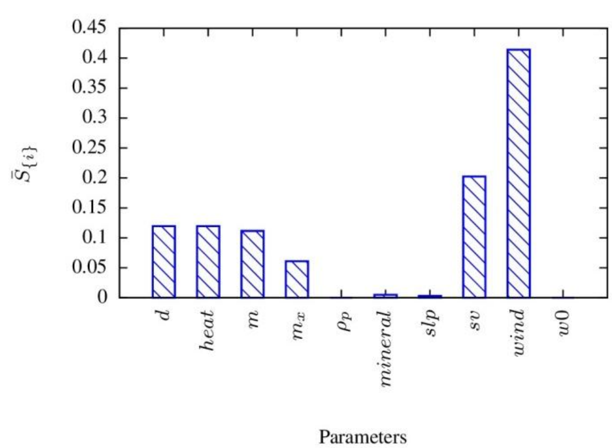
fuel depth	low heat content	fuel moisture content	moisture of extinction	particle density	mineral contents	slope	surface-area-to-volume ratio	wind	fuel loading

d	$heat$	m_{d1} m_{d2} m_{d3} m_{lh} m_{lw}	m_x	ρ_p	S_e S_t	slp	sv_{d1} sv_{d2} sv_{d3} sv_{lh} sv_{lw}	Θ wsp	$w0_{d1}$ $w0_{d2}$ $w0_{d3}$ $w0_{lh}$ $w0_{lw}$

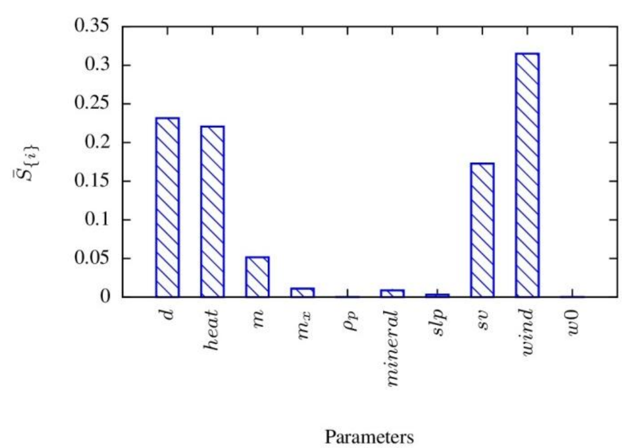
To compute the Sobol' global sensitivity indices, we employ the second order truncated ANOVA-HDMR, and expand each component function in terms of Legendre polynomials. The highest polynomial expansion orders for the first and second HDMR components are set to be 8 and 5, i.e., $R_1^1 = 8$ and $R_1^2 + R_2^2 = 5$ in equations (2) and (3). One random-start random permuted Halton quasi-random sequence (Ökten 2009) of size 2^{12} is generated to compute all expansion coefficients in (4) and (5), in addition to the output variance. All coefficients are then used to construct the Sobol' indices based on the analogous version of (6) that applies to groups of parameters.

Fig. 1 illustrates the total effects of the grouped parameters with respect to the model output *ros* for different fuel models. In all cases, the indices approximately add up to 1, meaning that interactions among parameters are very weak, which further validates our employment of a second order truncated ANOVA-HDMR. In view of the fact that total effects take interactions of parameters into consideration, they are tailor-made for identifying insensitive parameters.

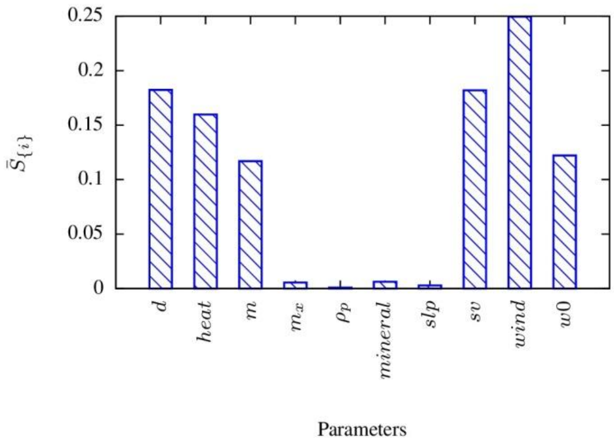
The total effects for all the six fuel models considered exhibit some similarities: the parameters ρ_p, mineral contents, and *slp* have small total effects. In other words, the impact of variation in these parameters on the output would be insignificant. On the other hand, the sensitivity indices of *d, heat, and wind* are all relatively large, indicating that the variation of *ros* is highly dependent on the variation of these parameters. Taking light logging slash for example, the three parameters account for about 85% of the total model variance. Taking control of the uncertainty associated with these parameters is crucial to the prediction of fire behaviors and reduction of fire risk.



(a)



(b)



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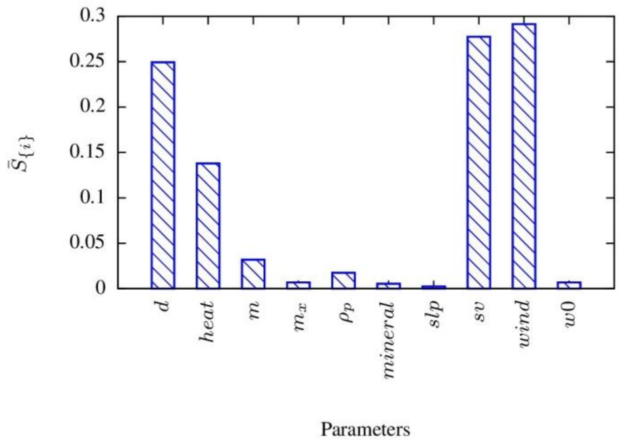

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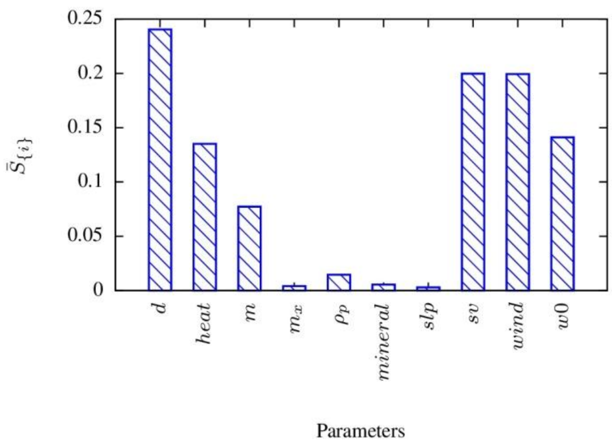
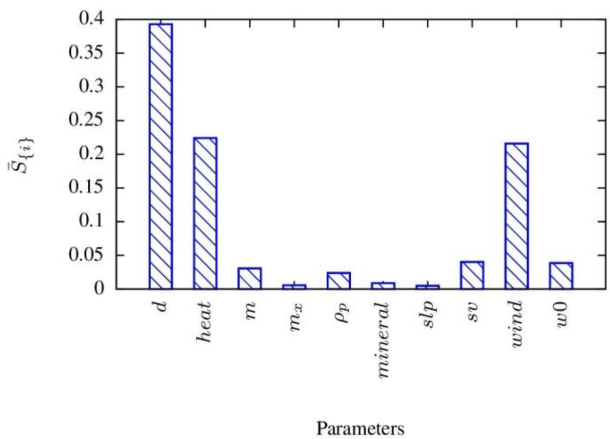


(e)



(f)

Fig. 1—Sobol' global sensitivity indices (total effects) for the Rothermel model with different fuel types: (a) SG, (b) TG, (c) CH, (d) (HL), (e) TI, (f) LLS. The considered output is ros. The indices are obtained by approximating the second order truncated ANOVA-HDMR with a Legendre polynomial expansion whose expansion coefficients are computed by quasi-Monte Carlo sampling.

We also observe that the sensitivity of a parameter varies significantly for different fuel models. For example, the parameter d explains around 40% of total model variance for light logging slash, but only 12% for the short grass fuel model.

The total effects of parameters m_x and sv show similarities among all types of fuel except one. For all fuel models except short grass, m_x is negligible, while for short grass fuels, m_x accounts for 6% of the total variance, making a non-negligible impact on the model output. Similar observations can be made for sv, which is insignificant for light logging slash, but responsible for around 20% of total variance in the other fuel models.

The remaining parameters, m_f and $w0$, are significant for part of the selected fuel models. For short grass, tall grass, chaparral and timber, m_f accounts for more than 5% of the total variance, and hence is considered as a source of uncertainty that cannot be ignored. The parameter $w0$ is a significant source for the chaparral and timber fuel models. However, it is insignificant for the rest of the models, especially for short grass, hard grass and hardwood litter.

Conclusions

Parametric uncertainty inescapably exists in wildland fire models, causing difficulty in fire behavior prediction. Uncertainty propagates from input parameters to model outputs through fire models, resulting in discrepancies between the model predictions and observations. While quantifying the uncertainty of the model outputs gives the distribution of model predictions, sensitivity analysis identifies which uncertain parameters are responsible for significant model variations. Once the significant parameters are identified, extra resources should be used in order to reduce their uncertainty. This is of vital importance to increase model robustness and reliability, as well as the reinforcement of wildland fire management.

In contrast to local sensitivity analysis which focuses on local rate of change of models, GSA considers variations of parameters in their entire uncertainty range, and therefore provides more informative and reliable results. We applied Sobol's variance-based GSA to the Rothermel model with six standard fuel models. To reduce the computational complexity of Sobol' sensitivity indices, a truncated ANOVA-HDMR approach with orthogonal polynomial expansion was employed. The results show that there are some parameters which are uniformly significant or insignificant for all fuel models. There are also parameters whose importance varies with different fuel models. In applications, these parameters need to be treated differently according to the type of fuel model. If a parameter is significant, then additional resources should be used to lower its uncertainty. If a parameter is insignificant, then it can be fixed at its mean value without affecting the total model variance.

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Are leaf and plant flammability important to the stand?

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Abstract: Factors such as leaf chemistry, dimensions, live moisture content and plant packing have been shown to affect the flammability of leaves and plants, and it has been proposed that this in turn affects the flammability of the entire stand. The implications of this are important for both fire behaviour and ecological modeling; on the one hand because differences in plant flammability may cause fire to behave in ways not accounted for by some models and on the other hand because current theories suggest that if plant flammability can affect the entire stand then frequent fire can potentially form a positive feedback with stand flammability.

Determining the influence of flammability traits on fire behaviour is not straightforward however, and various studies have failed to identify a link between foliar moisture and rates of spread in heath and crown fires. Rates of spread however have little relevance to stand scale impacts as they describe the speed at which the fire moves rather than the amount of vegetation consumed or scorched, and therefore have less importance to this question than do flame dimensions.

Empirical studies of the effect of flammability traits on fire behaviour are also limited in that they have been based on the assumption that the relationship is direct, rather than an emergent property arising from multiple drivers and exhibiting feedbacks and threshold changes that may confound trends within a given experimental range of conditions.

Fire behaviour modeling has been proposed as an acceptable methodology to determine whether leaf and plant flammability have an effect on behaviour, however the capacity for this is limited by the ability of available models to address the specific flammability traits in a physically meaningful way. The Forest Flammability Model (FFM) is presented as a process-driven approach that utilizes multiple flammability traits along with full forest geometry in a complex systems framework. The basic theory of the model is discussed along with a number of applied implications.

Additional Keywords: Fire behaviour, fire environment

Early detection of wildland and urban interface fires

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Abstract: Approximately 5 billion dollars in US revenue is allocated annually to the USDA Forest Service (USFS) for ~ 30,000 employees, 10,000 of whom are firefighters responsible for fire management on about 193 million acres according to the web sites >http://www.fs.fed.us/aboutus/budget/2013/fy2013-overview.pdf< and >http://en.wikipedia.org/wiki/United_States_Forest_Service<.
Considerable additional funding is allocated by the Government to NASA for space observation, and to local and State Forestry Agencies as grants to support, monitor and control wildland fires outside of the USFS jurisdiction. Additional State, county and local funds are provided for non-federal land protection. Detection of open area fires is typically performed by manned observatories, random reporting and aerial surveillance. Past and current autonomous approaches to long range forest fire detection and reporting are presented. Optical IR flame detectors have been previously developed. These typically experience a high number of false alarms and low flame detection sensitivity due to interference from solar and other causes and omission of collection optics. A combination of IR detectors has recently been used in a two or three color mode to reduce false alarms from solar, or background sources. A combination of ultra-violet C (UVC) and near infra- red (NIR) detectors has also been developed for flame discrimination. Relatively solar-blind basic detectors are available but can typically only detect a meter square flame zone up to about 30 meters.

We discuss the range and solar issues for IR and visible detectors and qualitatively define UV sensor requirements in terms of the mode of operation, collection area issues and flame signal output by combustion photochemistry. Innovative flame signal collection optics for multiple wavelengths using UV and IR as low false alarm detection of wildland fires at long range (8-10 km/ for a one meter square fire) in daylight (or darkness) have been developed. A circular array detector and UV-IR reflective and refractive devices including cylindrical or toroidal lens elements for the IR have been described. The dispersion in a refractive cylindrical IR lens characterizes the fire and allows a stationary line or circle generator to locate the direction and different flame IR 'colors' from a wide field of view. A line generator will produce spots along the line corresponding to the fire which can be discriminated with a linear detector (Engelhaupt *et al*. 2005 [10]). We demonstrate prototype autonomous sensors with electronic radio frequency digital reporting from various sites. Based on these results, we conclude that technological advancements make surveillance, detection and reporting of wildfires over large areas reliable and economically feasible.

Additional keywords: flame detection, fire sensor, autonomous reporting, UV, IR

Introduction

With such a vast array of available technology, an immediate response to better autonomous detection and reporting of wildland fires could be integrated into present systems within the wildland firefighting community. New and available technology must be further developed and implemented with available funding. Designs must be selected and developed by both industry and academic institutions. The activity should not be limited to the US, but also include participation by an international community of concerned agencies with each funding its portion of the research. A standardized system could then be rapidly developed and implemented which could be managed by present wildland fire personnel.

Fabrication of prototypes should be immediately pursued; testing of these longer range smoke and flame detection units should follow. In conjunction with this effort, it will be mandatory to improve transponders, satellite communications and local daisy-chain communication in the field. Then additional response - e.g. sprinklers, communication, alarms etc., can be developed for commercialization and individual home use to protect against an approaching wildfire.

For security, FCC approved communication links for secured areas can be added. Cell Phone Call-up and 'apps' can be added which assist in identifying and reporting hazardous conditions, invasive plants and other anomalies (James Miller, USFS [1]). Cameras can be added to systems with the detector alerting the observer to view a particular segment or area. Acoustic detection can be directional, discriminative, sensitive and very low cost. This would assist in assurance that no false alert is triggered. The system can be implemented by neighborhoods and communities to mesh with 'Smart' home or corporate systems with the primary goal of notifying first responders and those in imminent danger. Additional benefits could be military or police applications for single event weapons locating etc. Since gunfire emits a sharp UVC signal, this signal plus sound can be used to locate azimuth, direction and range using simple speed-of-sound principles. This has additionally been demonstrated by Dawn Research, Inc.

Background:

Between 1928 and 1934, GA Barker produced a large optical wildland fire detector using selenium infra-red detector technology (US Patent 1,959,702). He proposed various methods to keep daylight from saturating the detector. Protected areas lost $8.5M in resources in 1928; similar unprotected areas lost $74.0M. Sixty-eight percent of the considered resources of the era were under some form of observer protection.

Improved optical forest fire detection methods appeared many years later but still depended on observers as these were not autonomous. Present methods, such as satellites, provide transmitted reporting. Today we have on-line access to immediate space borne instrumentation imaging and recording of very large fires and the progression and direction of growth. This has been of enormous value to predict and control very large fires. However the detection and reporting of small fires is still dependent on individuals and their actions.

There is still no adopted method of general early detection and reporting of wildland fires. While certain satellite programs do provide a very global view of large fires, 90 minutes and some directions from controllers are required for each observational orbit. Thus the minimum size fire is typically more than 1 kilometer square before detection by satellite although improvements are expected. Satellites are indeed beneficial; none-the-less, several million acres are subjected to hundreds of thousands of fires annually. Note that not all fires result in the loss of valuable resources, homes or lives, and indeed some are controlled burns. However, the reported combined losses are still much higher than the cost of suppression.

Additionally, it may be advisable to better track the course of controlled burns in real-time near populated or certain other areas, to avert any accidental losses in property or lives. This may well require simply better communication systems.

Additional early detection and reporting would permit rapid responders to determine the risk and assign proper resources in order to protect lives and property in those crucial cases and to determine the extent to which a fire might be threatening assets.

Detection and communication improvement scope and purpose:

It is neither the intent nor purpose of this article to determine the case need to prevent, nor to encourage the required controlled clearance of overloaded forest floors due to environmental conditions in any specific instance. It is often possible to reduce the risks of wildfire damage by either clearing or controlled burning these flammable overloads which may exceed 30 tons per acre which is difficult to manage. As important as the clearing of dangerous conditions, is the need to mitigate the possibility of that action causing property damage beyond that which was intended. Many different case by case conditions prevail as described on the following web sites: >http://www.fs.fed.us/aboutus/budget/2013/fy2013-overview.pdf<,
>http://www.usfa.fema.gov/fireservice/prevention_education/strategies/wildland/<,
>http://www.blm.gov/or/districts/roseburg/plans/collab_forestry/files/TrueCostOfWilfire.pdf<.

This established, wildland fires sometimes rage out of control resulting in loss of property, wildlife and human lives. In the summer of 2007, wildfires burned over 2,711 km^{-2} (670,000 acres) and killed over 80 people in Greece. The same year in California, wildfires burned over 2,027 km^{-2} (500,000 acres) causing at least 14 fatalities. In the 1999 - 2003 five year period, the total burned area was the size of Ohio. A wildland fire near Los Alamos, New Mexico in May 2000, threatened the DOE weapons development site. The Rock House Fire burned 199,001 acres near McDonald Observatory, Fort Davis Texas in 2011 and this year (2013) a devastating fatality list resulted from the Yarnell Hill Fire in Arizona**.** Some may consider these extreme cases, but they occur, and the tragic losses could be substantially reduced in many cases by utilizing both early warning and better communication systems (perhaps autonomous in some cases).

Note again that we live in a fire-adapted ecosystem with carbon dioxide a requirement for photosynthesis and plant life. Wood and other cellulose based combustion products consist primarily of CO2, carbon based particulates and water. There are many cases where fires seriously added to the secondary damage done to all of us due to the high particulate concentration. Additionally wildfires contribute non-CO2 emissions of CO and numerous particulates and gases from terpenes and other lesser element oxidation products primarily due to smoke (particulate emission from pyrolysis, which is incomplete combustion). A proper early warning system will allow for monitoring controlled burns such as those which may endanger lives and property if they rapidly expand out of control. Large continental observation is conducted by satellite. Individuals are allowed use of NASA resources in real–time resolution and coverage, but have limited use of local real-time warning systems. Many wildland fires are observed and tracked by satellite with minimum starting resolution for most cases at about 1 kilometer square, permitting advanced fire growth ahead of resources

(See >https://earthdata.nasa.gov/data/near-real-time-data/rapid-response<).

Real-time detection and reporting approaches:

Currently small fires may be reported by either infra-red (IR) or short wavelength ultraviolet (UVC) sensors at close proximity. For an uncontained fire of one meter square maximum prior to reporting, commercial detectors are used in the proximity of flammable fuels, explosives, petroleum drilling and other hazardous conditions. These commercial detectors typically have a limited range of about 15 to 30 meters for a small fire of one square meter. By incorporating optical collection lenses or mirrors it has been possible to extend this range considerably. It is not difficult to provide an optical collection gain for IR sensors but typically only with increased sensitivity to false signals arising from solar or other causes. Another issue is that the field of view is narrowed with collection optics and the required area of concern is more difficult to view.

One approach is to have a unique staring telescope requiring a toroidal 360-degree viewing reflective lens. This lens will focus the field of view onto individual segments of an innovative circular segmented detector much like a linear array, except formed into a circle. Each segment then covers a particular field of view and is identified by the output signal as an increment of the 360-degree view from a known point of reference. Optional methods include more conventional collecting optics for UVC and/or IR wavelengths such as a telescope, which is rotated through 360 degrees, or other field of view. In either case, the output of the directional optical flame detector is connected to a digital transmitter which in turn broadcasts the needed information in real-time to a receiver network and to the nearest protection unit or other designated locations. This information can also be broadcast to a satellite network for immediate responsive actions.

The technology exists to provide early sighting of fires - daylight or darkness – and provide radio frequency (RF) transponder reporting. Advanced devices must be developed for terrestrial detection and reporting of open area fires with far better resolution, expedience and reporting methods. This information can be reported in real-time to the various responding authorities and to the public in general [10]. This could be implemented via satellite, general internet access, public warning systems and other methods in place.

Detectors capable of locating wildfires:

- Infra-red optical detectors / selective bandwidth - 1970's
- Multiple bandwidth detectors – UV – Vis – IR - 1980's
- Satellite detection – MODIS – NOAA - 1997 - Present
- Heat and smoke electro-optical sensors (wildfire) - 2000
- Camera scanning and digital decoding - 2002 - 2013
- Flicker detection proposed by D. Engelhaupt, 2001 Adopted - 2005
- Spectral Detection - 1975 - present
- Infra-red optical detectors / selective bandwidth Military IR Cameras and 1 Video Camera in Reconnaissance Plane (D. McKeown, WASP Program Manager, 585-475-7192,

Rochester Institute of Technology)
- UVC detectors capable of detecting approaching forest fire at ¼ mile, Fire Scout, Boulder CO
- Multiple responding modes using digital Tx/Rx technologies, Engelhaupt, (et al) [9, 10]
- IR detectors - Ambient Control Systems, Inc. Systems
- US Patent 8,369,563 – Advanced satellite detection – M. Zavogli [11]
- US Patent Appl. 20130009062, Infra-red bolometer for flame detection, B. E. Cole [12]
- US Patent Appl., WO 2011/032117 - Camera scanning and digital decoding, Ahmet Cetin [13]
- US Patent 6,329,921 – Flame detector and management system, D. Tindall [14]
- US Patent 7,256,401 – Flicker detection of flames - Garmer, et, al. [15]
- US Patent 7,541938, June 2009 – UVC Autonomous flame detection, D. Engelhaupt [16]

Specialty detectors in general include many types:

- Emission line detectors
- Secondary discharge gas ionization
- Bolometers
- Millimeter Wave
- Gas, Smoke, Chemical Detectors

Solid State – Semiconductors:

- GaAs, Se, PbSe, InSb, CsNO3, Si, Ge, SiC
- Optical
  - Infra-red, Visible, Ultraviolet
- IR Nano Technology Antennas
- Wide Bandgap Transition metal nitrides – GaN
- Combined IR Sensors – 'Plastic' PVF
- Solid State – Semiconductors
- Silicon based arrays
  - Photomultipliers
  - IR Nano Technology Antennas (not yet in use)
  - Cameras of many sorts including digital camera interrogation
  - Telescopes including digital devices incorporating these.

Ultra-violet optical detectors in general:

- Solid State – Semiconductors–Polyvinyl Fluoride (PVF) Optical Detectors - new
- Wide Band Gap Semiconductors such as silicon nitride
- Photomultipliers (UVC photon strikes plate and dislodges electron, ionizing biased inert gas to conduct, On – Off)
  - Gas Discharge Devices

- Geiger-Mueller Tubes
- Geiger Radiation Counters & UVC

Alternate Detectors in General:

- Bolometers – Broadband electromagnetic sensors
- Millimeter Wave – Lower frequency radar
- Chemical Detectors – Reactive surface – electrical

Active Fire Mapping Programs:

- Operational, satellite-based fire detection and monitoring program
- Managed by the USDA Forest Service Remote Sensing Applications Center Using NOAA Polar Orbiting Satellites (See Figures 1, 2a, 2b)
- (RSAC) located in Salt Lake City, Utah
- Active Fire Mapping program provides near real-time detection
- Characterization of wildland fire conditions in a geospatial context
- Continental United States, Alaska, Hawaii and Canada
- Detectable fire activity across administrative ownerships in United States and Canada are mapped and characterized by the programs
- High temporal image data collected by the NASA's Moderate Resolution Imaging Spectroradiometer (MODIS)
- Modis is currently the primary remote sensing data source of this program
- Daily observations of the United States and Canada
- Ideal monitoring and characterization of wildland fire activity
- Minimize product latency and deliver fire geospatial products
- Image data directly from orbiting spacecraft
- Program leverages technologies with other collectors of MODIS satellite data.

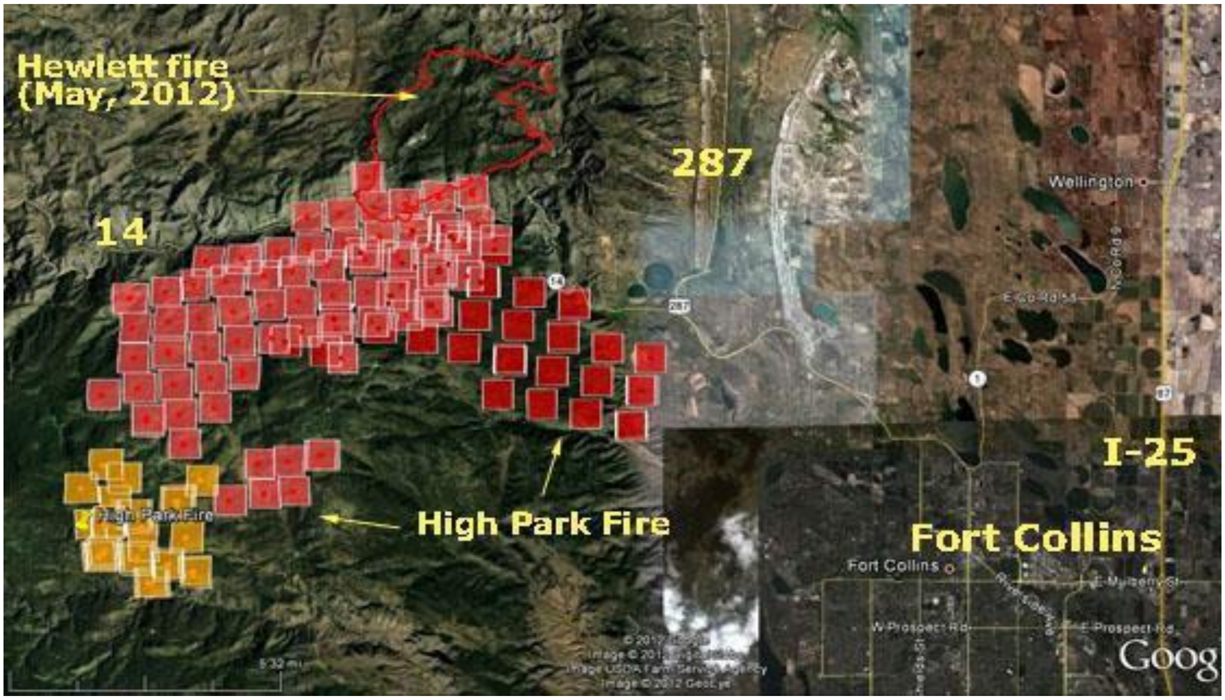
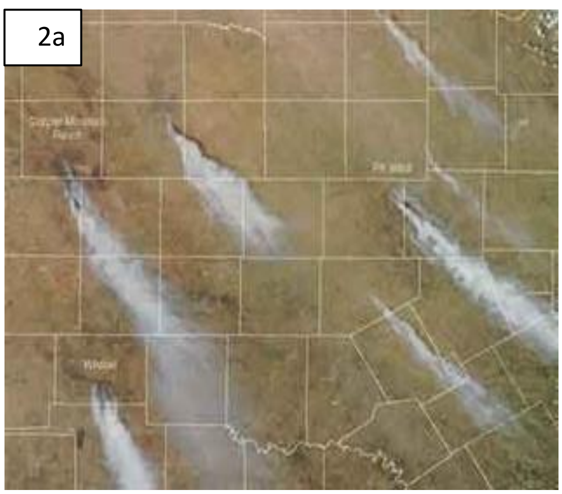


Fig. 1 May 2012 Colorado fires observed from space (http://wildfiretoday.com).



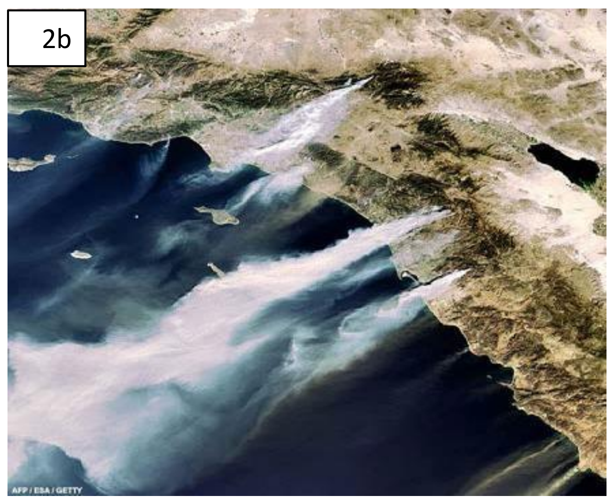


Fig. 2a Recent Texas Fires from Space **Fig 2b** Recent California fires from space, both accessed at (https://earthdata.nasa.gov/data/near-real-time-data/rapid-response)

Annual US losses due to Wildfire:

Many references are available to account for losses far exceeding suppression costs (See 1-8).

- Lives and injuries of many firefighters annually

- Lives and injuries of other humans and countless wild animals
- US forest losses in the millions of acres annually
- Cost of suppression approximately 2% of impact cost for 2003 San Diego Fires
- Approximately ½ ton of wood consumed per large tree burned, much of which is pollution
- Billions of dollars lost in fire-fighting, assets and revenues annually
- Homes, businesses, secured properties, water resources and recreation areas damaged or lost.

Note that as stated, not all wildfires result in serious damage or ecological losses and may indeed help reduce damage which may otherwise occur. The use of advanced detection systems may help guide the USDA Forest Service in the determination of the balance in potential damage to benefits and rapidly deploy the proper resources to gain early control with minimal loss.

Readily Available Technology Includes Capable UVC Optical Sensors:

UVC is weakly emitted in flames as a result of the decomposition of material when the outer orbital electrons collapse in the chemical changes taking place. Useful methods of detection therefore include UVC optical units with very special collection mirrors. UVC is not reflected from most common materials used for mirrors. Metals such as silver, aluminum, gold or even rhodium used for many precision mirror applications in IR or visible, will not function at all in the short UVC range. Likewise refractive lenses capable of operation in the UVC band are difficult and expensive to manufacture. So typical UVC flame sensors only collect a very low signal, especially when a small fire is considered. However certain special coatings including nickel phosphorus with very high content of phosphorus are found to be reflective in this wavelength. UVC mirrors can be fabricated which will permit use of the available detectors with as much as 100 times as much collection efficiency [2, 12].

UVC detection is unique in that the sunlight reaching the earth's surface and other artificial light sources are almost entirely free of UVC resulting in low false alarm detection.

- Electro-optical collector UVC and possibly acoustic detection methods
- Staring or scanning optical telescope designed to specifically detect flames from fires will selectively provide higher signal to noise for the fire against a sky background
- UVC
  - Combined IR and UVC – Catadioptric
  - Combined UVC and Acoustical emission detection.

Figures 3-9 below represent the systematic integration of optical collection gain UVC sensors, radio frequency transponders/receivers and a small electric helicopter assembled and tested at the University of Alabama in Huntsville. A digitally coded signal is transmitted by the built-in transponder which can be used to determine the location and the intensity of the detected flame. For a stationary detector, the signal indicates the fixed location. With the mobile unit, a small GPS device is required for location identification. The transmitted signal may be from a variety of protocols including a short range direct transmission digital chain, or used with a mobile phone or direct satellite connection for unlimited range [9, 10].

UVC sensors; with RF Tx/Rx transponders

Fig. 3 Left: Sensor with UVC collection mirror; right: no mirror

Fig. 4. Replicated UVC nickel phosphorus coated nickel, electroformed mirrors

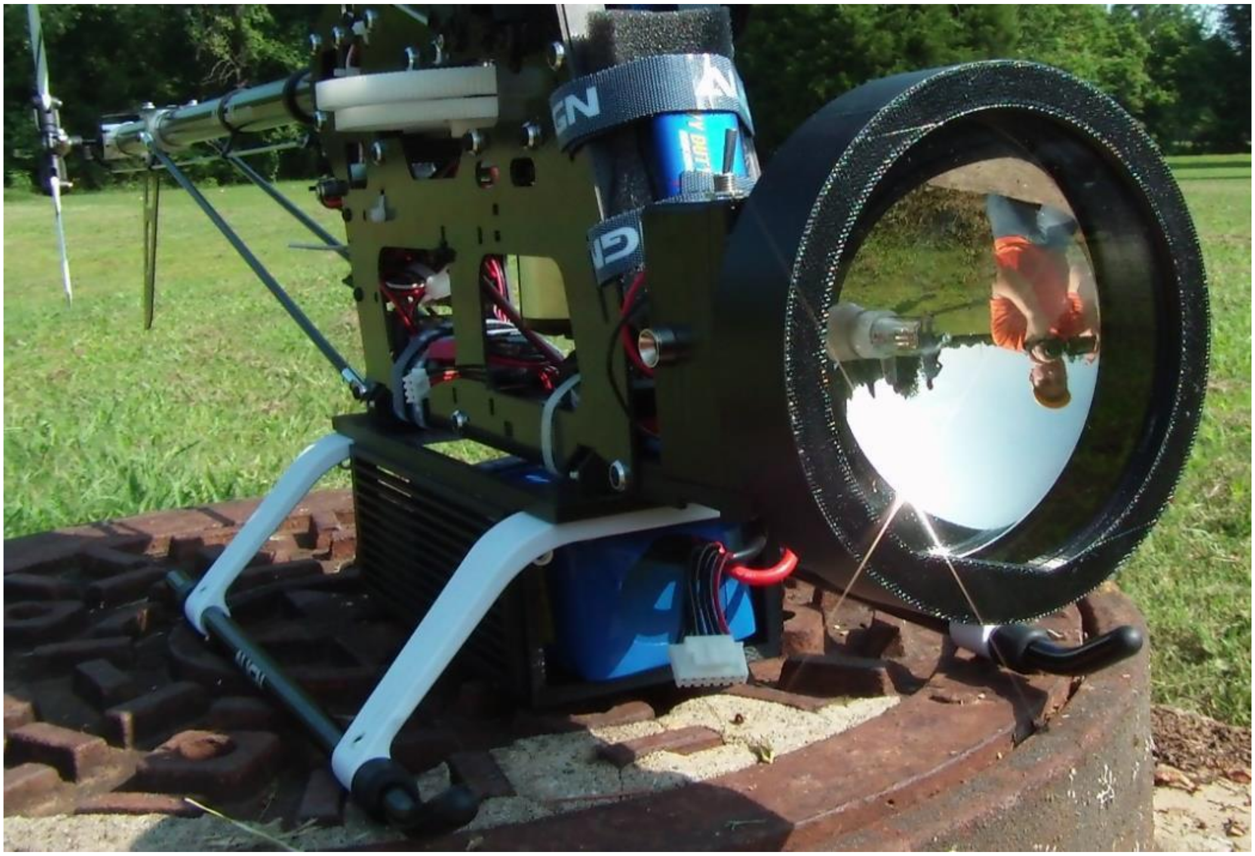


Fig. 5 UVC sensor/transmitter on UAV helicopter

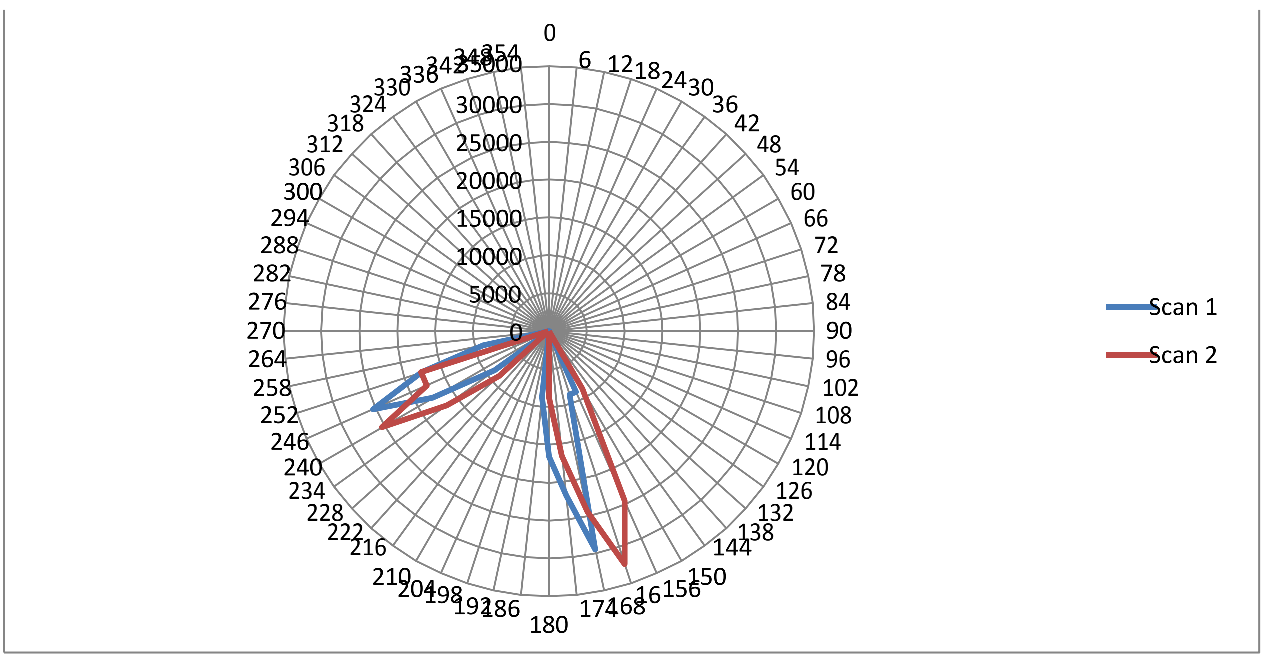


Fig. 6 Angular resolution of UVC flame detection of 2 cm^{-2} butane flame

UVC Sensor Output Vs. Distance in Feet

10000
0

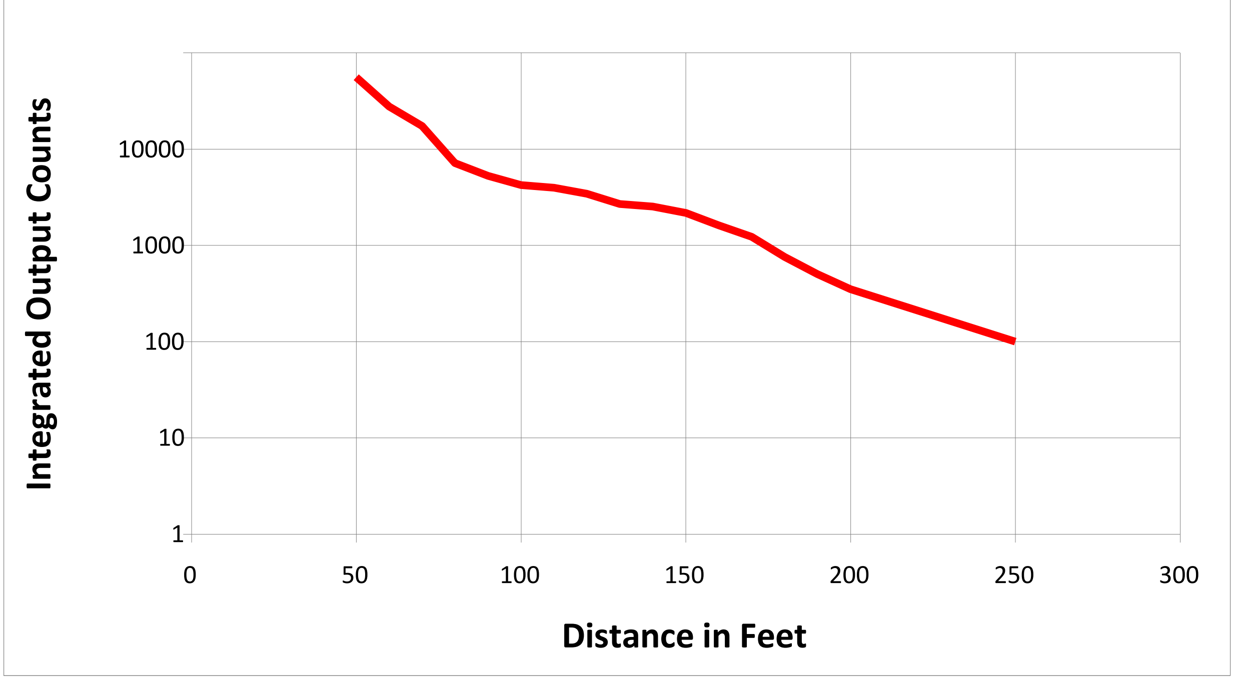


Fig. 7 Integrated output counts from UVC sensor vs. distance in feet from ~ 1 cm^2 flame
This represents the sensitivity of detection of an approximately 1 cm^2 butane lighter flame in full sunlight

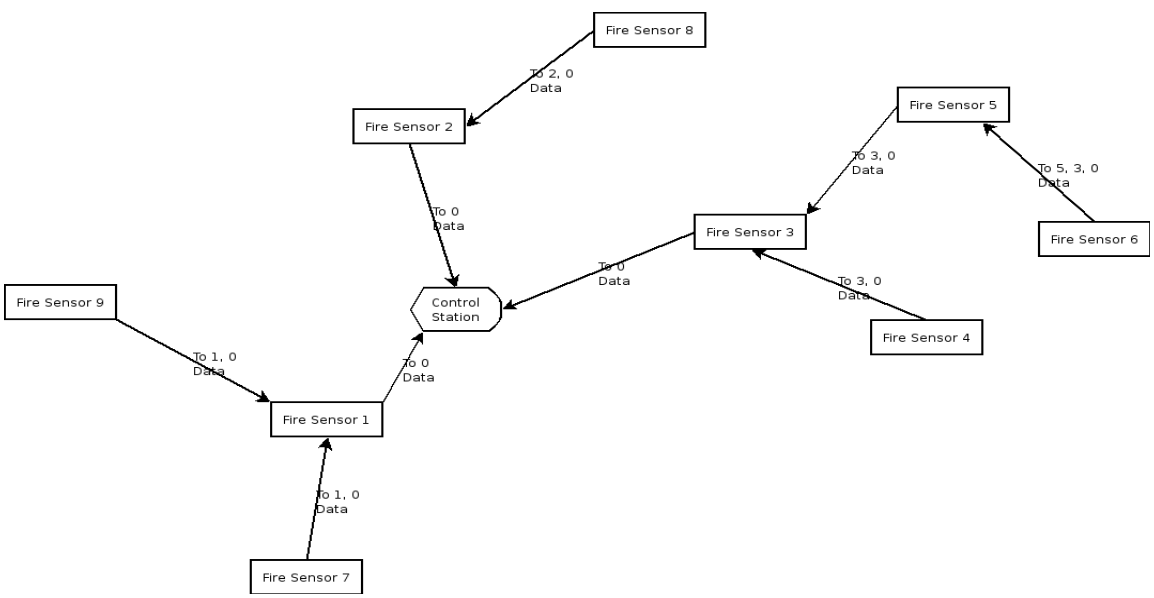


Fig. 8 Digital transmitters for location ID

Example Communication Network Improvements:

- The US Forestry Department has a high allocation of frequencies including emergency bands allocated in 2006 – 2007 from released TV bands

- The transmitter is digitally coded
- Code is recorded in the master transponder base
- The digital code is unique to segment and to the detector
- Signal received identified as to location and field of view
- Remote sensors will be preconfigured with address needed to reach control station, each sensor uses preconfigured 8 bit address to communicate with station,
- each Tx/Rx has unique 4 bit code plus 8 bit address

Whenever an intermediate sensor detects a packet with this ID at the start of the address string it will readdress the string and retransmit the packet.

Message Passing:

- Using this message passing scheme, sensors that are out of range of the control station will still be received
- Each detector/transmitter remains uniquely identified
- This is also known as Daisy-Chaining
- Identically addressed Tx/Rx pairs may be used with different codes to minimize interference and pass information to a common address at control station. Many schemes are possible.

Common digital data transmission modulation methods:

- Frequency-Shift Keying (FSK)
- Frequency-shift keying (FSK) is frequency modulation in which the modulating signal shifts the output frequency between predetermined values.
  - Amplitude-Shift Keying (ASK)
  - The simplest and most common form of ASK operates as a switch, using the presence of a carrier wave to indicate a binary one and its absence to indicate a binary zero or on-off keying (OOK).

Fig. 9 Example Interfaces

Agencies which will benefit from better detection and reporting of open area fires:

- Government agencies in wooded areas vulnerable to accidental fire or arson
  - Military installations
  - Federal & state agencies
  - Controlled burn 'Control'.
- Parks, Campsites
- Private Sector
  - Fuel storage facilities
  - Petroleum industry
  - Schools, neighborhoods, shopping areas etc.
  - Homes near wooded areas
  - Commercial aircraft and weather radar detector platforms
  - Chemical manufacturing and storage facilities.
  - Autonomous detection and reporting implementation:

Assemble prototypes and evaluate results

- Test selected systems for design effectiveness
- Populate area with very low cost ($300) detectors
- Consider Alternate aerial platforms for ensuing fires
  - Drones
  - Balloons
  - Small rockets
  - Commercial planes
- Test Tx/Rx options including power level and antennas
- ASK, FSK RF devices commercially available to 1 watt – 8 miles
- Dichroic, Yagi, parabolic, dipole, long wire Antennas (TBD)

Activity:

- Protect government agencies vulnerable to accidental fire or arson
- UVC capable mirrors used with Geiger Mueller detectors
- Interfaced enhanced fire detectors to transmitters/receivers
- UAV with UVC detector and RF transponder flown detectors demonstrated
- Programmed autonomous PC reporting schemes demonstrated
- Study advanced two color – three mode detector (UV-IR-Smoke) collection optics
- Presently available capability for high alert mode
    - Portable detection, cameras, GPS, cell phones
    - World Wide Internet communication
    - Interface to existing warning devices
    - Smart phone 'Apps'
    - Small belt worn receivers for security guards.

R&D Activities Recommended:

No single solution exists for such a widerange of complex issues, however better detection and communication methods would benefit many entities and perhaps save lives.

- Protect agencies vulnerable to accidental fire or arson
- Develop Better Understanding of flame photonics
- Develop better optical collection systems
- Test optical systems
- Refine autonomous reporting and unify communications amongst forestry agencies
- Implement detectors and reporting systems ASAP

Acknowledgements:

Darell Engelhaupt retired from the University of Alabama in Huntsville in 2011 and is presently On-Call for additional R&D. Several organizations and individuals significantly contributed to studies of wildland fire detection and reporting both before and after his retirement. Research from 2000 to present has involved the following: Center for Applied Optics, Pat Reardon, Lisa Blackwell, Chris Underwood, Ted Rogers and Brian Robinson. - Optics support; Mechanical Aerospace Engineering, Brian Landrum - Robotics Support. Student support from Dr. Landrum also has contributed to advancements - his students Josiah Thomas, Steven Jalbert, Stephen Sanders, Darrin Myles, Justin Hanna and Robert Branch are commended for their efforts on the implementation of the fire sensor for UAV and other applications. Lance Warden is to be commended for his work on the transponders and communications study at UAH as well.

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Recent Patents:

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12. US Patent Appl., 20130009062 Jan 10 2013 – Midwave and longwave infra-red Bolometer B. E. Cole
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14. US 6,329,921 Dec 11, 2001- Flame Detector Units and Flame Management systems – David Tindall et al
15. US 7,256,40,1August 2007- A system and method for detecting radiation indicative of fire, such as forest fire – William Garmer, et al
16. US 7541938, June 2009 – UVC Autonomous Long Range Open Area Flame Detection – D. Engelhaupt

Structure may be the key to predicting function during restoration of southern Appalachian forests

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Extended abstract: Hardwood ecosystems of the southern Appalachian Mountains were described historically as having open canopies, few shrubs, and rich forest floor vegetation (Van Lear and Waldrop1989, Sutherland and Hutchinson 2003); oak regeneration was more common than other species because of frequent fire (Brose and Van Lear 1998). Restoration is a common goal which usually involves re-introduction of fire, mechanical treatment, or both to alter stand structure. Appalachian hardwood ecosystems were developed by a broad array of natural disturbances including natural as well as anthropogenic fire (Brose *et al.* 2001, Waldrop *et al.* 2007). In some wildland/urban interface areas, air quality issues make prescribed burning problematic. Mechanical treatments, such as chainsaw felling of shrubs, may prove to be an acceptable alternative, but little information is available. This extended abstract describes a recent dataset that shows mechanical treatment, by itself, cannot get the job done.

In 2000, a team of federal, state, university, and private scientists and land managers designed the Fire and Fire Surrogate (FFS) study, an integrated national network to address the need for many types of information. At each of 12 sites distributed nation-wide, impacts of fuel reduction treatments were studied on a broad array of variables (see Youngblood *et al.* 2005). Treatments were designed to restore ecosystems by re-establishing an ecosystem process (fire), stand structure (mechanical fuel reduction), or both. Treatments at the southern Appalachian FFS site included a mechanical treatment (M) consisting of chainsaw felling trees >10 cm dbh and all shrubs (2002 and 2012), prescribed burning (B) (2003, 2006, 2012), mechanical and fire treatments combined (M+B) (2001) and an untreated control (C). This site is in Polk County, NC on the Green River Game Land, managed by the NC Wildlife Resources Commission. The forests of the study area were 80-120 years old, and showed no indication of past agriculture or recent fire. Forest composition is mixed-oak with pitch pine (*Pinus rigida* Mill.) and Table Mountain pine (*P. pungens* Lamb.) on xeric ridges and eastern white pine (*P. strobus* L.) in moist coves. A dense layer of ericaceous shrubs – mountain laurel, rhododendron (*Rhododendron maximum* L. and *R. minus* Michx.), flame azalea (*R. calendulaceum* (Michx) Torr.), and blueberry (*Vaccinium* spp. L.) – is found throughout.

Early results were described by Phillips *et al.* (2007), Waldrop *et al.* (2008), and Waldrop *et al.* (2010) but much is yet to be learned. With each successive burn, vegetation continues to change. However, we do not know how many burns (including frequency, seasonality, or firing technique) will be needed to reach the array of ecosystem objectives, to restore open woodlands, or to maintain quality wildlife habitat for desired species. Mortality of overstory hardwoods occurred each year but we do not know how to predict which trees will die or when they will die. Forest canopies could continue to open if more trees die or close if survivors grow to occupy the

gaps. A better understanding of canopy dynamics and its impacts on dead and live fuel and stand structure will allow a better job of establishing objectives and planning management activities to reach those objectives.

Through 10 (B and MB) or 11 (C and B) years of post-treatment measurement, basal area in C and M areas gradually increased as trees grew; there have been no significant differences between these two treatments at any time. The B treatment resulted in the death of a few overstory trees in 2003 and more died each succeeding year, especially after each additional burn. The initial burn was very hot with flame heights 3 to 4 meters because of heavy residual fuels from the mechanical treatment. Over time, basal area in this treatment was reduced by almost half.

All active treatments reduced shrub cover the first year after treatment and it remained significantly lower than in C plots throughout the study period. With time, however, shrub cover increased in the M (from 1 to 9 %) and M+B (for 0 to 7%) treatments as stump sprouts grew into the minimum size class for measurement. Shrub cover remained at about 4% in B plots throughout the study.

Ground cover was reduced by the B and M+B treatments the first year after burning, but was not affected by the M treatment without fire. Over time, ground cover in the B and M treatment areas was low (explained below) and at about the same amount as measured in C plots. Ground cover in M+B areas remained significantly higher than in C areas beyond the first year after the initial treatment.

Canopy openness was significantly greater in both B and M+B treatment areas than in C areas each year. The M+B treatment created the most open canopy by far and openness there did not change; even though surviving trees were likely filling open space, delayed mortality was sufficient to prevent canopy closure. In the B areas, openness was greater than in M areas the first year after treatment but there were no significant differences in any later year, possibly because trees in B areas grew faster from a fertilizing effect of fire and less competition.

The goal of increasing cover of graminoids was not successful in any of the treatment areas. Although the M+B treatment areas had significantly more cover than in other treatment areas, the total was never more than 2 ½ %. In M+B areas, graminoid cover decreased between the second and third burns; the 6 years between these burns was sufficient for shrubs, tree sprouts, smilax and other plants to grow tall enough to shade out grasses and sedges.

Numbers of oak seedlings and sprouts were stimulated by burning but not by chainsaw felling. Numbers in M areas never differed from those in C areas. However oak regeneration significantly increased after the first burn and remained significantly higher than in M and C areas throughout the study. A decline in oak numbers that occurred during the 6-year period between the second and third burns suggests the need for more frequent burning.

Each fuel reduction treatment changed stand structure differently resulting in different degrees of success in achieving restoration goals. Chainsaw felling of small trees and shrubs removed the shrub layer cover for 8 to 10 years; most sprouts did not grow back into the shrub layer (>1 m) during that time. This treatment left an intact overstory and forest floor. None of the target variables showed a positive response to this change in structure with the possible exception of fire behavior. Without a shrub layer, there was a vertical fuel break, especially after 8 to 10 years as felled decomposed stems were flat on the ground.

Prescribed burning alone removed a few overstory trees and removed the shrub layer but had little long-term impact on ground cover. Tree mortality was insufficient to create an open woodland community. Increases in graminoid cover, and oak regeneration were observed after each burn but proved to be temporary. These results suggest that hotter fires or treatments that remove more trees, along with more frequent prescribed burning are required to meet restoration objectives.

The combination of M+B treatments produced immediate and large reductions to basal area, shrub cover, and ground cover. Stand structure in these areas was closest to the desired open woodland condition with a 50% reduction in basal area and 30% canopy openness. However, understory shrubs, tree sprouts, and herbaceous plants quickly claimed the open forest floor and prevented successful growth of graminoids and oaks. These results agree with the substantial body of literature stating restoration will require numerous fires occurring more frequently than every 3 years.

Even though the stand structures produced in this study largely did not support desired objectives for most variables, progress was observed after prescribed burning, particularly when burning was done in combination will chainsaw felling of the shrub layer. With frequent burning the M+B areas may eventually support an open woodland community. These areas have an open canopy and improved wildlife habitat. Frequent burning will be needed for fuel reduction and spread of graminoids and oaks.

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Australian fuel classification - overview and framework

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Abstract: Quantifying fire prone vegetation is a challenge for wildland managers who need explicit fuel data to manage fire hazard, predict fire behaviour, understand suppression difficulty and evaluate fire impact to human and ecosystem values. The Australasian Fire and Emergency Services Authorities Council (AFAC) and the Forest Fire Management Group (FFMG) recognized the need for a national fuel classification to ensure a nationally appropriate method of characterizing and quantifying fuels.

As a key feature the Australian Fuel Classification should enable the categorization and organization of fuel complexes in order to capture spatial diversity as well as dynamic and structure complexity in a way that accommodates existing models for fire behaviour and assists development the next-generation of fire management Decision Support Systems.

This paper presents the results of a collaborative interagency effort to develop a nationally consistent and locally relevant fuel classification for fire management in Australia. Here we introduce the concept and framework for the Australian Fuel Classification (AFC), provide a general overview of the proposed AFC and highlight the interdependency on multiple data sources and applications. Finally, we discuss the need for a cohesive interagency effort to initiate and implement the AFC.

Effects of mechanical thinning on fuel consumption and emissions from prescribed burning in coastal North Carolina

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Abstract: Marine Corps Base Camp Lejeune (MCBCL) near Jacksonville, NC served as platform for field experiments that allow linking fuel condition and consumption with emissions of gaseous and fine particulate ($PM_{2.5}$) pollutants from prescribed burning (PB). The link between fuel consumption and PB emissions was experimentally investigated for undisturbed (control) fuels and compared with fuels that had received mechanical thinning via Hydro-Ax™ the winter before. PB experiments were conducted during the 2010 and 2011 dormant seasons. PB of hydro-axed fuels is believed to effectively help accelerate the restoration of longleaf pine (*Pinus palustris)* savannas in fire-dependent forest ecosystems. Fuel consumption measurements captured the moisture gradient from semi-mesic loblolly pine (*Pinus taeda*) forest to very mesic high-pocosin. In general, hydro-axe treatment yielded greater pre-fire fuel amounts and consumption of fuels, especially woody material, regardless of fuel moisture. Measured PB emissions included various reactive gases and particle phase organic compounds, water-soluble ionic species, organic and elemental carbon, and total $PM_{2.5}$ mass, as well as metallic and mineral $PM_{2.5}$ constituents. Applying the carbon mass balance, emission factors (EF) were calculated for the suite of aerosol species measured. Our results indicate that site vegetation variation is not driving the observed EF differences, which are therefore not confounded by either soil characteristics or vegetation differences, allowing direct comparison of fuel treatment effects on emissions. Gaseous EF averages from the two fuel types are similar, and EF variability is highest for acidic gases and isoprene. However, $PM_{2.5}$ mass and most $PM_{2.5}$ species EF from hydro-axed fuels are significantly lower than those from untreated control fuels. Therefore, removing a certain targeted amount of fuel by employing hydro-axing prior to PB not only accelerates needed forest restoration efforts but also provides significant air quality benefits due to lower primary $PM_{2.5}$ emissions. Organic carbon is the dominant $PM_{2.5}$ constituent in emissions from both fuel types, followed by elemental carbon, nitrate, potassium and chloride. More volatile organic compounds (VOC) are being emitted (per mass fuel consumed) from either fuel type under less efficient smoldering combustion conditions, which also promote higher emissions of inorganic $PM_{2.5}$ constituents, i.e. main ions (chloride, nitrate, sulfate) and major metal oxides, as well as organic sulfur compounds. Our EF values for VOC and $PM_{2.5}$ compare well with values published by the EPA Clearinghouse AP-42 (EPA, 1996) for similar fuel beds, while our EF for CO and CH_4 are less than a third of the corresponding AP-42 levels.

Additional keywords: air quality, smoke, combustion products

Introduction

Uncontrolled wildfires are a potential threat to life and property across the Nation. In order to reduce the magnitude of and damage from wildfires, prescribed fires are becoming an integral part of public land management practices. In the Southeastern United States (SEUS), reducing wildfire damage is only one of many objectives for employing prescribed burning (PB). Guided by the Endangered Species Act, the Department of Interior through the Fish and Wildlife Service recommends using PB throughout the U.S. to recreate the natural fire regimes needed to maintain the health of native forest ecosystems. Across the southeastern landscape, roughly 4 million ha (10 million acres) are treated every year, with most PB conducted between January and June, but wildfires occur year-round in the South (Wade *et al*. 2000; Haines *et al*. 2001). The longleaf pine (*Pinus palustris)* forests of the SEUS represent natural habitat of various threatened and endangered species such as the red cockaded woodpecker (*Picoides borealis*). Hence, private landowners and land managers on military installations alike use PB to restore and maintain the longleaf pine ecosystem.

Over the last few decades, the SEUS experienced substantial population growth, causing significant urban sprawl in an otherwise heavily forested region, making the wildland urban interface (WUI) an important aspect of fire management. PB is the largest single source of directly emitted primary (filterable and condensable) $PM_{2.5}$ in the SEUS (EPA region 4), emitting 25.1 % of the total from all 56 inventoried sectors (EPA 2008); wildfires and unpaved road dust follow with 14.2 and 9.4 %, respectively. Source apportionment modeling of $PM_{2.5}$ mass concentrations from 24 Speciation Trend Network sites suggests PB may contribute more than 30% of the annual $PM_{2.5}$ mass in the SEUS (Lee *et al*. 2007). Recent studies show that PB can significantly impact air quality (AQ) in neighboring urban communities, contributing to both the primary and secondary portions of ambient $PM_{2.5}$ mass; i.e. the directly emitted and atmospherically formed portions (Lee *et al*. 2005; Hu *et al*. 2008). The ecological reliance on PB combined with increased AQ pressure due to tighter regulatory constraints (imposed by federal NAAQS), necessitates a better understanding of the relationship between the desired fuel consumption and the undesired PB smoke emission.

The process of biomass combustion is a sequence of several stages from ignition, through flaming, to smoldering where the majority of criteria pollutants are released during PB (Mobley 1976; Andreae & Merlet 2001). All combustion types co-exist at any given time as wildland fire moves through the fuel. Therefore, the combined emissions are released into the atmosphere and the biomass combustion process is typically divided into a predominantly flaming and a predominantly smoldering stage. The extent and intensity of these combustion stages are largely dependent on the fuel condition and ambient meteorological conditions at the time of ignition. The following describes the procedures used to measure the fuel parameters that distinguish mechanically treated fuel from control.

Materials and methods

Fuel characterization and consumption

PB emissions were measured from MCBCL sites that had received hydro-axe fuel treatment (using trade-marked Hydro-Ax equipment) the winter prior to PB and compared with emissions from sites without treatment (control) in five experimental blocks. The five blocks were selected so that their vegetation communities fell along a continuous gradient extending from wet high-pocosin to xeric longleaf pine (low-pocosins were not present). Ordination methods such as NMS and CCA provided an estimate of community composition along this gradient that is suitable for correlation with the PB emission results. The winter prior to PB (i.e. 1 year prior to the experiment), MCBCL foresters hydro-axed all 1-ha (100-m x 100-m) plots that met the requirements for comparable emissions measurements from treated versus untreated fuel burns. Due to the steep hydrological gradient found in IE and the different burn requirements in its southern versus northern sections, the IE research plots were treated as two independent and different burn experiments IE-south (IEs) and IE-north (IEn), amounting to a total of five PB study sites on a hydrological gradient beginning with the wettest 'near pocosin' sites in IEs and ending with more well drained 'semi-mesic' sites in RB, with IEn, MF and HA located in between (see Fig. 1).

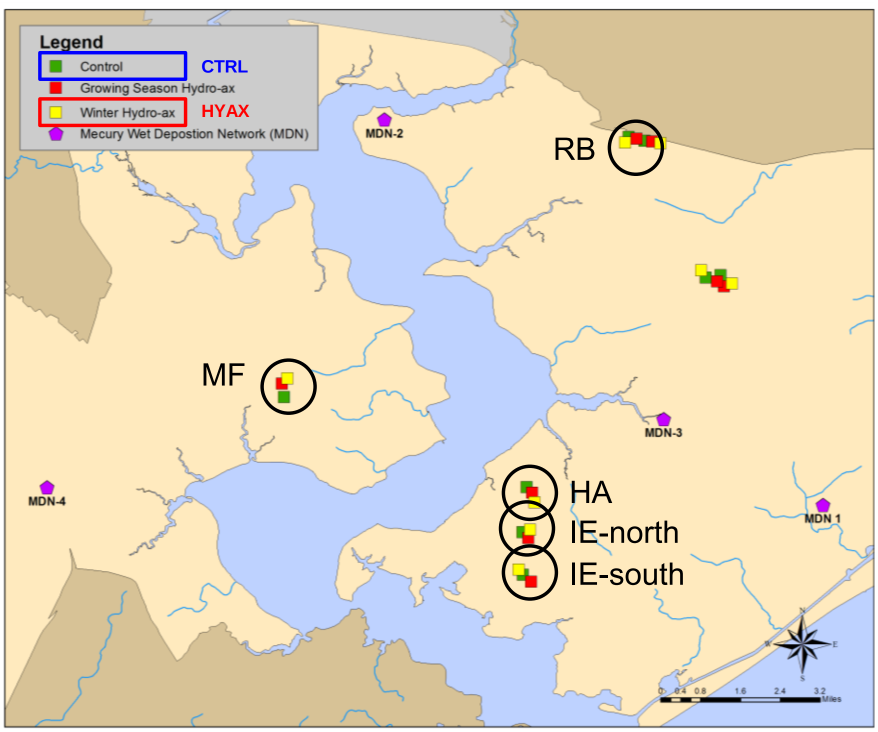

Fig. 1: Location of investigated vegetation plots on MCBCL (in beige) south of Jacksonville, NC along the New River Estuary on the Atlantic coast. Letters indicate specific MCBCL plot names with IE having been divided into a northern and southern portion for this study only.

Significant differences exist in the amount of accumulated fuel, mainly due to different degrees of fire suppression, and in fuel composition, which is largely a function of soil type and its associated moisture gradient. Treatment plots were designed to capture the moisture gradient from semi-mesic loblolly pine (*Pinus tadea)* forest to wet-mesic loblolly pine forest. Consequently, the species specific composition of the fuels varied significantly. As shown in Table 1, semi-mesic loblolly pine sites were dominated by red bay (*Persea borbonia*) and sweet gum (*Liquidambar styraciflua*), while wet-mesic loblolly pine sites also contained red maple (*Acer rubrum*) and gallberry (*Ilex glabra*). Due to loblolly pine domination in the overstory, pocosin plots had comparatively lower densities of sweet gum (*Liquidambar styraciflua*) and red bay, but had a high density of shrubs, including titi (*Cyrilla racemiflora*) and fetterbush (*Lyonia lucida*) in the understory. Table 1 compares species abundance in control and hydro-axed plots based on pre-treatment stem density measurements. The least mesic (driest) sites were dominated by sweet gum and red bay, while the more mesic (pocosin-like) sites were characterized by titi, fetterbush and loblolly pine. The hydro-axed plots were generally richer in sweet gum and red bay, while control plots had more gallberry, fetterbush, black tupelo (*Nyssa sylvatica*), greenbriar (*Smilax laurifolia*) and other species. Soil organic matter (OM) serves as surrogate parameter helping categorize the different experiment sites as explained below.

Table 1: Species %-abundance in treated (HYAX, red) and untreated (CTRL, blue) plots based on pre-treatment stem density measurements.

	Scientific name	*Liquidambar styraciflua*	*Persea palustris*	*Acer rubrum*	*Ilex glabra*	*Pinus taeda*	*Lyonia lucida*	*Cyrilla racemiflora*	Other*	OM
		Sweet gum	Red bay	Red maple	Gall berry	Loblolly pine	Fetterbush	Ti-ti		
RB	CTRL	58	10	5	0	0	0	0	27	5
	HYAX	94	2	0	0	0	0	0	4	8
HA	CTRL	19	68	2	0	2	0	0	10	15
	HYAX	25	75	0	0	0	0	0	0	9
MF	CTRL	12	8	0	33	25	0	0	22	14
	HYAX	17	21	36	0	2	0	2	21	28
IEn	CTRL	7	13	4	16	7	36	0	16	11
	HYAX	13	30	9	0	48	0	0	0	48
IEs	CTRL	0	9	0	5	0	57	0	30	68
	HYAX	11	21	23	2	0	0	41	3	18

*incl. oaks, black tupelo, American holly, ink berry, green briar and other minor species

In each vegetation plot, both before and after PB, fine and coarse woody debris and live and dead vegetation was harvested in each of five 1x1 m areas, whereby the 1 m^2 pre-fire areas were separated from the post-fire areas by at least 10 m. All materials were dried for at least 72 hours at 74 °C, and then weighed. Differences in before and after fuel mass provided an estimate of fuel consumption in the fire. Due to inclement weather conditions, only plots HA and IEs could be burned in 2010 (March 19 and 21, respectively), while the other 3 plots were burned in the 2011 dormant season (February 26, 28, and March 3 for RB, MF, and IEn, respectively). Each plot's biomass was sampled 2 to 8 weeks prior to PB and again 2-4 weeks after PB. Soil samples were collected from the top 10 cm of soil (incl. O and A horizons) at four points in each plot that were located at least 10 m away from each other. Soils were sent to Brookside Laboratory, New Knoxville, Ohio, for analysis of OM. Short-term moisture levels of the duff and above ground 1, 10 and 100 hour fuels were estimated from the FARSITE model (Finney 1998) using meteorological data from the New River Air Station at MCBCL. Soil moisture is expressed in percent fraction moisture holding capacity (m^3m^{-3}). Different hour fuels are defined as fuels with different diameters, ranging from 0-0.62 cm for 1h, 0.62-2.54 cm for 10h, to 2.54-7.62 cm for 100h fuels. Following procedures of CCA (Ter Braak 1986) and NMS (Kruskal 1964), vegetation composition scores CCA and NMS were determined in an ordination method using PC-ORD software (McCune and Mefford 2002).

All burns were conducted within a few hours during late morning and early afternoon. Fire weather conditions (as published by the National Weather Service's National Climatic Data Center via their Service Records Retention System in the Hierarchical Data Access System from http://has.ncdc.noaa.gov/pls/plhas/has.dsselect) varied between sunny and mostly cloudy with inversion burn-off temperatures between 40 and 73 F (4 and 23 °C). Winds were from all directions between 10 and 25 mph (4 and 11 ms^{-1}) with ventilation rates (VR) between 37,000 and 115,000. VR is the product of transport wind speed in mph and mixing height in feet, and plays an important role in the PB planning process. Except for the hydro-axed fuel bed in IEs, the fires were headfires, strategically lit to account for wind direction and wind speed, which governed fire spread. The fire in IEs' hydro-axed plot was hard to ignite due to high fuel moisture, whereby the more exposed IEs control plot allowed the wind to help spread the fire more quickly and even cause some isolated crown torching; hence two very different fires in the same experiment plot. The photographs in Fig.2 provide visual impressions of the fire behavior and inhomogeneity of the encountered fuel loadings in some of the experiment plots.

a) Hydro-Ax™ in action. b) Ignition of hydro-axed IEn. c) Flaming of IEn control fuel.

d) Flaming in hydro-axed MF. e) Flaming in hydro-axed RB. f) Smoldering RB control fuel.

Fig. 2: Image of the Hydro-Ax™ equipment during preparation of the plots in 2009 (a), and visual impressions of the different fuel loadings and fire behaviors during ignition (b), flaming (c-e), and smoldering (f). Emissions measurement equipment is visible in b and f.

PB emissions measurements

As already mentioned, the biomass combustion process is typically divided into a predominantly flaming and a predominantly smoldering stage. The following describes the technical approach for sample collection and methods employed for the chemical analysis of those samples. The burn areas on MCBCL were characterized by dense fuel loads and were difficult to access, requiring deployment of the measurement equipment on a highly mobile platform. In order to meet the specific requirements of size and mobility, an ACM was designed and constructed. By means of Table 2, the measurement methods are briefly summarized as follows.

The ACM payload consisted of two evacuated and flow controlled stainless steel canisters to measure VOC and two battery powered membrane pumps providing sample air flow through a cyclone, denuder-pair and filter pack sample train. Cans, denuders and filters constituted the sample media for the integrated measurement of aerosol composition. The front T and Q filters were used to quantify primary emissions, while the Quartz backup filters in both channels (QBT and QBQ) were used to assess impacts from semi-volatile species (Baumann *et al.* 2003). Other important payload components were a nephelometer for continuous $PM_{2.5}$ mass concentration measurement (model pDR-1500 from Thermo-Fisher Scientific) and a handheld CO/CO_2 monitor (model Qtrak-7565 from TSI). The air sample continuously measured by the pDR-1500 passed through a diffusion drier at the inlet upstream of the cyclone, yielding results that agreed well with those from the integrated filter measurements.

The T and Q sample substrates from the two otherwise identical ACM sampling trains underwent different laboratory analytical procedures. First, $PM_{2.5}$ mass was determined from gravimetric measurement of the T filter deposits, employing a robotic weighing system in a clean room environment. The T filter sample was then submitted to the non-destructive energy dispersive XRF analysis for the determination of numerous metallic and mineral elements contained in the $PM_{2.5}$ sample matrix, before it was extracted in pure de-ionized distilled water (~18 MΩ resistivity) and further analyzed for ionic content via IC and for water-soluble metals via ICPMS.

More than 100 POC, including key molecular markers, such as levoglucosan, pimaric acid, abietic acid, and retene, were analyzed and quantified from Q filter samples employing gas chromatographic mass spectrometry. Over 40 VOC species were measured from the can samples, including ethyne (acetylene) and 1,3-butadiene (potential carcinogen), aromatics and biogenics (isoprene, mono-terpenes) that are important PM precursors, as well as CO, CO_2, and CH_4. The IC analysis of the denuder extracts provided quantitative information on other reactive gases that play an important role in aerosol chemistry; i.e. NH_3, HONO, HNO_3, SO_2, and certain light organic (carboxylic) acids. The individual analytical methods and techniques have been described elsewhere (Coleman *et al.* 2001; Baumann *et al.* 2003; Schauer *et al.* 2003; Sheesley *et al.* 2004; Kellogg and Willis 2009; Kulkarni, 2010).

Right before ignition, the ACM was positioned in the center of the 1 ha control plot using an ATV. Once the initial most vigorous flaming phase ceased (usually 20 to 30 minutes after ignition), the sampling pumps were manually stopped, the denuder and filter sampling media were exchanged, flow rates were checked, and sampling resumed for another 2 to 3 hours. Although our main objective was to compare fuel treatment effects on fuel consumption and PB emissions, we hoped to capture predominantly flaming conditions during the short sampling period and predominantly smoldering conditions with the subsequent longer sampling period. Our measurement results show that this was not always the case as discussed later. Thanks to the close proximity of the control plot to the hydro-axe treatment plot, using the ATV allowed us to position a second identical ACM unit to capture corresponding flaming and smoldering dominated PB emissions from the treated fuel. A third ACM was deployed upwind and put in operation immediately before ignition to provide important background concentrations. All ACM units were equipped identically, providing real-time meteorological, trace gas and PM mass data, as well as discrete sample analyses for aerosol chemical constituents in the gas and particle phase. The suite of sample analytical measurements is summarized in Table 2. The high-resolution $PM_{2.5}$ mass, CO_2, and CO measurements averaged over the discrete sampling periods agreed well with the values obtained from the discrete samples to within 10%, 12% and 15 %, respectively.

Table 2: Aerosol species including over 40 VOC and 100 POC.

They were measured via discrete PB emission sample collection and laboratory analysis.CO, CO_2 and $PM_{2.5}$ mass concentrations were also measured in real-time. *…Ethyne (acetylene) and 1,3-butadiene (carcinogen) belong to family of alkynes and dienes, respectively. #... Thermal Optical Transmission according to Birch and Cary (1996). &… Gas chromatography with mass spectrometry/flame ionization detection/electron capture detection. $... Electro-chemical (CO) and non-dispersive infra-red (CO_2)

Group	Species	Sample Medium	Method
Crustals, light metals	Al, Ca, Cl, Fe, K, Mn, Na, S, Si, Ti / Co, Cr, Mg, Ni, V	ACM T filter	XRF/ICPMS
Heavy metals	Br, Cu, Pb, Zn / As, Ba, Cd, Rb, Sb, Se, Sr	ACM T filter	XRF/ICPMS

Alkaline, acidic gases	NH_3, HNOx, HCl, SO_2, formic, acidic, oxalic acids	ACM denuders	IC
Ionic PM species	Na, K, Mg, Ca, NH_4, Cl, NOx, SO_4, PO_4, formate, acetate, oxalate	ACM T filter	IC
PM-carbon	Elemental and Organic Carbon (EC, OC)	ACM Q filters	TOT#
VOC (>40 species)	Halog. HC, biogenic HC, alkyl nitrates, alkanes, alkenes (incl. ethyne, 1,3-butadiene), aromatics, CH_4, CO, CO_2	Whole-Air Canisters	GC-MS/FID/ECD&
POC (>100 species)	n-alkanes, n-alkenoic/alkanoic acids, resin acids, PAHs, hopanes, steranes, SOA Tracers	ACM Q filter	GC-MS
Real-time	CO, CO_2	in situ	EC, NDIR$
	$PM_{2.5}$ mass concentration	in situ	90^o scatter

Since the selected burn plots fall into specific fuel classes, distinguishing the hydro-axed type from control, we apply the carbon mass balance method (Nelson 1982; Radke *et al.* 1998; Battye and Battye, 2002; Sinha *et al.* 2004);), assuming that all of the combusted fuel carbon is emitted into 5 measurable forms of carbon, CO_2, CO, CH_4, VOC, and particulate C. For a certain fuel type *i*, the EF of a species *n*, is then calculated from the ratio of the mass concentration of that species to the total carbon concentration emitted:

$$EF_{ni} = f_{Ci} \bullet EF_{nCi} = f_{Ci} \bullet [n] / ([C]_{CO2} + [C]_{CO} + [C]_{CH4} + [C]_{VOC} + [C]_{pC}) \quad (1)$$

Hays *et al.* (2002) measured the carbon contents of several biomass types obtained from various forests in the SEUS and found it to be 42.6 % for aged needles of loblolly pine, which we used here (f_{Ci} = 0.426). The plot surveys provide important parameters that describe the fuel mix and condition, including vegetation classes, dead versus live mass fractions, FM and OM, all of which are presented in the Results section.

An important parameter describing combustion behavior, intensity and completeness is the MCE defined as the ratio of the moles of CO_2 to the combined moles of CO_2 plus CO emitted by the fire (Ward and Radke, 1993):

$$MCE = \Delta[CO_2] / (\Delta[CO_2]+\Delta[CO]) \quad (2)$$

where $\Delta[CO_2]$ and $\Delta[CO]$ are the excess mixing ratios of CO_2 and CO in the PB emissions relative to the background levels upwind. MCE is higher when flaming dominates over smoldering combustion. Thus, MCE values of 0.98-1.0 indicate *pure* flaming, while *pure* smoldering usually yields MCE values of 0.75-0.85. For the benefits of minimal AQ impact and maximum energy release, MCE would ideally approach the value of 1.0.

As mentioned above, our integrative PB emissions measurements in each vegetation plot were divided into a relatively short period (20-30 min) immediately after ignition, followed by a 2-3 hour period dominated by smoldering. Our MCE levels ranged overall between 0.84 and 0.998 averaging 0.94 ±0.04 with the shorter first periods averaging 0.94 ±0.02 and the longer subsequent periods 0.95 ±0.05, indicating that our assumption of either flaming or smoldering stage dominating over the other did not hold. Nevertheless, a time-weighted average of certain species' excess mixing ratio from the short and long period had to be used in order to determine its proper EF value that qualifies to be compared with the experimentally determined fuel consumption, fuel moisture and vegetation composition indicators (NMS and CCA ordination parameters). Except for the MCE related sensitivities of the fuel-type specific EF discussed later, the time-weighted EF averages were used.

Results and discussion

In this section, the two investigated fuel types, the mechanically treated (thinned) fuel and untreated control fuel, are characterized relative to their hydrological location; observed differences in consumption are presented first. These differences are then discussed in light of combustion behavior and numerically related to gas and particle phase emissions from a wide host of species on the basis of individual EF's. The newly developed fuel-specific EFs are then compared with values published in the available literature and in different applications that are relevant in the land managers' decision making process.

Fuel character and consumption

Soil organic matter (OM), which is influenced by site hydroperiod, increased along the spatial gradient from plot RB (the driest), over HA, MF, IE-north, to the wettest (IE-south) plot. Table 3 provides an overview of the measured fuel moisture levels, total pre-fire and consumed fuel amounts as well as relative fuel consumption for the two main fuel material categories, woody sticks and leaves. Also included are the vegetation composition scores CCA and NMS from the applied ordination method. More negative scores generally indicate more pocosin-like conditions.

The HYAX/CTRL column shows the ratio of averages from the corresponding five plots of each fuel type. It indicates that on average and relative to control, hydro-axe treatment made about twice as much fuel available for consumption, and almost three times (2.8) more fuel was consumed during PB. Woody fuel consumption was almost 9 times higher in absolute terms and 2 times higher in relative terms; i.e. the fraction of woody fuel consumed relative to that estimated by the pre-fire survey as being available on average in the hydro-axed plots was twice the corresponding fraction of the control. Moisture levels of the mechanically treated fuels (HYAX) were systematically lower than the corresponding control fuels in each plot.

Table 3: Total pre-fire fuel, different FM and FC levels - absolute and relative to pre-fire conditions, and vegetation composition indicators CCA and NMS for the two different treatment types investigated in the 5 different vegetation plots.

Fuel Type / Plot	CTRL					HYAX					CTRL	HYAX	HYAX/ CTRL
Parameter	RB	HA	MF	IEn	IEs	RB	HA	MF	IEn	IEs	AVG	AVG	
F-Tot g/m^2	1197	1132	830	963	907	723	2299	2275	1096	3784	**1006**	**2035**	**2.0**
FC-Tot g/m2	531	591	120	543	250	226	1561	1284	880	1693	**407**	**1129**	**2.8**
FC-Wd g/m2	119	41	40	68	240	80	1434	1193	350	1469	**102**	**905**	**8.9**
FC-Lvs g/m^2	412	550	80	475	10	146	127	91	530	224	**305**	**224**	0.7
FC-Rel %	44	52	15	56	28	31	68	56	80	45	**39**	**56**	**1.4**
FC-Wd %	37	24	28	32	53	37	84	68	86	57	**35**	**66**	**1.9**
FC-Lvs %	47	57	12	64	2	29	21	18	77	19	**36**	**33**	0.9
Soil-OM %	5	15	14	11	68	8	9	28	48	18	**23**	**22**	1.0
FM-Duff %	73	72	73	68	74	54	69	54	55	70	**72**	**60**	0.8
FM-1hr %	17	15	17	16	19	5	15	11	11	18	**17**	**12**	0.7
FM-10hr %	21	18	21	19	20	18	18	18	16	19	**20**	**18**	0.9
FM-100hr %	17	17	17	16	17	14	16	14	14	16	**17**	**15**	0.9
CCA	-0.9	-1.0	-1.8	-2.0	-1.8	-1.1	-0.5	-0.8	-2.0	-0.7	**-1.5**	**-1.0**	0.7
NMS	-0.2	-1.2	-0.8	-1.4	-1.7	-0.8	-0.7	-0.9	-1.3	-1.5	**-1.1**	**-1.0**	1.0

In support of the above table, Fig. 3 clearly shows that except for RB, hydro-axe treatment yielded greater amounts of pre-fire fuel and consumption of all fuels but especially woody material regardless of fuel moisture. Untreated control plots provided less pre-fire fuel available for combustion, of which PB also consumed less relative to the fraction consumed in the treated plots, especially for MF and IEs control plots, where duff and 1h fuels had highest moisture levels.

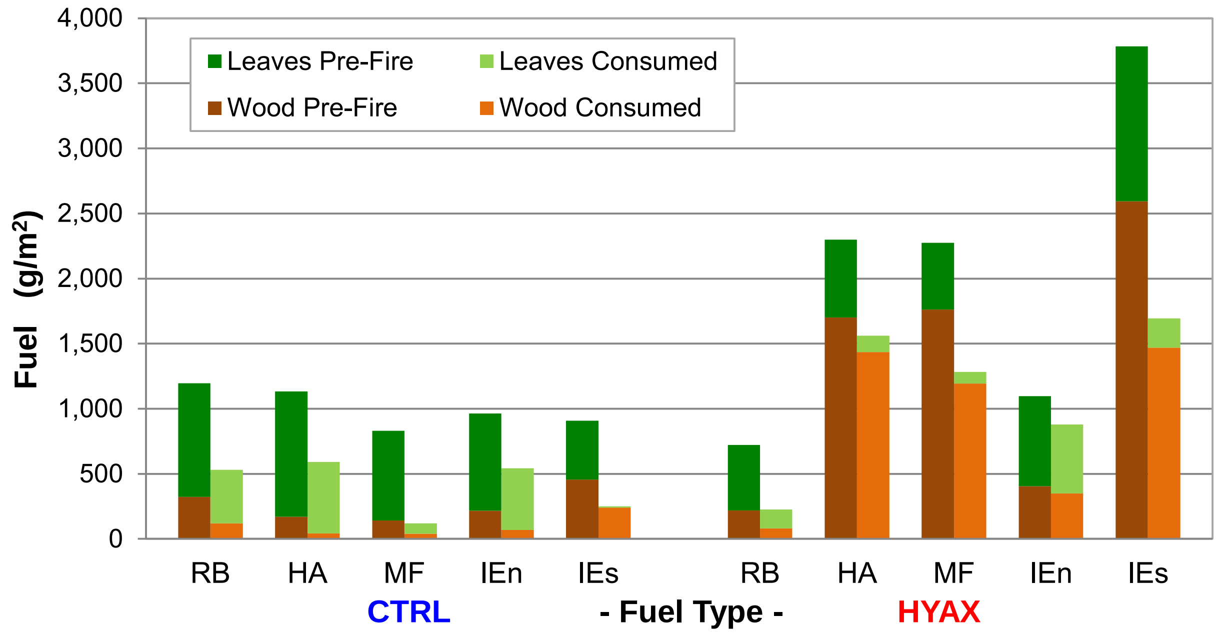

Fig. 3: Total fuel from pre-fire sampling and consumed fuel for different fuel types and plots.

In order to investigate the existence and strengths of relationships between the different fuel parameters, a correlation matrix was established across all parameters shown in Table 3 for the HYAX and CTRL data sets separately. Table SM1 lists the statistically significant relationships, showing only two relationships being equally important for both fuel types: *1*) the fraction of leaves consumed is proportional to its total mass consumed, and *2*) fuel moistures of the 100-hr fuels correspond exactly (1:1) with the moisture levels found in the duff. However, moisture levels of the 1-hr fuels vary differently among the different fuel types. While for HYAX they strongly increase with the amount of total pre-fire fuel as well as with the amounts of consumed total and woody fuels, they increase only with the fraction of woody CTRL fuel consumed but decrease with the amount and fraction of CTRL leaves consumed; i.e. more CTRL leaf material was consumed when 1-hr fuels were drier. The only other apparently inverse relationship exists between the CCA vegetation community scores and HYAX fuel consumption: The more pocosin-like the stand, the more leaves (total amount and fraction) were consumed in the mechanically thinned plots. Under less pocosin-like conditions, more fuel was consumed, but in the CTRL plots only. The proportionality between total amount and fraction of fuel consumed was upheld only for CTRL but not for HYAX fuels. On the other hand, only HYAX data revealed a strong positive relationship *a*) between fuel consumed and pre-fire fuel amount, i.e. consumption (both total and woody fuel) increased with fuel loading, and *b*) between woody and total fuel consumed, i.e. the consumption of woody material scaled linearly with that of all treated materials.

Fuel-Emissions relationships

All aerosol emissions measured *in situ* via ACM are characterized in terms of reactive gas-phase and particle-phase chemical species EF calculated according to Eq. 1 and expressed in g-species' mass per kg-fuel mass consumed. All reported EF values are based on net emissions, since the corresponding background concentrations have been subtracted. Fuel treatment specific differences (HYAX vs. CTRL) in the relationships between measured fuel parameters and species' EF were gauged by linear regression. The EF values entering the linear regression matrix were determined in two different ways: *1*) by treating the two EF measurements from the shorter flaming-dominated phase and the subsequent longer smoldering-dominated phase separately, and *2*) by combining the two into a single time-weighted EF average. Considering the same level (i.e. 95% confidence) of significance in r between the two methods, Table 4a and 4b show that relatively few species' emissions are sensitive to FC and dead FM.

Tables 4a and 4b show statistically significant relationships when data from both fuel types combined entered the cross-correlations. In general, relatively few species' emissions are sensitive to the underlying sampled fuel conditions. None of the linear relationships between fuel consumption and fuel moisture on the one hand with gas and particle-phase aerosol species emissions on the other hand are very strong or statistically significant. Of all the species measured (see Table 2), only the EF values from the group of alkanes and halo-carbons decrease with increasing consumption of leaves and relative consumption of all fuels, respectively. Aerosol species' EF values correlate negatively with fuel parameters except for CO_2 and MCE, which correlate positively albeit very weakly with the amount of leaves consumed. This may be an effect of more leaves being burned (which are harder to ignite) when combustion during the initial flaming stage is more intense and subsequently at higher temperature. Higher fuel moisture levels yield overall lower S and N emissions in the particle phase (in form of sulfate and ammonium, respectively) and lower 1,3-butadiene and acetylene emissions. There is a weak trend towards lower emissions of gaseous aromatics and alkanes but higher emissions of particle-phase EC as more fuel is consumed.

Table 4a: Statistically significant r-values for relationships between certain fuel parameters and species' EF values, using EF values from both short and long sampling periods independently for both fuel types combined.

$p<0.05$ for $r>0.442$	MCE	CO g/kg	CH_4 g/kg	Toluene g/kg	<8C Alkanes g/kg	Halo-C g/kg	$SO_4^{=}$ g/kg	NH_4^{+} g/kg
F-Avail g/m2				-0.48				
FC-Tot g/m2			-0.45	-0.44	-0.48			
FC-Lvs g/m2					-0.46			
FC-Rel %						-0.47		
FM-Duff %							-0.51	-0.51
FM-1hr %	0.46	-0.46	-0.45				-0.52	-0.56
FM-100hr %							-0.52	-0.53

Table 4b: Statistically significant r-values for relationships between certain fuel parameters and species' EF values, using EF values from both short and long sampling periods combined (as weighted average) for both fuel types combined.

$p<0.05$ for $r>0.624$	MCE	CO g/kg	CO_2 g/kg	1,3-Butadiene g/kg	<8C Alkanes g/kg	Halo-C g/kg	Acetylene g/kg	EC g/kg
FC-Tot g/m2								0.72
FC-Wd g/m2								0.67
FC-Lvs g/m2	0.72	-0.72	0.66		-0.69	-0.74		
FC-Rel %						-0.64		
FC-Lvs %						-0.64		
FM-Duff %				-0.67				
FM-1hr %				-0.74			-0.67	
FM-100hr %				-0.69				

Gas-phase PB emissions and EF

Table 5 and Fig. 4 show the weighted EF averages from each vegetation plot comparing the untreated control fuels (CTRL) with the hydro-axed fuels (HYAX) for gaseous emissions. For clarity, some species have been reduced to groups, especially for the large number of VOC species determined from the whole air canister samples. LOAg pertains to mainly formic and acetic acids in the gas-phase with corresponding salts in the particle-phase LOAp. The groups of <8C-Alkanes, <5C-Alkenes and <9C-Aromatics are governed by ethane, ethene plus propene, and benzene plus m/p-xylenes, respectively. Note that the most dominant aromatic species, Toluene is graphed individually. The group of Halo-C is dominated by methyl-chloride, a typical biomass burning marker, towering two orders of magnitude above other Halo-C species, while Alkyl-NO3 combustion products are governed primarily by methyl-nitrate followed by a distant ethyl-nitrate (ca. 20-30% of methyl-nitrate). Units are g/kg except for NMHC, which are in g-carbon per kg-fuel mass burned.

Gaseous emissions of NH_3, HNO_x (primarily HONO and HNO_3 secondarily), aromatics (esp. Toluene), and biogenic VOC (LOAg, a-Pinene and Isoprene) are significant. All these gas species are reactive and play important roles in the atmospheric formation of ozone and new particles (inorganics and SOA). It is important to note that these reactive gas species are not only a direct product of combustion, but are also emitted from the underlying soil and leaves during the pre-ignition phase of combustion. These species' EF values also exhibit the biggest variability among the different vegetation plots relative to the longer lived acetylene, 1,3-butadiene and halo-carbons. Values for each individual plot are tabulated in the Supplemental Materials (see Table SM2).

Table 5: Average, standard deviation and relative standard deviation of MCE and EF of gaseous species and compound groups for PB emissions from CTRL and HYAX fuel types of the 5 vegetation plots, in descending order of the overall average.

		CTRL			HYAX			HYAX/
		AVG	STD	RSD	AVG	STD	RSD	CTRL
MCE	-	**0.955**	0.03	0.03	**0.946**	0.02	0.02	0.99
CO2	g/kg	**1450**	77	0.05	**1434**	58	0.04	0.99
CO	g/kg	**43.2**	26.4	0.61	**51.3**	21.2	0.41	**1.19**
NMHC	gC/kg	**2.46**	1.38	0.56	**2.59**	1.30	0.50	1.05
CH4	g/kg	**1.65**	1.34	0.81	**1.83**	1.17	0.64	1.11
<5C Alkenes	g/kg	**0.82**	0.44	0.53	**0.89**	0.45	0.51	1.09
LOAg	g/kg	**0.84**	1.32	1.57	**0.66**	0.50	0.77	**0.78**
<9C Aromatics	g/kg	**0.45**	0.20	0.45	**0.55**	0.33	0.59	**1.24**
<8C Alkanes	g/kg	**0.39**	0.26	0.66	**0.37**	0.18	0.50	0.94
NH3	g/kg	**0.33**	0.12	0.38	**0.29**	0.17	0.57	0.88
HNOx	g/kg	**0.33**	0.38	1.15	**0.27**	0.20	0.74	**0.81**
a-Pinene	g/kg	**0.27**	0.22	0.81	**0.17**	0.11	0.63	**0.66**
Toluene	g/kg	**0.22**	0.12	0.53	**0.23**	0.11	0.48	1.09
Acetylene	g/kg	**0.18**	0.08	0.45	**0.25**	0.14	0.55	**1.35**
Isoprene	g/kg	**0.10**	0.09	0.85	**0.15**	0.12	0.76	**1.48**
SO2	g/kg	**0.09**	0.05	0.62	**0.08**	0.05	0.63	0.95
1,3-Butadiene	g/kg	**0.06**	0.02	0.35	**0.08**	0.05	0.54	**1.42**
Halo-C	g/kg	**0.026**	0.021	0.80	**0.029**	0.007	0.23	1.11
COS	g/kg	**0.007**	0.005	0.75	**0.008**	0.003	0.43	1.14
Alkyl-NO3	g/kg	**9E-04**	1E-03	1.22	**0.001**	7E-04	0.53	**1.46**
DMS	g/kg	**6E-04**	6E-04	1.03	**3E-04**	3E-04	0.83	**0.55**

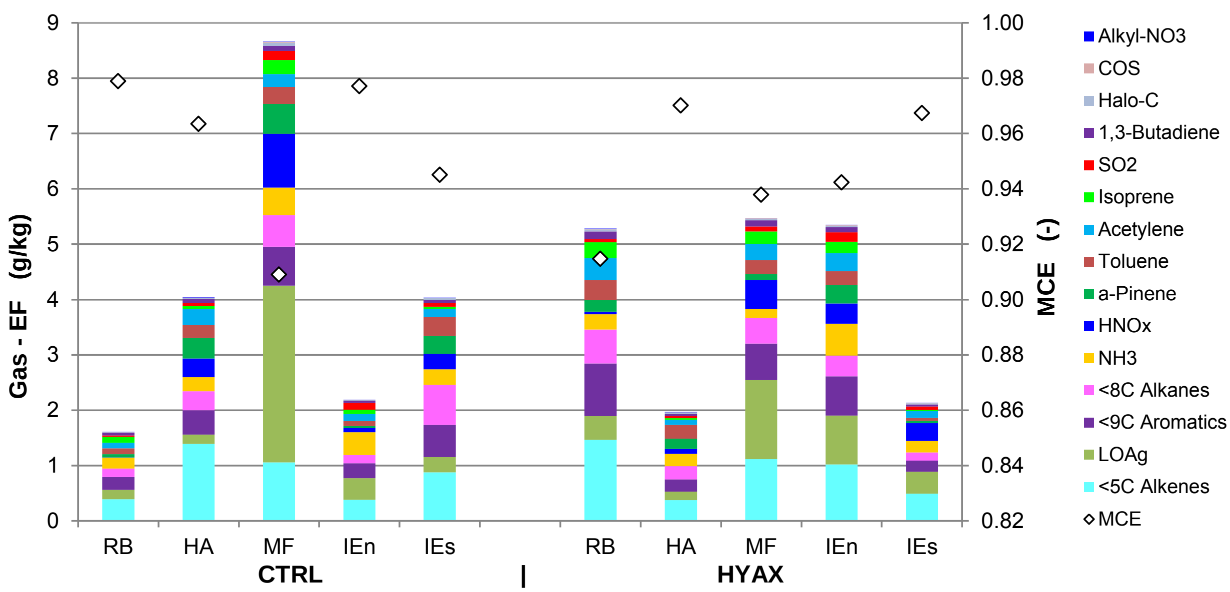

Fig. 4: EF values in g/kg for gaseous species and compound groups from the 5 plots of the two different fuel types. MCE is plotted against the right-hand axis. Numeric values are listed in Table SM2.

Among the 3 sulfur species, SO_2 had an order of magnitude higher emissions than COS, and dimethylsulfide (DMS) being another order of magnitude lower. A biogenic organosulfur compound $(CH_3)_2S$ abundant in the marine environment and produced by degradation of the precursor dimethylsulfoniopropionate (DMSP) emitted by bacteria and phytoplankton in the upper ocean waters, DMS yielded overall lowest EF values. While DMS is thought to have a lifetime of 1-2 days due to heterogeneous photo-oxidation to sulfate aerosol, COS exists in the atmosphere for several years before decomposing to CO_2 and H_2S during plant uptake and deposition to ocean water, respectively.

Table 5 lists the numerical values of the data plotted and quantitatively compares potential treatment effects on average EF by means of the ratio of HYAX to CTRL average EF values (last column). Relative to control, mechanical thinning causes significant EF increases in isoprene, alkyl-nitrates, 1,3-butadiene, acetylene, aromatics and CO, while significantly less DMS, α-pinene, LOAg, and HNO_x are emitted per unit fuel mass burned. Both formic and acetic acids each make up about 50% of the LOA_g emissions for both fuel types (0.84 ±1.3 and 0.66 ±0.5 g/kg for CTRL and HYAX, respectively, with oxalic acid contributing well below 10%) followed by NH_3 with 0.33 ±0.12 and 0.29 ±0.17 g/kg for CTRL and HYAX, and an average NH_3/CO ratio of 15 ±9 and 10 ±5 ppbv/ppmv, respectively. Ammonia emissions are associated with smoldering combustion (Griffith *et al.* 1991; Lacaux *et al.* 1996), and emanate from the degradation of N compounds in the fuel materials. The large variability reflects the variable influence of smoldering emissions in the individual integrated sample, which is also reflected in the MCE values shown in Fig. 4. The NH_3/CO range between 4 and 31 ppbv/ppmv (see Table SM3) confirms the observations from open-path FTIR spectroscopy laboratory experiments of pine needle combustion (Yokelson *et al.* 1996, 1997).

In order to assess plausibility and sensitivity of our results towards fuel mix and conditions, Fig. 5 compares some of our gaseous species EF results with values from different studies cited in the literature (Schauer *et al.* 2001; Sinha *et al.* 2004; Lee *et al.* 2005; Burling *et al.* 2011). Burling *et al*. (2011) report most recent PB measurements made in February and March of 2010 at the MCBCL, the Holly Shelter Game Land (HS) and airborne onboard a Twin Otter aircraft. HS is a 30,000 ha (75,000 acre) SE coastal plain area in Pender county immediately west of MCBCL. For our comparison, we used the average from 5 PB emission samples taken at MCBCL unit ME on March 1st 2010 (in the following abbreviated *PNNL-CL*) and 5 from the 'sand ridge' and adjacent low-lying areas of HS on March 5th 2010 (*PNNL-HS*). The *PNNL-CL* emissions were from: *a*) a recently hydro-axed area with re-sprouted fetterbush shrubs, *b*) an untreated moderate density understory of red bay, red maple, gallberry and fetterbush under a moderate density loblolly pine canopy and, *c*) an area of regrown small shrubs of fetterbush and swamp titi with grasses. The *PNNL-HS* emissions were primarily from PB of pine litter and understory shrubs in a loblolly pine dominated stand.

The airborne measurements (*PNNL-TO*) were made in smoke plumes intercepted between 150 and 1,000 m above the flame front of routine PB applications in managed forests in the MCBCL and HS areas between February 11th and March 5th 2010, including the above burns that were sampled on the ground. Since all reported EF values were based on an assumed 50% carbon content of the consumed fuel mass, we adjusted them here, in order to reflect our assumed 42.6% fuel-C content.

The Lee *et al*. (2005) values (*Pine_GA*) used in our comparison are an average from several ground-based PB experiments carried out in April 2004 at Forts Benning and Gordon in central Georgia. These stands were dominated by a 50/50 mix of loblolly and longleaf pine with a shrub understory and surface fuels comprised primarily of pine needles which carried the fires. EF values reported by Sinha *et al*. (2004) are from prescribed fires in the miombo woodland savanna and the dambo grassland savanna, prevalent savanna types in southern Africa, labeled *Wood_Africa* and *Grass_Africa*. Smoke samples were taken aboard an instrumented research aircraft during the dry season (May-October) of 2000, at ~300 m above ground and between 0.3 and 14 km downwind of the fires. The Schauer *et al*. (2001) values (*Pine_CA*) were obtained from fireplace combustion experiments of western pine wood.

The species and compound groups on the abscissa of Fig. 4 are sorted in descending order of the HYAX values (in red). The large differences in EF(CO) indicate different combustion intensities and efficiencies, hence it is not surprising that the dead stump smoldering during the *PNNL-CL* with the highest EF(CO) caused the lowest average MCE of 0.81 followed by 0.87 and 0.88 from the PB of pine litter and shrubs in *PNNL-HS* and *Pine_GA*. The airborne measurements indicate MCE levels between 0.94 and 0.96, about the same as the average CTRL and HYAX with each 0.95. The fires with the poorest MCE also have the highest average EF values for CH_4, alkenes, acetic acid, NH_3, acetylene, isoprene and 1,3-butadiene. Aircraft derived EF values are lowest for acetic acid, NH_3 and isoprene, which seem to have reacted away in the airborne plumes within the 10 to 30 minutes of average transport times. EF of longer lived species like CH_4, acetylene and CH_3Cl agree well between ground and airborne measurements when the combustion intensity (MCE) is similar. Similar comparisons will be made for particle-phase species in the following section.

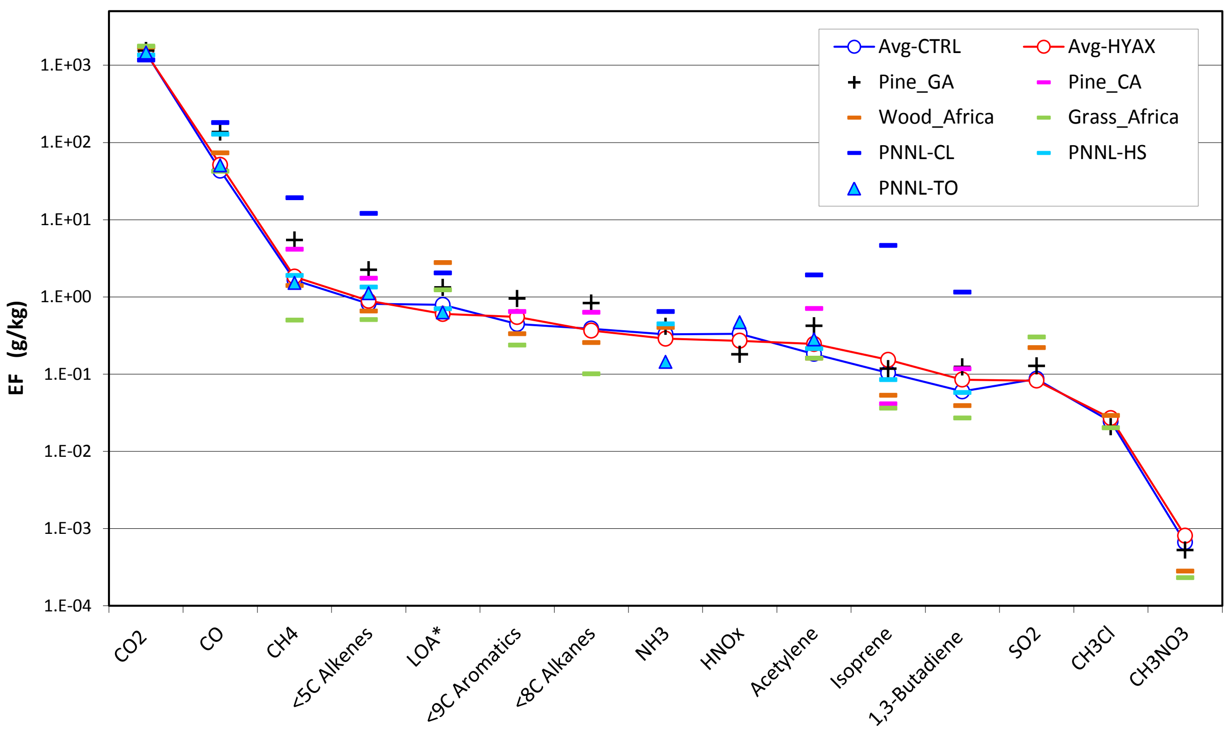

Fig. 5: EF comparison of certain gaseous species and VOC groups from different studies. Here LOA* comprise only formic and acetic acids. *Pine_GA* from Lee *et al.* (2005), *Pine_CA*

from Schauer *et al.* (2001), *Grass/Wood_Africa* from Sinha *et al.* (2004), *PNNL-CL/HS/TO* from Burling *et al.* (2011).

Particle-phase PB emissions and emission factors (EF)

Table 6 and Fig. 6 focus on the particle phase ($PM_{2.5}$) species EF values resulting from the ACM aerosol measurements made at the burn sites. Similar to the gaseous emissions, the large number of POC species determined from quartz filter samples (see Table 2) has been reduced to groups. The table and figure present absolute results in descending order, corresponding to the above profiles for the gaseous species. For clarity in presenting the results, some particulate constituents are combined into different groups; e.g. (*MMO*) is the sum of masses of the oxides of Al, Ca, Fe, K, Si, and Ti in their highest oxidation states, i.e. Al_2O_3, SiO_2, K_2O, CaO, Fe_2O_3, and TiO_2. The group of *Alkali Metals* is comprised of Li +Na +Mg +Rb +Sr +Ba, and the group of *Heavy Metals* reflects the sum of Cr +Mn +Ni +Cu +Zn +As +Se +Cd +Sb +Pb without assuming any oxidation states. As a general rule for either group, values of the less uncertain elements detected via either ICPMS or XRF were used. For example, Na, Mg, Ti, and Cu detected by XRF were only used to compare with other published EF values and not officially reported, due to low fluorescent yields, broad *region of interest* (*ROI*, a sensitivity measure specific to XRF analysis), and/or detection limit issues. Detailed data quality indicators for both XRF and ICPMS analytical methods are presented elsewhere (Baumann *et al*., 2012).

A correction factor to account for OOE was calculated from the $PM_{2.5}$ mass balance and introduced to account for elements associated with the amount of OC measured via TOT off Q filter samples (Birch and Cary 1996). OOE is assumed here to be equal to the amount of unidentified mass, i.e. the difference between the total gravimetric mass and all identified components (ions, metal oxides, other elements, EC and OC). Oxygen is in our case the most important OOE due to its abundance and central role in fuel combustion. Hence, with the sum of OOE plus OC being assumed, total OM in the emitted fine PM, oxygenated carbon species are most likely the ones causing elevated OM. Organic compounds constitute the overwhelming bulk contribution to the fine PM emissions from both fuel types. On average, the OM fraction of total $PM_{2.5}$ mass emitted from both CTRL and HYAX fuels is 96 ±2 % and 94 ±4 %, respectively.

Table 6 compares potential treatment effects on average EF by means of the ratio of the HYAX to CTRL average EF values (last column). Excluding the single outliers for OC/EC and OM/OC in each data set from the 5 fuel plots listed in Table SM3, yields similar averages of OC/EC (24 ±9 and 26 ±20) and OM/OC (1.5 ±0.3 and 1.4 ±0.1) for CTRL and HYAX fuels, respectively. The single OC/EC outliers for CTRL and HYAX (412 and 788, from MF and RB respectively in Table SM3) occurred also for the lowest MCE of 0.91, indicating higher contributions from smoldering emissions, which cause a shift to higher OC and lower EC due to less complete combustion (Khalil and Rasmussen 2003). Most OC/EC values range from 8 to 45 and encompass a range of values found in previous laboratory simulations; i.e. *a*) 6.3 ±9 from fireplace combustion of loblolly and slash pine materials found by Fine *et al*. (2002), *b*) 23.2 ±32determined by Hays *et al*. (2002) in laboratory type simulations of the open burning of loblolly pine and wire grass/loblolly pine needle mix, resembling most closely the fuel burnt in our study, and *c*) 40 ±3 in pine logs fireplace emissions from Schauer *et al*. (2001). Similarly, less intense combustion with lower MCE yields more levoglucosan, causing extremely high levoglucosan/EC ratios for the two poorest combustions (22.1 and 32.8 in Table SM3 for CTRL-MF and HYAX-RB, respectively). The remaining ratios are highly correlated negatively with MCE for both fuel types but especially for the mechanically thinned fuel.

Table 6: EF of $PM_{2.5}$ species and compound groups, plus other calculated values.

		CTRL			**HYAX**			**HYAX/**
		AVG	STD	RSD	AVG	STD	RSD	**CTRL**
$PM_{2.5}$	**g/kg**	**14.96**	17.36	1.16	**12.30**	6.21	0.51	**0.82**
OC	g/kg	**8.14**	8.00	0.98	**8.77**	4.88	0.56	1.08
sum-POC	gC/kg	**1.05**	1.05	1.00	**0.95**	0.50	0.53	0.90
Levoglucosan	gC/kg	**0.486**	0.42	0.87	**0.441**	0.19	0.43	0.91
Resin Acids	gC/kg	**0.252**	0.31	1.24	**0.212**	0.17	0.78	**0.84**
Alkanoic As	gC/kg	**0.146**	0.13	0.92	**0.153**	0.09	0.57	1.05
PAH	gC/kg	**0.074**	0.09	1.25	**0.040**	0.03	0.77	**0.54**
Sterols	gC/kg	**0.028**	0.03	1.03	**0.029**	0.02	0.70	1.03
Alkanes	gC/kg	**0.027**	0.02	0.84	**0.030**	0.02	0.69	1.11
Alkenoic As	gC/kg	**0.020**	0.02	1.24	**0.017**	0.01	0.77	0.87
Dicarbox. As	gC/kg	**0.012**	0.01	0.61	**0.015**	0.00	0.31	**1.22**
LOAp	gC/kg	**0.007**	0.01	1.28	**0.007**	0.00	0.59	0.97
Aromatic CAs	gC/kg	**0.001**	0.00	0.93	**0.001**	0.00	0.53	**0.76**
EC	g/kg	**0.20**	0.18	0.89	**0.28**	0.20	0.71	**1.36**
MMO	g/kg	**0.070**	0.090	1.29	**0.096**	0.068	0.71	**1.37**
K^+	g/kg	**0.031**	0.033	1.08	**0.056**	0.053	0.96	**1.81**
Cl^-	g/kg	**0.051**	0.062	1.20	**0.055**	0.029	0.53	1.07
NO_3^-	g/kg	**0.033**	0.033	1.02	**0.032**	0.021	0.65	0.98
$SO_4^=$	g/kg	**0.016**	0.014	0.87	**0.025**	0.019	0.74	**1.55**
NH_4^+	g/kg	**0.009**	0.006	0.67	**0.012**	0.008	0.64	**1.25**
F^-	g/kg	**0.015**	0.019	1.31	**0.011**	0.006	0.56	**0.73**
Alkali Ms	g/kg	**0.008**	0.008	1.04	**0.011**	0.011	0.98	**1.36**
Heavy Ms	g/kg	**0.008**	0.010	1.32	**0.006**	0.002	0.33	**0.79**
$nonSO_4$-S	g/kg	**0.006**	0.007	1.20	**0.003**	0.002	0.60	**0.59**
sumPOC/OC	%	**12.6**	2.4	0.19	**11.0**	0.7	0.06	0.87
$nonSO_4$-S	%	**54**	8	0.14	**49**	16	0.33	0.91
OOE	g/kg	**6.40**	9.33	1.46	**3.01**	1.59	0.53	**0.47**
OM	g/kg	**14.54**	17.17	1.18	**11.78**	6.27	0.53	**0.81**
OM/OC	-	**1.51**	0.3	0.21	**1.39**	0.1	0.09	0.92
OC/EC	-	**24**	9	0.36	**26**	20	0.76	1.10
NH_3/CO	ppb/m	**15**	9	0.58	**10**	5	0.52	**0.66**

As = Acids, CAs = Carboxylic Acids

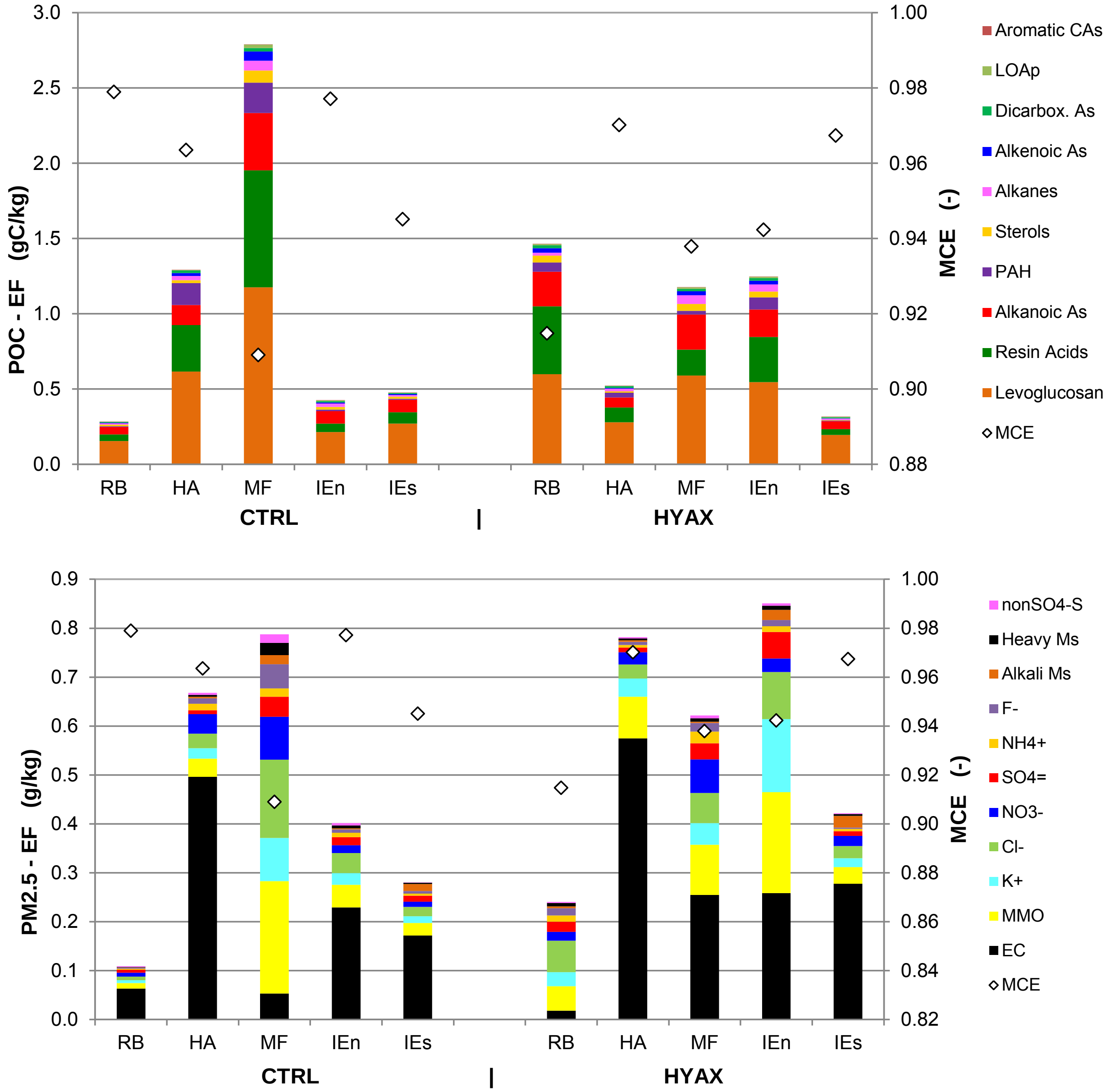

Fig. 6: EF values of $PM_{2.5}$ organic compounds and compound groups in gC/kg (top) and inorganic species and groups (bottom) from the 5 plots of the two different fuel types. MCE is plotted against the right-hand axis. Numeric values are listed in Table SM3.

Table 6 compares potential treatment effects on average EF by means of the ratio of the HYAX to CTRL average EF values (last column). Excluding the single outliers for OC/EC and OM/OC in each data set from the 5 fuel plots listed in Table SM3, yields similar averages of OC/EC (24 ±9 and 26 ±20) and OM/OC (1.5 ±0.3 and 1.4 ±0.1) for CTRL and HYAX fuels, respectively. The single OC/EC outliers for CTRL and HYAX (412 and 788, from MF and RB respectively in Table SM3) occurred also for the lowest MCE of 0.91, indicating higher contributions from smoldering emissions, which cause a shift to higher OC and lower EC due to less complete combustion (Khalil and Rasmussen 2003). Most OC/EC values range from 8 to 45 and encompass a range of values found in previous laboratory simulations; i.e. *a*) 6.3 ±9 from fireplace combustion of loblolly and slash pine materials found by Fine *et al*. (2002), *b*) 23.2 ±32determined by Hays *et al*. (2002) in laboratory type simulations of the open burning of loblolly pine and wire grass/loblolly pine needle mix, resembling most closely the fuel burnt in our study, and *c*) 40 ±3 in pine logs fireplace emissions from Schauer *et al*. (2001). Similarly, less intense combustion with lower MCE yields more levoglucosan, causing extremely high levoglucosan/EC ratios for the two poorest combustions (22.1 and 32.8 in Table SM3 for CTRL-MF and HYAX-RB, respectively). The remaining ratios are highly correlated negatively with MCE for both fuel types but especially for the mechanically thinned fuel.

One important finding is that PB of hydro-axed fuels yields on average 18% less $PM_{2.5}$ emissions (per kg fuel burned) than the PB of control fuels. The lower $PM_{2.5}$ emissions, however, contain ca. 8% more OC, which is the largest contributor to $PM_{2.5}$ mass for both fuel types. The fraction of OC explained by individual POC species is 12.6 ±2 % and 11.0 ±1 % for CTRL and HYAX fuel emissions, respectively. The variability and magnitude in differences among the two fuel types and 5 experiment plots is remarkable, as highlighted by the HYAX/CTRL ratios in the right hand column of Table 6. Considering absolute emissions relative to CTRL, PB of mechanically treated (HYAX) fuels yield on the one hand significantly lower EF values for OOE, PAH, non-sulfate S, fluoride, aromatic carboxylic acids, heavy metals, OM, $PM_{2.5}$ mass and resin acids (governed by dehydroabietic acid), and on the other hand higher EF values for potassium, sulfate, MMO, alkali metals, and EC. The latter species are even more enhanced in the mass fractions of the $PM_{2.5}$ emitted from HYAX fuels due to the 18 % lower EF in $PM_{2.5}$.

Fig. 7 compares the average profile of species emissions relative to $PM_{2.5}$ mass from both fuel types (control and hydro-axed), with profiles from other fuels, sites and studies (Schauer *et al*. 2001; Fine *et al*. 2002; Chow *et al*. 2004; Lee *et al*.; 2005). The figure is organized in descending order of the HYAX (red) profile and illustrates its systematic difference to the CTRL profile resulting from the different fuel treatment. Most elemental and ionic $PM_{2.5}$ fractions from HYAX fuel emissions are higher than those from CTRL fuels, except for calcium and lead. The comparison of several elements detected using both XRF and IC methods show the before-mentioned uncertainties of Na and Mg detection via XRF. But it also shows that mass fractions of other water-soluble elements (i.e. chloride, potassium, sulfate-S, and calcium ions) are consistently lower than the corresponding XRF-totals and are highly correlated across all 20 samples (two per fuel type and plot). This suggests that a significant fraction of those elements is locked up inside the PM matrix, hindering solubility and requiring more rigorous extraction; (e.g. by acid microwave digestion and subsequent ICPMS detection). Reasons for such PM matrix effects are subject to further investigation, helping to inform about certain particle formation during PB.

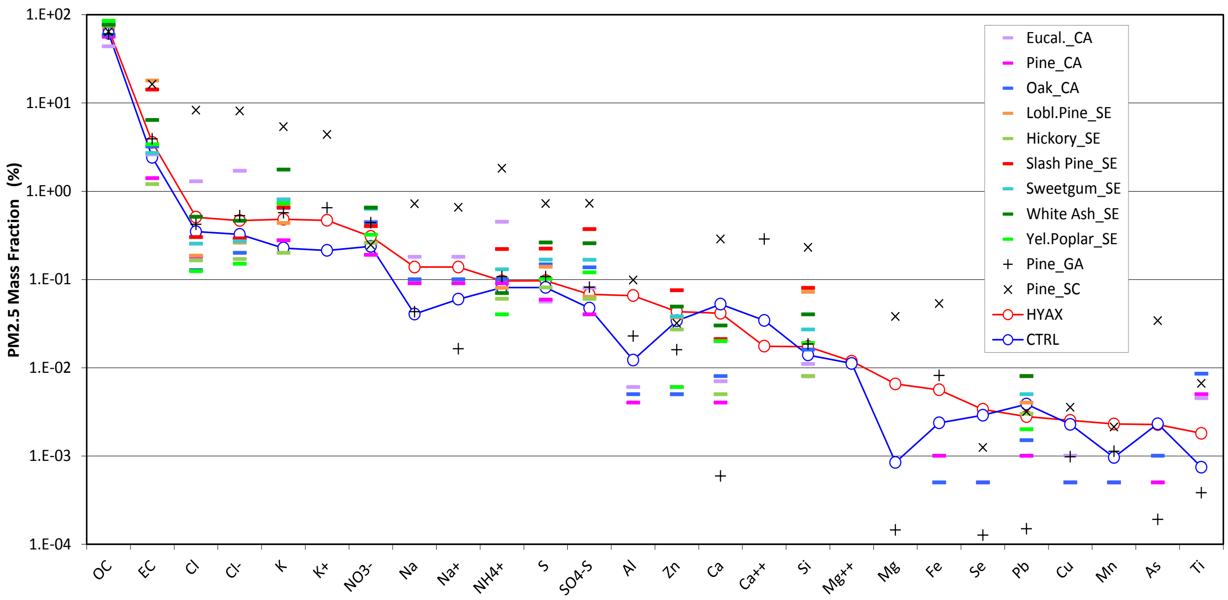

Fig. 7: Comparison of emission profiles relative to $PM_{2.5}$ mass from fuels in California (CA), the Southeastern U.S. (SE), South Carolina (SC) and Georgia (GA).

Fig. 7 also shows $PM_{2.5}$ chemical composition results from four other emission tests, three from fireplace burnings and one from *in situ* PB measurements. Schauer *et al.* (2001) used 3 main soft and hard wood fuel types obtained from the Western U.S. (extension *CA*), whereas Fine *et al*. (2002) and Chow *et al*. (2004) measured fireplace emissions from 6 different fuels of the Southeastern U.S. (*SE*) and from South Carolina (*SC*), respectively. However, similar dilution sampling systems were used by all investigators to simulate cooling and dilution effects of the atmosphere. Lee *et al*. (2005) measured PB emissions in situ during routine applications in longleaf and loblolly pine dominated forests of central GA. Considering the logarithmic scale, the figure exhibits a large variability in $PM_{2.5}$ composition from these different tests, owing to the different fuels, fuel conditions and combustion environments. While OC fractions range between 44 and 100%, fractions of other elements vary up to two orders of magnitude. The 62 and 69 % OC fraction of our average HYAX and CTRL fuel emissions are in the middle of the overall range but our crustal and mineral PM emissions are higher (excl. K and Si). This points to an important difference in fuel mix relative to the other investigations, in that our fuels contained significantly higher amounts of chlorophyll containing materials (leaves and needles), where these minerals (esp. Cl, Al, Zn, Ca) are accumulated in higher biomass concentrations than in woody material.

Fuel treatment effects on combustion (MCE) and emissions (EF)

The following describes the relationships we found between gas and particle-phase species' EF and MCE, comparing effects of the hydro-axed fuel type with those from control. These relationships are based on linear regressions of individual species' or species groups' EF values with the coincident MCE values. Tables SM4 and SM5 in the Supporting Material compare linear correlations among EF values for gaseous and particulate emissions from CTRL and HYAX fuels, respectively, including MCE. Note that in contrast to the fuel related comparisons, for which we used the time-weighted averages of the EF from the two subsequent measurement periods (20-30 minutes flaming dominated followed by the 2-3 hours smoldering dominated phase), here all EF values entered the regressions with MCE individually. Thus, since we are comparing effects from the two different fuel types, each regression is based on 10 data pairs with MCE always assumed to be the independent and EF the dependent variable. A linear regression with n=10 data pairs is statistically significant ($p <$ 0.05) when the Pearson product-moment correlation coefficient r is greater than 0.625 for a positive correlation, smaller than -0.625 for a negative correlation, or when the coefficient of determination R^2 is greater than 0.391. Chemical species yielding a strong negative r (anti-correlated with MCE) point to their preferred formation during the smoldering dominated phase of the combustion process. Other species showing a less negative or even positive r (correlating with MCE) indicate a lower sensitivity to smoldering and instead a greater potential of being formed during flaming.

As expected, EF(CO_2) correlates strongly positive with MCE and EF(CO) strongly negative with the latter relationship being strongest for both fuel types. The only other gaseous species showing a positive correlation for both fuel types are the alkyl nitrates, suggesting their preferred formation under complete combustion conditions during the flaming stage. Except for alkanes and NH_3, the HYAX regression correlations are 'less negative', indicating a lower sensitivity of those species' emissions under combustion conditions that are conducive to smoldering. This is especially true for reactive organic species like α-pinene, toluene and isoprene, although these correlations lack statistical significance. EF slopes of inorganic species' like HONO and SO_2 show a weak trend in change from negative to positive, suggesting that flaming processes may become more important for those species' emissions when the fuel is hydro-axed. Many species that show a statistically significant relationship for the control fuel yield less strong relationships when mechanically thinned fuel is combusted. Besides the before mentioned toluene and isoprene, this is also true for the groups of NMHC, (LOAg), and aromatics; incl. (COS), a relatively long-lived unreactive compound. It is currently unclear why COS emissions become less dependent on MCE when burning hydro-axed fuel. Methyl chloride and the group of halo-carbons in general show similar EF-MCE dependencies for either fuel type.

It is also unclear why isoprene shows a statistically significant positive correlation with COS for both fuel types, while negatively correlated (albeit weakly) with DMS. Treated fuels show isoprene emissions closely related to other VOC species which is not seen in emissions from control fuels, except for 1,3-butadiene and <9C aromatics. On the other hand, isoprene and α-pinene emissions from CTRL fuels correlate positively with some POC species including levoglucosan, whereas HYAX fuels show this only for PAH and resin acids. In contrast to HYAX fuels, levoglucosan emissions from CTRL fuels correlate with combustion intensity, HNOx and particulate PAH but not with SO_2, sulfate and EC as mentioned above.

In summary, while the burning of control fuel yields strong negative correlations for CO, COS, methane, halo-carbons, aromatics, NMHC, toluene, isoprene, alkanes, nitrous and nitric acids, light organic acids, and ammonia, equally significant relationships are found only for CO, methane, halo-carbons, alkanes, and ammonia when hydro-axed fuels are burned; i.e. a largely reduced number of species maintain that strong and consistent decrease in emissions with increasing combustion efficiency. Emissions of more reactive species like toluene, isoprene, light organic and inorganic acids are much more variable and inconsistent among the hydro-axed fuel beds. Fuel specific differences in particle-phase species emissions show similar characteristics. Similar ranking of control fuel emissions shows levoglucosan, various organic acids, OC, $PM_{2.5}$, major ions and MMO exhibiting a strong and consistent decline with increasing MCE. For hydro-axed fuels, however, these relationships are less clear, less consistent and much more variable. Inorganic species and elements tend to even cause a change in slope, showing a trend towards an increase in emissions with increasing MCE, suggesting preferred contributions of these species emissions from flaming combustion of hydro-axed fuels. Only EC shows a positive (albeit weak) correlation with MCE for both fuel types, pointing to its characteristic formation in flaming combustion (Grisdale 1953).

Comparison with EPA Clearinghouse AP-42

Our new EF values for *in situ* PB are compared with corresponding data published by the Emission Factor and Inventory Group (EFIG) from the U.S. EPA Office of Air Quality Planning and Standards (OAQPS). The AP-42 series is the principal means by which EFIG documents its EF library, and EF for wildfires and prescribed burning are published in Chapter 13 of AP-42 (EPA 1996), accessible via http://www.epa.gov/ttn/chief/ap42/ch13/final/c13s01.pdf. Table 7 compares the AP-42 EF for PB of a 65/35 short/long pine needle fuel mix assuming a 2/1 smolder/flaming weighted average, with the correspondingly weighted EF average $PM_{2.5}$, CO, CH_4 and NMHC values for the fuels from our study.

Table 7: Comparison of this study's EF with corresponding AP-42 values (EPA, 1996), incl. EF for total N.

EF	AP-42		CTRL		HYAX		HYAX/
	avg	std	avg	std	avg	std	CTRL
PM2.5, g/kg	**12.0**	5.0	**15.0**	17.4	**12.3**	6.2	0.82
CO, g/kg	**158.0**	83.8	**43.2**	26.4	**51.3**	21.2	1.19
CH4, g/kg	**5.6**	3.2	**1.6**	1.3	**1.8**	1.2	1.11
NMHC, gC/kg	**3.7**	1.8	**2.5**	1.4	**2.6**	1.3	1.05
Total N, g/kg			**1.9**	0.7	**1.7**	0.3	0.93

While the average $PM_{2.5}$ value from our hydro-axed fuel compares well with AP-42, the value from our control fuel is 18 % higher; i.e. in addition to removing three times more fuel, hydro-axing the fuel also bears the benefit of emitting 18 % less $PM_{2.5}$ per mass fuel removed. Both our CO and CH_4 EF are less than a third of the corresponding AP-42 levels, with treated fuels producing 19 and 11 % more CO and CH_4 emissions per mass fuel burned, respectively. The same trend exists for non-methane hydrocarbons (NMHC here used synonymously with

VOC), except that *a*) hydro-axing produces only ~5 % higher NMHC emissions per kg fuel, and *b*) both our fuel types' EF are within 35 % of the AP-42 level.

Although not part of AP-42, EF, values for total nitrogen (N) are listed at the bottom of the table for comparison of its relative magnitude between fuel types. Total N was determined from the sum of all N-containing gas and particle phase species measured. Since NOx emissions were not measured, we assumed them from the linear relationship with MCE for similar fuel given by Burling *et al*. (2011). Nitrogen (N) emissions are in part caused by the N contained in the fuel, and in part dependent on the combustion parameters governing the access of air (hence N_2) to the combusting fuel and the subsequent dissociation of N_2 forming either thermal or prompt NO. Our EF values for total N average for both fuel types very similarly, between 1.7 and 1.9 g/kg with hydro-axed fuel generating on average only 7 % less total N per kg fuel. However, the variability within fuel type is significant, with a systematic shift to higher total N emissions from more pocosin-like (moister) fuel beds. Since both fuel types combusted on average at very similar MCE levels, the 7% lower N emissions per kg treated fuel may indicate lower concentration or combustibility of fuel-N in the hydro-axed fuel, which would point to a greater retention of this nutrient in the mechanically treated fuel.

EF sensitivity to KBDI dryness index

The Keetch-Byram Drought Index (KBDI) is a continuous reference scale for estimating dryness of soil and duff layers that tracks fire danger and thus wildfire intensity and especially severity. The KBDI is an important parameter in the PB decision process of the land managers at MCBLC. A higher value indicates a higher risk of a PB escaping. This index is based on a daily water balance, where a drought factor is balanced with precipitation and soil moisture (assumed to have a maximum storage capacity of 8 inches) and is expressed in hundredths of an inch of soil moisture depletion. The KBDI ranges from 0 to 800, with 0 representing no moisture depletion, and 800 representing absolutely dry conditions. It falls into four categories and on the days when the PB experiments were conducted at the individual research plots RB, HA, MF, IEn, and IEs, the corresponding KBDI values were 107, 56, 79, 94, and 75, respectively, falling all into the lowest category where soil moisture and large class fuel moistures are high and considered to not contribute significantly to fire intensity. Although the KBDI values apply to untreated (CTRL) fuels, we assume the same values for the hydro-axed test plots in the following evaluation. Table 8 shows linear regression statistics between EF and KBDI, assuming EF values of the main pollutant and GHG species emissions (i.e. $PM_{2.5}$, CO_2, CO, CH_4, NMHC and total N) being linearly dependent on the sub-regional KBDI fuel conditions.

Table 8: Linear regression statistics assuming pollutant species' EF dependence on sub-regional KBDI from routine forecasts.

		CTRL				**HYAX**			
		p-val.	R^2	**SLP**	y-ICPT	p-val.	R^2	**SLP**	y-ICPT
PM2.5	g/kg	0.732	0.043	**-0.19**	30.2	0.093	0.616	**0.25**	-8.4

CO2	g/kg	0.484	0.165	**1.61**	1318	0.036	0.762	**-2.61**	1648
CO	g/kg	0.504	0.152	**-0.53**	86.9	0.028	0.793	**0.97**	-28.8
CH4	g/kg	0.354	0.267	**-0.04**	4.6	0.049	0.723	**0.05**	-2.4
NMHC	gC/kg	0.221	0.412	**-0.05**	6.2	0.057	0.701	**0.06**	-2.0
Total N	g/kg	0.906	0.005	**-0.003**	2.1	0.118	0.569	**-0.013**	2.8
MCE	-	0.517	0.144	**0.001**	0.9	0.028	0.792	**-0.001**	1.0

Grey highlights indicate statistical insignificance (p>0.05).

Surprisingly, all species EF except Total N yield a significant relationship for the hydro-axed fuel but not for the control fuel. For KBDI values within the lowest category (where high fuel moistures do not contribute significantly to fire intensity), the mechanical thinning causes a KBDI sensitivity in that decreasing fuel moisture yields significantly increasing levels of $PM_{2.5}$, CO, CH_4 and NMHC per kg consumed fuel. The control fuel shows the opposite trend, although at a level of low statistical significance. Negative slopes are seen for CO_2 and MCE, suggesting that hydro-axed fuels within that highest fuel moisture range combust less efficiently and therefore yield lower CO_2 emissions with lower fuel moistures. The same negative trend can be seen also for total N, possibly owing to the before mentioned hypothesized greater N retention in hydro-axed fuel.

Summary conclusions and implications

Fuel consumption was characterized in experimental research plots that incorporated a midstory removal treatment by Hydro-Ax™ followed by PB, capturing the moisture gradient from semi-mesic loblolly pine forest to wet-mesic loblolly pine forest. Hydro-axe treatment yielded about twice the amount of pre-fire fuel and almost three times more consumption of fuels, especially woody material regardless of fuel moisture. The fuel parameters investigated were the amount of pre-fire fuel, the total and relative amount of fuel consumed,, different fuel moistures, and site hydroperiods reflecting both fuel conditions and vegetation composition. Variations in vegetation type as reflected in CCA or NMS scores and variation in soil characteristics as indicated by soil organic matter content were relatively small and showed no relationship to the emissions of most chemical species. Only a few species' emissions correlated weakly with some of these fuel parameters, in particular the total and relative amount of fuel consumed and different fuel moistures reflecting short-term above ground fuel conditions. The poor correlations of these fuel measures with EF suggest that the encountered small site vegetation variation is not the driving factor in explaining the observed large variability in EF values for most species. Differences in emissions between treatments (control versus hydro-axe) are therefore not confounded by either soil characteristics or vegetation differences, allowing direct comparison of treatment effects on emission factors.

Considering possible effects from the fuel treatment (hydro-axe and control) alone, average gaseous EF from the two treatment types are similar, and EF variability is highest for acidic gases and isoprene. However, $PM_{2.5}$ mass and most $PM_{2.5}$ species EF from hydro-axed fuels are significantly lower than those from untreated control fuels. Therefore, removing a certain targeted amount of standing vegetation by employing hydro-axing prior to PB, provides significant air quality benefits due to lower total $PM_{2.5}$ emissions, although CO, CH_4 and NMHC emissions are slightly enhanced. Comparison with EPA's AP-42 emissions inventory shows that our *in situ* PB emission factors are distinctly lower than the laboratory simulation based AP-42, with similar magnitude only for $PM_{2.5}$ emissions from treated fuel and control fuel being almost 20 % higher. The distinctly lower CO and CH_4 emissions point to our *in situ* combustion process being more effective and complete, which is also indicated by the relatively high MCE of 0.95 for both treated and untreated fuels. Combustion efficiencies which the AP-42 values are based on, are lower (MCE < 0.92), suggesting that access of combustion air to our *in situ* fuel might have been significantly better.

Emission levels of ammonia, certain aromatic and biogenic VOC (α-pinene and isoprene) were significant from all study plots. Ammonia emissions (i.e. EF) are among the largest of all inorganic gas species, exceeded only by CH_4, CO, and CO_2, while α-pinene and isoprene rank 2nd and 9th among all VOC EF. All of these gas species play an important role in the atmospheric formation of ozone and secondary $PM_{2.5}$ (i.e. SOA).

Organic carbon (OC) is the dominant $PM_{2.5}$ constituent in emissions from our burns, followed by elemental carbon (EC), nitrate, potassium and chloride. More volatile OC compounds are being emitted from either fuel type under less efficient (smoldering) combustion conditions, which also promote higher emissions of inorganic constituents like major ions (esp. chloride, nitrate sulfate), major metal oxides, and non-sulfate S. Since other organic elements (OOE); i.e. elements that are associated with OC and are part of the emitted $PM_{2.5}$ organic mass (OM = OC+OOE), also increase with smoldering (i.e. with decreasing combustion efficiency), it is plausible to assume that such conditions are conducive to the formation of highly oxygenated compounds containing N and S similar to compounds found in photo-chemically aged polluted air masses, such as e.g. organosulfates formed by the photo-oxidation of isoprene in the presence of acidified sulfate seed aerosols (Surratt *et al*. 2010). Non-sulfate S constitutes a large fraction of total S in $PM_{2.5}$ emitted from both fuel types but it is currently unknown how the water-insoluble S is embedded in the PM matrix and whether some of it will ultimately oxidize to its highest oxidation state during atmospheric dilution and transport away from the PB source.

Correlations of main pollutant species' EF with the KBDI drought index revealed a somewhat reverse relationship in that mechanical thinning causes a significant increase in emissions of $PM_{2.5}$, CO, CH_4 and NMHC per kg fuel consumed when drought levels increase. The control fuel shows the opposite trend, although at a lower level of statistical significance. The KBDI indicates relative dryness of upper soil and duff layers. The values for our test fuel beds ranged between 56 and 107, all falling into the lowest fire danger category with high soil and fuel moistures limiting fire intensity. Total N emissions correlate negatively with KBDI in that lowest category for both fuel types but at a steeper and statistically more significant slope for hydro-axed fuel, suggesting that volatilization of N is lower in moister fuels and that hydro-axed fuel beds may retain this nutrient better than control fuel beds at any particular fuel moisture level.

From a practical land management perspective, the above results suggest to plan and conduct PB towards the goal of minimum primary $PM_{2.5}$ emissions. The mechanisms involved in forming additional (secondary) $PM_{2.5}$ pollution downwind via complex SOA processes are difficult to predict with the currently available tools. However, the benefit of achieving an almost 20% reduction in primary $PM_{2.5}$ emissions per kg fuel removed when employing Hydro-axing, is significant and important to consider. Since PB effectively removes three times more Hydro-axed fuel than untreated fuel, meteorological conditions conducive for PB should be exploited and PB applied on burn areas with mechanically thinned fuel beds, in order to accelerate necessary forest restoration efforts.

Acknowledgement

Special thanks to Susan Cohen, Daniel Becker, and all staff members from MCBCL's Environmental Management Division for technical and logistical support in the field; to Jeff DeMinter and Steve Geis from UWI Madison for POC analyses and to Brent Love and Simone Meinardi from UC Irvine for VOC analyses; to Brad Edgerton, Brad Gingrey, Chad Haker, Trini and Dave Long from ARA and NCSU for field and lab support; and to Dale Wade retired USDA Forest Service scientist for valuable help in improving this manuscript. Funding was provided by the U.S. Department of Defense (DoD) through its Strategic Environmental Research and Development Program under SERDP Project RC-1413. This publication does not indicate endorsement by DoD, nor should the contents be construed as reflecting the official policy or position of DoD. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by DoD.

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Appendix A. **Acronyms used in this paper**.

ACM = Aerosol composition monitor
Alkyl-NO3 = Alkyl nitrates
AQ = Air quality
ATV = All-terrain vehicle
CCA = Canonical correspondence analysis
COS = Carbonyl sulfide
CTRL = Untreated control plot
DMS = Dimethyl sulfide
EC = Elemental carbon
EF = Emission factor(s)
EPA = U.S. Environmental Protection Agency
FC = Fuel consumption
FM = Fuel moisture
HA = Zone within MCBCL
Halo-C = Halocarbon(s)
HYAX = Plot with mechanically thinned fuel using hydro-ax™
IC = Ion chromatography
ICPMS = Inductively coupled plasma mass spectrometry
IE = Zone within MCBCL
IEn = Zone within MCBCL, northern portion
IEs = Zone within MCBCL, southern portion
LOAg = Light organic acids in the gas phase
LOAp = Light organic acids in the particle phase
MCBCL = Marine Corps base Camp Lejeune
MCE = Modified combustion efficiency
MF = Zone within MCBCL
MMO = Major metal oxides
NAAQS = National Ambient Air Quality Standards,
NMHC = Non-methane hydrocarbon(s)
NMS = Non-metric multidimensional scaling
OC = Organic carbon
OM = Organic matter
OOE = Other organic element(s)
PB = Prescribed burn
$PM_{2.5}$ = Particular matter with aerodynamic diameter less equal to 2.5 microns
POC = Particle-phase organic compound(s)
Q = Quartz
QBQ = Quartz filter behind quartz filter
QBT = Quartz filter behind Teflon filter
RB = Zone within MCBCL
SEUS = Southeastern United States
SOA = Secondary organic aerosol

T = Teflon
TOT = Thermal optical transmission
VOC = Volatile organic compound(s)
WUI = Wildland urban interface
XRF = X-ray fluorescence

Table SM1: Statistically significant Pearson's correlation coefficients (r) between different fuel parameters from within the two fuel types, CTRL in blue and HYAX in red.

Statistical significance at the 95% confidence level was achieved for r > 0.848 based on the 5 samples (vegetation plots) per fuel type.

p<0.05 for r>0.848	CTRL F-Avail_g/m2	FC-Tot_g/m2	FC-Wd_g/m2	FC-Lvs_g/m2	FC-Rel_%	FC-Wd_%	FC-Lvs_%	Soil-OM_%	FM-Duff_%	FM-1hr_%	FM-10hr_%	FM-100hr_%	CCA	NMS
F-Avail_g/m2	1.00												0.89	
FC-Tot_g/m2	0.90	1.00		0.94	0.97		0.92							
FC-Wd_g/m2	0.90	0.96	1.00			0.99		0.85						
FC-Lvs_g/m2				1.00	0.91		0.98			-0.87				
FC-Rel_%					1.00		0.93							
FC-Wd_%					0.98	1.00				0.88				
FC-Lvs_%				0.95			1.00			-0.86				
Soil-OM_%								1.00						
FM-Duff_%									1.00			1.00		
FM-1hr_%	0.90	0.96	0.88						0.86	1.00				
FM-10hr_%											1.00			
FM-100hr_%									1.00	0.89		1.00		
CCA				-0.88			-0.95						1.00	
NMS														1.00
p<0.05 for r>0.848	HYAX F-Avail_g/m2	FC-Tot.g/m2	FC-Wd_g/m2	FC-Lvs_g/m2	FC-Rel.%	FC-Wd_%	FC-Lvs_%	Soil-OM_%	FM-Duff_%	FM-1hr_%	FM-10hr_%	FM-100hr_%	CCA	NMS

Table SM2: EF values (all in g/kg except NMHC is in gC/kg) of gaseous species and compound groups for PB emissions from CTRL and HYAX fuel types of the 5 vegetation plots, in descending order of average EF.

	CTRL RB	CTRL HA	CTRL MF	CTRL IEn	CTRL IEs	HYAX RB	HYAX HA	HYAX MF	HYAX IEn	HYAX IEs
MCE	0.98	0.96	0.91	0.98	0.95	0.91	0.97	0.94	0.94	0.97
CO2	1,515	1,460	1,323	1,504	1,448	1,359	1,490	1,410	1,414	1,495
CO	20.8	35.2	84.3	22.4	53.6	80.6	29.2	59.5	55.1	32.1
NMHC	1.10	2.86	4.39	1.15	2.80	4.03	1.32	3.32	3.20	1.10
CH4	0.53	1.76	3.71	0.36	1.87	3.15	0.56	2.55	2.25	0.62
<5C Alkenes	0.39	1.39	1.05	0.38	0.87	1.46	0.37	1.12	1.02	0.49
LOAg	0.17	0.17	3.20	0.39	0.28	0.43	0.15	1.43	0.88	0.40
<9C Aromats	0.24	0.44	0.70	0.27	0.58	0.95	0.23	0.66	0.71	0.20
<8C Alkanes	0.15	0.34	0.57	0.15	0.72	0.61	0.24	0.46	0.37	0.15
NH3	0.20	0.26	0.50	0.41	0.28	0.28	0.22	0.16	0.58	0.21
HNOx	0.00	0.34	0.97	0.07	0.28	0.05	0.09	0.52	0.37	0.32
a-Pinene	0.06	0.37	0.54	0.03	0.32	0.21	0.18	0.11	0.33	0.04

Toluene	0.11	0.23	0.31	0.09	0.34	0.37	0.25	0.25	0.25	0.05
Acetylene	0.10	0.30	0.24	0.13	0.15	0.40	0.09	0.30	0.33	0.12
Isoprene	0.11	0.04	0.25	0.08	0.04	0.28	0.04	0.22	0.21	0.02
SO2	0.03	0.06	0.16	0.12	0.06	0.06	0.03	0.09	0.17	0.06
1,3-Butadiene	0.04	0.07	0.09	0.04	0.06	0.14	0.04	0.11	0.10	0.04
Halo-C	0.009	0.018	0.059	0.010	0.033	0.037	0.032	0.028	0.026	0.019
COS	0.003	0.007	0.015	0.002	0.006	0.011	0.002	0.009	0.010	0.007
Alkyl-NO3	0.0003	0.0026	0.0009	0.0003	0.0002	0.0008	0.0005	0.0012	0.0015	0.0022
DMS	0.0001	0.0013	0.0001	0.0002	0.0010	0.0004	0.0007	0.0001	0.0002	0.0002

Table SM3: EF of $PM_{2.5}$ species and compound groups, plus other calculated values (see text) from CTRL and HYAX fuel types of the 5 vegetation plots, in descending order of average EF.

		CTRL					HYAX				
		RB	HA	MF	IEn	IEs	RB	HA	MF	IEn	IEs
MCE	-	0.98	0.96	0.91	0.98	0.95	0.91	0.97	0.94	0.94	0.97
PM2.5	**g/kg**	3.15	10.75	45.54	9.52	5.84	18.58	7.00	16.00	15.56	4.39
OC	g/kg	2.28	8.08	21.93	4.66	3.74	14.34	4.82	10.45	11.60	2.62
sum-POC	gC/kg	0.28	1.29	2.79	0.42	0.48	1.47	0.52	1.18	1.25	0.32
Levoglucosan	gC/kg	0.154	0.616	1.175	0.214	0.270	0.598	0.278	0.590	0.546	0.194
Resin Acids	gC/kg	0.044	0.309	0.779	0.055	0.075	0.451	0.098	0.172	0.301	0.039
Alkanoic As	gC/kg	0.049	0.134	0.381	0.083	0.083	0.230	0.067	0.233	0.182	0.053
PAH	gC/kg	0.006	0.145	0.202	0.010	0.007	0.062	0.032	0.024	0.081	0.003
Sterols	gC/kg	0.009	0.020	0.080	0.018	0.014	0.046	0.010	0.046	0.038	0.005
Alkanes	gC/kg	0.010	0.027	0.066	0.023	0.010	0.020	0.017	0.057	0.047	0.010
Alkenoic As	gC/kg	0.004	0.020	0.062	0.006	0.007	0.029	0.005	0.026	0.024	0.001
Dicarbox. As	gC/kg	0.005	0.018	0.022	0.009	0.007	0.019	0.012	0.016	0.018	0.008
LOAp	gC/kg	0.002	0.003	0.023	0.005	0.002	0.009	0.002	0.010	0.009	0.003
Aromatic CAs	gC/kg	0.000	0.002	0.002	0.000	0.000	0.001	0.001	0.001	0.001	0.000
EC	g/kg	0.06	0.50	0.05	0.23	0.17	0.02	0.57	0.25	0.26	0.28
Cl-	g/kg	0.0075	0.0296	0.1599	0.0411	0.0190	0.0643	0.0285	0.0617	0.0960	0.0251
K+	g/kg	0.0058	0.0215	0.0886	0.0236	0.0139	0.0291	0.0372	0.0443	0.1494	0.0182
NO3-	g/kg	0.0083	0.0401	0.0875	0.0162	0.0109	0.0180	0.0250	0.0686	0.0276	0.0208
SO4=	g/kg	0.0055	0.0075	0.0409	0.0162	0.0120	0.0209	0.0095	0.0329	0.0545	0.0094
F-	g/kg	0.0024	0.0110	0.0494	0.0065	0.0053	0.0146	0.0064	0.0177	0.0131	0.0027
NH4+	g/kg	0.0021	0.0136	0.0171	0.0094	0.0045	0.0128	0.0056	0.0236	0.0116	0.0048
nonSO4-S	g/kg	0.0012	0.0042	0.0171	0.0050	0.0005	0.0021	0.0022	0.0058	0.0051	0.0014
MMO	g/kg	0.011	0.037	0.230	0.046	0.025	0.050	0.085	0.103	0.206	0.034
Alkali Ms	g/kg	0.000	0.003	0.019	0.002	0.015	0.004	0.003	0.003	0.021	0.024
Heavy Ms	g/kg	0.001	0.004	0.025	0.005	0.002	0.007	0.004	0.007	0.008	0.004
sumPOC/OC	%	12	16	13	9	13	10	11	11	11	12
nonSO4-S/S	%	40	62	56	48	11	23	41	35	22	31
OOE	g/kg	0.77	2.02	22.92	4.47	1.84	4.02	1.43	4.97	3.26	1.36
OM	g/kg	3.05	10.10	44.85	9.14	5.58	18.37	6.25	15.42	14.86	3.98
OM/OC	-	1.34	1.25	2.05	1.96	1.49	1.28	1.30	1.48	1.28	1.52
OC/EC	-	36	16	412	20	22	788	8	41	45	9
NH3/CO	ppb/m	15	12	10	31	9	6	13	4	17	11

Table SM4a: Statistically significant r-values (in bold) for correlations between MCE and EF for gaseous and particulate emissions from CTRL fuel.

Statistical significance at the 95% confidence level was achieved for r > 0.63 based on 2 EF sets per each of the 5 vegetation plots.

p<0.05 for r>0.63	MCE	CO2	CO	CH4	Isoprene	a-Pinene	Toluene	1,3-Butadiene	Acetylene	<8C Alkanes	<5C Alkenes

MCE		**0.98**	**-1.00**	**-0.93**	**-0.73**	-0.58	**-0.81**	-0.57	-0.20	**-0.71**	-0.37
CO2	**0.98**		**-0.97**	**-0.95**	**-0.72**	-0.62	**-0.75**	-0.54	-0.22	**-0.66**	-0.40
CO	**-1.00**	**-0.97**		**0.92**	**0.73**	0.56	**0.82**	0.59	0.21	**0.72**	0.38
CH4	**-0.93**	**-0.95**	**0.92**		0.56	**0.79**	**0.74**	0.35	0.04	**0.69**	0.29
Isoprene	**-0.73**	**-0.72**	**0.73**	0.56		0.12	0.55	**0.78**	0.43	0.38	0.39
a-Pinene	-0.58	-0.62	0.56	**0.79**	0.12		0.45	-0.20	-0.44	0.57	-0.12
Toluene	**-0.81**	**-0.75**	**0.82**	**0.74**	0.55	0.45		**0.63**	0.35	**0.93**	0.56
1,3-Butadiene	-0.57	-0.54	0.59	0.35	**0.78**	-0.20	**0.63**		**0.85**	0.36	**0.80**
Acetylene	-0.20	-0.22	0.21	0.04	0.43	-0.44	0.35	**0.85**		0.09	**0.91**
<8C Alkanes	**-0.71**	**-0.66**	**0.72**	**0.69**	0.38	0.57	**0.93**	0.36	0.09		0.32
<5C Alkenes	-0.37	-0.40	0.38	0.29	0.39	-0.12	0.56	**0.80**	**0.91**	0.32	
<9C Aromatics	**-0.87**	**-0.85**	**0.88**	**0.72**	**0.74**	0.34	**0.89**	**0.77**	0.50	**0.77**	0.62
LOAg	**-0.65**	**-0.76**	0.62	**0.73**	0.48	**0.64**	0.30	0.08	-0.10	0.37	0.07
Halo-C	**-0.90**	**-0.93**	**0.88**	**0.94**	0.56	**0.75**	**0.70**	0.28	-0.02	**0.71**	0.24
COS	**-0.93**	**-0.96**	**0.92**	**0.91**	**0.77**	0.58	**0.73**	0.60	0.31	0.60	0.51
DMS	-0.27	-0.18	0.29	0.27	-0.21	0.20	0.29	0.11	0.10	0.13	0.30
SO2	-0.30	-0.30	0.31	0.10	0.45	-0.42	0.19	**0.65**	**0.65**	0.01	0.40
NH3	**-0.64**	**-0.63**	**0.65**	0.39	**0.64**	-0.02	0.42	**0.67**	0.50	0.25	0.42
HNOx	**-0.67**	**-0.76**	**0.64**	**0.86**	0.31	**0.87**	0.43	-0.04	-0.24	0.53	-0.02
Alkyl-NO3	0.21	0.10	-0.21	-0.15	-0.03	-0.30	0.00	0.38	**0.76**	-0.15	**0.76**
PM2.5	**-0.75**	**-0.86**	**0.72**	**0.79**	0.56	0.61	0.39	0.25	0.07	0.39	0.19
OC	**-0.79**	**-0.90**	**0.77**	**0.86**	0.61	**0.63**	0.46	0.33	0.15	0.42	0.29
EC	0.17	0.12	-0.16	-0.26	-0.14	-0.40	-0.01	0.37	**0.72**	-0.18	**0.71**
K+	-0.60	**-0.69**	0.59	0.55	0.61	0.08	0.34	0.56	0.51	0.23	0.43
Cl-	-0.62	**-0.72**	0.60	0.59	0.60	0.21	0.32	0.45	0.37	0.27	0.30
F-	**-0.75**	**-0.86**	**0.72**	**0.83**	0.55	**0.64**	0.40	0.24	0.06	0.40	0.20
SO4=	-0.57	**-0.63**	0.56	0.39	0.62	-0.05	0.37	0.61	0.54	0.29	0.44
NO3-	**-0.73**	**-0.82**	**0.72**	**0.81**	0.57	0.58	0.45	0.38	0.18	0.37	0.25
NH4+	-0.42	-0.45	0.43	0.35	0.29	0.10	0.24	0.43	0.39	0.10	0.30
LOAp	**-0.71**	**-0.82**	**0.68**	**0.74**	0.57	0.60	0.35	0.20	0.01	0.39	0.11
nonSO4-S	**-0.70**	**-0.82**	**0.67**	**0.72**	**0.63**	0.49	0.33	0.34	0.19	0.29	0.26
Levoglucosan	**-0.82**	**-0.91**	**0.80**	**0.90**	0.58	**0.64**	0.52	0.39	0.22	0.43	0.40
PAH	-0.57	**-0.66**	0.55	**0.78**	0.22	**0.93**	0.29	-0.12	-0.32	0.33	-0.05
Alkanes	**-0.69**	**-0.80**	**0.67**	**0.65**	**0.72**	0.29	0.41	0.57	0.46	0.31	0.45
Alkanoic Acids	**-0.79**	**-0.90**	**0.77**	**0.81**	**0.64**	0.51	0.48	0.43	0.28	0.41	0.41
Alkenoic Acids	**-0.75**	**-0.87**	**0.72**	**0.86**	0.53	**0.70**	0.42	0.22	0.05	0.41	0.24
Arom Carbo As	**-0.63**	**-0.72**	0.61	**0.82**	0.30	**0.89**	0.37	0.02	-0.16	0.36	0.12
Dicarbo Acids	**-0.77**	**-0.84**	**0.76**	**0.81**	0.51	0.60	0.49	0.43	0.27	0.34	0.43
Sterols	**-0.70**	**-0.79**	**0.69**	**0.65**	**0.72**	0.17	0.44	0.62	0.51	0.32	0.48
Resin Acids	**-0.64**	**-0.75**	0.61	**0.82**	0.34	**0.89**	0.33	-0.06	-0.26	0.39	0.00
MMO	**-0.69**	**-0.80**	**0.66**	**0.72**	0.60	0.40	0.35	0.35	0.23	0.33	0.27
Heavy Ms	-0.54	**-0.64**	0.52	0.55	0.59	0.13	0.29	0.45	0.38	0.22	0.29
Alkali Ms	-0.30	-0.31	0.29	0.38	0.08	0.30	0.49	0.04	-0.03	**0.67**	0.00

Table SM4b: Statistically significant r-values (in bold) for correlations between gaseous and particulate EF from CTRL fuel.

Statistical significance at the 95% confidence level was achieved for r > 0.63 based on two EF sets per each of the 5 vegetation plots.

p<0.05 for r>0.63	<9C Aromatics	LOAg	Halo-C	COS	DMS	SO2	NH3	HNOx	Alkyl-NO3	PM2.5	OC	EC
<9C Aromatics		0.46	**0.72**	**0.83**	0.17	0.40	**0.76**	0.41	0.07	0.61	**0.63**	0.17
LOAg	0.46		**0.86**	**0.75**	-0.24	0.00	0.35	**0.85**	-0.09	**0.94**	**0.92**	-0.21
Halo-C	**0.72**	**0.86**		**0.90**	0.10	-0.01	0.38	**0.84**	-0.19	**0.83**	**0.86**	-0.26

COS	**0.83**	**0.75**	**0.90**		0.15	0.20	0.56	**0.69**	0.05	**0.81**	**0.87**	-0.04
DMS	0.17	-0.24	0.10	0.15		0.00	0.13	-0.04	0.00	-0.11	-0.05	0.28
SO2	0.40	0.00	-0.01	0.20	0.00		**0.71**	-0.06	0.17	0.24	0.26	0.26
NH3	**0.76**	0.35	0.38	0.56	0.13	**0.71**		0.16	-0.01	0.57	0.53	0.32
HNOx	0.41	**0.85**	**0.84**	**0.69**	-0.04	-0.06	0.16		-0.18	**0.85**	**0.87**	-0.38
Alkyl-NO3	0.07	-0.09	-0.19	0.05	0.00	0.17	-0.01	-0.18		-0.03	0.04	**0.79**
PM2.5	0.61	**0.94**	**0.83**	**0.81**	-0.11	0.24	0.57	**0.85**	-0.03		**0.98**	-0.08
OC	**0.63**	**0.92**	**0.86**	**0.87**	-0.05	0.26	0.53	**0.87**	0.04	**0.98**		-0.09
EC	0.17	-0.21	-0.26	-0.04	0.28	0.26	0.32	-0.38	**0.79**	-0.08	-0.09	
K+	0.56	0.60	0.51	0.62	-0.14	**0.77**	**0.66**	0.51	0.22	**0.75**	**0.78**	0.11
Cl-	0.56	**0.71**	0.57	**0.64**	-0.23	**0.68**	**0.66**	**0.63**	0.11	**0.84**	**0.84**	0.01
F-	0.56	**0.94**	**0.85**	**0.82**	-0.12	0.22	0.45	**0.90**	-0.01	**0.98**	**0.99**	-0.16
SO4=	**0.69**	0.54	0.45	0.55	-0.20	**0.76**	**0.86**	0.32	0.16	**0.70**	**0.65**	0.28
NO3-	0.58	**0.65**	**0.66**	**0.75**	0.07	0.43	0.52	**0.80**	0.01	**0.83**	**0.88**	-0.13
NH4+	0.46	0.12	0.14	0.32	0.29	**0.73**	**0.72**	0.27	0.10	0.45	0.45	0.28
LOAp	0.58	**0.95**	**0.81**	**0.77**	-0.23	0.20	0.56	**0.83**	-0.10	**0.99**	**0.95**	-0.14
nonSO4-S	0.60	**0.91**	**0.75**	**0.80**	-0.19	0.33	0.62	**0.76**	0.07	**0.98**	**0.97**	0.00
Levoglucosan	**0.64**	**0.82**	**0.84**	**0.90**	0.13	0.26	0.49	**0.85**	0.11	**0.92**	**0.97**	-0.03
PAH	0.30	**0.71**	**0.72**	**0.64**	0.17	-0.29	0.10	**0.88**	-0.16	**0.73**	**0.75**	-0.27
Alkanes	**0.68**	**0.75**	**0.64**	**0.77**	-0.19	0.58	**0.71**	**0.63**	0.23	**0.89**	**0.90**	0.13
Alkanoic Acids	**0.68**	**0.91**	**0.85**	**0.89**	-0.04	0.31	0.59	**0.77**	0.13	**0.96**	**0.98**	0.04
Alkenoic Acids	0.56	**0.95**	**0.88**	**0.86**	-0.05	0.10	0.40	**0.90**	0.02	**0.96**	**0.99**	-0.13
Arom Carbo As	0.41	**0.72**	**0.75**	**0.73**	0.22	-0.21	0.19	**0.86**	-0.03	**0.77**	**0.80**	-0.14
Dicarbo Acids	**0.65**	0.61	**0.68**	**0.81**	0.36	0.32	0.61	**0.70**	0.12	**0.81**	**0.85**	0.13
Sterols	**0.65**	**0.69**	**0.63**	**0.75**	-0.16	**0.67**	**0.65**	0.57	0.20	**0.81**	**0.85**	0.06
Resin Acids	0.40	**0.89**	**0.84**	**0.74**	0.00	-0.23	0.19	**0.93**	-0.14	**0.86**	**0.87**	-0.27
MMO	0.55	**0.88**	**0.75**	**0.76**	-0.22	0.44	0.53	**0.77**	0.08	**0.93**	**0.94**	-0.08
Heavy Ms	0.44	0.62	0.51	0.57	-0.28	**0.67**	0.46	0.58	0.15	**0.72**	**0.76**	-0.10
Alkali Ms	0.29	0.28	0.38	0.18	-0.27	0.21	-0.04	0.51	-0.11	0.28	0.29	-0.36

Table SM4c: Statistically significant r-values (in bold) for correlations between particulate EF from CTRL fuel.

Statistical significance at the 95% confidence level was achieved for r > 0.63 based on two EF sets per each of the 5 vegetation plots.

p<0.05 for r>0.63	K+	Cl-	F-	SO4=	NO3-	NH4+	LOAp	nonSO4-S	Levoglucosan	PAH
K+		**0.98**	**0.77**	**0.88**	**0.77**	**0.64**	**0.71**	**0.80**	**0.76**	0.23
Cl-	**0.98**		**0.85**	**0.88**	**0.82**	**0.63**	**0.82**	**0.88**	**0.79**	0.35
F-	**0.77**	**0.85**		**0.63**	**0.85**	0.39	**0.96**	**0.96**	**0.95**	**0.75**
SO4=	**0.88**	**0.88**	**0.63**		0.56	0.61	**0.69**	**0.75**	0.57	0.06
NO3-	**0.77**	**0.82**	**0.85**	0.56		**0.72**	**0.78**	**0.83**	**0.91**	**0.72**
NH4+	**0.64**	**0.63**	0.39	0.61	**0.72**		0.39	0.48	0.49	0.24
LOAp	**0.71**	**0.82**	**0.96**	**0.69**	**0.78**	0.39		**0.97**	**0.85**	**0.71**
nonSO4-S	**0.80**	**0.88**	**0.96**	**0.75**	**0.83**	0.48	**0.97**		**0.90**	**0.65**
Levoglucosan	**0.76**	**0.79**	**0.95**	0.57	**0.91**	0.49	**0.85**	**0.90**		**0.77**
PAH	0.23	0.35	**0.75**	0.06	**0.72**	0.24	**0.71**	**0.65**	**0.77**	
Alkanes	**0.92**	**0.95**	**0.87**	**0.86**	**0.85**	0.61	**0.86**	**0.94**	**0.86**	0.46
Alkanoic Acids	**0.81**	**0.85**	**0.96**	**0.73**	**0.80**	0.41	**0.93**	**0.96**	**0.95**	**0.64**
Alkenoic Acids	**0.69**	**0.76**	**0.99**	0.54	**0.83**	0.32	**0.94**	**0.94**	**0.96**	**0.81**
Arom Carbo As	0.31	0.41	**0.78**	0.14	**0.76**	0.31	**0.73**	**0.70**	**0.84**	**0.98**
Dicarbo Acids	**0.65**	**0.67**	**0.79**	0.52	**0.90**	**0.71**	**0.73**	**0.80**	**0.91**	**0.76**

Sterols	**0.98**	**0.96**	**0.83**	**0.86**	**0.78**	0.54	**0.77**	**0.86**	**0.82**	0.31
Resin Acids	0.38	0.51	**0.88**	0.25	**0.72**	0.17	**0.86**	**0.80**	**0.84**	**0.95**
MMO	**0.91**	**0.95**	**0.96**	**0.78**	**0.81**	0.43	**0.91**	**0.94**	**0.88**	0.53
Heavy Ms	**0.96**	**0.95**	**0.78**	**0.76**	**0.76**	0.49	**0.68**	**0.76**	**0.73**	0.26
Alkali Ms	0.39	0.43	0.35	0.29	0.33	0.09	0.29	0.20	0.26	0.09
Alkanes		**0.92**	**0.83**	0.54	**0.78**	**0.95**	0.60	**0.93**	**0.87**	0.27
Alkanoic Acids	**0.92**		**0.96**	**0.71**	**0.81**	**0.89**	**0.79**	**0.95**	**0.77**	0.25
Alkenoic Acids	**0.83**	**0.96**		**0.85**	**0.81**	**0.77**	**0.93**	**0.91**	**0.69**	0.28
Arom Carbo As	0.54	**0.71**	**0.85**		**0.83**	0.40	**0.94**	0.57	0.31	0.06
Dicarbo Acids	**0.78**	**0.81**	**0.81**	**0.83**		**0.68**	**0.73**	**0.70**	0.55	0.04
Sterols	**0.95**	**0.89**	**0.77**	0.40	**0.68**		0.48	**0.94**	**0.95**	0.37
Resin Acids	0.60	**0.79**	**0.93**	**0.94**	**0.73**	0.48		**0.70**	0.41	0.19
MMO	**0.93**	**0.95**	**0.91**	0.57	**0.70**	**0.94**	**0.70**		**0.91**	0.41
Heavy Ms	**0.87**	**0.77**	**0.69**	0.31	0.55	**0.95**	0.41	**0.91**		0.51
Alkali Ms	0.27	0.25	0.28	0.06	0.04	0.37	0.19	0.41	0.51	

Table SM5a: Statistically significant r-values (in bold) for correlations between MCE and EF for gaseous and particulate emissions from mechanically thinned HYAX fuel.

Statistical significance at the 95% confidence level was achieved for r > 0.63 based on 2 EF sets per each of the 5 vegetation plots.

p<0.05 for r>0.63	MCE	CO2	CO	CH4	Isoprene	a-Pinene	Toluene	1,3-Butadiene	Acetylene	<8C Alkanes	<5C Alkenes
MCE		**0.95**	**-1.00**	**-0.89**	-0.09	-0.01	-0.32	-0.10	-0.05	**-0.94**	-0.39
CO2	**0.95**		**-0.95**	**-0.93**	-0.26	-0.03	-0.42	-0.30	-0.30	**-0.95**	-0.59
CO	**-1.00**	**-0.95**		**0.88**	0.08	0.01	0.31	0.08	0.04	**0.93**	0.38
CH4	**-0.89**	**-0.93**	**0.88**		0.49	0.21	0.58	0.42	0.35	**0.93**	**0.68**
Isoprene	-0.09	-0.26	0.08	0.49		0.40	**0.76**	**0.86**	**0.75**	0.37	**0.84**
a-Pinene	-0.01	-0.03	0.01	0.21	0.40		0.46	-0.10	-0.15	0.18	0.04
Toluene	-0.32	-0.42	0.31	0.58	**0.76**	0.46		0.58	0.43	0.57	0.62
1,3-Butadiene	-0.10	-0.30	0.08	0.42	**0.86**	-0.10	0.58		**0.94**	0.31	**0.92**
Acetylene	-0.05	-0.30	0.04	0.35	**0.75**	-0.15	0.43	**0.94**		0.22	**0.90**
<8C Alkanes	**-0.94**	**-0.95**	**0.93**	**0.93**	0.37	0.18	0.57	0.31	0.22		0.58
<5C Alkenes	-0.39	-0.59	0.38	**0.68**	**0.84**	0.04	0.62	**0.92**	**0.90**	0.58	
<9C Aromatics	-0.09	-0.23	0.08	0.42	**0.88**	**0.73**	**0.70**	0.56	0.47	0.38	**0.64**
LOAg	-0.34	-0.44	0.33	0.42	0.41	-0.17	0.13	0.53	0.49	0.45	0.55
Halo-C	**-0.87**	**-0.71**	**0.88**	**0.68**	-0.15	0.11	0.26	-0.26	-0.38	**0.77**	-0.02
COS	-0.26	-0.41	0.25	0.52	**0.68**	0.31	0.28	0.59	0.60	0.37	**0.71**
DMS	-0.03	-0.16	0.02	-0.09	-0.33	0.03	-0.07	-0.24	-0.04	0.01	-0.10
SO2	0.14	-0.06	-0.15	-0.07	0.05	-0.44	-0.21	0.39	**0.63**	-0.18	0.33
NH3	**-0.72**	**-0.74**	**0.72**	0.51	-0.27	0.04	-0.04	-0.23	-0.06	0.60	0.09
HNOx	0.21	0.20	-0.21	-0.10	0.22	-0.41	-0.25	0.39	0.30	-0.20	0.16
Alkyl-NO3	0.30	0.31	-0.30	-0.28	-0.12	-0.28	-0.51	0.00	0.04	-0.43	-0.12
PM2.5	-0.52	**-0.73**	0.51	**0.68**	0.59	-0.03	0.59	**0.74**	**0.79**	**0.66**	**0.90**
OC	-0.46	**-0.70**	0.44	0.61	0.48	-0.04	0.45	**0.65**	**0.77**	0.56	**0.80**
EC	0.09	-0.10	-0.10	-0.17	-0.24	-0.17	-0.24	-0.03	0.21	-0.08	0.04
K+	0.05	-0.17	-0.06	0.02	0.11	-0.29	-0.03	0.38	**0.63**	-0.06	0.36
Cl-	-0.24	-0.46	0.22	0.36	0.30	-0.35	0.20	0.61	**0.79**	0.24	**0.66**
F-	-0.31	-0.55	0.30	0.45	0.50	-0.29	0.40	**0.78**	**0.84**	0.45	**0.82**
SO4=	**-0.67**	**-0.74**	**0.66**	0.62	0.02	-0.37	0.08	0.27	0.40	0.54	0.43
NO3-	0.06	-0.14	-0.07	0.06	0.19	-0.47	-0.03	0.53	0.58	0.02	0.44
NH4+	**-0.68**	**-0.76**	**0.68**	**0.79**	0.35	-0.23	0.38	0.52	0.46	**0.72**	**0.67**
LOAp	-0.51	**-0.72**	0.49	**0.75**	**0.76**	0.23	**0.65**	**0.77**	**0.78**	**0.70**	**0.94**
nonSO4-S	0.42	0.16	-0.43	-0.20	0.22	-0.24	-0.03	0.47	**0.66**	-0.33	0.37

Levoglucosan	-0.30	-0.53	0.29	0.34	0.15	-0.34	0.10	0.46	**0.65**	0.33	0.56
PAH	-0.45	-0.43	0.45	0.56	0.34	**0.88**	0.54	-0.11	-0.16	0.54	0.14
Alkanes	-0.18	-0.39	0.16	0.29	0.25	-0.29	0.06	0.51	**0.63**	0.23	0.52
Alkanoic Acids	**-0.65**	**-0.82**	**0.64**	**0.69**	0.32	-0.29	0.30	0.57	**0.64**	**0.69**	**0.73**
Alkenoic Acids	-0.21	-0.45	0.20	0.42	0.59	-0.32	0.41	**0.87**	**0.92**	0.34	**0.84**
Arom Carbo As	-0.46	-0.61	0.45	0.34	-0.13	-0.26	0.03	0.13	0.32	0.42	0.33
Dicarbo Acids	-0.35	-0.56	0.34	0.31	-0.01	-0.19	0.05	0.23	0.45	0.35	0.41
Sterols	-0.14	-0.39	0.12	0.34	0.52	-0.35	0.31	**0.83**	**0.91**	0.26	**0.79**
Resin Acids	-0.60	**-0.64**	0.59	**0.78**	0.56	**0.70**	**0.72**	0.25	0.20	**0.71**	0.52
MMO	0.03	-0.21	-0.05	0.00	0.07	-0.27	-0.05	0.35	0.59	-0.01	0.35
Heavy Ms	0.06	-0.19	-0.08	0.10	0.20	-0.28	0.08	0.49	**0.71**	-0.03	0.52
Alkali Ms	0.23	0.24	-0.22	-0.11	0.11	**0.76**	-0.09	-0.29	-0.26	-0.21	-0.19

Table SM5b: Statistically significant r-values (in bold) for correlations between gaseous and particulate EF from mechanically thinned HYAX fuel.

Statistical significance at the 95% confidence level achieved for r > 0.63 based on two EF sets per each of the 5 vegetation plots.

p<0.05 for r>0.63	<9C Aromatics	LOAg	Halo-C	COS	DMS	SO2	NH3	HNOx	Alkyl-NO3	PM2.5	OC	EC
<9C Aromatics		0.28	-0.08	**0.66**	-0.15	-0.16	-0.11	-0.08	-0.26	0.46	0.36	-0.14
LOAg	0.28		0.04	0.32	-0.26	0.39	0.22	0.57	-0.20	0.40	0.47	0.14
Halo-C	-0.08	0.04		-0.08	-0.07	-0.49	0.56	-0.32	-0.34	0.11	0.03	-0.34
COS	**0.66**	0.32	-0.08		-0.01	0.17	0.13	0.21	0.39	0.57	0.55	0.07
DMS	-0.15	-0.26	-0.07	-0.01		0.26	0.55	-0.58	-0.06	0.29	0.44	**0.87**
SO2	-0.16	0.39	-0.49	0.17	0.26		0.23	0.32	0.18	0.38	0.58	0.60
NH3	-0.11	0.22	0.56	0.13	0.55	0.23		-0.39	-0.24	0.39	0.52	0.49
HNOx	-0.08	0.57	-0.32	0.21	-0.58	0.32	-0.39		0.50	-0.16	-0.09	-0.22
Alkyl-NO3	-0.26	-0.20	-0.34	0.39	-0.06	0.18	-0.24	0.50		-0.23	-0.17	-0.01
PM2.5	0.46	0.40	0.11	0.57	0.29	0.38	0.39	-0.16	-0.23		**0.94**	0.34
OC	0.36	0.47	0.03	0.55	0.44	0.58	0.52	-0.09	-0.17	**0.94**		0.55
EC	-0.14	0.14	-0.34	0.07	**0.87**	0.60	0.49	-0.22	-0.01	0.34	0.55	
K+	-0.06	0.29	-0.37	0.25	0.40	**0.94**	0.35	0.19	0.17	0.47	**0.68**	**0.63**
Cl-	0.03	0.28	-0.16	0.43	0.37	**0.79**	0.36	0.08	0.14	**0.78**	**0.87**	0.51
F-	0.28	0.54	-0.11	0.50	0.32	0.57	0.27	0.14	-0.05	**0.91**	**0.92**	0.49
SO4=	-0.21	0.43	0.40	0.17	0.12	0.58	**0.67**	0.10	-0.07	0.55	**0.66**	0.22
NO3-	-0.05	0.59	-0.39	0.25	0.28	**0.64**	0.05	0.46	0.15	0.45	0.59	0.59
NH4+	0.13	0.60	0.42	0.25	-0.08	0.19	0.34	0.12	-0.33	**0.67**	**0.63**	0.02
LOAp	**0.70**	0.52	0.10	**0.75**	0.15	0.28	0.34	-0.06	-0.22	**0.94**	**0.89**	0.23
nonSO4-S	0.05	0.18	**-0.74**	0.22	0.43	**0.78**	-0.09	0.17	0.16	0.41	0.56	**0.68**
Levoglucosan	0.00	0.47	-0.11	0.33	0.57	**0.75**	0.55	0.01	-0.05	**0.76**	**0.90**	**0.77**
PAH	0.61	-0.08	0.52	0.32	0.02	-0.43	0.38	-0.49	-0.38	0.14	0.12	-0.23
Alkanes	0.05	**0.70**	-0.20	0.36	0.32	**0.77**	0.38	0.40	0.06	0.56	**0.77**	0.62
Alkanoic Acids	0.14	**0.66**	0.26	0.44	0.28	0.51	0.60	0.11	-0.15	**0.85**	**0.90**	0.44
Alkenoic Acids	0.27	0.56	-0.19	0.52	0.10	**0.65**	0.11	0.36	0.08	**0.82**	**0.85**	0.32
Arom Carbo As	-0.12	0.18	0.15	0.18	**0.79**	0.48	**0.75**	-0.37	-0.15	**0.69**	**0.78**	**0.79**
Dicarbo Acids	-0.01	0.33	-0.01	0.27	**0.76**	**0.64**	**0.72**	-0.24	-0.13	**0.70**	**0.85**	**0.86**
Sterols	0.22	0.58	-0.29	0.47	0.19	**0.74**	0.13	0.33	0.06	**0.80**	**0.85**	0.45
Resin Acids	**0.70**	-0.01	0.51	0.51	0.03	-0.30	0.35	-0.49	-0.37	0.53	0.42	-0.22
MMO	-0.03	0.35	-0.39	0.26	0.60	**0.88**	0.42	0.10	0.10	0.53	**0.75**	**0.83**
Heavy Ms	0.02	0.15	-0.44	0.29	0.53	**0.80**	0.21	-0.06	0.05	**0.66**	**0.77**	**0.69**
Alkali Ms	0.43	-0.38	-0.15	0.44	0.05	-0.32	-0.05	-0.20	0.34	-0.29	-0.26	-0.10

Table SM5c: Statistically significant r-values (in bold) for correlations between particulate EF frommechanically thinned HYAX fuel.

Statistical significance at the 95% confidence level was achieved for r > 0.63 based on two EF sets per each of the 5 vegetation plots.

p<0.05 for r>0.63	K+	Cl-	F-	SO4=	NO3-	NH4+	LOAp	nonSO4-S	Levoglucosan	PAH
K+		**0.86**	**0.63**	0.61	0.56	0.12	0.37	**0.72**	**0.78**	-0.25
Cl-	**0.86**		**0.85**	**0.73**	0.61	0.47	**0.64**	**0.68**	**0.88**	-0.20
F-	**0.63**	**0.85**		0.53	**0.75**	0.61	**0.82**	0.61	**0.88**	-0.19
SO4=	0.61	**0.73**	0.53		0.34	**0.67**	0.44	0.17	**0.68**	0.02
NO3-	0.56	0.61	**0.75**	0.34		0.49	0.39	**0.77**	**0.77**	-0.53
NH4+	0.12	0.47	0.61	**0.67**	0.49		**0.63**	0.14	0.55	0.05
LOAp	0.37	**0.64**	**0.82**	0.44	0.39	**0.63**		0.33	**0.64**	0.35
nonSO4-S	**0.72**	**0.68**	0.61	0.17	**0.77**	0.14	0.33		**0.70**	-0.45
Levoglucosan	**0.78**	**0.88**	**0.88**	**0.68**	**0.77**	0.55	**0.64**	**0.70**		-0.22
PAH	-0.25	-0.20	-0.19	0.02	-0.53	0.05	0.35	-0.45	-0.22	
Alkanes	**0.78**	**0.75**	**0.78**	**0.63**	**0.88**	0.53	0.55	**0.68**	**0.88**	-0.23
Alkanoic Acids	0.56	**0.77**	**0.88**	**0.79**	**0.65**	**0.80**	**0.78**	0.36	**0.88**	-0.02
Alkenoic Acids	**0.70**	**0.87**	**0.95**	0.57	**0.74**	0.58	**0.76**	**0.63**	**0.79**	-0.23
Arom Carbo As	0.57	**0.71**	**0.69**	0.60	0.49	0.43	0.51	0.44	**0.88**	-0.06
Dicarbo Acids	**0.71**	**0.76**	**0.75**	0.61	0.60	0.42	0.58	0.58	**0.95**	-0.05
Sterols	**0.74**	**0.88**	**0.95**	0.55	**0.82**	0.58	**0.72**	**0.75**	**0.86**	-0.31
Resin Acids	-0.13	0.13	0.17	0.20	-0.35	0.34	**0.66**	-0.26	0.03	**0.88**
MMO	**0.94**	**0.82**	**0.72**	0.51	**0.70**	0.16	0.43	**0.78**	**0.89**	-0.27
Heavy Ms	**0.77**	**0.88**	**0.74**	0.46	**0.68**	0.36	0.51	**0.90**	**0.85**	-0.30
Alkali Ms	-0.23	-0.35	-0.45	-0.48	-0.47	-0.55	-0.06	-0.18	-0.42	0.56
Alkanes		**0.80**	**0.80**	0.60	**0.75**	**0.85**	-0.10	**0.85**	**0.69**	-0.37
Alkanoic Acids	**0.80**		**0.81**	**0.77**	**0.80**	**0.81**	0.26	**0.63**	0.59	-0.49
Alkenoic Acids	**0.80**	**0.81**		0.50	0.59	**0.98**	0.11	**0.69**	**0.71**	-0.44
Arom Carbo As	0.60	**0.77**	0.50		**0.96**	0.56	0.14	**0.72**	**0.69**	-0.32
Dicarbo Acids	**0.75**	**0.80**	0.59	**0.96**		**0.67**	0.12	**0.85**	**0.77**	-0.26
Sterols	**0.85**	**0.81**	**0.98**	0.56	**0.67**		0.03	**0.77**	**0.80**	-0.46
Resin Acids	-0.10	0.26	0.11	0.14	0.12	0.03		-0.16	-0.01	0.35
MMO	**0.85**	**0.63**	**0.69**	**0.72**	**0.85**	**0.77**	-0.16		**0.82**	-0.24
Heavy Ms	**0.69**	0.59	**0.71**	**0.69**	**0.77**	**0.80**	-0.01	**0.82**		-0.27
Alkali Ms	-0.37	-0.49	-0.44	-0.32	-0.26	-0.46	0.35	-0.24	-0.27	

Data assimilation of fuel moisture in WRF-SFIRE

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Abstract: Fuel moisture is a major influence on the behavior of wildland fires and an important underlying factor in fire risk. We present a method to assimilate spatially sparse fuel moisture observations from remote automatic weather stations (RAWS) into the moisture model in WRF-SFIRE. WRF-SFIRE is a coupled atmospheric and fire behavior model which simulates the evolution of fuel moisture in idealized fuel species based on atmospheric state. The proposed method uses a modified trend surface model to estimate the fuel moisture field and its uncertainty based on currently available observations. At each grid point of WRF-SFIRE, this information is combined with the model forecast using a nonlinear Kalman filter, leading to an updated estimate of fuel moisture. We demonstrate the effectiveness of the method with tests in two real-world situations: a region in Southern California, where two large Santa Ana fires occurred recently, and on a domain enclosing Colorado.

Introduction

The WRF-SFIRE model (Mandel *et al*. 2011) couples an established model of the atmosphere (WRF) (Skamarock *et al.* 2008), together with a model simulating fire behavior (SFIRE). Both components are connected via physical feedbacks — weather conditions enter the fire model and the emitted heat and vapor fluxes enter the weather model and directly perturb the state of the atmosphere in the vicinity of the fire. WRF-SFIRE has evolved from CAWFE (Clark *et al.* 2004). Similar models include MesoNH-ForeFire (Filippi *et al.* 2011). Recently, the WRF-SFIRE code has been extended by a fuel moisture model and coupled with the emissions model in WRF-Chem (Kochanski *et al.* 2012; Mandel *et al.* 2012). The current code and documentation are available from OpenWFM.org. A version from 2010 is distributed with the WRF release as WRF-Fire (Coen *et al.* 2012; OpenWFM 2012).

The behavior of fire is highly sensitive to fuel moisture content. Evaporation of moisture in the fire consumes heat, which cannot then contribute to fire propagation. With increasing fuel moisture content, the spread rate decreases, and eventually, at the extinction moisture level, the fire does not propagate at all (Pyne *et al*. 1996). The fuel moisture content depends on vegetation properties and on atmospheric conditions.

This paper reports on an effort to use fuel moisture observations supplied by remote automatic weather stations (RAWS) to adjust the state of the fuel moisture model in WRF-SFIRE.

Methods

The moisture model

The fuel moisture model in WRF-SFIRE (Kochanski *et al.* 2012; Mandel *et al.* 2012) simulates N_k idealized, homogeneous fuel species. Such fuel species are commonly referred to by their drying/wetting time lag T_k as 1-hour, 10-hour, and 100-hour fuel (Pyne *et al.* 1996). The moisture content in each idealized fuel species is simulated on a coarse grid, while the actual fuel used in the fire propagation is a mixture of these species on a much finer grid, where the fire simulation takes place. At each point of the coarse grid, the moisture content of each fuel species is simulated independently by a first order differential equation with time lag T_k. The solution of the differential equation approaches asymptotically an equilibrium fuel moisture content. The equilibrium depends on atmospheric conditions (temperature, relative humidity, pressure) and on whether the current fuel moisture approaches the equilibrium from above (drying) or from below (wetting). If the fuel moisture is between the drying and the wetting equilibria, it does not change. The effect of rain is modeled by the same type of time-lag equation, with the time lag value dependent on the rain intensity.

Denote the fuel moisture content of the k-th idealized fuel species with time lag T_k by m_k, stored as a dimensionless proportion of kg of water per kg of wood. The fuel moisture model is described mathematically by the ordinary differential equation

$$\frac{d}{dt} m_k = \begin{cases} \frac{S - m_k(t)}{T_r}\left(1 - \exp\left(\frac{r(t) - r_0}{r_k}\right)\right) & \text{if } r(t) > r_0 \text{ (soaking in rain),} \\ \frac{E_d(t) - m_k(t)}{T_k} & \text{if } r(t) \le r_0,\ m_k(t) > E_d(t) \text{ (drying),} \\ \frac{E_w(t) - m_k(t)}{T_k} & \text{if } r(t) \le r_0,\ m_k(t) < E_w(t) \text{ (wetting),} \\ 0 & \text{otherwise,} \end{cases} \qquad (0.1)$$

where $E_d(t)$ is the drying equilibrium, $E_w(t)$ is the wetting equilibrium, S is the rain saturation level, r_0 is the threshold rain intensity, $r(t)$ is the current rain intensity, r_k is the saturation rain intensity, T_k is the drying/wetting time lag, and T_r is the asymptotic soaking time lag in very high-intensity rain. The fuel coefficients T_k, r_k, and r_0 can be specified for each idealized fuel class by the user. By default, the equilibria $E_d(t)$ and $E_w(t)$ are computed from WRF atmospheric variables at the Earth surface following the Canadian fire danger rating model (Van Wagner and Pickett 1985). In particular, $E_d(t) - E_w(t) > 0$ is constant. For the rain regime, by default, the equilibrium is taken as $S = 2.5$ and the coefficients T_r, r_0, and r_k were identified to match the behavior of the fuel soaking in rain in Van Wagner and Pickett (1985). The differential equation is solved by a numerical method exact for any length of the time step for constant coefficients. This is important because fuel moisture modeling may be done on a much larger time scale (hours) than fire behavior modeling (seconds) (See Kochanski *et al.* (2012) for further details).

The present method assimilates observations into current fuel moisture level $m_k(t)$ and the equilibria $E_d(t)$, $E_w(t)$, and S. We postpone the reasons for not assimilating the time lags to the discussion. Since the equilibria are computed from external quantities, a standard solution is to extend the state of the model to also contain perturbations of the equilibria. Adding the perturbations to the model (0.1), we get an extended dynamical system for the variables m_k, ΔE, and ΔS,

$$\frac{d}{dt}m_k = \begin{cases} \dfrac{S + \Delta S(t) - m_k(t)}{T_r}\left(1 - \exp\left(\dfrac{r(t) - r_0}{r_k}\right)\right) & \text{if } r(t) > r_0 \\ \dfrac{E_d(t) + \Delta E(t) - m_k(t)}{T_k} & \text{if } r(t) \le r_0,\ m_k(t) > E_d(t) + \Delta E(t) \\ \dfrac{E_w(t) + \Delta E(t) - m_k(t)}{T_k} & \text{if } r(t) \le r_0,\ m_k(t) < E_w(t) + \Delta E(t) \\ 0 & \text{otherwise,} \end{cases} \quad (0.2)$$

$$\frac{d}{dt}\Delta E = 0,$$

$$\frac{d}{dt}\Delta S = 0.$$

We write the discretization of the extended model (0.2) as

$$\mathbf{m}(t_{i+1}) = f(\mathbf{m}(t_i), E_d(t_i), E_w(t_i), r(t_i)), \quad (0.3)$$

where the extended fuel moisture model state is

$$\mathbf{m}(t_i) = (m_1(t_i), m_2(t_i), \ldots, m_{N_k}(t_i), \Delta E(t_i), \Delta S(t_i)). \quad (0.4)$$

The introduction of the shared assimilated parameters ΔE and ΔS transforms the isolated equations for each fuel species into a coupled system. The coupling provides a natural pathway for propagating observation-based state updates from the observed fuel species to the unobserved species within the dynamical model. The effect of data assimilation of 10-hr fuel moisture observations on other types of fuel (1-hr, 100-hr) will be investigated elsewhere, whereas in this paper we focus on the effect of data assimilation on the model state of the 10-hr fuel.

Extended Kalman Filter

We use the Extended Kalman Filter (EKF) (Simon 2010, §13.2.3) to assimilate independently the fuel moisture field at each grid point as estimated by the trend surface model presented in the next section. At each time step, the EKF combines the extended moisture model state $\mathbf{m}(t)$ given by (0.4) with the information given by the moisture data and its variance.

The EKF tracks the evolution of the state mean and covariance, assuming that the initial state was normally distributed, $\mathbf{m}(t_0) \sim \mathrm{N}\,(\mathbf{m_0}, P_0)$. As the initial state $\mathbf{m_0}$, we use the equilibrium moisture at t_0, which is computed from WRF variables, and estimated covariance P_0. Subsequently, we model the evolution of the fuel moisture using the function f from (0.3) with the Jacobian

$$J_f(t_i) = \nabla f(\mathbf{m}(t_{i-1}), E_d(t_{i-1}), E_w(t_{i-1}), r(t_{i-1})).$$

The observation operator is $g(\mathbf{m}(t_i)) = m_l(t_i)$, and its Jacobian is

$$J_g(t_i) = \nabla g(\mathbf{m}(t_i)) = (0, \ldots, 1, \ldots 0),$$

where 1 is at the position of the observed fuel species in the extended state vector. The EKF first predicts the new mean and variance of the model state as

$$\begin{aligned}\hat{\mathbf{m}}(t_i) &= f(\mathbf{m}(t_{i-1}), E_d(t_{i-1}), E_w(t_{i-1}), r(t_{i-1})) \\ \hat{P}(t_i) &= J_f(t_{i-1}) P(t_{i-1}) J_f^T(t_{i-1}) + Q,\end{aligned}$$

where Q is the process noise covariance. If no observations of fuel moisture are available at t_i, then the predicted mean and covariance become the mean and covariance of the state distribution in the next time step,

$$\mathbf{m}(t_i) = \hat{\mathbf{m}}(t_i), \quad P(t_i) = \hat{P}(t_i).$$

If, however, observations $\mathbf{d}(t_i)$, with error covariance S_i, are available, then the mean and covariance of the state are updated according to the formulas

$$\begin{aligned}
K(t_i) &= \hat{P}(t_i) J_g^T(t_i) \left(J_g(t_i) \hat{P}(t_i) J_g^T(t_i) + S_i \right)^{-1} \\
\mathbf{m}(t_i) &= \hat{\mathbf{m}}(t_i) - K(t_i)(g(\hat{\mathbf{m}}(t_i)) - \mathbf{d}(t_i)) \\
P(t_i) &= \left(I - K J_g(t_i) \right) \hat{P}(t_i).
\end{aligned}$$

Transporting of observations to grid points

We use a variant of the trend surface modeling approach (Schabenberger and Gotway 2005, §5.3.1) to transport observed information across space from the RAWS locations to each grid point. We prefer this method to a full universal kriging approach and argue our viewpoint in the discussion section. The assumed form of fuel moisture observation $\mathbf{Z}(s)$ at location s is

$$\mathbf{Z}(s) = \boldsymbol{\beta}_1 \mathbf{X}_1(s) + \cdots + \boldsymbol{\beta}_k \mathbf{X}_k(s) + e(s) = \mathbf{x}(s)\boldsymbol{\beta} + e(s),$$

where the fields $\mathbf{X}_j$, called covariates, are known at every location s, $\boldsymbol{\beta}_j$ are unknown regression coefficients, the error $e(s)$ is independent at each grid point and $\mathbf{x}(s) = [\mathbf{X}_1(s), \mathbf{X}_2(s), \ldots, \mathbf{X}_k(s)]$ is a row vector of covariates at location s. The error $e(s)$ is assumed to have zero mean and consist of an independent observation error with variance $\gamma^2(s)$, assumed to be known, and an unobservable microscale variability with variance σ^2, which is the same at every location s (Cressie 1993). We write the observation model in compact matrix form,

$$\mathbf{Z} = \mathbf{X}\boldsymbol{\beta} + e, \; e \sim \mathrm{N}(0, \Sigma), \quad \Sigma = \Gamma + \sigma^2 I. \qquad (0.5)$$

where $\Gamma = \mathrm{diag}\left(\gamma^2(s)\right)$.

The coefficients $\boldsymbol{\beta}_k$ and the microscale variability variance σ^2 are estimated from the data. Given the microscale variance σ^2, observations $\mathbf{Z}_\mathbf{s}$, and covariates $\mathbf{X}_\mathbf{s}$ at the same locations $\mathbf{s}=(s_1,s_2,\ldots,s_n)$, the regression coefficients $\hat{\boldsymbol{\beta}}$ are determined from weighed least squares as

$$\hat{\boldsymbol{\beta}}=(\mathbf{X}_\mathbf{s}^\mathrm{T}\Sigma_\mathbf{s}^{-1}\mathbf{X}_\mathbf{s})^{-1}\mathbf{X}_\mathbf{s}^\mathrm{T}\Sigma_\mathbf{s}^{-1}\mathbf{Z}_\mathbf{s}, \qquad (0.6)$$

where $\Sigma_\mathbf{s}$ is the submatrix of the covariance matrix corresponding to the locations of the observations. To estimate the microscale variability variance σ^2, we numerically solve the equation

$$\sum_{i=1}^{n}\frac{\hat{e}\left(s_i\right)^2}{\gamma^2\left(s_i\right)+\hat{\sigma}^2}=n-k \qquad (0.7)$$

for $\hat{\sigma}^2$, where $\hat{e}_i\left(s_i\right)=\hat{\mathbf{Z}}(s_i)-\mathbf{x}\left(s_i\right)\hat{\boldsymbol{\beta}}$ are the regression errors at location s_i. Both $\hat{\beta}$ and $\hat{\sigma}^2$ are found by an iterative method starting from $\hat{\sigma}^2=0$: In each iteration, the method first computes $\hat{\boldsymbol{\beta}}$ from (0.6) and then $\hat{\sigma}^2$ from (0.7). The observation $\mathbf{d}(t_i)$ injected into the EKF at the grid point s is then $\mathbf{x}\left(s\right)\hat{\boldsymbol{\beta}}$, with the estimated variance

$$\hat{\sigma}^2+\mathbf{x}\left(s\right)(\mathbf{X}\left(\mathbf{s}\right)^\mathrm{T}\Sigma\left(\mathbf{s}\right)^{-1}\mathbf{X}(\mathbf{s}))^{-1}\mathbf{x}\left(s\right)^\mathrm{T}.$$

Mathematical derivation and properties of this estimator will be studied elsewhere.

We use up to $k=8$ covariates X_i. Some of the covariates can be omitted by the user. The most important covariate is the current forecast of fuel moisture from the WRF-SFIRE moisture model. Additionally, three other variables are extracted from WRF: the temperature at 2 m, the surface pressure and the current rain intensity, all strongly affecting the fuel moisture equilibrium. These covariates capture the effect of local atmospheric state on the evolution of fuel moisture and thus can be expected to approximate the spatial structure of the fuel moisture field. The remaining four covariates are constant in time and model the effects of spatial and topographical features on fuel moisture. They are latitude, longitude, elevation of each grid point, and a constant vector. The latitude and longitude facilitate modeling of domain-scale spatial linear trends. The elevation accounts for the effect of terrain profile on fuel moisture, and the constant covariate allows for the adjustment of a mean difference between the model and the observation stations. The strategy of using multiple covariates in the model aims to capture as much of the spatial structure in the deterministic component of the model as possible since the random component of a trend surface model does not account for any spatial dependence structure.

Results

We have performed two case studies. For the first one, the region of Southern California has been selected, where two massive Santa Ana fires (Witch Creek and Guejito) burned 56,796 ha in October 2007, leading to $18M in damage and two fatalities (Keeley *et al*. 2009). For the second test case, a period of six consecutive days was selected with the domain covering the State of Colorado, with no fire. The two case studies use the WRF-SFIRE model based on WRF 3.3 and WRF 3.4 configurations, respectively. No data assimilation has been performed in the atmospheric model, which was initialized and driven by the North American Regional Reanalysis (Mesinger *et al*. 2006).

WRF output data was stored in 10 minute intervals, which was also the time step for the moisture model in the presented test cases. In the data assimilation step, all observations within 30 min of the current time were gathered and processed. Larger time windows have a smoothing character, while smaller time windows produce more time-resolved snapshots of the fuel moisture field but introduce larger variance into the data assimilation step as fewer observations enter the assimilation step at each time point. The 30-min assimilation window was selected as a balance between the two requirements based on multiple simulations with different time windows.

The RAWS which supplied fuel moisture observations have 10-hr fuel stick sensors and their observations and metadata were obtained from the MesoWest[1] website. The fuel moisture observations are provided as the number of grams of water in 100 g of pine wood. Before assimilation, these are rescaled to a dimensionless value in the range 0 to 1, in order to match the representation of the fuel moisture in the model.

As data on the variance of fuel moisture observations from RAWS was not available, a constant variance of $\gamma^2(s) = 0.01^2$ was attributed to each observation, which corresponds to a standard deviation of 0.01. In future, it is expected that more accurate data differentiating the quality of measurements from RAWS will be available. When available, this information can then be directly used by the current method.

The assimilation algorithm uses the full set of eight covariates in the trend surface model in both simulations. During the simulation, $N_k = 3$ idealized fuel species were modeled: 1-hr, 10-hr and 100-hr fuel. We focus on reporting the results obtained for the 10-hr fuel.

The Kalman filter was initialized at each grid point with the equilibrium fuel moisture at the time of the start of the simulation with $P_0 = 0.01I$, indicating a high uncertainty in the initial state. The process noise covariance for the ten minute time step was chosen as

$$Q = \mathrm{diag}(1\times10^{-4}, 5\times10^{-5}, 1\times10^{-5}, 5\times10^{-5}, 5\times10^{-5})$$

[1] http://mesowest.utah.edu/

Southern California

The San Diego area of Southern California has been selected to test the applicability of the algorithm, as a region experiencing frequent severe wildfires associated with Santa Ana events. During these periods, strong Santa Ana winds bring very hot and dry air from the Nevada desert, rapidly reducing the fuel moisture and increasing fire danger. This test case presents an example of a realistic application of the fuel moisture data assimilation algorithm. The objective is to spin-up the fuel moisture content prior to a fire simulation and increase the accuracy of fire moisture and fire spread forecasts. With this in mind, the spin-up time should be short, so as not to impact the total spin-up time of the model prior to ignition, as simulating fire behavior is computationally demanding.

The simulation was performed for a period from 7/21/2007 12:00 UTC to 7/24/2007 12:00 UTC in a 4-domain configuration. The outer domain (d01), responsible for resolving the large-scale flow responsible for generating the Santa Ana winds, had a resolution of 36km and covered a region of 4320×3072 km. A set of 3 finer domains has been nested within this domain, in order to gradually provide more detailed representation of the terrain and meteorological conditions in the area of interest. The nested domains (d02, d03 and d04) had resolutions of 12 km, 4 km and 1.33 km respectively (see Fig. 1). The 3D atmospheric state was resolved on a vertically-stretched grid, with 37 levels of gradually decreasing vertical resolution — from 20 to 500 m. The domain nesting used in this study is shown in Fig. 1.

Hourly fuel moisture observations were available from ten RAWS located in the domain d04 as shown in Fig. 2. Only the RAWS station Palomar Mountain (PAMC1) had missing values in the simulated time period – 17 observations.

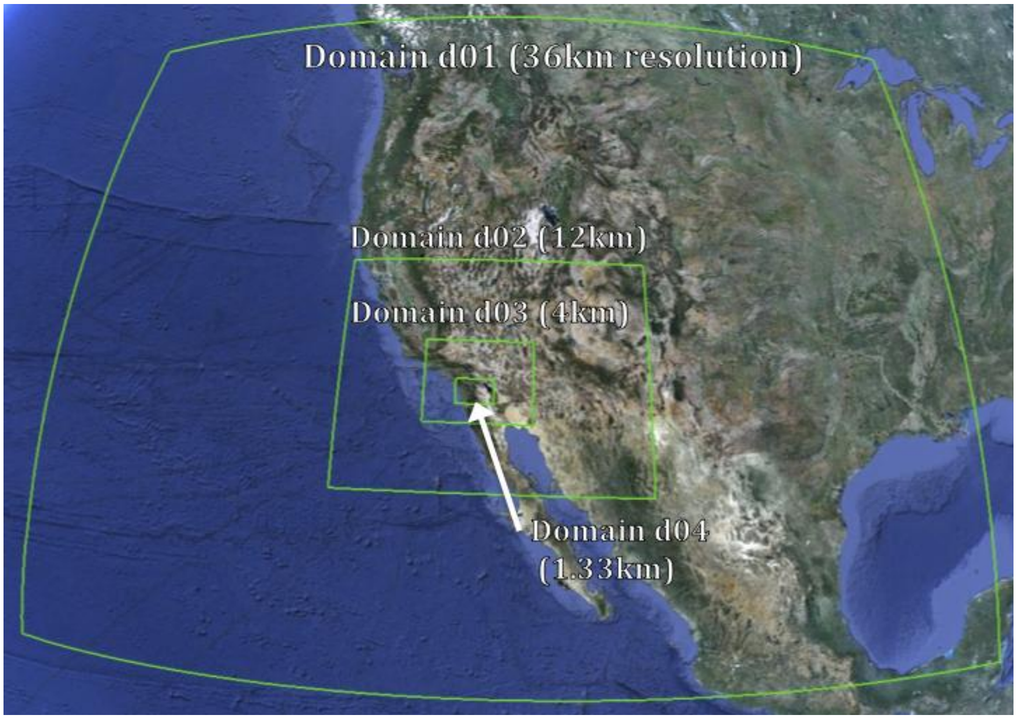

Fig. 1: The nested domain configuration for the Southern California simulation**.**

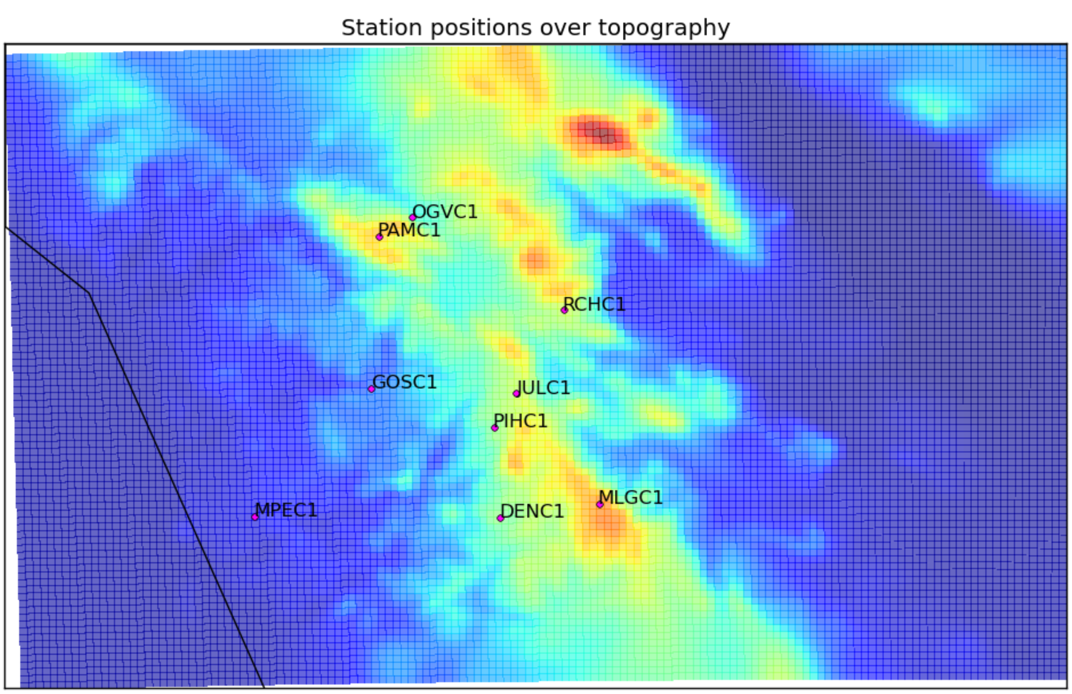

Fig. 2: Positions of stations supplying fuel moisture observations in the domain d04 overlaid on topography.

The estimates of microscale variability variance are in the bottom panel of Fig. 3. The estimates of the microscale variability are initially high as WRF itself spins up and the spatial structure of the fuel moisture field in WRF is initialized from equilibrium conditions. After about 4 h, the microscale variability variance stabilizes and does not increase above 0.005. The mean square differences of the assimilated model state and station observations and of the model with no assimilation and the station observations are shown in Fig. 3, top panel. At the time the microscale variability variance stabilizes, the mean squared difference between the observations also reaches its stable value.

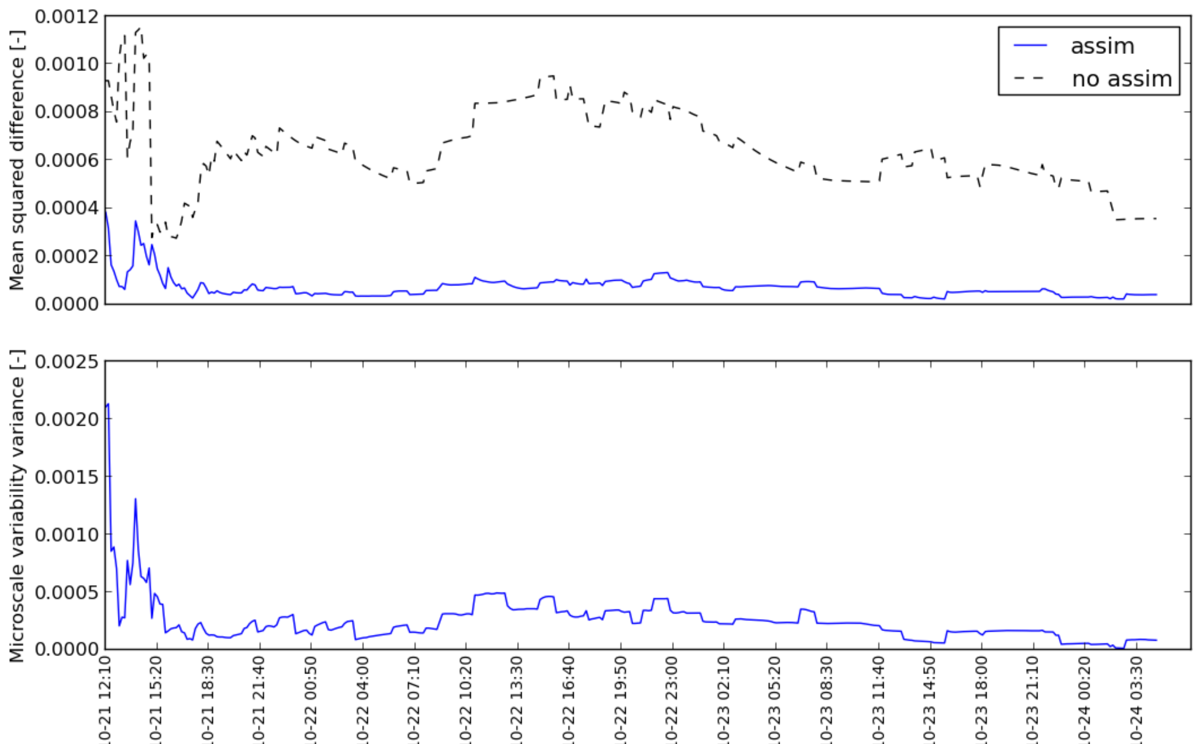

Fig. 3: The mean square differences between non-assimilated and assimilated fuel moisture state estimates and RAWS observations (top) and microscale variability variance estimates as a function of time (bottom) for the Southern California test.

An example 10-hr fuel moisture distribution map obtained towards the end of the simulated timespan is shown in Fig. 4.

We summarize that in this study the spin-up time was short (4 h) and it will not impact the total spin-up time of the fire simulation prior to fire ignition. The data assimilation method was able to reduce the difference between observations and model forecasts substantially. While in this study, the number of covariates ($k = 8$) was close to the number of RAWS stations observed, there were no apparent issues of numerical stability.

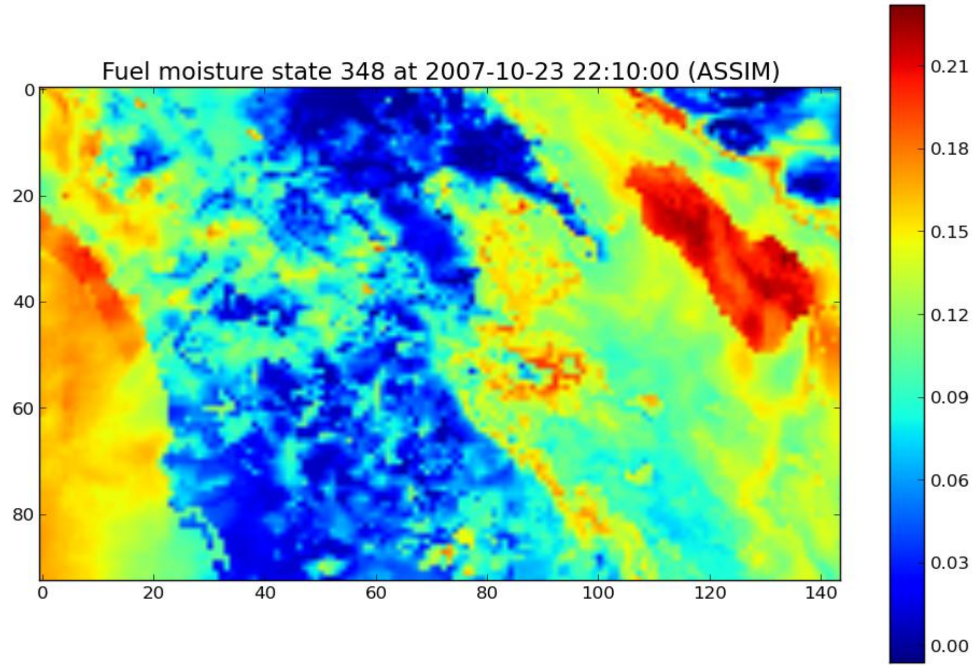

Fig. 4: A fuel moisture map of the 10-hr idealized fuel species obtained during the Southern California simulation run. In the bottom left part of the image, the coastline is clearly visible and in the top right corner of the image, the Salton Sea is prominent. Time is in UTC.

Colorado

The Colorado experiment was selected as a large-scale scenario representing the use case where the presented algorithm will be applied to estimate moisture content of dead fuel operationally for the purposes of fire risk estimation. Colorado presents a difficult challenge for any data assimilation algorithm, as an area experiencing complex weather patterns. The interactions between the synoptic flow and Colorado's mountainous landscape lead to local weather conditions with strong spatial variations. The dramatic changes in elevation and insolation translate into significant near-ground moisture and temperature variations across relatively small spatial distances, which are often too fine to be captured by a relatively coarse grid of a mesoscale model. The sharp gradients in meteorological variables due to high spatial variability of the meteorological fields and topography may also numerically destabilize the model and deteriorate the quality of weather forecasts. Colorado also often experiences severe droughts that lead to high fire danger and severe fires (like the Fourmile Canyon Fire (2010) and Waldo Canyon Fire (2012)), which makes it a suitable site for testing and deployment of fuel moisture assimilation algorithms.

The WRF simulation was run from 6/1/2013 00:00 UTC to 6/6/2013 00:00 UTC in a single domain configuration covering Colorado with a 2 km grid with 264 x 200 nodes. Observations were obtained from a total of 42 RAWS in the Colorado area positioned as shown in Fig. 5. This set of RAWS was selected out of a total of 52 RAWS listed as active in the Colorado area on the MesoWest website after removing stations yielding suspicious data (sensors yielding only one value indicating possible damage) and stations that supplied no observations in the given timespan. The 10-hr fuel moisture observations from the RAWS were supplied hourly.

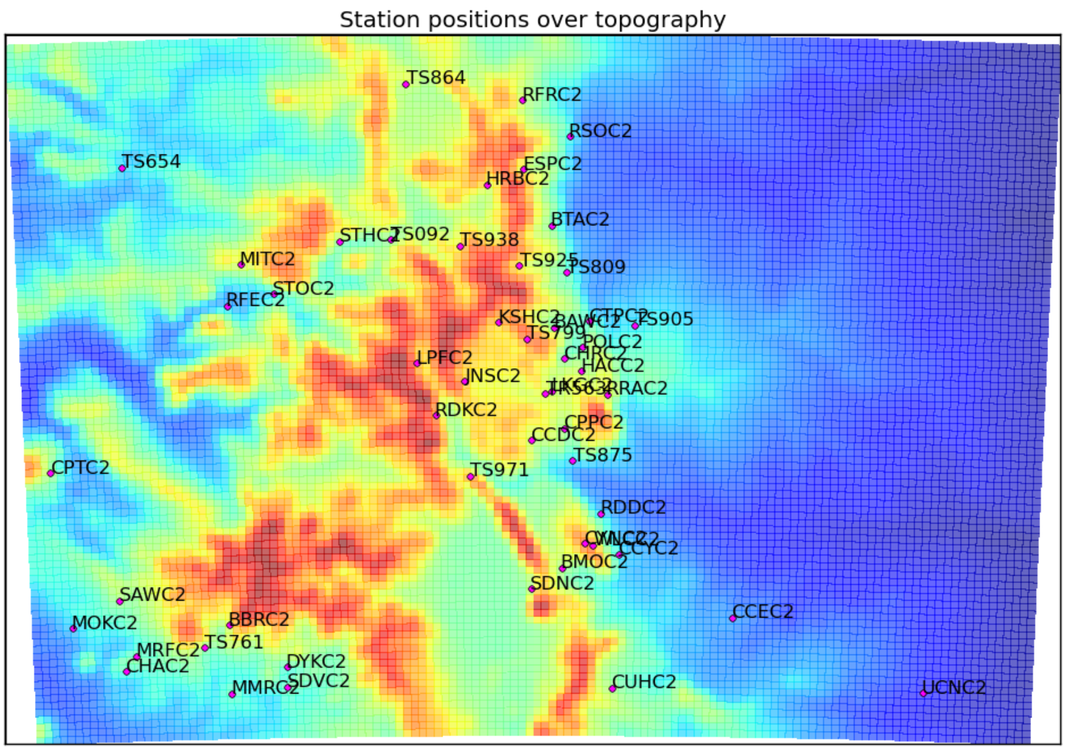

Fig. 5: Positions of stations supplying fuel moisture observations overlaid on Colorado topography.

The estimates of microscale variability are shown in Fig. 6, bottom panel. There are three spikes in the microscale variability coinciding with precipitation events captured by WRF-SFIRE. At 2 km spatial resolution, the simulation may not resolve these structures sufficiently, in addition to being possibly inaccurate without data assimilation in the atmospheric state. The trend surface model uses covariates obtained from the WRF model and it is thus unable to immediately capture the local changes in fuel moisture caused by precipitation. The estimates of microscale variability variance are thus increased in these episodes, which increases the uncertainty of the fuel moisture values from the trend surface model entering the extended Kalman filters at each grid location.

The mean square differences of the assimilated model state and station observations are shown in Fig. 6, top panel. As in the Southern California test case, it is clear that the mean square differences are substantially reduced even during precipitation events. An example fuel moisture map for 10-hr fuel is shown in Fig. 7.

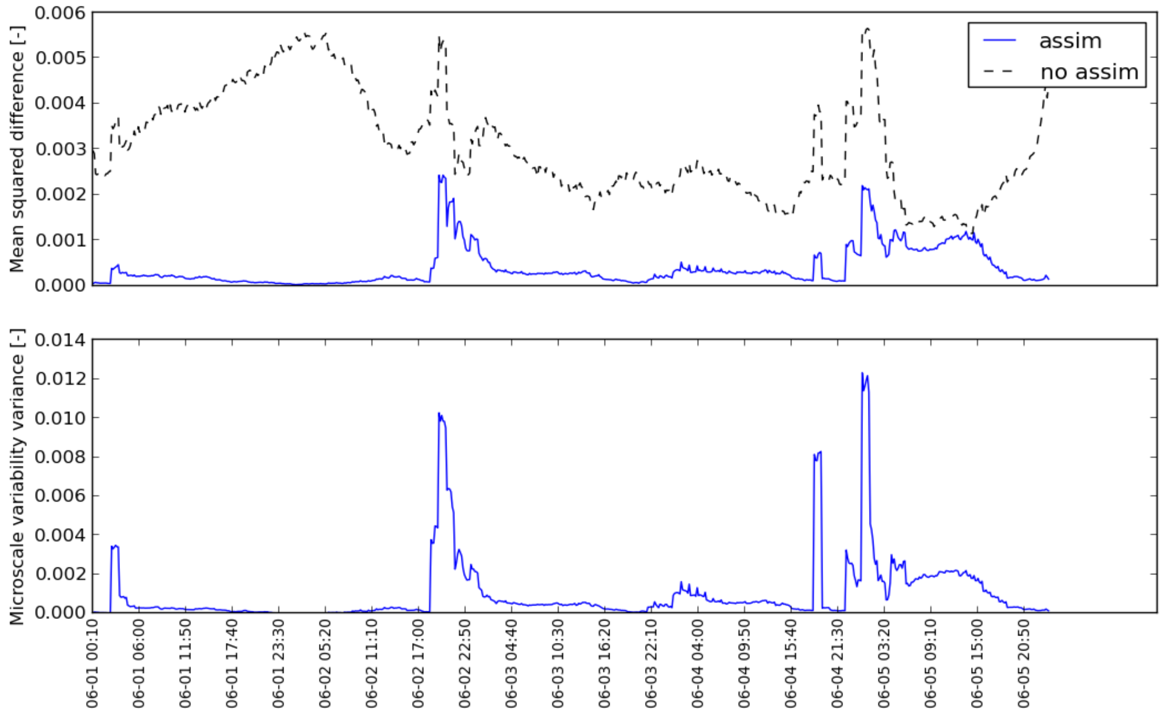

Fig. 6: The mean square differences between non-assimilated and assimilated fuel moisture state estimates and RAWS observations (top) and microscale variability variance estimates as a function of time (bottom) for the Colorado test case.

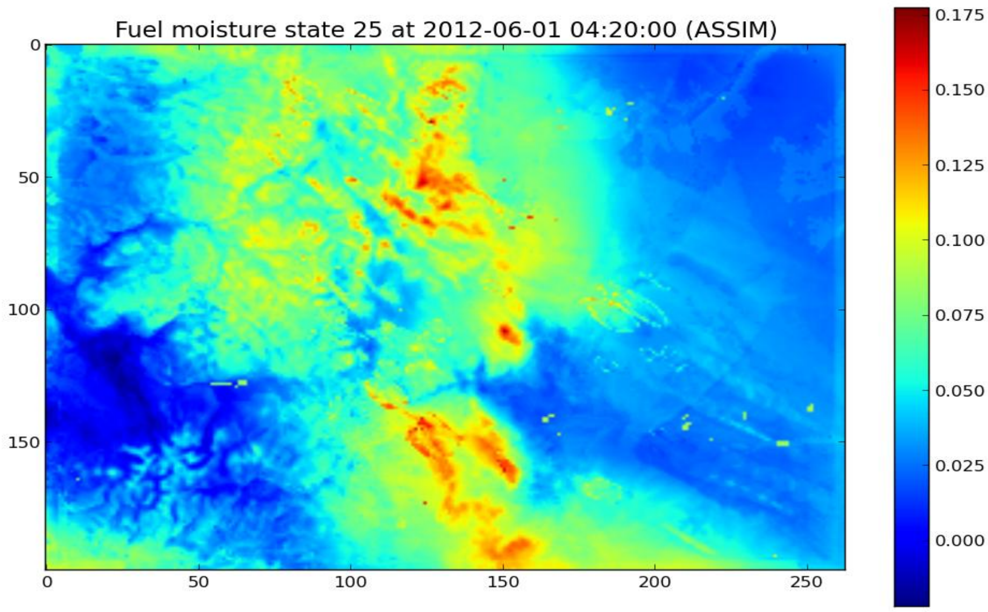

Fig. 7: An example fuel moisture map of the 10-hr idealized fuel species obtained toward the beginning of the Colorado simulation run. The time is in UTC.

This simulation shows that although complex atmospheric phenomena may increase the uncertainty of the fuel moisture estimates temporarily, the data assimilation system does not exhibit computational instability in these instances and is able to recover quickly.

Discussion

Assimilating the time lags of idealized fuels

The assimilation of time lags for the idealized fuels is entirely possible but not useful in the context of the aims of the data assimilation method. Fuel moisture from the idealized fuel species is transformed into estimates of fuel moisture in one of thirteen different vegetation classes by weighted averaging, which requires 1-hour, 10-hour and 100-hour idealized fuel species as input. By assimilating time lags, we would in effect model different idealized fuel species than required by the subsequent users of the results. Nevertheless, during development of the method simulation runs were conducted with assimilation of time lags and it was found that the effect of data assimilation on time lags was negligible. Assimilation of fuel time lags is thus neither desired nor effective.

Trend surface modeling and universal kriging

The objective of the proposed method is its integration in an operational fuel moisture assimilation mechanism. Strong emphasis on the stability and predictability of the numerical algorithms is thus important in addition to minimal user intervention requirements. In complex terrain, a complicated model of covariance, perhaps including multiple terrain characteristics, would be necessary to exploit any potential spatial relationships in the observed data. An examination of variograms of fuel moisture observations in the Front Range region of Colorado has not uncovered a convincing distance-related structure. The question of the ultimate efficacy and stability of a complex covariance model remain. Finally, universal kriging is typically used in much smaller or much larger domains, at scales where assumptions on smoothness of the terrain and ambient conditions facilitate the construction of distance-based models of covariance.

At the mesoscale range of the current simulations, non-stationarity induced by weather phenomena and terrain properties makes use of universal kriging methods challenging in the least.

Future developments

In future research, use of data assimilation methods adjusting the atmospheric state is expected to significantly improve the function of the presented assimilation mechanism, especially during the appearance of transient complex weather patterns.

The effects of data assimilation on other modeled idealized fuel species (1-hr, 100-hr) will be investigated. These fuel species are only indirectly affected by the 10-hr observations due to coupling in the extended model state and no direct observations of the fuel moisture of these species are available to the authors at this time that would facilitate a performance analysis of the assimilation method.

Conclusion

In this paper, we have presented a method for assimilation of remote automatic weather station 10-hr fuel moisture observations into the fuel moisture model in WRF-SFIRE. The method was constructed for the primary purposes of improving fire behavior modeling in on-demand fire modeling scenarios and for operational fire risk estimation. We have demonstrated on two real-world examples that the proposed method adjusts the model forecasts towards the station observations, is able to function in complex topography and recover from transient disturbances, such as precipitation events.

Acknowledgments

This research was partially supported by the National Science Foundation (NSF) grants AGS-0835579 and DMS-1216481, National Aeronautics and Space Administration (NASA) grants NNX12AQ85G and NNX13AH9G, and the Grant Agency of the Czech Republic grant 13-34856S. The authors would like to thank the Center for Computational Mathematics University of Colorado Denver for the use of the Colibri cluster, which was supported by NSF award CNS-0958354. This work partially utilized the Janus supercomputer, supported by the NSF grant CNS-0821794, the University of Colorado Boulder, University of Colorado Denver, and National Center for Atmospheric Research.

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Mid- to long- term fuel treatment impacts on forest structure and fuel loads in California

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Extended Abstract

Introduction

Under the guidance of the National Fire Plan and the 10-Year Comprehensive Strategy, the use of fuel treatments to reduce the likelihood of catastrophic fires has increased over the past decade. The FLAME Act of 2009 and resulting National Cohesive Wildland Fire Management Strategy re-iterated the need to address wildland fire and fuels management. The most effective treatments alter both canopy fuels and surface fuels, creating more resilient forest structure. The short-term effectiveness (1 to 2 yr) of fuel treatments to abate undesirable fire behavior and effects is well studied and known (i.e., Stephens and Moghaddas 2005; Vaillant *et al.* 2009; Fulé *et al.* 2012; McIver *et al.* 2012). Mid- to long- term effectiveness of fuel treatments is not quite as well understood. The longevity of fuel treatment effectiveness to alter potential fire behavior is a crucial question for managers preparing plans for fuel hazard reduction, prescribed burning, fire management, forest thinning, and other land management activities. To understand fuel treatment effectiveness, quantification of impacts on fuel loads and canopy characteristics over time is needed.

Methods

As a part of the Fuel Treatment Effectiveness and Effects Monitoring in the Pacific Southwest Region project, National Forests in California each provided a minimum of one candidate fuel treatment project from 2000 through 2006. Up to six permanent plots were randomly placed in each project area. All plots were sampled prior to treatment (P00), then 1 yr post (P01), 2 to 3 yr post (P03), 4 to 5 yr post (P05), 7 to 8 yr post (P08), and 10 yr post-treatment (P10) as possible. Some plots do not have data for all post-treatment intervals due to various uncontrollable circumstances. The field sampling protocol was based on the National Park Service Monitoring Handbook (USDI NPS 2003) with some modifications to optimize sampling efficiency (Vaillant *et al.* 2009). The plots included data collection on forest floor and surface fuels, understory vegetation, and trees.

Plots were grouped into treatment-forest type combinations for analysis (Fig. 1). Prescribed fire (FIRE) treatments were treated with only fire. The mechanical treatment (MECH) included a thinning treatment followed by a surface fuel treatment. Plots were assigned to three forest types based on dominant tree species, similarities in fuel characteristics, and expected fire behavior, including: yellow pine (YP) dominated stands, red fir (*Abies magnifica*) (RF) which consisted of short needle conifers dominated by red fir, and mixed conifer (MC) which included the remainder of plots where two or more conifer species shared dominance.

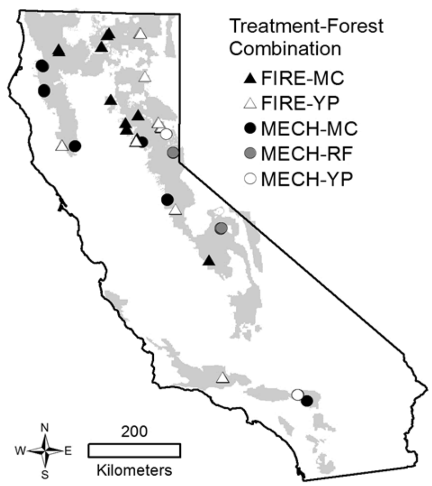

Fig. 1. Location of all plots depicting treatment-forest combinations. FIRE – fire-only treatment, MECH – mechanical treatment, MC – mixed conifer forest, YP – yellow pine dominated forest, RF – red fir dominated forest.

Results

A great deal of spatial and temporal variability in fuel loads between and within treatment-forest combinations were found. Our dataset indicated a great deal of variability; the lack of clear fuel reduction or accumulation trends was apparent in our time series for a few FIRE and most MECH treatment metrics. The inconsistent trends are common, given the spatial variability in surface fuels, and the overall variability within one project area and across similar treatment and forest types (Keane *et al.* 2012). Chiono *et al.* (2012) also did not find temporally consistent trends but rather even more variability where the post 5 to 7 yr period was often higher or more typically lower than prior and latter sampling periods. A large part of our temporal variability had to do with uneven sample sizes; both P05 and P10 have a very low number of plots.

By 8 years post treatment (P08), live understory fuel load recovered to, or exceeded, that of P00 on all MC sites and for FIRE YP sites. This live fuel load recovery could lead to higher fire hazard in later years as associated shrubs become more decadent. The composition of the understory vegetation (proportion of dead versus live material and ignitability), and height will both impact potential fire behavior. Although using a different method to quantify potential ladder fuels, Chiono *et al.* (2012) found shrub cover in treated stands exceeded non-treated controls 2 to 4 yr after treatment in both Jeffrey pine (*Pinus jeffreyi*) and mixed conifer stands.

Forest structure was affected more by MECH treatments than FIRE treatments. MECH treatments reduced tree density more than did FIRE treatments in most size classes. The MECH treatments removed trees of all size classes, and the reductions were fairly stable over time. The FIRE treatments reduced both seedling and pole-sized trees but did not impact overstory tree density much between P00 and P01. Overstory density decreased through P05 as a result of delayed mortality from FIRE for both forest types. Canopy cover, canopy bulk density, and tree density were reduced and canopy base height increased on all plots; however, changes were more pronounced and stable from MECH treatments. Canopy base height increased from treatment through P02 for all treatment-forest combinations relative to P00 and then declined through P10 except for FIRE-MC where P10 canopy base height was extremely high. This peak can be explained by the small sample size in P10. The fact that canopy base height is continuing to decrease could have implications for crown fire activity; if canopy base height is low enough, the stands have a potential for increased passive crown fire in later years relative to P01 and P02. Chiono *et al.* (2012) found a similar increase followed by a decrease in Jeffrey pine stands; however, the decline did not start until more than 8 years after treatment. Stephens *et al.* (2012) had findings similar to Chiono *et al.* (2012) in stands treated mechanically.

Acknowledgments

We acknowledge funding for this research from the USFS Region 5 Fire Aviation and Management and Joint Fire Sciences program (JFS 09-01-1-01). This project would have never gotten off the ground without the passion and drive of Jo Ann Fites-Kaufman. We thank the countless number of field crew members over the past 12 years, especially K. McCrummen for serving as crew lead during the past five years. Thank you to all the fire and fuels specialists on all the National Forests in California for providing invaluable insight and information about their fuel treatments.

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Effects of fire on wading bird foraging habitat and resources

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Abstract: Prescribed fire is commonly used to manage upland habitat for the benefit of wildlife; however, how wetland fire effects translate to impacts on wetland-dependent species is poorly understood. Preliminary studies in cattail-dominated marshes suggest that long-legged wading birds (i.e., herons, egrets, ibises, storks, spoonbills, order Ciconiiformes) are attracted to recently burned areas. This may be due to shallower water, increased prey density, or availability of prey. To further explore this issue, we conducted a number of studies to quantify fire effects on primary producers and consumers, determine whether wading birds prefer burned areas, and establish reasons why wading birds may prefer these areas. Immediately after the burn, primary producers increased in biomass, while fish responded temporarily in abundance. Immediately after the fire, wading birds were found in greater numbers in burned areas than in the adjacent sloughs, but this changed as water levels dropped and prey moved to the sloughs. Thus, the open habitat created by fire over shallow water probably enhances availability of fish to wading birds, resulting in an increased number of wading birds in burned areas immediately after the fire.

Air pollution prediction by coupling atmosphere-fire models WRF and SFIRE with WRF-Chem

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Abstract: The need to accurately predict pollution from wildland fires is acute and, in fact, the lack of such information has become a major obstacle in the prescribed fire authorization process. WRF and SFIRE model wildland fire spread in a two-way interaction with the atmosphere. The surface heat flux from the fire causes strong updrafts, which in turn change the winds and thus fire spread. Fire emissions, estimated from the burning organic matter, are inserted in every time step into WRF-Chem tracers at the lowest atmospheric layer. The buoyancy caused by the fire is modeled to simulate plume dynamics, and the chemical transport algorithm in WRF-Chem predicts pollution spread. We discuss the choice of combustion models and compatible chemical transport models in WRF-Chem, and demonstrate the results using a case study. Although some components of this system have yet to be field validated, this paper serves as a proof of concept which can serve as a springboard for future work.

Additional Keywords: Fire emissions, wildland fire simulation, wildland fire case study, smoke transport, smoke dispersion

Introduction

Adverse smoke effects on air quality and visibility are a major concern when planning prescribed burns. The Federal Wildland Fire policy and Clear Air Act significantly broadened existing regulatory and management requirements by making assessment of air quality and visibility impacts from wildland fires mandatory. Because fire emissions can contribute to a violation of the National Ambient Air Quality Standards, wildland fire managers should always consider the impacts of smoke on air quality and visibility. In this paper, we unveil a method to facilitate such assessment by increasing the functionality of the coupled atmosphere-fire model WRF-SFIRE, by coupling another model to it which predicts smoke emissions, dispersion, and their effect on local and regional air quality.

Smoke forecasting is a very complex problem that spans many disciplines. In order to estimate smoke spread and its effects on air quality, one first has to assess fuel consumption and convert it into emission fluxes of the particular chemical species (or smoke in general). Next the vertical profile of the smoke and its injection height have to be estimated, based on combustion rate, wind velocity at various altitudes and atmospheric stability. Knowledge of smoke injection characteristics and near surface wind velocities allows estimation of smoke dispersion and deposition. The last step is to model the chemical processes associated with downwind smoke dispersion in order to assess smoke impacts on air quality. As described above, smoke dispersion is clearly a multidisciplinary problem, albeit with one common denominator – the weather, which determines fuel moisture and influences fire behavior that in turn determines smoke injection height. Weather also governs smoke dispersion and chemical reactions that take place as the smoke plume moves downwind. From this standpoint, building a smoke prediction model and coupling it to an existing weather forecast system seems to be a logical choice. We present a first attempt toward creating such a system in this paper.

There is a wide suite of tools of various complexity levels that can be used to help assess smoke dispersion. They range from simple Gaussian smoke models like VSMOKE (Lavdas 1996) and SASEM (Sestak and Riebau 1988) (which predict the area affected by smoke based on fuel type, fire area and wind conditions), through puff models such as CALPUFF (Scire 2000), to complex multi-model systems like BlueSky (Larkin *et al*. 2009) which predict emissions, dispersion and air quality effects associated with wildland fires. A critical review of these and other smoke transport models can be found in Goodrick *et al*. (2012).

Since the weather plays a key role in fire propagation and the fate of emissions, meteorological information is required to accurately predict smoke dispersion and its impact on air quality. In the simplest case, a user just inputs wind velocity. Note that in complex systems like BlueSky, weather parameters are calculated/predicted in a separate numerical weather model and the results fed into various components of the system. For instance, plume rise algorithms use weather data to estimate vertical smoke distribution, and chemical transport models such as CMAQ, use it to predict dispersion and chemical reactions as the plume travels down-wind. WRF-SFIRE is based on a similar principle, but all components are integrated around the weather forecasting system. The model predicts air quality impacts by comprehensively resolving fire spread, heat release during flaming combustion, emissions, plume rise, and down-wind smoke dispersion and associated chemical reactions without any external components.

Model description

The core of the system is the WRF-SFIRE model, which is a two-way coupled fire atmosphere model based on WRF (Skamarock *et al*. 2005). It predicts fire spread based on local meteorological conditions, taking into account the feedback loop between the fire and atmosphere (Mandel *et al.* 2011). In order to capture the effect of local weather on fuel characteristics, WRF-SFIRE is also coupled with a fuel moisture model which allows the model to predict fuel moisture based on local meteorology (Kochanski *et al.* 2012). The fire model is also coupled with WRF-Chem so the smoke emitted from the fire is transported downwind and undergoes chemical reactions resolved by WRF-Chem. The diagram showing the WRF-SFIRE model components is presented in Fig. 1.

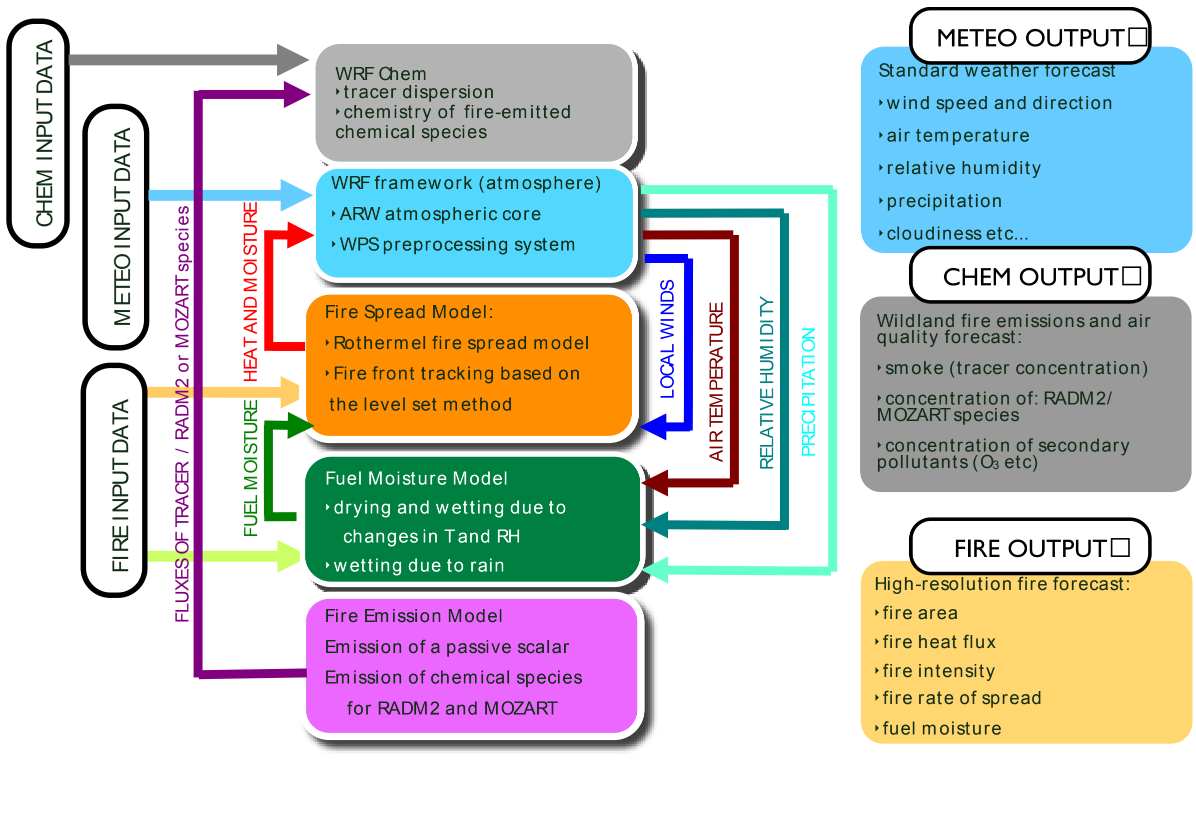


Fig. 1. Diagram of WRF-SFIRE coupled with moisture model and WRF-Chem

In each model time step, the near-surface wind from WRF is interpolated vertically to a logarithmic profile and horizontally to the fire mesh to obtain height-specific wind that is input into the Rothermel fire spread model (Rothermel 1972). A fuel type is selected from the 13 categories in Anderson (1982). Each category includes a value for fuel mass, depth, density, surface-to-volume ratio, moisture of extinction, and mineral content. The fuel moisture content is computed based on relative humidity, air temperature and precipitation amount and duration as predicted by the atmospheric component of WRF. Based on these fuel properties and WRF-SFIRE winds, the fire spread rate at every refined mesh point is computed. After ignition, the amount of fuel remaining is assumed to decrease exponentially over time, with the time constant dependent on fuel properties following BRUNUP algorithm as described in Albini (1994). The latent and sensible heat fluxes from the fuel burned are inserted into the lowest levels of the atmospheric model, assuming exponential decay of the heat flux with height. The full description of the WRF-SFIRE model can be found in Mandel *et al.* 2011. The current code and documentation are available from http://www.OpenWFM.org. A version from 2010 is distributed with the WRF release as WRF-Fire (Coen *et al.* 2012; OpenWFM 2012).

Two mechanisms are used to generate smoke emissions in the model. In the most complete form, smoke is treated as sum fluxes of WRF-Chem compatible chemical species found. Fluxes of each chemical species are computed separately and inputted into the first layer of WRF-Chem.

WRF-SFIRE currently uses FINN global emission factors (Wiedinmyer *et al.* 2011), which are based on MODIS land cover types. Therefore, the first step in WRF-SFIRE is to convert standard fuel categories in Anderson (1982), to MODIS Land Cover Types (see Fig. 2). After this conversion, combustion rates are computed for each fire grid point based on the mass of fuel consumed within one time step. In the next step, emission fluxes are computed as the products of the combustion rates and fuel-specific emission factors. The FINN emission factors are directly compatible with the Model for Ozone and Related chemical Tracers (MOZART) (Emmons 2010), so if that is the chemical scheme chosen by a user, the fluxes computed as described above are fed directly into WRF-Chem. If another chemical scheme is to be used within WRF-Chem, the MOZART-compatible chemical fluxes have to be converted to the set of species compatible with that chemical scheme. WRF-SFIRE natively computes emissions of the chemical species required by the MOZART chemical scheme. The RADM2 chemical scheme is supported as well through remapping of chemical species, as described by Emmons *et al.* (2010).

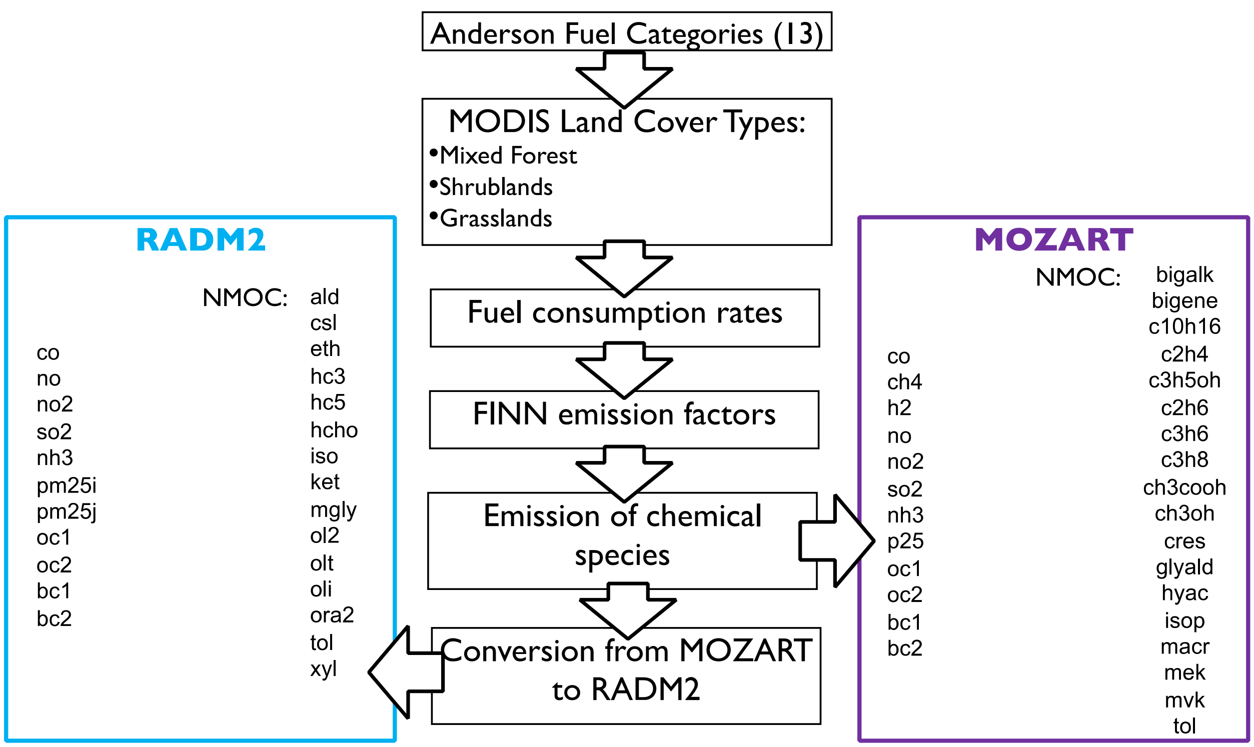


Fig. 2. Computation of emissions in WRF-SFIRE coupled with WRF-Chem.

Treatment of the smoke as a mixture of the chemically active species that undergo chemical and physical processes in the atmosphere is computationally intensive, since each additional chemical species leads to another 3D scalar equation, in addition to the complex mathematical representation of the chemical reactions. In order to reduce this computational cost, WRF-SFIRE users can select a simplified smoke representation through a passive scalar. In this case, instead of resolving the concentration of all the species listed in Fig. 2, only one variable is added to the

WRF computations (tr_8), which is a scalar and does not react in the atmosphere. If the simplified version of the smoke treatment is chosen, the execution of WRF-Chem is bypassed and the dynamical WRF core handles transport of the smoke directly. In this simplified mode, the tracer flux is proportional to the combustion rate.

Model setup

Fire spread and emissions from the two 2007 Santa Ana fires reconstructed through simulation in this case study were driven by strong easterly Santa Ana winds induced by a high-pressure system located over northern Nevada. As the pressure built up and the high pressure system moved eastward, very strong and gusty Santa Ana winds brought very warm, dry air from the Nevada desert into the San Diego area. Wildland fires are driven by local winds, often of a different velocity than the main synoptic flow. Regional topography and land use mosaic can interact with the large-scale flow, creating specific local weather conditions that drive wildfire behavior. In order to model development and movement of this large-scale weather system including the Santa Ana winds it generated, together with the local circulation which was dictated by the complex topography of southern California, WRF was configured with four nested domains: D01, D02, D03, and D04, of horizontal-grid sizes 32km, 8km, 2km, and 500m, respectively. This domain setup is shown in Fig. 3. The fire model uses 30m-resolution elevation and fuel data, while the atmospheric model uses ~1.5km resolution MODIS land use representation.

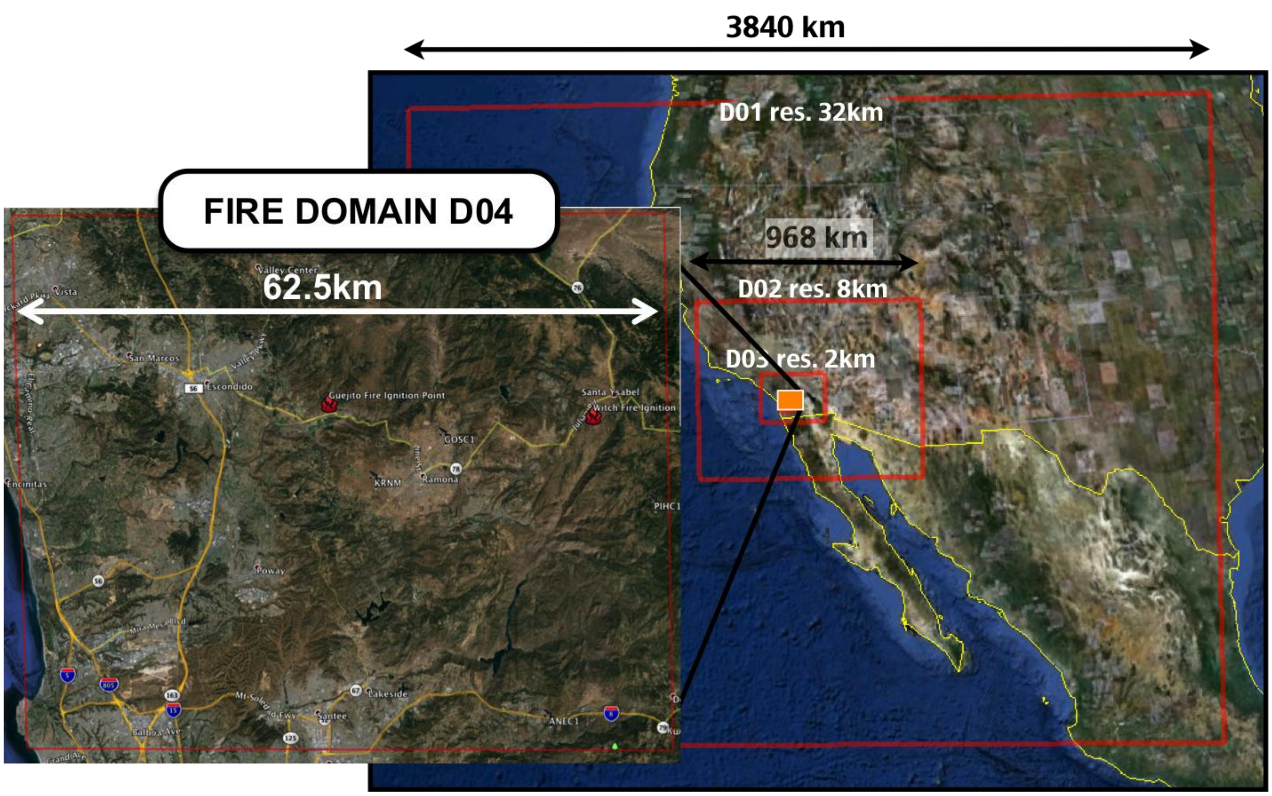


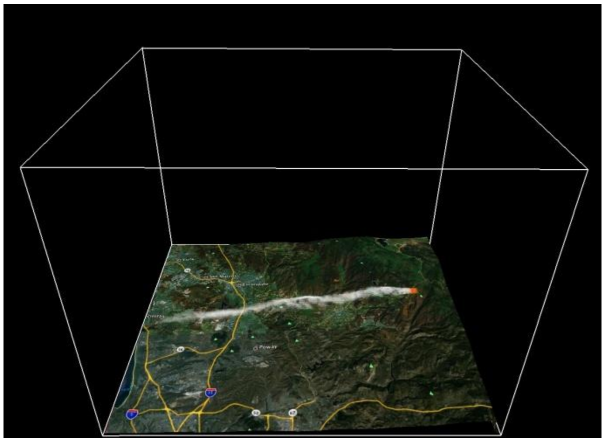
Fig. 3. The multi-scale WRF setup in this study, including locations of fire origin and local meteorological stations used for model validation. Horizontal domain resolutions vary from 32km (D01) to 500m (D04).

The model test was initialized and driven by the North American Regional Reanalysis (Mesinger *et al*. 2006), and run for a period of 48h starting on 10.21.2007 5:00 a.m. local time (12:00 UTC). The two reconstructed fires were initialized as point ignitions, and allowed to spread freely across the fuel mosaic driven by local winds. The fire-emitted heat and moisture were fed into the atmospheric grid in order to mimic the fire-atmosphere coupling. The spatially-variable fuel moisture was initialized based on observations at the nearest weather station and kept constant throughout the simulation. A detailed description of model configuration and datasets used for model initialization can be found in Kochanski *et al*. (2013).

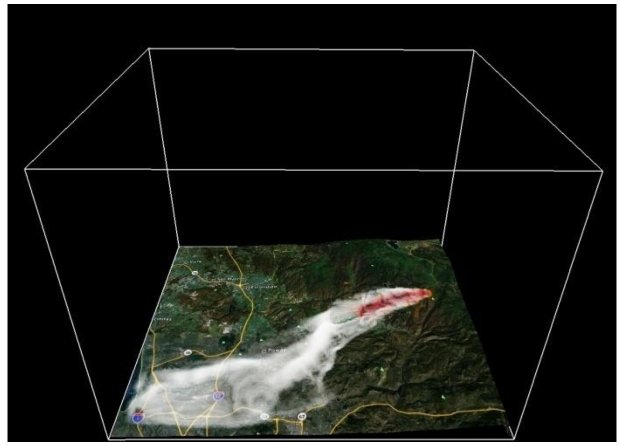
Results from the simulation of two 2007 Santa Ana fires

The Witch fire started at 12:15 p.m. local time, roughly 7 h since the beginning of the simulation. The very strong Santa Ana wind blowing from ENE at a speed of up to 19 m/s (42.5 mph) with little variation in simulated direction rapidly pushed the fire toward Encinitas and confined the smoke to a long narrow downwind trajectory (see Fig. 4a). For the comparison between the simulated and observed fire progression reader is referred to Fig. 6 in Kochanski *et al*. 2013. As the fire progressed and the flanks expanded, the plume footprint also widened as shown in Fig. 4b. Since the model estimates emissions based on the combustion rate, emissions within the fire perimeter are not uniform. Smoke production was rapid and strong at the head of the fire and along the forward flanks, while inside the fire perimeter where available fuel had been substantially depleted, emissions were less intense. Fig. 4b shows smoke prediction 6 hours after ignition (5 h after the snapshot in Fig. 4a was taken). The area affected by smoke was now much larger than that shown in Fig. 4a. A slight change in wind direction in the western half of the domain pushed the smoke much further south than would be expected from the initial plot (Fig. 4a), so the smoke footprint now covered a big part of the southwestern corner of the simulation domain. Note the sharp southeastern edge of the plume where steep canyons channel the flow limiting lateral smoke dispersion.

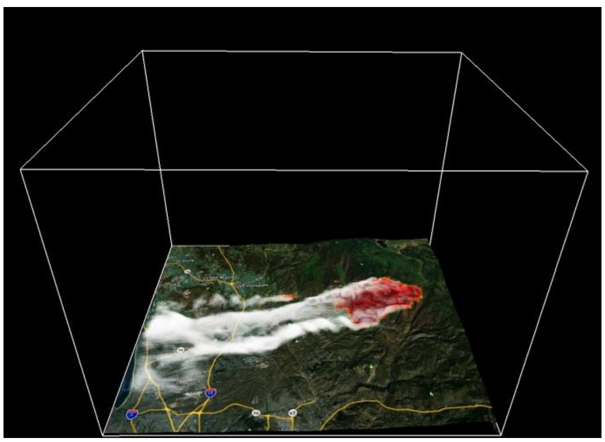
On October 22nd at 1:00 a.m., the Guejito fire started nearby in the Guejito Creek drainage, on the South Side of California State Route 78. Fig. 4c shows the fire perimeters and smoke propagation two hours after ignition of the Guejito fire.



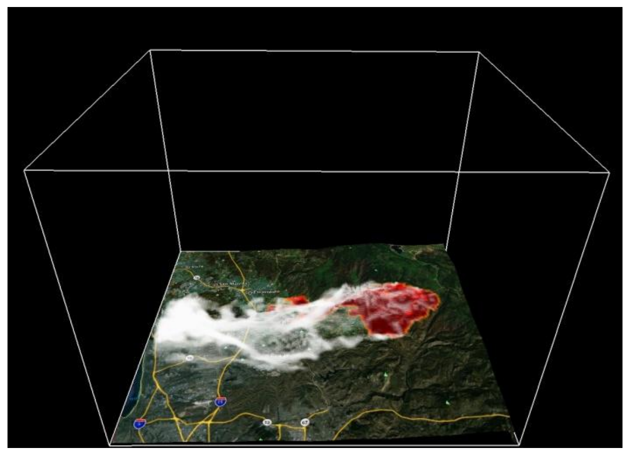
a) 10.21.2007 13:15 local time 1h after ignition of the Witch fire



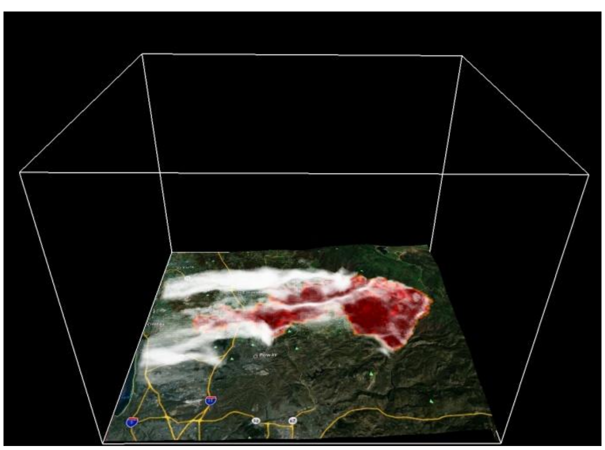
b) 10.21.2007 18:15 local time 6h after ignition of the Witch fire

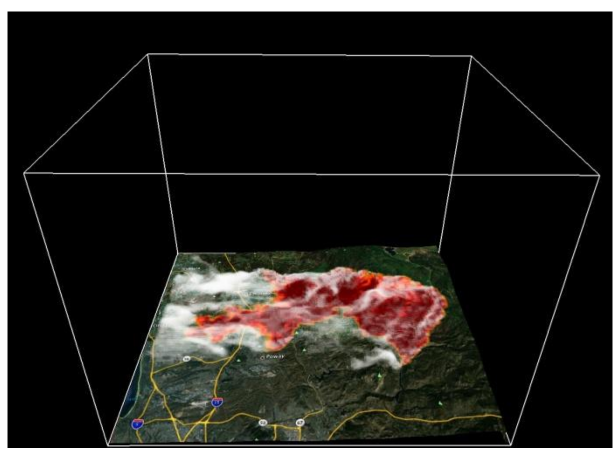


c) 10.22.2007 03:00 local time 2h after ignition of the Guejito fire



d) 10.22.2007 06:00 local time 5h after ignition of the Guejito fire





e) 10.22.2007 17:00 local time 36h into simulation

f) 10.23.2007 05:00 local time 48h into simulation

Fig. 4. Depiction of the Witch and Guejito fires at various time steps in domain d04 of the simulation run. Smoke is white, dark red fill represents black area (fire out), and orange shows active fire.

Fig. 4c shows two separate fires emitting smoke independently, and even though the Guejito fire was much smaller, its contribution to the overall smoke pall is clearly visible in the southern part of Escondido. As both fires expanded and approached each other, their plumes combined (Fig. 4d) before the actual fire perimeters merged. Note the non-homogeneous smoke production at that moment. As the Witch fire approached Ramona, its western edge (head) became relatively inactive (Fig. 4e), which reduced smoke in that region. At that time step, there were two distinct smoke plumes, one formed by the Guejito fire and the northern flank of the Witch fire, and the second formed primarily by the southwestern head of the Witch fire. Fig. 4f presents the situation at the end of the simulation run after both fires merged. The former Guejito fire extended several kilometers southward and became a strong source of fire emissions affecting Poway area. Interior areas of active fire, as well as those along the eastern edge of the Witch/ fire contributed to the overall smoke pall. This figure shows a very complex fire and smoke emissions pattern. The fire continues to be pushed westward by the wind with multiple hot spots all along the perimeter as well as within the interior.

The nesting capabilities of WRF (used in this study) allow for running the model in multi-scale configurations, where the outer domain, set at relatively low resolution, resolves the large-scale synoptic flow, while the gradually increasing resolution of the inner domains allows realistic representation of smaller and smaller scales required for realistic rendering of fire behavior and smoke emissions (Fig. 5a-b). The two-way coupling between the domains allows for feedback between the inner and outer domains.

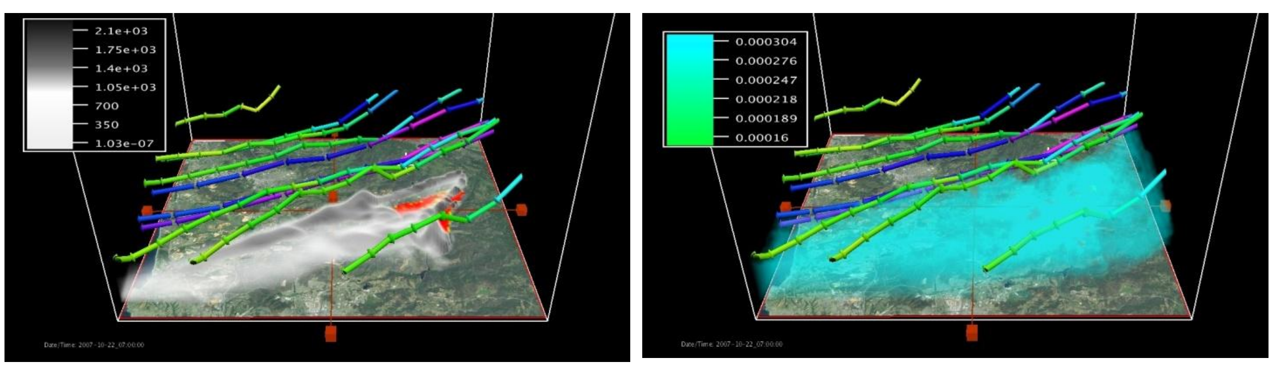
a) WRF domain d03 (2km res) for 10.23.2007

b) MODIS image for 10.23.2007

Fig. 5a-b. Smoke dispersion within domain d03 (2km resolution) simulated by WRF a) and MODIS satellite image b). The red color fill in 5a represents the fire area projected from the nested fire domain d04 (500m resolution), red contours in 5b represent remotely detected hot spots (regions of the highest fire intensity).

This mechanism is used to transfer the smoke plume from the innermost, high-resolution fire domain to the coarser outer domains to resolve large scale smoke transport. An example of the smoke dispersion within the coarser domain d03 is shown in Fig. 5a. Fig. 5b presents corresponding satellite image from MODIS (The Moderate Resolution Imaging Spectroradiometer). Note that the MODIS image presented in Fig. 5b represents an overall picture of the smoke produced from all fires in the region. The WRF simulation (Fig. 5a) shows only the effects of the Witch and Guejito fires. Nonetheless, there is a visible resemblance between the simulated and observed smoke dispersion. The aerial extent of the smoke is similar and even some of the smoke dispersion features off the coast of San Diego are visible in the WRF simulation. The hot spots in the MODIS image (Fig. 5b) also correspond with the simulated active fire regions presented in Fig. 4a.

The results presented above come from the simplified WRF simulation in which smoke was represented as a passive tracer not reacting chemically in the atmosphere. Results from the same case, but run with the full chemical smoke representation are shown in Fig. 6 below.



a) CO concentration (ppmv) for 10.22.2007 00:00 local time

b) NO2 concentration (ppmv) for 10.22.2007 00:00 local time

Fig. 6. Fire emissions from domain (d04) simulated by WRF-SFIRE coupled with WRF-Chem. Color stream lines show the snapshot of the flow on 10.22.2007 at 00:00 local time. Orange file beneath the left panel represents fire area.

Emission predictions for all chemical species and aerosols are based on fuel type and combustion rate. Therefore concentration plots for all chemical species in the fire area are very similar. As an example of the model output, we have selected the concentration plots of carbon monoxide (CO) and nitrous dioxide (NO_2), which are shown in Fig. 6a and 6b respectively.

Fig. 7 shows the streamlines overlaid over the ozone concentration simulated for the outer domain d03 (2km resolution). The streamlines indicate strong downslope Santa Ana winds pushing the fire to the coast. The elevated ozone concentrations in the wake of the Witch and Guejito fires suggest fire emissions are leading to formation of tropospheric ozone.

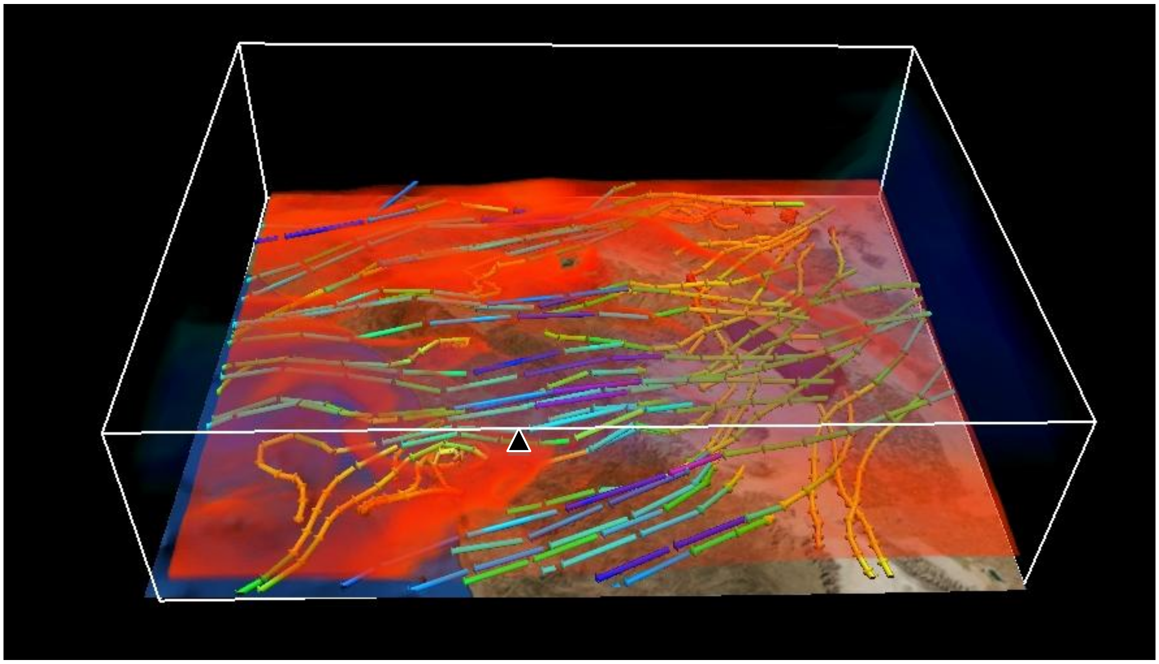


Fig. 7. Elevated ozone concentration in the wake of the Witch and Guejito fires simulated in domain d03. The black triangle shows approximate location of the Witch fire ignition.

1. Conclusion

We have presented a scheme for coupling the emissions from a coupled atmosphere-fire model WRF-SFIRE into the atmospheric chemistry and transport model WRF-Chem. In this study, we showed results from the very first numerical simulations performed by a two-way coupled system of fire and weather with output to a chemical transport model, allowing simulation of fire spread, smoke emissions and dispersion, as well as smoke chemical transformations in a stand-alone model. Since it is a first attempt toward creating such a system, and the smoke emissions component has not been validated yet, the results shown at this stage should be treated as a proof of concept, highlighting only general capabilities of WRF-SFIRE coupled with WRF-Chem.

We believe the new capabilities added to WRF-SFIRE significantly increase its potential as a tool for future use by natural resource managers. Now fire spread predictions can be directly linked with smoke emissions, transport, and chemical conversion to predict smoke and air quality impacts in one system. The increased levels of detail provided by this system, such as locations of high reaction intensity, smoke emissions and plume injection height provide a more comprehensive understanding of the fire environment and downwind ramifications of a wildland fire.

One should keep in mind all the limitations of the fire component of the system, which is based on the Rothermel (1972) model. The fire spread model provides only the head fire rate of spread. The fire spread along the fire perimeter is computed based on the local wind speed component normal to the level set function describing the fire perimeter, which may lead to underestimation of the fire extent normal to the wind direction. Also, the situations of fire propagating downslope, or cross-slope are not accounted for by the original fire morel. In the system discussed in this paper, the slope correction factor enhances cross-wind upslope fire propagation, but it does not reduce the downslope rate of spread.

The model does not distinguish between flaming and smoldering. The only effect of larger fuels on the emissions is that they burn and emit smoke longer, but the chemical composition of the smoke is the same as during the initial flaming stage.

The rate of spread coming from the Rothermel model is intended to describe fires propagating in a steady state. In the system described above, this assumption may be violated as the wind speed changes each time step. The model instantaneously accelerates the fire, while in reality it takes some time before the rate of speed reaches its new value. This effect is clearly visible in the FireFlux experiment, where under similar wind conditions the initial fire propagation (up to the first, main tower) was much slower than between the main and the short tower (Clements 2007).

The fuel types, fuel moisture and topography are not uniform in the whole domain either. However, it should be noted that the fire model is integrated over very short times (3 s time step for the most inner domain). That means that even at highest possible rate of spread coming from the Rothermel model, the uniformity of the fuel and moisture within each step is theoretically preserved, since within one tome step fire cannot propagate through more than one fuel cell.

Assuming underlying model assumptions are not violated and the internal equations are validated by further field testing, the high level coupling between the model components will facilitate studying complex interactions between a fire and the atmosphere, including radiative and microphysical effects of the aerosols released into the atmosphere by fire plumes.

Acknowledgements

This research was partially supported by the National Science Foundation (NSF) grants AGS-0835579 and DMS-1216481, and National Aeronautics and Space Administration (NASA) grants NNX12AQ85G and NNX13AH9G. This work partially utilized the Janus supercomputer, supported by the NSF grant CNS-0821794, the University of Colorado Boulder, University of Colorado Denver, and National Center for Atmospheric Research.

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Proceedings of 4th Fire Behavior and Fuels Conference, February 18 – 22, 2013, Raleigh, North Carolina, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Linking smouldering experiments with simple cellular automata models of smouldering fire

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Abstract: Smouldering combustion is of particular relevance in ecosystems with carbon rich soils, such as peatlands (Rein 2013; Turetsky *et al.* 2011). Topical examples of large peatland fires are the tropical peatland fires in Indonesia and the Russian peatland fires near Moscow, which have caused habitat loss and large-scale greenhouse gas emissions (Hoscilo *et al.* 2011; Page *et al.* 2002).

Modelling of smouldering fires has received little attention, but papers are now appearing in the literature which characterize the behaviour of smouldering peat fire across a range of environmental conditions (e.g. Hadden *et al.* 2013; Cancellieri *et al.* 2012; Reardon *et al.* 2009; Frandsen 1997; Prat *et al.* 2013). We are assimilating these data into simple cellular automata models of smouldering combustion in order to estimate changes in smouldering process rates under varying conditions of moisture and oxygen. Our cellular automata models are 2D and divide the fuel up into a square grid of cells. Our earlier models (Belcher *et al.* 2010) assigned each cell to one of three possible states (peat, oxidizing and ash), while the model we describe here uses five states (peat, pyrolysizing, char, oxidizing and ash). Initially the majority of cells are unburnt peat. At each time step, a cell has a probability of changing state, with this probability being a function of the surrounding cell states. The transition probabilities per time step of the model are Prob(Peat $\rightarrow$ Pyrolysizing) = $\beta_1 \square n_C + \beta_2 \square\, n_O$; Prob(Pyrolysizing $\rightarrow$ Char) = $\sigma_{P;}$ Prob(Char $\rightarrow$ Oxidizing) = $\beta_3 \square n_{O;}$ Prob(Oxidizing $\rightarrow$ Ash) = σ_O where n_C and n_O are the number of 'char' and 'oxidizing' cells, respectively, in the nearest eight neighbours; $\square\beta_1$ and β_2 are the probabilities per time step per neighbouring cell that a cell in the 'peat' state will start pyrolysis; β_3 is the probability per time step per neighbouring cell that a cell in the 'char' state will start oxidation; σ_P is the probability per time step that a cell in the 'pyrolysizing' state will become char and; σ_O is the probability per time step that a cell in the 'oxidizing' state will become ash. This simple characterization of smouldering combustion captures the fundamental steps in smouldering combustion but leaves out the details of chemical reaction rates and the details of heat transport through the material.

The cellular automata model is fast to simulate, which allows the model's parameters to be fitted to experiment using Approximate Bayesian computation (Toni *et al.* 2009). Simulated and experimental data can be directly compared for quantities such as propagation speed of the combustion front, the time taken to burn a fixed amount of fuel and the mass loss rate. The

parameter sets that best capture the experimental data can then be selected. We fitted the model to experimental smouldering data on propagation speed and burn time for peat moisture contents of 0%, 25%, 50%, 75% and 100% (Prat *et al.* 2013). These results show that the transition to oxidation (β_3) and the rate of oxidation (σ_O) are the only two parameters that show a response to changing peat moisture content, and the time scale for oxidation, $1/\sigma_O$, is constrained to be longer than the time scale for pyrolysis, $1/\sigma_P$ (Table 1).

Our initial results show that these simple cellular automata models can reproduce global properties of smouldering experimental data, provide information about parameter ranges and the constraints upon state transition rates under different experimental conditions. More complex models that explicitly incorporate heat and moisture transport (e.g. Holt 2008) and chemical reactions may provide a more precise description of smouldering propagation, but at the expense of being harder to parameterize from relatively little experimental data. Future research will compare the performance of the model presented here against other modeling approaches.

Additional keywords: peat moisture content, fire behavior, approximate Bayesian computation

Table 1: The median and quartiles (in brackets) for model parameters from a selected subset of simulations.

From $1.3x10^{-6}$ simulations, we selected those with a propagation speed and burn duration within 20% of the experimental data. All simulations had a 50x50 grid, a time step of 6 s, and each cell was 0.4x0.4cm

Moisture Content	β_1 ($x10^{-1}$)	β_2 ($x10^{-1}$)	β_3 ($x10^{-3}$)	σ_P ($x10^{-1}$)	σ_O ($x10^{-3}$)
0%	1.9 [0.2-2.4]	1.6 [0.7-2.4]	6.8 [6.2-8.2]	1.1 [0.4-1.9]	1.4 [1.2-1.6]
25%	1.7 [1.0-2.5]	1.6 [0.6-2.2]	3.4 [3.1-3.7]	1.5 [0.9-1.9]	4.2 [2.6-6.0]
50%	1.7 [0.8-2.4]	1.4 [0.6-2.2]	3.4 [3.0-4.3]	1.5 [0.9-2.5]	6.2 [4.2-10]
75%	1.6 [0.8-2.5]	1.3 [0.2-2.2]	2.9 [2.9-3.3]	1.7 [0.7-2.3]	6.1 [3.9-8.2]
100%	1.6 [0.8-2.4]	1.1 [0.3-2.2]	3.1 [3.1-3.8]	1.4 [0.6-2.4]	6.7 [4.4-9.9]
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Special Session 2: Fire culture: using the humanities to revive the ancient link of people and fire in southeastern North America … and around the world

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Session Speakers:

Johnny Stowe

Abstract: The use of fire is unique to humans, People have for scores of thousands of generations used fire to shape landscapes and lifeways, and conversely, fire has shaped us -- warming our hearths and our hearts. This inextricable link continues today, although it is often taken for granted, unrecognized, ignored, and even denied. The operational, technical and quantitative aspects of wildland fire management (especially of fire prevention and suppression), as well as certain related elements of the human dimensions of landscape fire (e.g. surveys of perceptions and information exchange), have grown by leaps-and-bounds in the last few decades. This must continue as landscapes become increasingly fragmented, society changes and wildfire hazards increase. But despite these major, much-needed advances, we have largely missed something in our human dimensions efforts. Over the last century, at least in the United States, the role of the humanities in wildland fire has been given short shrift. We encourage the global wildland fire community to increase its efforts to make people aware of the multicultural ways in which people and fire are connected -- through art, literature, philosophy, and history. This concept arose first and most notably from Stephen Pyne, whose prescient pearls of erudition include the idea that "Prescribed fire doesn't need another policy. It needs a poet." Beginning in the Northern Rockies -- one of the primary paths along which fire came into the New World -- by looking through the lens of current projects in Banff National Park -- and then centering on longleaf pinelands and other pyrophyllic ecosystems in Southeastern North America -- we focus on people as part of these fire-landscapes, and highlight implications of these contemporary human-fire links for the rest of the globe.

Reed Noss

See separate expanded abstract in the Special Session 2 folder

Philip Juras

Abstract: Is a picture worth a thousand fires? Nineteenth century portrayals of America's frontier landscapes by artists such as Thomas Moran and Albert Bierstadt played an important role in the development of an American conservation ethic. Their dramatic portrayals of untamed nature and the awesome forces that shaped it fed an American conceptualization of wilderness that has influenced a century of private land use and public policy. Wildland fire, though certainly one of the powerful forces that shaped the landscapes these artists depicted, was generally missing from their perspectives. Coming mainly from long-settled, fire-suppressed parts of the East, it is likely that these artists neither understood the role of fire in the environment nor spent enough time in fire dependent environments to observe it firsthand. Had they, the conservation discussions sparked by their paintings might have been different. In presenting my own artwork, informed by history, natural sciences, and volunteer time spent on controlled burns in my home state of Georgia, I offer a southeastern view of the effects those artists missed. These paintings depict active fires such as "Heading Fire" (fig 1.) on the Wade Tract of Arcadia Plantation in Thomasville, Georgia, as well as the Eden-like landscapes they produce, pictured in "Longleaf Glade" (fig. 2) on nearby Greenwood Plantation. These are two of the finest, fire managed, old growth longleaf pine stands that remain in the lower southeastern coastal plain. To experience these remnants is to journey back to the vast fire dependent landscape inhabited and managed by Native Americans for thousands of years—landscapes that would later serve as the first impression of the new world for European and African arrivals. By recreating historically fire adapted landscapes on canvass, these paintings offer another means to support the benefits of prescribed fire in today's discussion of land management. In this way, a picture may indeed be worth a thousand (prescribed) fires.

Fig.1. *Heading Fire*, Wade Tract, Arcadia Plantation, Thomasville, Georgia, Oil on canvas, 48" x 72", Philip Juras, 2013
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Fig. 2. *Longleaf Glade*, Greenwood Plantation, Thomasville, Georgia, Oil on canvas, 40" x 60", Philip Juras, 2008

Rhett Johnson

Abstract. Fire in the longleaf ecosystem: using the popular media for opposing outcomes. The nation has had a long love/hate relationship with woodland fire, much of it based on terrible experiences in the West and in the Lake States. The southeastern region of the country perhaps more than any other region regards, and has regarded, fire differently. The Southeast, with a high

fire frequency ‘fueled’ by frequent lightning strikes and a flammable fuel base, due in some degree to frequent fire, evolved into a fire driven ecosystem across most of the uplands and across several forest ecotypes, notably longleaf pine, centuries before human settlement. In addition, native ignited fires, perhaps landscape in scale, were apparently regular in the pre-history, pre-settlement period. Estimates are that these societies co-existed with fire for at least 10,000 years. DeSoto and, later, Bartram were among the early observers who noted the use and effect of fire in Southern forests and wrote about it in their chronicles. Other early explorers in the region talked of the constancy of smoke over much of the region as they traveled the rivers of Virginia, North Carolina, and South Carolina. Others described the open nature of the upland forests, with a paucity of woody brush.

European settlers, either learning from their predecessors on the landscape or bringing at least a rudimentary knowledge of fire with them from western Europe, continued the use of deliberate fire much to the same ends; land clearing for agriculture, reducing woody shrubs and improving travel and visual access, improving hunting and game animal habitat, with the additional goal of improving grazing for livestock, primarily cattle. John Muir, in his travels across the region in the late 19th century, described a landscape similar to that described by both DeSoto and Bartram.

In the early 20th century, federal natural resource officials spurred by catastrophic and lethal fires in the western US and the Lake States, adopted a fire suppression stance, pulling out all stops to keep fire out of the forest. The nascent forestry profession joined in these efforts, with fire regarded as a threat to both lives and resources. The regulations were applied nationwide, in stark contrast to the prevailing and traditional practices in the Southeast. The Dixie Crusaders campaigned across the region, using multiple media, hammering home the message that fire should be kept out of the forest and suppressed at all costs. Southerners, particularly rural Southerners, resented both the ‘intrusion’ into their lives by ‘outsiders’ and the break from established practice. Walt Disney’s Bambi terrified a generation of children and was used by federal and state organizations to argue against fire in the forest until Disney objected, not to the message, but the use of its characters. The U.S. Forest Service responded with the quickly iconic Smokey Bear, a spectacular success that endures into today.

Still, Southerners continued to use fire as a tool in the forest in defiance of the law and the prevailing national sentiment. One study supported by the U.S. Forest Service suggested that rural Southern men set fires in the forest for recreation, being too lazy to work or otherwise get off the porch.

Even before fire exclusion became a national policy, some natural resource professionals, notably wildlife biologists, botanists, and range specialists, suggested fire might be a natural process and necessary to the health of some southern (and other) forest ecosystems. Early proponents included H.H. Chapman, Herbert Stoddard, Roland Harper, Aldo Leopold, and eventually Henry Hardtner. Despite strong opposition, these pioneers championed both the cultural and ecological utility of fire in southern forests, particularly longleaf pine ecosystems. In fact, Stoddard learned about the use of fire in the dry prairies and pine savannahs of central Florida as a boy, with forage production as a goal. Scientists like Harper recognized and understood the role fire plays in the life cycles of many Southeastern forest communities. These early scientists, the forerunners of today’s ecologists, wrote copiously in support of fire and defended their position in popular and professional forums for decades before grudging acceptance by the established professional community.

In this classic confrontation between 'common' or 'folk' knowledge and science, the battle for public acceptance was key to the continued use of this natural tool in forest community management. During the late 19th and early 20th centuries, for instance, it was common for rural yards to be 'swept' clean to bare sand or earth, removing all vegetation that might carry fire to the dwelling. Fire was such a commonly used tool in the forests surrounding homesites that houses and other structures were otherwise at risk. I can remember my great-grandmother, when viewing a 'modern' yard complete with lawn, commenting derisively, 'Those must be trifling (lazy, no-account) people'. In the popular literature, public opinion was shaped in one direction by Norman MacLean's 'Young Men and Fire'. A fine writer, MacLean wrote compellingly of the dangers forest fires could pose to life and property. Stephen Pyne has written of fire in the forest and its role over time, combining science, history, and opinion to chronicle its use and misuse in America and across the world. A spate of new works strives to achieve the opposite result. Janisse Ray's works, especially 'Ecology of a Cracker Childhood', educated a generation of young Americans about longleaf forests and fire. Roger Reid's 'Longleaf', written for a pre-teen and teenage audience, did much the same thing for a younger generation, explaining the naturalness of fire and how it can be used. Albert Way's biographies, 'Managing Longleaf' and 'Conserving Southern Longleaf' describe both the history and culture of the southern quail plantation community and the struggle to develop management regimes to restore natural forest conditions using fire. Bailey White, a popular folklorist, novelist, and public radio essayist, has presented a case for fire in the forest in the contents of her humorous and gentle novels, particularly 'Quite a Year for Plums'. Public television joined in the fray, with programs like *Discovering Alabama* and those of the Georgia Department of Natural Resources providing lovely visuals that were aimed at general audiences and extolling the utility of fire in upland Southern ecosystems.

The Nature Conservancy, National Wild Turkey Federation, Tall Timbers Research Institute, U.S. Forest Service Southern and Southeastern Research Stations, and the Jones Ecological Research Center produced research reports, conducted symposia, and supported the wise use of fire in the forest, targeting and reaching both professional and general audiences. The Longleaf Alliance, an organization with the single focus of restoring longleaf forest ecosystems, produced many popular brochures, management manuals, and research publications with fire as an essential element in the content. Academies, workshops, and field days for professionals, land managers, and landowners have led to a wider acceptance and understanding of ecological fire in the region. Perhaps the culmination of the efforts so far might be the book, 'Longleaf: Far as the Eye Can See', published in 2012 by the University of North Carolina Press. Compelling imagery and supporting text have made this book popularly successful both in the region and outside it. Exposure to an audience outside the natural resources community has excited an interest in the longleaf ecosystem and its dependence on fire that rivals the reach of Bambi. The book's combination of forest and fire ecology and the longleaf forest's role in shaping the culture of the region has resonated with the public beyond the imagination of the book's authors.

Fire remains a controversial social issue. There are inherent risks and obvious ecological benefits. The preventative role of fire in lessening the danger of catastrophic wildfires is clear to practitioners and managers, but less widely accepted by the general public. Lingering concerns about impacts on wildlife continue to surface in debates about fire. Convincing landowners and land managers to manage with fire is a difficult task -- interacting with the general public in the face of concerns about the wildland/urban interface and air quality is even more challenging.

Lightning fire, anthropogenic fire, and other factors maintain southern grassland

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Extended Abstract. Grasslands of various types, including savannas and woodlands dominated by longleaf and other pines, were a prominent part of the southeastern United States ('the South') prior to European settlement. Fossil evidence, including fossil pollen and bones and teeth of savanna-associated vertebrates, suggests that savanna and related vegetation dominated the lower portion of the South (the Coastal Plain) for much of the last 20 million years, with intermittent connections along a Gulf Coastal Corridor to similar vegetation in the Great Plains, southwestern U.S., and Mexico. The abundance of endemic species (more than anywhere else in North America, north of Mexico, besides the California Floristic Province) and archaic monotypic genera associated with grasslands in the Coastal Plain also suggests great antiquity (Sorrie and Weakley 2001). The Coastal Plain is now recognized as a global biodiversity hotspot[1]

Various factors maintained savanna/grassland vegetation across the South, including climate change (i.e., occasional periods of dry climate, which favored grasses over trees), lightning fire, mega-herbivores, hydrology, and extreme soils and aspects. With the arrival of humans from Asia more than 14,000 years ago, mega-herbivores declined and fire probably became even more important in the maintenance of southern grasslands. The role of humans in creating and maintaining grasslands has been controversial, with some anthropologists and popular writers claiming that humans created virtually all grasslands in the South and elsewhere. Evidence suggests, however, that climatic conditions and lightning ignitions in the Coastal Plain (Fig. 1) were more than adequate to maintain grassland prior to widespread alteration of the landscape by EuroAmericans. To the north, lightning remained prevalent, but burning by Native Americans and by later white settlers was also important for maintaining grassland in some areas. Some southern grasslands, especially on extreme substrates such as saline barrens, are capable of persisting for long periods of time with little or no fire.

The importance of fire and other factors in maintaining grasslands in the South apparently varied among grassland types, but also within particular types over time. Research for my book, *Forgotten Grasslands of the South* (Noss 2013), confirmed previous estimates (e.g., by Cecil Frost) that the most exposed portions of the landscape in the Coastal Plain burned at 1-3 year intervals under a lightning fire regime. The Florida dry prairie (Fig. 2), the most species-rich treeless grassland in North America, originally covered some 1.2 million acres and burned even more frequently than pine savannas, probably at 1-2 year intervals over much of the landscape. The highly endangered Florida Grasshopper Sparrow, strictly endemic to Florida dry prairie, does not nest successfully after more than 24 months without fire. Conservation and restoration of grasslands in the South will require human action, working with natural processes, on a scale

[1] Sorrie, *et al*, in preparation.

perhaps unprecedented in North America.

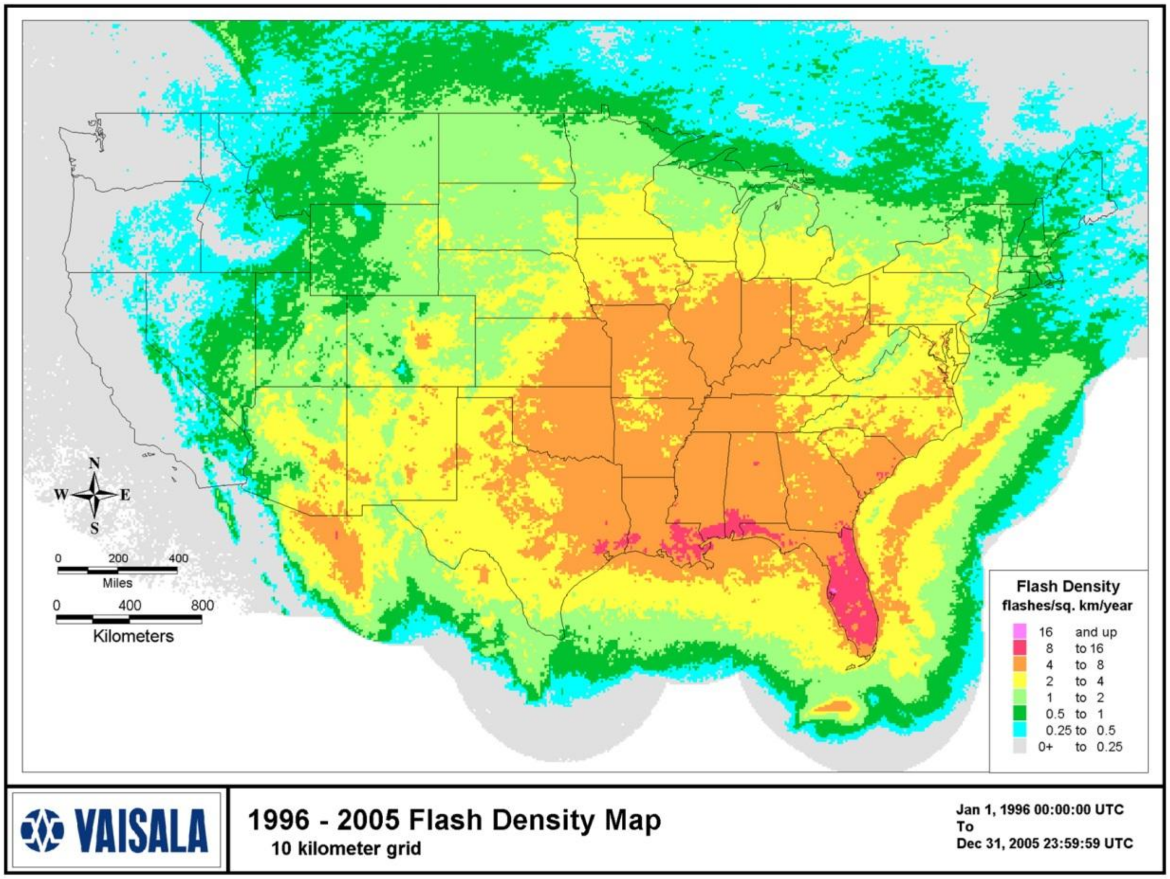

Fig. 1. The high frequency of lightning across much of the southeastern United States, especially in the lower Coastal Plain, is more than enough to explain the dominance of this region by savanna/grassland and other pyrogenic vegetation. From NOAA/National Weather Service.

Fig. 2. Florida dry prairie at Kissimmee Prairie Preserve State Park. Once covering more than 1.2 million acres, this unique natural community has been reduced by more than 90%, mostly through conversion to monoculture pasture. Photo by Reed Noss.

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Honoring those that have come before us: introductory remarks to the George M. Byram special session tribute

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Abstract. This paper constituents the remarks made during the introduction of the special session 'Standing on the Shoulders of a Giant: A Tribute to George M. Byram (1909-1996) – Pioneering Scientist in Forest Fire Research' held on February 20, 2013, at the International Association of Wildland Fire's 4th Fire Behavior and Fuels Conference in Raleigh, North Carolina.

Additional keywords: fire behavior, forest fire research.

Introduction

Paying homage to those individuals who have been leaders in a particular aspect of wildland fire represents a noble activity (e.g. Agee *et al.* 1991). The phrase 'standing on the shoulders of a giant' refers to 'Understanding and building on the research and works created by notable thinkers of the past' (http://en.wikipedia.org/wiki/Standing_on_the_shoulders_of_giants).

The agenda for this special tribute session to George M. Byram is as follows:

- Honoring Those That Have Come Before Us: Introductory Remarks to the George M. Byram Special Session Tribute – Martin E. Alexander
- George M. Byram: Father of Wildland Fire Science – Dale D. Wade
- The Early Years of George M. Byram – Darold E. Ward
- George M. Byram -- A Forest Fire Research Pioneer: Perspectives of a Colleague – Ralph M. Nelson, Jr.
- Learning From Those Who Came Before Us: Closing Remarks to the George M. Byram Special Session Tribute – Martin E. Alexander

Background information

I first heard the name George Byram (Fig. 1) over 40 years ago. In the spring of 1972 I was a sophomore attending forestry school at Colorado State University in Fort Collins. Davis (1959) was the textbook for our forest fire control course and it featured two of George Byram's seminal publications (Byram 1959a, 1959b).

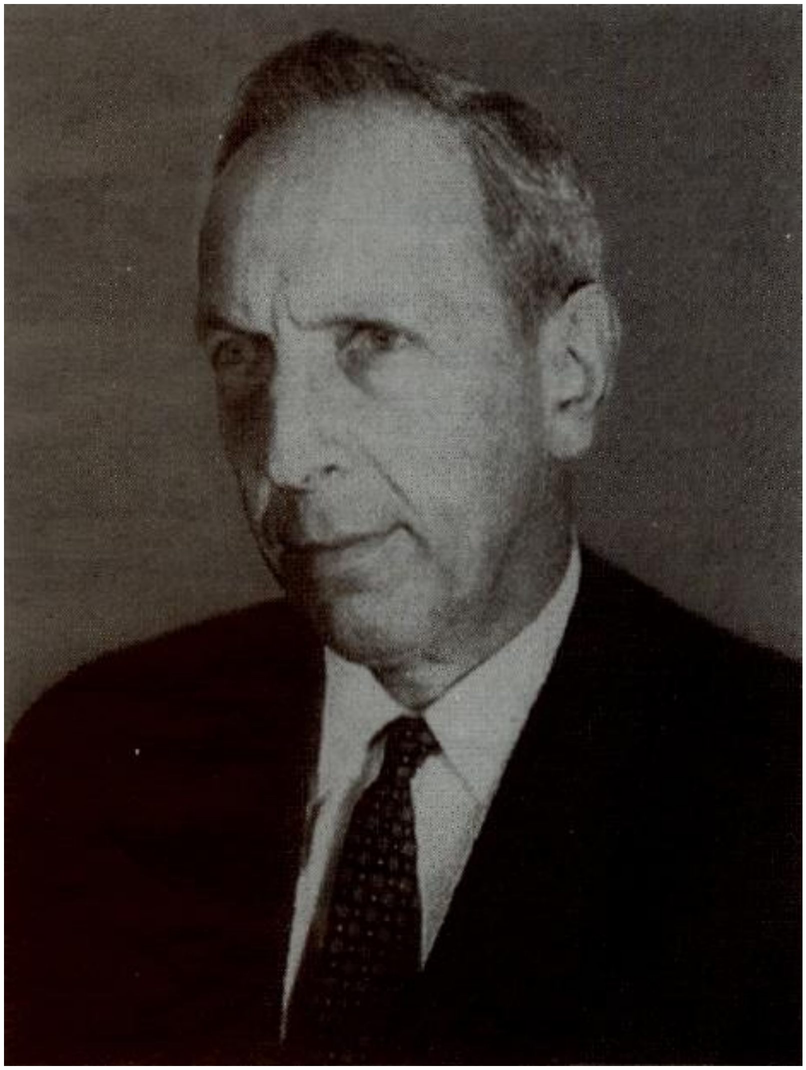

Fig. 1. Photo of George M. Byram, taken in the early 1960s (from Nelson 1996).

I can think of no individual during the formative years of wildland fire research that has had more of a lasting impact scientifically, on both fire research and fire management, than George Byram. He was recognized as one of 23 individuals that have influenced wildland fire policy and knowledge globally (from Omi 2005, p. 80):

> *'George Byram made contributions in nearly every area of forest fire research … Perhaps he is best known for the fireline intensity and drought descriptors that still bear his name, although his biggest contributions may have been his passion for precise definitions and quantitative measures of fire behavior. He was one of the first to study fire whirls, and to recognize the scaling issues with modeling of large fire behavior. His chapters 3 and 4 in*

the 1959 book Forest Fire: Control and Use *by Kenneth P. Davis, are still classics for understanding the combustion of forest fuels and fire behavior.'*

Byram spent most of his U.S. Forest Service career in Asheville, North Carolina, moving to the Southern Forest Fire Laboratory (SFFL) in Macon, Georgia in 1964. Several of his lasting contributions to wildland fire science bear his name and rightly so. For example, Byram's fireline intensity (Byram 1959a), the Keetch-Byram Drought Index (Keetch and Byram 1968), Byram's wind profiles (Byram 1954, 1955), and Byram's Convection Number (Byram 1959b; Nelson 1993a, 1993b), just to name a few.

The impetus for the special session

The genesis for this special session tribute is similar to the comment made by Charles E. 'Mike' Hardy in his1977 final contract report that led to the publication of Hardy (1983). He had the following to say after his retirement from a career in forest fire research with the U.S. Forest Service in regards to the legendary figure Harry T. Gisborne:

> *'It became … clear to me that an ever-increasing number of our new, younger scientists knew little of this man and his accomplishments – the vital beginnings of the program*.'

The vast majority of us never had the good fortune to personally meet George Byram or hear him speak at a conference. However, there are several folks still around that got to know him on both a professional and a personal basis including Ralph Nelson, Jr., Dale Wade and Darold Ward who have now all retired from full-time work following distinguished careers in forest fire research with the U.S. Forest Service.

These three gentlemen worked with George Byram at the SFFL in the early to mid 1960s until his retirement in 1968. In preparing their presentations for this conference, they have sought out others, most notably Wayne Adkins and Bob Martin, for additional perspectives on George Byram, but whom unfortunately were not be able to physically attend this conference.

The opportunity to learn

Byram's publications would certainly constitute one form of his endearing legacy in wildland fire science, but what was George Byram, the man, like? The intent of this special session is to provide conference attendees with a unique opportunity to learn more about one of the true pioneers in forest fire research.

It is my opinion that we have much to learn from the likes of pioneers in fire behavior research such as Byram as we look to the future. There are many other notable figures that contributed to the steady advancement in understand of wildland fire behavior (Scott *et al*. 2013).

I have a deep admiration for those that have come before us. We take a lot of things for granted nowadays (e.g. software, equipment, photography). They faced a multitude of unknowns as they forged ahead. Their work, both published and unpublished, can serve as a source of inspiration to the present generation of fire researchers and those that follow. Some of the stories shared by their colleagues provide insights into their personalities that we all would do well to try and emulate.

Acknowledgments

I would especially like to thank the International Association of Wildland Fire and the Joint Fire Science Program for supporting in part my attendance at the special tribute session to George M. Byram. I'd also like to thank David R. Weise and Diane M. Smith for their assistance in locating certain photos used in my presentation.

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George Byram: father of fire science

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Abstract: George Byram's accomplishments read like the tree of fire science knowledge. The magnitude of his contributions tower above those of other fire science icons. Looking at the scope, importance and continued relevance of his contributions, one cannot help but reach the conclusion that George Byram is truly **The Father of Fire Science**. He concentrated on providing solutions to seemingly intractable problems faced by fire managers. Time after time, he demonstrated his ability to describe the basic physical concepts underlying the problem in question, formulate the necessary mathematical equations, and then describe the practical applications of his work. In so doing, Byram provided true solutions that continue to stand the test of time. He is responsible for the mathematical underpinnings for disciplines such as forest fuel combustion science, fire behavior, fire modeling, fire effects, fire detection, fuel moisture diffusion, fire danger rating, fire documentation, extreme (blow-up) fire behavior, mass (mega) fires, energy release and its interaction with the atmosphere, and firefighter safety.

My presentation highlights some of George's contributions to fire science and fire management and ends with a few memories and anecdotes that provide insight into the personality traits that defined this gentleman and endeared him to those of us who had the distinct privilege and pleasure to be influenced by George's personal standards and professional ethics, as well as his wisdom and knowledge; we are better individuals as well as scientists thanks to George!

Introduction and background

Although George is perhaps best known for his hands-on publications (A partial list can be found in Appendix A), what stands out in my memory is his answer when I asked his advice after transferring to the Southern Forest Fire Laboratory in 1965 – '*create knowledge that fire managers can understand and use*'. The fact that George grew up on a farm undoubtedly influenced his desire to provide practical solutions that could be immediately put to operational use. Many of today's fire scientists don't seem to be able to grasp this concept and are more interested in quickly establishing a publication record of half-baked, improperly tested ivory-tower ideas. They are not willing to invest the large amount of time in the field observing fire which is a prerequisite to understanding the fundamentals of fire behavior; the unverified computer solutions they unleash on the wildland fire community thus tend to be band aids that require continual patches in an attempt to make them conform to actual wildland fire behavior. I have paraphrased statements on page 27 of a recent book by Reed Noss (Noss 2013)

> Too many of today's researchers devote their attention to computer models which, however useful, are not real; those who spend time in the field observing the variation in natural phenomena such as wildland fire with an open mind learn many interesting and useful things – things that researchers stuck behind their computers never learn.

Byram recognized that vicarious research pales before direct field experiments and thus spent time observing the problem to be solved before advocating a line of attack. Once George settled on an approach, he would come up with the appropriate terms and definitions, formulate mathematical equations to prove his solution, field verify them, and then write up and present the practical applications of his work. More often than not, the mathematical proof of his solution was recorded in a marked up draft on yellow paper or an internal Final Report, but not published unless one of his colleagues offered to co-author the paper with him. Ralph Nelson Jr., a close friend of George, is aware of several such unpublished derivations (some of which have unfortunately, apparently been lost). George, however, was quick to share his insights and unpublished engineering solutions with anyone who asked and would often continue to provide guidance, and analytical help thereby enabling others to extend his work.

He was one of those rare individuals without an ego or self-promoting agenda. Unfortunately this collaboration was not preserved for posterity unless his name was added as a co-author, or he was mentioned in the publication acknowledgements section. Over the years, I and others have been told by various scientists that Byram was the reason for their successful solution of a problem because of his willingness to share unpublished work, insights and a suggested research approach; a good example being the mathematical underpinnings of what evolved into the National Fire Danger Rating System. George did not seek credit for his ideas and unpublished work; his goal was to provide solutions, not build a self-serving publication record. He was not a 'type A' personality like many pioneer fire leaders with a strong (in many cases overbearing) presence; nonetheless when he spoke, people paid attention because they knew it was to impart knowledge and not to pontificate and exaggerate for personal gain. His leadership, mentoring and collaboration/correspondence with both novices and distinguished colleagues around the world, often behind the scenes, substantially extended the knowledge of a wide range of fire management disciplines.

Some of George's contributions are associated with his name, such as Byram's (AKA fireline or frontal) intensity, the Keetch-Byram Drought Index, and Byram's adverse wind profiles and associated smoke columns; but many are not. He provided an array of concepts including combustion rate (reaction- or Rothermel's- intensity), moisture time lags (1, 10, 100 and 1000 hour fuels), available fuel, and lethal time-temperature thresholds. His analytical work using thermal dynamics and fluid mechanics paved the way for a wide array of work on combustion processes and fire effects. He derived the scaling laws that allow the behavior of wildland fire to be reproduced on a smaller scale for more detailed study in the laboratory. He developed the physical theory and was the force behind the mathematical equations for fire propagation and energy release that tie fire behavior to atmospheric conditions including erratic fire behavior such as fire whirls, and the transition from 2-dimensional to 3-dimensional (blow-up) fires. He greatly improved a lookout's ability to detect fires, devised a formula to facilitate estimating fire size, contributed to suppression manning guides, and developed a list of red flag and watch-out criteria for fireline personnel. He was instrumental in developing an index that relates relative drought to fire management, was involved in examination of the thermal properties of fuels, the spotting process, firebrand characteristics and ignition probability, mechanisms of fire damage, and wildland fire documentation methodology. It is no exaggeration to state that George was involved directly or indirectly in virtually every aspect of fire science except heavy equipment design, air quality, and economics. His uncanny ability to clearly elucidate and define seemingly intractable problems, then compartmentalize and prioritize the various components into a comprehensive, orderly plan is perhaps exemplified by his 1960 problem analysis for the Southern Forest Fire Laboratory which laid out a visionary plan of attack for numerous yet unsolved problems. Current fire researchers would do well to familiarize themselves with this document, a copy of which can be found in Appendix B.

Fire detection work

When George Byram transferred to the Appalachian Forest Experiment Station in 1936, one of his assignments was to improve the capability of fire lookouts to identify smoke plumes. Names like the Smoky Mountains and Blue Ridge Mountains correctly portray typically impaired long-range visibility in this region. His research included work on atmospheric transparency, design of several haze meters, theories relating visual acuity to smoke column brightness, and development of a reliable eye-test for lookouts in fire towers that was picked up and used by the military in World War II. Dr. Ward discussed George's visibility contributions in more detail in his presentation.

Fire danger rating work

Fire management organizations would like to know the likelihood of a fire starting on a given day and how vigorously it is likely to burn once ignited. Such information would be very helpful in making daily manning (now called 'staffing') decisions. This need was the impetus for George to begin work on fire danger rating. His 1940 publication described the effects of sun and wind on fuel moisture and fire behavior. His low-key, unassuming approach and personal demeanor are obvious in the abstract of the publication summarizing that work which states '*Some may wish to challenge the practical significance of these findings or their validity under all conditions. Considerable further experimentation will be needed to tell the whole story. In any case, the subject is worthy of thought*.' George went on to undertake much of that '*considerable further experimentation'* over the ensuing 3 decades. The first comprehensive southern fire danger rating system was unveiled in 1938. George invented the Appalachian fuel moisture scale for weighing sticks which was a major improvement over the then-current Gisborne method in that it eliminated the necessity of using sticks that had to have a dry weight of exactly100 grams. George's scale was quickly adopted throughout North America and overseas. Although Byram is not typically associated with development of the National Fire Danger Rating System, George was the 'behind-the-scenes' brains; he, devised the basis for the NFDRS by developing the mathematical equations that express the rate of moisture diffusion in woody fuels, the concept of time-lag which characterizes the length of time it takes wood of different diameters to respond to changes in atmospheric moisture, and derived the mathematical expressions for the Buildup and

Burning Indices. George demonstrated their practical value by conducting field experiments to establish relationships among several atmospheric variables and equilibrium moisture content useful in making both long and short range manning decisions. Keith Arnold, former Director of US Forest Service Research, confirmed that '*George Byram developed the concept and application of fire danger rating…'*. The value of George's contributions was recognized in 1949 when he received a coveted Superior Service Award from the US Department of Agriculture.

Fuels work highlights

Byram guided Walt Hough in development of the concept of available fuel (the amount of fuel consumed under a given set of burning conditions numerically equal to fuel consumption) and total energy release (the total amount that would be released when a fuel is completely consumed). George established a linear relationship between the ratio of flame height to flame depth and a dimensionless number for the available fuel load. He showed that residence time (also called reaction time) in combustion room crib fuelbeds is a function of moisture content, and stick size and specific gravity.

Combustion and fire behavior work

George's interest in combustion and fire behavior resulted in break-through discoveries and innovative concepts for describing these phenomena. It would be hard to overstate the significance of Byram's contributions in this area; he provided the foundation for forest fuel combustion and was able to model this process. His fire system model included the earth's gravitational field, the earth's atmosphere expressed as a compressible fluid, a boundary surface beneath the atmosphere, and a heat source at or near the boundary surface; he published three papers describing parts of this fire system, but never did get around to solving the final piece (converting back from a pure heat source to wildland fuels). Nonetheless, his model was considered robust enough to describe all fires regardless of size or intensity. George's pioneering work on the burning characteristics of fuels resulted in the concept and definition of combustion rate (which Rothermel 'rediscovered' a decade later and called reaction intensity). George found this rate to be closely related to fuel drying rate and used it to classify fuel complexes based on their blowup potential. An integral part of this work was his discovery that in fuels with a specific gravity less than 0.45, the rate of fire spread increases rapidly as fuel moisture content drops below 10 percent; such fuels include conifer and hardwood foliage, twigs and moss. George called them 1-hr time-lag fuels. He demonstrated that these fine fuels are primarily responsible for fire spread. George graphed the effects of wind, slope and fuel moisture on rate of spread for combustion room crib fires, although to my knowledge this work has never been fully verified under actual field conditions.

George was fascinated by extreme and erratic fire behavior, and the factors governing these unexpected, dangerous and abrupt increases in energy output. He showed that convection as dictated by atmospheric stability (or lack thereof), rather than radiation, was the major determinant of large fire behavior and went on to develop the concept of fire intensity for a line of fire. This very useful measure of a line fire's rate of energy production is the product of the fuel's heat of combustion, the unit area weight of fuel consumed, and the fire's rate of spread. This term is the basis for determining both how to attack a wildfire and the severity of the fire's impact on the landscape. The noted Canadian fire researcher, Charles Van Wagner once observed '*Fire intensity thus conceived contains about as much information about a fire's behavior as can be crammed into one number*'.

Byram spent 1950 in California working with an elite group of scientists tasked with prediction of fire spread and behavior after a mass ignition event such as a nuclear explosion. George recognized the value of field documenting a wide variety of fires to determine their characteristics, strongly endorsing and promoting such efforts. The several boxes of early fire documentations (along with numerous datasets and photographic records dating back to before WW ll) were lost to posterity when the Southern Forest Fire Laboratory was closed in the 1986 National Fire Reorganization.

In the late1950s, George was a member of the team that investigated fire danger, fire behavior and the potential of prescribed fire to reduce hazardous fuel buildups in the pocosins (think swamp on a hill) of eastern North Carolina. Available fuel loads in this fuel complex are some of the highest in the South and spring wildfires often involve live tree crowns, exhibit mass spotting and fire whirls, and release enough energy to overpower the effects of surface wind. Sometimes these columns develop cap clouds that are violent enough to produce precipitation (Dr. Ward and Dr. Nelson both mention fires documented in that area that support George's power of the wind vs power of the convection column [Pf/Pw or Nc as it is often denoted] hypothesis). George calculated at least 6 tons of available fuel per acre was required before erratic fire behavior could occur.

As the number of days without precipitation increases, the underlying organic soils in pocosins dry to the point where they will ignite, significantly increasing the difficulty of suppression and releasing copious amount of smoke that make nearby nighttime travel virtually impossible. George undoubtedly experienced such scenarios firsthand which may well have prompted him to attack each of these problems. In any event he collaborated with John Keetch to produce the Keetch-Byram Drought Index, an indispensable tool used by people involved with daily manning and readiness decisions, as well as by prescribed burners to regulate consumption of coarse woody debris and deep duff which typically results in fine-root mortality and subsequent overstory mortality.

Byram collaborated with Ralph Nelson Jr. to derive the basic scaling laws for modeling both mass fires (those that develop when a shower of embers drops onto a receptive fuel bed) and pulsating fires (those that alternate between periods of slow and rapid spread due to plume growth and subsequent decay). He showed that convection patterns above a fire depend upon fire intensity, the speeds of both surface and upper winds, atmospheric stability, and topography. George examined combustion column motion and shape characteristics as fire behavior indicators. He developed a list of adverse wind profiles and associated smoke column characteristics for use on going fires that signal the transition from 2 to 3 dimensions (blow-up conditions). Attention to these watch-out situations vastly improved firefighter safety. George directed Hubert Clements' work with fire brands to describe the factors that determine ember lift-off, the height to which they will rise, and travel distance (time) before being consumed or dropping to the surface. This information can be used to predict the spotting distance of various types and sizes of firebrands. George also guided Hal Blackmarr's research to determine the ignition probability of different sized embers landing on a homogeneous pine litter fuelbed under a range moisture conditions.

George showed that fire whirlwinds are the primary phenomena that produce erratic pocosin fire behavior, and that the rapid spread of high-intensity fires depends largely on violent convection in these fire whirls. George collaborated with Bob Martin to determine the responsible factors and threshold values necessary for their formation. They successfully reproduced fire whirls in the lab and mathematically described the increased fuel consumption and associated horizontal and vertical wind speeds. Wayne Adkins took high-speed movies of combustion room fire whirls so George could measure the rotational and vertical flame velocities after injecting copper sulfate or sodium chloride into the base of the flame. When I began work at the SFFL, our outreach activities would always involve a Plexiglas fire whirl chamber where we would generate 10^+ ft high fire whirls to the awe of children and adults alike.

Wayne Adkins, a disciple of George's, developed a video image analysis system that allowed the scaling and measurement of fire behavior parameters as prescribed fires traverse wildland fuels. These video recordings could be analyzed frame by frame into temporal and spatial values of flame length, height, tilt, area and relative position that with elapsed time, could then isolate variations in rate of spread to specific combinations of fuel and weather variables. This work provided a tool for additional field verification of Byram's work on combustion, flame-front characteristics and fire spread. Wayne's system utilized the concept of the virtual horizon which George suggested could also be used to measure smoke plume height from an airplane, but to my knowledge has yet to be investigated.

Fire use

Byram must have begun thinking of the intentional use of fire in southern pine stands and the factors that determine tree damage early in his career. His initial experiments determined plant characteristics and threshold values that enabled young southern pines to survive low-intensity fires, especially grass-stage longleaf pine infected with brown spot disease. Paul Siggers had previously demonstrated fire could control this disease and Byram extended his work to show fire resistance of young longleaf was due to physical attributes such as large buds (high heat capacity) covered with a downy layer of insulating tissue that were further protected by long needles that formed a protective sheath. Forest managers were concerned that longleaf sapling mortality was typically higher on their burns than on higher intensity wildfires. George worked with Anson Lindenmuth to show that using headfires instead of backfires greatly reduced mortality in young longleaf because headfires are cooler near the ground than backfires.

George collaborated with Bob Martin to quantify the factors involved with fire induced tree stem cambial mortality. Practical results included the fact that the lightweight bark of southern pines provided considerably better insulation than the denser bark of many hardwoods and that the thermal conductivity of water-saturated bark is 50 % higher than that of dry bark. The above findings can be put to good use when writing prescriptions to control unwanted competition in southern pine stands.

George explained the relationship between basic thermal processes and damage to live vegetation. His 1958 US Forest Service Research Note contained four graphs that took much of the guesswork out of prescribed fire and its effects on live vegetation; it: 1) graphed height of crown scorch as a function of initial vegetation temperature, 2) plotted the time necessary to reach the lethal cell threshold at various temperatures, 3) showed headfires are cooler near the ground than backfires and, and 4) plotted effects of wind speed on rate of spread of low-intensity head- and back-fires. Because of Byram's work, resource managers could now conduct burns with confidence that the burn would accomplish their objectives without damage to yellow pine stands. The millions of acres successfully burned throughout the South each year provide mute testimony that this 2-page research note is the most important fire-use document ever written!

George Byram's legacy

The above synopsis hardly does justice to the phenomenal impact George Byram has had on wildland fire science. He excelled at providing solutions to practical problems faced by fire managers and continually demonstrated his ability to describe basic physical concepts and formulate mathematical relationships that govern the problem in question. In so doing, George provided true solutions that have withstood the test of time. He created both basic and operationally useful knowledge that current fire researchers continue to cite as they extend Byram's pioneering work. His chapters on fuels, combustion, and fire behavior in *Fire Control and Use*, first published in 1959, continue to be a 'must read' for every budding fire scientist. His solutions and guides continue to be taught at both basic and advanced fire training courses worldwide. George Byram's accomplishments provide the trunk and main branches of the tree of fire science knowledge. The breadth, depth, importance and durability of his contributions lead to the inescapable conclusion that George Byram is truly **The Father of Fire Science**.

I think some of the reasons for his enduring success are that he developed mathematical proofs for his theories and always <u>field verified</u> (What a refreshing philosophy compared to today's purveyors of untested crapolla) the operational solutions he developed before publishing them in user-friendly language in outlets that natural resource managers read. Once this was done, George would move on to the next problem, rather than taking the year or so necessary to publish the theoretical derivation in some highfalutin scientific journal that land managers were not likely to see. But this should not suggest that George cut corners. He invariably documented the theory and step by step work that led to his conclusions and freely distributed them to anyone that asked; and he did not worry about unscrupulous individuals not giving him proper credit. His goal was to provide knowledge so natural resource managers could do a better job.

George was interested in other pursuits as well. He was a mushroom connoisseur and grew them in his basement. He also enjoyed painting and although fairly talented, to my knowledge he never sold any of his works. He was an accomplished photographer and interested in reported sightings of UFO's. As a young scientist, I was in awe of George; he was always busy, either writing on a legal-size pad of yellow paper in his office or conducting experiments in the combustion room or wind tunnel. However, his door was usually open and he would graciously take whatever time was needed to educate me, but having said that, I did not want to interrupt his train of thought with some minor question, so I generally waited until coffee break. In retrospect I kick myself for missing a great opportunity to learn the nuances of fire behavior from this fountainhead of fire knowledge.

Below is a list of recollections of various colleagues that provide insight into the personality traits that defined this pioneer of fire research and endeared him to those of us who had the distinct privilege and pleasure to cross paths with the Father of Fire Science. I contacted the following individuals regarding their recollections of George: Ted Ach, Wayne Adkins, Stephen Boyce, Walt Hough, Bill Johansen, Bob Martin, and Dave Van Lear

- Wayne Adkins happened to mention to George that 'everybody' was using his flame length-fire intensity relationship. This upset George, and although Wayne does not know why, one can surmise that it was because the equation was being used in fuel complexes far beyond the lowland South Carolina southern pine communities used to derive the relationship.
- George would sometimes invite Wayne to his office during coffee break to talk about their shared interests of photography and UFOs. George obtained a copy of a 'National Investigations Committee On Aerial Phenomena' report which outlined what investigators had found regarding supposed alien spacecraft landings; he would use the depth of the soil depression data given in this report to calculate weights of the UFOs. George gave some credibility to the reported sightings.
- On one occasion, George complimented Wayne on his photos of flames and Wayne explained the procedure he used. George was impressed and fully endorsed the method.
- Wayne was trying to use movies taken at the normal 64 frames per second to capture fire behavior and combustion products for Walt Hough, but wasn't totally successful. Walt told him to get the procedure worked out - and he did. Wayne told George about it and George was again impressed; giving his approval and suggesting that Wayne could also use his method to measure smoke column heights from airplanes. Wayne retired before he had the opportunity to try it for that purpose, but he did use the same method in his image analysis system; it involves the concept of the virtual horizon.
- When Bob Martin came to work at the Southern Forest Fire Laboratory in 1958, he wanted to meet Byram so he called him to set up an appointment. When Bob arrived in Asheville, he called George and reconfirmed their appointment the following morning, but when Bob arrived at George's office, the lights were out and the door closed, so he wandered down the hall and introduced himself to John Keetch. John seemed somewhat perplexed and said George was not scheduled to work that day so Bob called him at home and was invited to come over. George had suffered from back problems and Bob was ushered into his bedroom where George was in the midst of back exercises. Bob was very impressed with the system of pulleys and ropes that George had rigged up over his bed to facilitate his exercise regimen.
- Bob remembers another meeting with George in Asheville, when the Station Director walked by. The Director had a bloody mouth and told them he had just come back from the dentist where he had a tooth removed. George looked him in the eye and responded by saying '*he had just come back from the barber where he had some hair removed'* which Bob found hilarious and unsuccessfully tried to keep a straight face.
- One winter George discovered that his house was infested with termites so he read up on their control and found they could not survive below a particular temperature threshold. He waited until the forecast called for temperatures to remain below that threshold for several days, turned off the heat, opened the windows and moved his family into a motel. When they returned home days later, the termites were all dead, but he had forgot to turn off the water so the pipes had frozen and burst and he ended up spending considerably more than if he had called a pest control company in the first place.

- Bob Martin really enjoyed working for George because George treated him as an equal and valued his input making Bob feel as though he worked with George rather than for him.
- An Assistant Director once told Bob Martin that George's only shortcoming was that once George found the answer to some perplexing question that had baffled others, he saw no reason to publish the mathematical/physics-based derivation. He would simply write a brief paper describing the operational usefulness of his findings and move on to the next challenge.
- George was a perfectionist in everything he did. When he and Bob Martin first envisioned constructing a fire whirl chamber, they would get together on Saturdays to construct and test prototypes. This pursuit soon turned into Fridays and Saturdays and finally Thursdays, Fridays and Saturdays. Bob would get exasperated with George because whenever George saw him rough-cut a board, George would grab another and make a precision cut telling Bob to do a better job.
- Bob and George finished their fire whirlwind work in 1963 and produced a finished manuscript before Bob left Macon. Bob was under the impression that George had sent the manuscript to a journal for publication, but did not hear anything about it for several years and figured it had been rejected. He was thus very surprised seven years later when it was finally published. Bob called George and asked about the delay; George replied that it had taken him a few years to get around to submitting it.
- George was on Martin's PhD committee and showed up unannounced at Bob's dissertation defense. He didn't say much, but at the conclusion told Bob to take a look at a specific page because there might be an error on it. Bob spent most of the night going over the text and formulas on that page without finding anything wrong. He met George the next day and George simply pointed out a mistake in one of the formulas and corrected it for him, with the comment that none of the other committee members caught it because they did not understand what Bob was doing.
- Bill Johansen also suffered from back problems so George wrote out his exercise regimen and gave it to Bill. Bill has faithfully followed it for the past 45+ years and has had no back pain since soon after he began the routine.
- George had a dirt floor basement in his house where he grew mushrooms. He confided to Johansen that on rare occasions when he could not identify a mushroom, he would first give the family dog a bite and watch the reaction. If all went well, he would then test it on his wife before he would try it. Bill doesn't think his wife ever realized she was his food taster.
- Ted Ach remembers George was always either deep in thought or jotting things down on a legal size pad of yellow paper (George retired in 1968 before desktop computers changed our lives).
- One morning several folks were in the 2nd floor hallway on their way downstairs for coffee break when they observed George leave his office, walk across the hall, open the door to the supply closet and walk in. He immediately reemerged, shut the door without saying anything, opened the door to the stairway and followed them downstairs for coffee.
- Ralph Nelson Jr once observed George, deep in thought, forget to open the wind tunnel door before attempting to enter. He made it on his second try.

Acknowledgements

Thank you Faith Ann Heinsch, Missoula Fire Sciences Laboratory for providing a clear copy of Byram's 1960 Problem Analysis. And thank you Ralph Nelson for making numerous corrections and suggestions on the several drafts I sent you – it is a better paper because of your diligence and eagle-eye.

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Appendix B. Byram's 1960 Problem Analysis and proposed research program for the Southern Forest Fire Laboratory

Proceedings of 4th Fire Behavior and Fuels Conference, February 18 – 22, 2013, Raleigh, North Carolina, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Draft
June 9, 1960

A Problem Analysis and Proposed Research Program for the Southern Forest Fire Laboratory

by

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I. INTRODUCTION

The studies outlined and discussed in this problem analysis represent a program of work which will be centered in the Southern Forest Fire Laboratory at Macon, Georgia. The analysis is based on the assumption that the work of the laboratory is one of several integral but independent parts of the overall fire research program. It is further assumed that the basic purpose and functions of such a laboratory are to meet the overall research needs of the Southeastern States and the national needs in certain basic fields of fire science. The term "fire laboratory" will in general be used to designate related programs of work being done over an extensive area rather than just within the four walls of a building.

Much of the work within the laboratory facility itself will be of a long-term basic nature. Considerable research will be in support of other parts of the overall program, such as experimental field studies or mathematical and theoretical investigations of convection processes. For this reason the laboratory studies may not appear to have the immediate practical significance that some of the field studies appear to have. However, the laboratory work may contribute substantially to success in other phases of the research program. For example, if certain scaling studies prove to be successful in the laboratory, then work on large scale test fires in the field may be more effective and accomplished with less effort than if the basic laboratory work had not been done.

Some problems, such as those concerning basic combustion processes, will be studied almost entirely within the laboratory facility. At the other extreme will be studies in which little laboratory research is needed. However, there will be relatively few problems which can be solved wholly in the laboratory or studied entirely in the field. Most studies will benefit from a joint field-laboratory approach.

It may be desirable to revise this problem analysis within the next 12 or 15 months. By that time new personnel now coming to the laboratory will have their work well underway with more definite plans for the future. These plans should be incorporated in the problem analysis.

Basic research and applied research. During the last few years the terms "basic" research and "applied" research have become so frequently used by fire research personnel that one might assume that these terms had the same meaning for everyone. However, it was soon found in the preparation of this analysis that such was not the case and that different individuals sometimes had quite different ideas as to what these two terms meant. For example, some had a tendency to make a distinction on the basis of work location; laboratory projects were considered more basic than work in the field. Others were inclined to consider work in the physical sciences as more basic than work in the life sciences. Some made the distinction primarily on the basis of level of difficulty and tended to identify difficult research as basic research.

In view of the various shades of meaning that are given to the terms "basic" research and "applied" research, it is desirable to have working definitions of these two terms on which most research men can in general agree even though they might differ on specific details. Such definitions are proposed in Appendix I. They may appear to be somewhat oversimplified but appear to be adequate for the purpose of this report.

Program presentation. Because of the interdependence of the field and laboratory phases of most of the research program, no attempt has been made to separate problems into field and laboratory groups. Because of the large number of individual problems and studies, grouping on the basis of problem relatedness seemed to be the more convenient approach. The program outline is presented first and followed with discussions of the different fields of research. These discussions have purposely been made rather general. It seemed more appropriate at this time to outline the different fields and to indicate the kind of problems for which solutions appear most urgent, than to go into detailed technical discussions of specific problems. The details of specific programs of work in a given field should appear in the work plans prepared by the men who will be doing the research in those fields.

II. PROGRAM OUTLINE

The following outline is a detailed listing of studies which would be carried on either in the laboratory or in related field experiments. The arrangement or sequence of study groups is somewhat arbitrary, but an attempt was made to make the sequence one of increasing dependence on prior groups. For example, fire danger rating research is placed well along in the list because work in this field depends heavily on the progress in the preceding fields. On the other hand, ignition and combustion studies con be token as an appropriate starting point in a fire research program.

A. IGNITION, COMBUSTION, AND FUELS

1. Basic studies of the combustion process.

   a. Theoretical and experimental work in the physics and chemistry of combustion.

   b. Establish standard solid fuels and fuel arrangements for burning tests.

   c. Rate of energy release tests with standard fuels

      (1) Tests in atmospheres containing different proportions of O_2 and N_2, O_2 and CO_2, air and H_2O. Moisture content of standard fuels to be held constant.

(2) Tests in atmospheres of air and air mixed with O_2 and with different moisture contents of the standard fuels.

2. Laboratory studies with model fires (moving and stationary)

   a. Determine effect of independent variables.

3. Heat balance studies – the heat yield and its variability.

   a. Investigate the efficiency of the combustion process in fuels of different sizes, different arrangements, and with different rates of air supply.

   b. Determine radiation loss and the effect of fuel moisture on the heat yield in laboratory test fires.

   c. Determine heat yield on test fires in the field.

4. Properties and behavior of firebrands.

   a. Flaming firebrands

      (1) Determine types of material most likely to flame; determine effect of moisture content on flaming tendency.

      (2) Study aerodynamics properties of flaming firebrands such as their terminal speed in free fall.

   b. Glowing firebrands

      (1) Determine effect of kind of material and moisture content on tendency for glowing, Determine limiting moisture contents for glowing in different substances.

      (2) Determine terminal speed in free fall.

   c. Determine ignition probability for both flaming and glowing firebrands as a function of moisture content in different types of fuels. This would be an empirical field and laboratory study.

5. Fuels, energy, and fire behavior.

   a. Further development of basic fuel concepts and their relationship to fire behavior.

   b. Develop methods of fuel measurement in the field in terms of the basic fuel factors.

c. Study the combustion rate as a possible method of rating and comparing fuels in terms of their basic fire behavior potential.

(1) Determine effect of size of burning area on the combustion rate.

(2) Determine effect of fuel moisture and wind speed on the combustion rate.

d. For different fuel and stand types, determine how fuel characteristics, fuel moisture, fuel moisture distribution, and fire intensity affect the available fuel and the available fuel energy.

6. Thermal properties of forest fuels.

a. Determine thermal properties of a wide range of forest fuels, such as litter or duff, wood, punk, individual leaves and needles, and organic soils. Properties to be determined are specific heat, density, thermal conductivity, heat of combustion, heat of decomposition, and spectral absorption factors.

b. Determine energies for ignition of fuels by radiation.

7. Combustion and smoldering tests in organic soils.

a. Determine limiting moisture content for smoldering in organic soils.

b. Determine whether ground fires in organic soils are supported primarily by a combustion reaction or by an exothermic decomposition reaction as well as combustion.

B. FIRE BEHAVIOR

1. Case studies of individual fires. Directed primarily toward the major or unusual fire, but some lesser fires will also be case studies.

a. Assemble surface and upper air weather data which accompanied selected fires.

b. Assemble comprehensive data on fuels and stand type for individual fires –do the same for topography.

c. Assemble detailed behavior data on the fires such as rate of forward spread, height and characteristics of flames, presence of whirlwinds, appearance and characteristics of the convection column, and the distance and characteristics of spotting.

d. Analyze behavior of individual fires and its relation to the associated fuel, weather, and topographic factors.

e. Study methods for obtaining measurements on some of the behavior characteristics of fire such as speed of convection column updrafts, convection column temperatures, and surface pressure changes within the interior of a large convection column (see section on fire measurement).

2. Experiments with test fires–to be planned fires in the field which would cover a rather wide range of intensity but with maximum intensities considerably less than for high-intensity fires, probably not more than 4,000 Btu's per second per foot for moving fires nor more than a total intensity of 4 x 10^7 Btu's per second for stationary fires.

a. Study possible use of slash fires as high-intensity test fires.

b. Types of studies for test fires--convection studies, heat balance studies, measurements of behavior characteristics (see also A-3).

c. Instrumentation of test fires including time-lapse movies (see section on fire measurement).

d. Slow-motion movie study of flames and fire fronts (see section on fire measurement).

3. Fire system models research (analytical and experimental).

a. Analytical work in the thermodynamics and fluid mechanics of free and forced convection; investigation of convection which is a combination of both free and forced convection; development of criteria for differentiating between the two; free convection and the blowup process.

b. Development of fire system models.

(1) Requirements that a model must meet.

(2) Component parts of a fire system model.

(3) Models with heat sources

(4) Models without heat sources—the weightless gas equivalent of a heat source.

c. Development of scaling methods for experiments in convection modeling.

d. Investigation of fire whirlwinds and vortices using different energy sources. Laboratory studies on small model whirlwinds.

e. Experimental studies of forced and free-forced convection with heat sources in the wind tunnel. Tests to be made over a wide range of values of the energy rate number.

f. Laboratory studies of free convection with fires and other heat sources in the free convection room.

4. Fire propagation.

a. Make an intensive analytical study of the mechanics of fire propagation and fire spread.

b. Field and laboratory studies of fire spread.

C. **FIRE USE AND FIRE EFFECTS**

1. Mechanisms of fire damage

a. Determine thermal properties of tree stems such as density, specific heat, thermal conductivity and variations in stem geometry.

b. Investigate heat transfer process in the needles, twigs, and main stem of a tree.

c. Biochemical or biophysical studies.

(1) Investigate the biochemical processes involved in the injury of plant tissue by heat.

(2) Develop a definition and criterion of lethal temperature.

(3) Determine time-lethal temperature relationships for leaves, needle and cambium tissues.

2. Field studies in fire damage and its relation to such factors as fire intensity, ambient temperature, duration of elevated temperature, and season of year.

a. Develop burning techniques for hardwood control

b. Develop mortality indicators.

3. Field studies in prescribed burning

a. Development of methods and techniques of burning.

(1) Measure rate of growth of intensity of head fires starting from a point source in different fuels and under different burning conditions. Make similar measurements for head fires and flank fires starting from a line source. Look into possibilities of using dimension analysis in this type of work.

(2) Investigate possibilities of head fires and flank fires for prescribed burning in cold weather. Determine their limitation in terms of ambient temperature, fuel characteristics, fuel flammability, wind speed, fire intensity, and stand conditions.

(3) Study firing techniques and burning patterns for speeding up the prescribed burning process.

b. Determine the range of weather conditions and fuel conditions under which different techniques of burning can be conducted.

D. FIRE METEOROLOGY

1. Studies of the meteorological elements controlling fire behavior.

a. Behavior of the wind and temperature fields of the atmosphere –primarily within 10,000 feet of the surface.

b. Structure and behavior of dry cold fronts. Circulation within the front (especially in the vicinity of the frontal surface), vertical and horizontal wind profiles in different parts of the front, and vertical and horizontal temperature profiles.

c. Study the short period (5 to 15 minute) fluctuations in the vertical wind profile. Study the hour-by- hour diurnal changes in the vertical wind profile and their relationship to the vertical temperature profile and stability conditions--an experimental and analytical study. Both single and double theodolite methods to be used.

d. Determine the sequence of meteorological elements during and preceding severe fires such as wind profile, temperature profile, surface relative humidity, surface temperature, surface wind, and surface upper air synoptic patterns.

2. Determine basic causes of meteorological conditions associated with extreme fire behavior.

a. The low-level jet wind.

(1) Analytical approach.

(2) Statistical investigations through the use of weather records--determine frequency of occurrence and geographical extent of low-level jet winds as well as their diurnal variation.

(3) Modeling experiments in the laboratory.

(4) Determine relationship of high-level jet to vertical and horizontal air movement in the lower atmosphere—primarily below 10,000 feet.

b. Low relative humidity.

(1) Study meteorological processes which produce low relative humidity at the earth's surface, such as subsidence and cold front passage.

3. Investigations bearing on prescribed burning.

a. Determine sequence of meteorological elements during and preceding periods suitable for prescribed burning—direction and speed of surface winds, relative humidity, temperature and rainfall.

b. Study the persistence in speed and direction of the surface winds during the seasons for prescribed burning.

4. Studies in forecasting improvement and monitoring of key weather factors.

a. The movement and passage of dry cold fronts.

b. The onset of subsidence or other conditions which produce low humidities at the surface.

c. The development, occurrence, and duration of low-level jet winds and the vertical wind profile in general.

d. Problems associated with the forecasting of surface wind speed, surface temperature, surface wind direction, relative humidity, and rainfall.

e. Development of unusual turbulence and instability.

f. Study of the use of frequent pilot balloon soundings for monitoring the vertical wind profile in the vicinity of large fires. Also during periods of dry weather and severe burning conditions.

g. Determine the ability of an observer to learn to estimate the vertical wind profile and wind conditions aloft by the use of sounding balloons but without a theodolite.

E. **FIRE EXTINGUISHMENT**

1. Ignition, combustion, and fire extinguishment.

    a. Study the effect of chemicals on basic ignition and combustion processes.

    b. Determine how chemicals promote or inhibit ignition and combustion.

    c. Determine the relationship of the various fuel characteristics, including moisture content to the combustion rate; determine those changes in characteristics which reduce the combustion rate. (see also the studies in the section on Ignition, combustion and fuels,)

2. Energy studies of the relation of the application of water (and water plus chemicals) to the rate of energy release of fires burning in solid fuels.

    a. By burning specially designed cribs, determine the relationship of the rote of energy release and rate of change of rate of energy release to (1) fuel or crib characteristics, and (2) rate of application of water and water plus chemical. Evaluate in terms of energy relationships.

3. Studies in the application of basic knowledge in combustion, fire behavior, and fire extinguishment to fire suppression techniques.

    a. Development of techniques for low-intensity fires.

    b. Development of techniques for high-intensity fires.

F. **RESEARCH IN FIRE DANGER MEASUREMENT**

1. Fuel moisture studies.

    a. Determine equilibrium moisture contents for specific but widely different fuels such as grass, decayed wood, pine needles, and organic soils.

    b. Rate of drying investigations.

        (1) Establish standard drying conditions and determine if rate of moisture loss in forest fuels con be approximated by exponential functions if temperature and relative humidity are constant.

        (2) Measure the moisture timelag constant for a variety of fuels and fuel sizes such as twigs, logs, grass, and litter of varying depth.

(3) Determination of effect of variables such as wind, sunshine, temperature, and relative humidity on the moisture timelag constant of different sizes and types of fuel.

(4) Determine if dimensionless timelag ratios for different fuels (exposed under identical conditions) are independent of wind, temperature, and humidity.

c. Determine moisture content of living vegetation and moisture content trends in different types of living fuel such as green brush and tree crowns, as a function of time of year and degree of drought buildup.

d. Determine the effect of periodic daily variation of wind, sunshine, temperature, and relative humidity on the moisture content of various types of fuels including different types of indicator sticks.

e. Determine long-term moisture changes in the heavier components of the various fuel types.

f. Study mechanism of water replenishment in different fuels.

g. Drought investigation for both organic and in-organic soils.

(1) Determine water absorbing characteristics of organic soils. Determine moisture content below which they become water repellent.

h. Development of methods for maintaining a moisture budget on various forest fuels having different timelags.

i. Determine effect of radiation (solar and terrestrial) and wind on forest fuel temperature.

2. Theory and concepts of fire danger rating

a. Develop further the multiple index concept.

b. For heterogeneous fuels determine relationship between the timelag constant, the length of drying time, and the available fuel.

c. Study of fire danger variables and analysis of integrating methods and devices.

3. Dimensional analysis study of the fire weather variables.

G. INSTRUMENTATION AND METHODS OF MEASUREMENT

1. Fire measurement.

a. Low-intensity fires

(1) Determine what variables should be measured.

(2) Develop methods of measurement of temperature in flame zone and in the convection zone above the flames.

(3) Develop methods for measuring speed of updrafts in flame and in convection zone. Investigate use of slow-motion photography for closeup work.

(4) Investigate use of high heat capacity receivers for heat and temperature measurement in the flame and convection zone of fires.

(5) Investigate use of low heat capacity receivers of low emissivity for flame temperature measurement.

(6) Develop instrumentation for the laboratory wind tunnel and convection room.

b. High-intensity fires.

(1) Determine what variables should be measured

(2) Investigate photographic methods including the time-lapse camera for studying motion in the convection column.

(3) Investigate possible use of radar and ultrasonics for "looking into" interior of high intensity fires.

(4) Develop methods and instruments for measuring indrafts and entrainment into the convection column over large fires.

2. Fuel measurement

a. Develop instruments and methods for measuring heat yield of fuels in the laboratory and in the field on test fires.

b. Develop radiometers and other types of heat receivers for use in tests on combustion methods of fuel rating.

3. Fire danger instruments; measurement of atmospheric factors.

a. Improve and simplify fire danger instruments and develop new instruments as needed.

b. Develop simplified sounding equipment and methods for estimating the wind profile in the field.

H. FIRE CONTROL MANAGEMENT

1. Fire prevention.

    a. Develop methods for improving statistics of fire causes and classes of people who start fires.

    b. Application of behavioral sciences for determining why people start fires.

    c. Develop methods for estimating or measuring the effectiveness of fire prevention efforts. An example is the use of burning index for "taking out" the effect of weather on fire occurrence rate.

2. Detection.

    a. Study effectiveness of different detection methods such as towers, planes, and patrols under different burning conditions and degrees of visibility.

    b. Study specific problems associated with each of the several detection methods.

    c. Development of detection systems which may combine tower, plane, and patrol; methods.

    d. Visibility and detection research. Investigate new principles of smoke and fire detection, such as radar, television, and infrared detecting devices.

3. Suppression.

    a. Cooperative studies in developing and testing new methods of fire suppression (such as the use of chemicals for both ground and air application).

    b. Development of small suppression equipment of certain types which need laboratory development and testing.

    c. Field tests of new techniques in fire extinguishment.

4. Studies of the relative effectiveness of different fire control systems and methods.

    a. Economic and cost analysis studies.

    b. Use of operations research in the overall field of fire control.

    c. Development of fire control systems.

III. IGNITION, COMBUSTION, AND FUELS

From the standpoint of fire behavior combustion may be defined as the chemical chain reaction which supplies a fire's driving energy. For all forest fires this reaction is between the oxygen of the atmosphere and the woody fuels of the forest. Likewise, for the vast majority of urban and industrial fires the reaction is also between atmospheric oxygen and solid or liquid fuels. The combustion process is described in greater detail elsewhere.[1]

Ignition may be defined in an elementary way as the beginning of the combustion reaction. Actually, ignition is a more complex concept in that it can be visualized as a part of the combustion chain reaction. Probably some of our most basic research will be in the field of ignition and combustion.

Basic studies of the combustion process. This group of studies would be done almost entirely within the laboratory. Theoretical and experimental work in the physics and chemistry of combustion would be a very difficult field and would require highly trained personnel. The work would also be of a long-term nature. Some of the combustion tests with standard fuels and different composition of atmospheres could be done in connection with the fuels research described later. Although recent work on fire system models indicates that an understanding of the large-scale convective processes, which dominate extreme fire behavior, does not require an understanding of the fundamental ignition and combustion processes, nevertheless, there are many good reasons for increasing our knowledge in these fields, for example, the development of chemical methods of fire extinguishment may depend heavily on basic research in the physics and chemistry of ignition and combustion. Also progress in ignition and combustion studies should contribute to quantitative predictions of rate of spread and fire intensity when the mechanisms of fire propagation are better understood.

Laboratory studies on model fires (moving and stationary). Work on model fires[*] with solid fuel (specially prepared cribs of wood) has been underway at the Pacific Southwest Forest Experiment Station at Berkeley, California, for over a year. A similar study will be started at Macon this summer. Heat balance work in this study may lead to more precise knowledge of the heat yield of forest fuels--a very essential quantity in fire behavior calculations.

Determination of heat yield. Some of the most important calculations in fire behavior arc energy calculations. One of the significant quantities entering into such calculations is the heat yield per pound of fuel burned. The heat yield is defined as the energy flowing into the fire system and it represents the driving energy of fire behavior. Numerically it is equal to the heat of combustion minus certain losses. These losses are not as yet precisely known, but under some conditions they are probably large. If so, then there is considerable uncertainty in the heat yield. These losses arc composed primarily of a radiation loss and a "loss" due to incomplete

[1] Combustion of Forest Fuels. Chapter 3, Forest Fire: Control and Use, by K . P. Davis. McGraw-Hill, 1959

[*] It should be noted that the term “model fire” has a considerably different meaning than the term “fire system model” used later.

combustion. The loss resulting from the presence of water in the fuels is comparatively small and it can be calculated if the fuel moisture content is known.

The determination of the heat yield as a function of variables such as size and intensity of fire, fuel moisture, and fuel characteristics is essential before the energy involved in fire behavior phenomena can be precisely known.

Present computations are based on heat yield values which may range from 5,000 to 7,000 Btu's per pound of fuel, but these values are uncertain. Work on this problem would be a joint field- laboratory job with most of the early work being done in the laboratory. Later the main effort will probably be in the field.

Properties and characteristics of firebrands. An essential part of the mechanism of fire propagation in major fires is the continuous establishment of new ignition points ahead of the main fire front. Although radiation and turbulent flame movement can produce new ignition points near the fire, the main source of these points is from embers or firebrands falling ahead of the burning front or "spotting," as it is called. The area density of these ignition points (that is, the number of new fires starting per unit area) at a given distance from the main fire depends on the number of firebrands falling per unit area and the ignition probability associated with each firebrand. The number of firebrands, in turn, depends on the quantity and quality of the material available for spotting as well as the convective characteristics of the fire. The ignition probability will depend on the characteristics of the firebrand, its moisture content, and the nature and moisture content of the fuel and vegetative ground cover. Firebrands can be separated into two main groups--flaming and glowing. Flaming firebrands consist of light, dry material, such as leaves and grass which burn out rather rapidly. For this reason their effect probably does not extend more than a few hundred feet ahead of the fire. Glowing firebrands consist of punky decayed wood, pieces of duff, bark, and other material which will permit smoldering. The ignition probability for glowing firebrands is much less than for flaming firebrands, but the effect of glowing firebrands probably extends over much greater distances (up to several miles in some instances). Some firebrands may be of the flaming type during the first part of their flight and the glowing type during the latter part of their flight.

An investigation of the properties and characteristics of firebrands would be a major study and a very important one. Probably the most urgent specific problem is to determine how ignition probability is affected by fuel moisture. The indications are that this probability increases rapidly with decreasing fuel moisture. The study would include work on a number of problems such as the thermal characteristics of flaming and glowing firebrands and their aerodynamic properties including the determination of terminal velocities in free fall tests.

Work on this study would be carried on in both the laboratory and the field, but probably with the majority of the work in the field.

Fuels, energy, and fire behavior. Further development of new fuel concepts from the standpoint of energy and rate of energy release may make it possible to rate and eventually classify fuel in terms of their fire behavior potential. Preliminary work is sufficiently promising to make this a high priority field of study. There appear to be definite fuel factors or fuel functions which have specific meanings in terms of energy, rate of energy release, and fire behavior. Probably one of the simplest of these, as well as the most important, is the concept of available fuel and the associated concept of available fuel energy. The available fuel is a widely variable quantity and is defined as the quantity of fuel which will actually burn. The available fuel depends primarily on the moisture content of the different fuel components and to a lesser extent on the fuel size and arrangement. It also depends on fire intensity; a slow spreading backfire will burn less fuel than a fast moving head fire when burning conditions are severe*. The available fuel energy is defined as the energy which is released when the available fuel burns. In some fuel types which contain components that require a long time to burn out, it is necessary to distinguish between available fuel energy and the fuel energy available for convection. It is the latter energy that determines the major behavior characteristics of high-intensity fires. Probably for most large fires in the fuels of the Southeast, those two energies are the same but this might not be true for parts of the West where large limbs and logs make up a considerable part of the total fuel.

The design of future experiments in fuel studies may be strongly influenced by the development of the basic fuel concepts. An example is the possible use of the combustion rate concept in rating or comparing different fuels by special combustion tests, although the procedure has not yet been tested. The combustion rate is defined as the rate of energy release per second per unit of ground area. A convenient unit is Btu per second per square foot. It should not be confused with fie intensity which is an entirely different kind of quantity and is expressed in different units. However, they are closely related, fire intensity being equal to the mean combustion rate across the burning front multiplied by the width of the burning front. The combustion rate is likely to have rather unusual but useful properties. It will be dependent on fuel moisture and fuel arrangement, but its time integral during a complete burning test may be nearly constant. The combustion rate may be nearly independent of wind velocity and it may be but little affected by size of burning area.

In addition to the combustion experiments in fuel rating and comparison, there would be work in the development of methods of fuel measurement in the field.

The preceding series of studies would require both field and laboratory work.

Thermal properties of forest fuels. Measurement of thermal properties such as specific heat, density, thermal conductivity, heat of combustion, and heat of decomposition for a number of fuels would be a laboratory study, as would be the determination of ignition energies. Representative fuels to be studied would be litter or duff, wood, punk, individual leaves and needles, and organic soils. This would be a laboratory study.

Combustion studies in organic soils. The large fires in the Southeastern states in recent years have demonstrated the importance of organic soils in the occurrence of major fires and the difficulty of their suppression. Fire suppression is far more difficult on organic than inorganic soils in time of drought. There are a number of problems for which solutions would benefit fire control methods. One example is the relationship between the inflammability of these soils and their moisture content—in particular the determination of the moisture content below which

* As fire intensity increases, brush and tree crowns may start to burn and in so doing become a part of the available fuel. However, there may be exceptions when the fuel moisture is high and only the surface fuels burn and then only in part. For example, there is probably little difference between the relative amounts of fuel burned by the comparatively low-intensity head fires and backfires ordinarily used in prescribed burning.

organic soils will smolder and continue to burn. Another example is the determination of the moisture content below which organic soil fuels repel water.

It is possible that ground burning is not a true combustion process but may, in part at least, be an exothermic reaction not requiring oxygen. If so, this might have considerable bearing on suppression methods. This problem could be studied by replacing the air in a volume of organic soil with inert helium or nitrogen and observing if fire in the soil is extinguished.

The use of chemicals and wetting agents in suppressing fire in organic soil shows some promise and should have more study.

This series of studies will require a joint field-laboratory approach.

There are other areas of work such as the Lake States, New England, and Alaska in which either organic soils or deep duff constitute a difficult fire suppression problem.

IV. FIRE BEHAVIOR

There is considerable justification in assuming that the principal fire behavior problems arise almost entirely from a relatively small number of fires. A few percent of the total number of fires, either because of high intensity, large size, unusual behavior, or various combinations of these attributes, account for most of the total damage and safety threat resulting from all fires. It is the field of fire behavior and the closely allied field of fire meteorology which contain a large number of the major and most urgent fire problems.

The increased forest fire research effort that is now taking place nationally and the current widespread interest in fire behavior probably can be attributed to a large extent to less than a dozen fires in the last 10 years and to a lesser extent to the major fires in earlier years. However, as yet only a relatively small part of our total fire research expenditures goes into fire behavior research. Even so, we are already well along in the development of the general fire behavior concepts and even in the solution of some of the major problems.

Nevertheless, there are important areas in which a greatly increased effort is needed. For example, there are difficult problems in fluid mechanics and fire systems models which have received little attention. This is especially true of those phases of fire behavior (and other fields of fire research as well) which involve difficult analytical work, but it is the area in which the return on the research investment would probably be a maximum.

There are several different approaches to the study of fire behavior which should give even better results in combination than individually. These are, (1) case studies of individual fires, (2) experimental test fires in the field, and (3) fire system models research.

Case studies of individual fires. The most effective method thus far for studying fire behavior has been the case study technique or rather the case study method combined with analytical work. This approach is likely to become increasingly important as the fire behavior program develops and the field men acquire a feeling for the different fire behavior phenomena to look for on specific fires. Briefly, the case study method consists of three separate steps. First, is the assembling of detailed information on the behavior characteristics of the fire such as rate of spread, height of flames, pattern and distance of spotting, presence of fire whirlwinds, and characteristics of the convection column included with the fire behavior information are data on fuel quantity and characteristics, as well as on the topographic factors. The second step is the assembling of information on the burning index, the buildup index, surface weather, and atmospheric conditions aloft. The data will include surface wind speeds and direction, surface temperature, surface relative humidity, speed and direction of the winds aloft (up to at least 10,000 feet above the surface), temperatures aloft and the relative humidities aloft. The third step is an analysis of the data and information obtained in the preceding two steps. Energy calculations, computation of basic variables, and computation of the energy rate number for different heights above the fire are part of this work.

The Southeastern States contain what is probably the best fire behavior study area in the United States. This is the Coastal Plains region of eastern North Carolina, about 2 million acres of which is the organic soils type. If one were to set up the requirements for a field fire behavior "workshop," this area would meet most all of them but one; namely, topography. However, since rough topography is so prevalent in most areas of the country where fires occur, it is desirable to have at least one region where topographic effects are lacking. The incidence, or frequency, of high-intensity fires in the North Carolina Coastal Plain is probably greater than in any other area of comparable size in the country. There is a wide range in quantity and kinds of fuel located on soils which range from the inorganic sandy types to organic soils 6 or 8 feet deep. There is a wide range in the various meteorological factors and it may be found that this area receives more than its share of the adverse wind conditions which favor the development of high-intensity fires. This is indicated indirectly by the history of shipwrecks off Cape Hatteras, as well as more directly by the unusual wind profiles which frequently occur over the Hatteras station.

The amount of work on the case study method should be expanded. One way of doing this would be through the formation and training of a fire behavior team. This possibility is discussed in more detail in Appendix II.

The full time of one man could well be spent on case studies. Very little laboratory work would be involved.

Fire system models research (analytical and experimental). This major study is basic to the whole field of fire behavior. Analytical work in the thermodynamics and fluid mechanics of free and forced convection will be an integral part of the overall job and should determine the design of the laboratory and field experiments. Analytical methods are essential in the study of convection, the development of fire systems concepts, and in the development of scaling laws. Laboratory and field experimental programs will follow the analytical work or run concurrently with it.

A fire system model[2] may be defined as a group of concepts in terms of which the various phenomena of fire behavior and fire propagation can be described and predicted. These concepts are essentially mathematical in nature. Although a fire system model differs greatly from a model fire, or scaled fire model, both may be very much involved in the same experiment.

Laboratory experiments with small scale model fires, or heat sources other than fires, in the convection room or wind tunnel will constitute a new type of work in fire research. Just how fruitful these small scale model studies will be is a complete unknown at the present time. An unfavorable aspect is the very large scaling factor which must exist when a major fire is reproduced on a laboratory scale. This factor may be as large as 10,000 to 1. Some discouraging

[2] Forest Fire Behavior. Chapter 4, Forest Fire: Control and Use, by K.P. Davis. McGraw-Hill, 1959.

problems have also risen in connection with the modeling of convection columns in the wind tunnel.

On the other hand, there are several encouraging aspects to the possible success of small scale model studies of heat sources. One is the dimensionless energy rate number which indicates the possibility of scaling convective phenomena. Another is the fact that fire whirlwinds can be reproduced on a very small scale. Although on a high-intensity fire these whirlwinds can occasionally approach the size and intensity of a tornado, they can easily be reproduced as small as 1.5 inches in diameter with flames 15 to 18 inches in height.

This would be a laboratory centered study, but with considerable field work required.

The mechanism of fire propagation. At the present time it is very difficult to predict in advance the rate of spread, the rate of energy release, and the behavior characteristics of a fire even if the fuel and weather variables are known. In the past I have attributed most of this difficulty in anticipating fire behavior to certain short-comings in our basic knowledge of ignition and combustion. However, it is likely that the overall problem goes much deeper and that lack of knowledge in combustion and ignition processes is incidental to the main problem. However, after the mechanism of fire propagation has been established, quantitative prediction of rate of spread and fire intensity will require more information on the ignition and combustion processes then we now have.

Work thus far with a fire system model shows that it is possible to replace a fire with an energy source[3] that does not involve heat yet leaves the convective characteristics of the system unchanged. Since the storm characteristics and other violent behavior features of a major fire have a convective origin, it would thus appear that more basic knowledge of ignition and combustion is not necessarily a prerequisite for a better understanding of unusual or extreme fire behavior.

A more immediate need is the development of mathematical concepts in terms of which fire propagation and fire behavior can be described. Conceivably fire spread could be described by a partial differential equation analogous to that for heat conduction in a medium with internal heat sources. However, a general equation which would cover situations where fire spread resulted primarily from discrete ignition points ahead of the main flame front would have to represent considerably more than a simple heat transfer process. Possibly the fire system model investigations will lead to an equation of this type. Such an equation would also have to account for the so-called "levels" of fire behavior, or discontinuities in fire intensity, which are described elsewhere.[1]

A study of fire propagation is closely related to, and is dependent on, the fire system model work.

Field experiments with test fires. Tests with planned fires in the field represent the closest approach to the case study method on actual full-scale fires. These test fires would necessarily have a considerably lower intensity than the higher intensity wildfires. Probably the intensity should not exceed 3,000 or 4,000 Btu per second per foot of fire for moving fires, nor 4×10^7 Btu per second for stationary fires. Experiments on fires of this type would not be started until

[3] The weightless gas equivalent of a heat source. Page 10, Annual Report, 1958. Southeastern Forest Experiment Station.

work in the preceding studies was well underway. It should be emphasized that work on scaling laws and modeling is just as applicable to these fires (and case study fires for that matter) as it is to the small scale laboratory fires.

Instrumentation would be the major problem on test fires, because it should include measurements of updraft velocities in the convection column, temperatures in the convection column, and measurement of quantities from which fire intensity could be calculated.

V. FIRE USE AND FIRE EFFECTS

Excluding the threat to life and developed property, the ultimate significance of wildland fire is determined by its effects. These effects separate readily into two groups—damages and benefits. Fire prevention, fire suppression, and fire control planning in general all exist because of the damages that fires do. On the other hand, the use of fire for fuel reduction, hardwood control, regeneration, disease control, and grazing improvement is possible because fire has a beneficial as well as a destructive side.

However, it is not always possible to separate these two aspects of fire; both can exist simultaneously. Also, the behavior of prescribed fire is sometimes difficult to predict. To better understand the mechanisms through which fire exerts its effects, and to anticipate with greater certainty the behavior of low- to medium-intensity fires, a number of problems must be solved in the fields of heat transfer, biophysics and biochemistry, fuels research, and fire behavior.

Mechanisms of fire damage. The lethal effects of fire are controlled by complex heat transfer processes that are not fully understood. These processes take place in all parts of the tree, although the lethal effects are most pronounced in the crown and in the main stem near the ground. Good progress is now being made in a heat transfer study in tree stems by a cooperative project between the Southern Forest Fire Laboratory and the University of Michigan. This is the first attempt to solve the difficult heat transfer problems associated with fire damage. Even in a homogeneous cylinder the transient heat transfer processes would be very complex, but in a tree stem with varying thermal properties, as well as geometric irregularities (bark fissuring) in the heat receiving surface, they are even more so.

Previous work on fire damage mechanisms in tree crowns has shown that for equal fire intensities, the height of the scorch line should be considerably greater in hot weather than in cold. For constant fire intensity, it is possible to compute mathematically the relationship between the height of scorch line and the ambient temperature. This relationship has an important practical application in prescribed burning and should be extended (with the help of heat transfer studies) to some of the complex lethal effects in buds and smaller stems.

Most of the studies in this group would be done, or at least started, in the laboratory and then followed by considerable field work.

Field studies in fire damage. This would be a group of field experiments using test fires to determine the relationship between the effects of fire on forest stands and variables such as fire intensity, ambient temperature, duration of elevated temperature, and season of the year. Fire damage studies on wildfires would also be in this group as would the development of fire damage indicators and criteria.

Probably but little laboratory work would be needed for these studies except for the development of instrumentation which should be kept relatively simple.

Field studies in prescribed burning. Through the years there has been a gradual development by administrative field personnel in the techniques of prescribed burning. The progress they have made indicates that a planned research effort to improve and develop prescribed burning procedures could be very worthwhile. The approach would be an essentially empirical one, but with an application of all available information on fire behavior and fire effects.

Most of the laboratory work needed for this study would come through the fire behavior work.

VI. FIRE METEOROLOGY

Fire meteorology may be defined as that part of the field of forest meteorology which is associated with the occurrence, behavior, effects, and uses of fire. It is a more general term than fire weather, which it includes.

From the standpoint of fire control operations, the field of fire meteorology probably contains some of the most important and highest priority problems in fire research. From the standpoint of the contribution that the solution of its problems would make to better fire control, fire meteorology could well be regarded as the potential "break through" field. For example, on a specific fire control operation a highly precise forecast of the key weather factors controlling fire behavior, such as wind speed and direction (both surface and aloft), could possibly mean the difference between carrying out a routine suppression job and dealing with a major conflagration. Also, solutions of the most important problems in ignition, combustion, and even in fire behavior itself, might in themselves mean little to the fire control effort if the trend of the key weather factors remains uncertain and undetermined; most of the contribution of the solution of these problems becomes effective only when certain key problems in fire meteorology are solved.

However, it must be remembered that the clarification and isolation of the meteorological problems, such as the identification of the key meteorological factors influencing fire behavior, require a high degree of progress in the solution of the basic fire behavior problems. Actually, there is no sharp dividing line between the fire behavior and the fire meteorology problems. Many of the latter can be regarded as extensions of the former.

Studies of the behavior of the meteorological factors related to fire behavior. The purpose of the study of this group of problems is to better understand the trend of the significant fire weather elements, their rhythmic annual and daily variations, and the irregular and random variations that are always taking place. Its purpose is also to gain a better understanding of the meteorological structure of the atmosphere when large or unusual fires occur as well as during periods of weather suitable for prescribed burning. The structure of dry cold fronts, short period fluctuations in the vertical wind profile, the sequence of the meteorological elements during and preceding high-intensity fires (and the analogous sequence during good prescribed burning weather) are also examples of studies in this group.

Little or no laboratory work would be required in these investigations.

Basic causes of meteorological conditions associated with extreme fire behavior. It will be difficult for meteorologists to forecast the low-level jet wind until its basic causes are known, hence an investigation of these unusual winds to determine their relationship to the other meteorological elements remains a top priority job. Another problem in this group is the possible effect of the high-level jet stream on lower level meteorological conditions (including the low-level jet wind) which influence fire behavior.

Conditions which produce low relative humidities at the surface, such as subsiding dry air from aloft, should be better understood. This is equally true of certain conditions which are the result of interactions between specific meteorological situations and topography. The foehn, or Santa Ana, type wind is an example.

At least one of these studies will require modeling work in the laboratory.

Forecasting improvement and monitoring of the key weather factors. Because of its exacting requirements, fire weather forecasting is one of the most difficult types of forecasting. Investigations which will eventually result in better forecasts of weather factors controlling fire behavior may be considered as high priority studies. Because work in this field would ordinarily be outside the scope of fire research, it would necessarily require a cooperative program with the Weather Bureau and other meteorological organizations.

Owing to the difficulties inherent in improving forecasting techniques, alternate solutions, or partial solutions, to the forecasting problem should also be tried. One promising possibility, at least insofar as the vertical wind profile is concerned, is a technique to monitor the upper winds by means of frequent pilot balloon soundings.

With the possible exception of instrumentation needs, laboratory work would not be required in this group of studies.

VII. FIRE EXTINGUISHMENT

If the intensity of a fire decreases until a point is reached at which the intensity decline is irreversible, then from that point on the fire can be described as undergoing extinguishment. In some examples, such as a burning match, only a slight decrease in intensity is needed to bring about extinguishment which then occurs very rapidly. In other cases, such as fire burning in a large volume of punky decayed wood, the intensity must be decreased almost to the vanishing point before extinguishment is induced. Also the process is very slow.

Fire extinguishment can be visualized in terms of breaking, weakening, or in some way interrupting the chain reaction of combustion. There are three main components in the combustion chain reaction which are often represented by the three sides of a triangle. These are fuel, oxygen, and high temperature. Any action which removes any one of these three sides will result in extinguishment. Any action which weakens any side of the triangle to the extent that the intensity is brought below the irreversible point will eventually produce extinguishment. Any action which interferes with the interacting mechanisms between the three combustion components can likewise eventually result in extinguishment. There are thus different pathways or approaches to the fire extinguishment problem in which research might be effective.

Ignition, combustion, and fire extinguishment. The studies in this group would concern the basic physical and chemical nature of combustion. They would include investigation of the effect of chemicals on basic combustion processes which would be the basis of work in the development of the theory of fire retardants. These studies would require a highly trained physical chemist and probably should be concentrated at just one of the fire laboratories. They are closely related to the studies in the section on ignition, combustion, and fuels.

Energy studies of the relation of the application rate of water (and water plus chemicals) to rate of energy release of fires burning in solid fuels. Even some of the simpler relationships involved in fire extinguishment processes are still unknown. One example is the effect of water application rate to the rate of energy output of a fire. A small stream of water may appear to have but little effect on the rate of energy output for a hot fire burning in a crib of logs; the fire may continue to increase its intensity even while the water is being applied. Increasing the rate of water application sufficiently will eventually bring about a decline in fire intensity. However, the quantitative relationships are still mostly unknown as are some of the variables involved. Analogous problems exist for a mixture of water and chemicals applied to fire.

These studies would be started in the laboratory using small crib fires. They would then be carried to large crib fires in the field.

VIII RESEARCH IN FIRE DANGER MEASUREMENT

The field of fire danger measurement is intended to unify general fire research knowledge and develop methods for its application in fire control and fire use. Owing to gaps in basic knowledge and inadequacies in basic fire science, work in the field of fire danger measurement in the past has necessarily been of an empirical nature. However, increasing progress in the more basic fields of fire science is already contributing to current work in fire danger measurement.

Fuel moisture studies. The wide fluctuation in the quantity of available fuel and its flammability are a result of corresponding variations in the quantity and distribution of moisture in the heterogeneous forest fuel complex. A large part of fire danger rating procedures is equivalent to “keeping books” on the quantity and distribution of fuel moisture. For this reason there will be a continuing need for better fuel moisture studies. Some of the most urgent are detailed studies of drying and moisture replenishment processes designed primarily for the purpose of measuring the relative drying rate for a variety of fuels such as grass, twigs, logs, and duff or litter of varying depth. These studies would require both field and laboratory work.

Closely related to drying rate studies are investigations of the periodic variations in the moisture content of the different fuel components. These fuel moisture variations are induced by corresponding periodic variations, or cycles, in temperature, humidity, and rainfall. Only two of these cycles are regular and precise. The 24-hour daily cycles of temperature and humidity change induce a corresponding cycle in the fuel moisture content. Its effect is greatest for the fine and rapidly drying fuels. It is almost negligible for material such as heavy limbs and logs. On the other hand the 365-day annual, or seasonal, cycle of temperature, humidity, and precipitation variation has a pronounced effect on the moisture content of the heavy fuels. Superimposed on both the daily and annual cycles are wet and dry periods of more or less random lengths which exert their effects in different ways on the various fuel components.

Development of instruments for fire danger measurement. The instruments needed for fire danger measurement will depend on the system or methods in use and may change as the methods change. Fuel moisture indicator sticks are still the basic element in most systems, but there appears to be considerable interest in the possibility of replacing the sticks with measurements of the weather variables which control fuel moisture-temperature, relative humidity (or dewpoint), sunshine, and rain. Both systems have their advantages and problems. The fuel moisture sticks are simple and direct, but they represent the moisture content of only one fuel sample out of an infinite population of fuel sizes which may range from thin grass blades to large logs and from a thin layer of fluffy leaves to deep duff and organic soils several feet deep. More samples (that is, more indicator sticks of different sizes) could be used, but this would complicate both the procedure and the instrumentation.

The use of the basic weather variables has considerable flexibility and is probably simpler from the instrumentation standpoint. On the other hand, the "meters" or devices for computing indices may have to be more complex.

Probably an instrument development program for fire danger instruments could be done pretty much in one part of the country. Therefore, what is done at one fire laboratory may depend on the plans developed for this work by the other laboratories.

Instrument development would be a laboratory job with field testing.

Development of new concepts in fire danger measurement. Currently one of the most important phases of this field (and one in which there is much interest) is the development of new concepts intended to relate different but specific attributes or characteristics of fire to significant independent variables in the fire environment (that is, fuels, forest cover, topography, and atmosphere or weather). Originally, effort in fire danger meter development was directed toward the development of a single index which would represent the integrated effect of the independent variables on some specific characteristics (or possibly combination of characteristics). It is now fairly well recognized that a single index can at best only approximately represent more than one fire characteristic. For example, the daily fire occurrence rate in a specific land area and the average forward rate of spread of these fires depend on about the same independent variables. However, they are two entirely different fire characteristics with quite different functional relationships to the independent variables.

The limitations of a single index are leading to a multiple index concept. Most of the fire danger rating systems in current use have two indexes and it is likely that more will eventually be used.

For any given temperature and humidity (or temperature and dewpoint), the timelag constant is independent of fuel moisture and depends only on the fuel properties. These characteristics of the timelag constant make it a very promising quantity in the description and eventual classification of complex heterogeneous fuels. Possibly such a fuel could be regarded as a population consisting of a large number of classes or subgroups each having a different timelag constant.

The development of concepts needed in fire danger measurement and in the general application of basic knowledge of fire control and fire use should be a continuing field of work. This work might well include a dimensional analysis or dimensional study of the numerous variables entering into fire danger ratings. It might also include the development and simplification of the various types of computing methods and devices which could be used in fire danger measurement, such as circular slide rules, linear slide rules, charts, and tables.

The multiple index concept can be extended to the idea of intermediate indexes, some of which have significant properties and uses. One of these is a flammability index which for any given fuel depends only on fuel moisture. Because the flammability index does not depend on wind, it is subject to far less variation, both in space and time, than the burning indexes. It is conceivable that it would be possible to combine a single basic inflammability index with different functions of wind speed to obtain quantities such as fire occurrence index, a forward rate of spread index, a fire intensity index, or even a blowup index if the upper winds and certain fuel variables were included.

Although an intermediate index such as an inflammability index is simpler than those which include wind, it is not simple in terms of the more complex fuels which are heterogeneous as to moisture distribution, fuel size, and geometry of arrangement. One of the most promising concepts for rating the inflammability of such fuels, as well as for estimating their available fuel energy* is the timelag concept. Drying processes, like many other natural phenomena in which some quantity decreases with time, are of an exponential (or approximately exponential) nature. Such a process can be described in terms of a simple single quantity, the timelag constant, which has the dimensions of time.

IX. INSTRUMENTATION AND METHODS OF MEASUREMENT

Some of the problems of instrumentation and techniques of measurement have already been discussed, or at least mentioned, in some of the other sections. However, instrumentation and problems of measurement will be a major field of work and can be considered as a specific problem group.

There are several separate steps in developing the instrumentation work. First, is recognition of instrument needs and types of measurements which need to be made (both in the laboratory and in the field). Second, is the investigation of existing instruments and measurement techniques to determine if they can be adapted, either wholly or in part, to the existing fire research needs. Third, is the development and design of essential new instruments and measurement systems.

The field of instrumentation extends throughout most of our work and ranges from comparatively simple low-cost devices and procedures, such as some of the simpler weather instruments, to the complex and costly task of obtaining difficult measurements on high-intensity fires.

Except for certain types of relatively low-cost general purpose instruments, the purchase, design, or development of new instruments and equipment should come when planning of an experiment or study is well along and the need for specific instrumentation is very clear. Otherwise, there is considerable risk of acquiring expensive equipment for which careful advance planning might indicate but little need,.

X. FIRE CONTROL MANAGEMENT

* The available fuel energy could also be expressed in the form of an intermediate index.

The field of fire control management should represent the ultimate focal point of the results of fire research in all of the supporting fields of investigation, both basic and applied. Because of the extent and complexity of the various problems in fire control management and because many of these are not at present closely related to the laboratory work, only a brief outline of the general problems is given. However, when the Fire Division becomes more active in the field of fire control management research, a separate detailed analysis should be prepared for this segment of the Division's work.

APPENDIX I – BASIC AND APPLIED RESEARCH

"Basic" research is defined as investigative work intended to produce new truths or to create new knowledge. Because this knowledge may represent a fundamental principle or basic truth, it will be characterized by an enduring aspect, or posses a quality permanence, essential for the creation of more new knowledge through continuing research. Basic research thus builds on itself without limit, although at the same time it supplies the foundation material in the limited and specific goals of applied research.

The terms fundamental research and basic research are usually used interchangeably, although the term fundamental might be more appropriate for work in pure science.

"Applied" research may be defined as research specifically directed to meet certain needs or to solve definite problems. Unlike the results of basic research, those of applied research do not necessarily possess the quality of permanence nor are they required to do so. A product of applied research whether it be a machine, an instrument, or a method of doing something, is very likely to change with time. It may even eventually disappear or be replaced with an improved product. The continuous replacement and renewal of the results of applied research is as an important a factor in an advancing technology as is the addition of new research products.

Possibly some of the differences of opinion as to what constitutes basic and applied research arise from the assumption that they are mutually exclusive fields. Actually, they may often appear to be identical and no sharp dividing line between basic and applied science can be established. For example, there are some types of research to which either or both terms could be applied. Also, basic research must often be undertaken to fill gaps in essential knowledge before applied research can make progress toward the solution of a specific problem.

The methodology and research tools may be considered identical for both basic and applied research. Probably the best distinction between the two is on the basis of intent and purpose—not on methodology, subject matter, study location, nor level of difficulty. Often basic work is done by more highly trained people using more advanced methods of study, but sometimes the opposite is true. Some industries, for example, may use their best scientific talent and most advanced methods on their applied research problems. In some instances their less gifted people are more likely to be working in basic research.

APPENDIX II – FIRE BEHAVIOR TEAM

Large fires in the Southeastern States often build up rapidly and make their major run within a few hours after the beginning of their buildup. For this reason it is difficult for research personnel to travel to a fire in time to make observations while it is making its main run. Better communication and faster transportation would help but a more effective procedure would be possible through the formation and training of a fire behavior team. Such a team would be stationed in areas in which high-intensity fires would be likely to occur and might remain there for a period of weeks. The location of a team would be based on a combination of factors such as fuel type, buildup index, drought index, and the fire history of an area. These areas might be anywhere from north Florida to New Jersey. Since at least a few large fires occur nearly every year in the North Carolina Coastal area, the crew could be stationed there for 5 or 6 weeks each spring unless severe burning conditions developed elsewhere.

The fire behavior team would be a group of 5 or 6 men each of whom would be trained for specific jobs. One, or possibly two, would have time-lapse cameras. Two more would take pilot balloon soundings, surface weather, and sample the fuels for moisture, energy content, and basic characteristics. One man would serve as a plane observer and photographer. Another would stay with the ground crews working nearest the head of the fire.

The training and use of a fire behavior team would require careful planning and organization. Even during a relatively severe season there would be periods when fires would not be burning and the team would have to be occupied with other work. Also, to work effectively in any given area the team members would need to be thoroughly familiar with the location and condition of roads, as well as with fuel and cover types. This would require considerable map study and actual travel in the areas (both ground and air) which should be done before the team is stationed in a given location for fire observation work. It might be advisable to start with, say, three men and build up the team over a period of two or three years to its final size.

The Early Years of George M. Byram

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Abstract: George M. Byram was an outstanding fire researcher having published many papers regarding the fundamentals of fire. His understanding of fire began early on the Byram Ranch in Bear Valley located in Grant County, Oregon between Canyon City and Burns. He was born in Burns in 1909 one year after the Malheur National Forest (NF) was established by President Theodore Roosevelt. The Family cattle ranch was established by his grandfather who came to the area soon after gold was discovered along Canyon Creek in 1862. Fire was used frequently for maintaining quality grazing on the NF both by cattlemen and sheep men. The Malheur NF surrounds the ranch on three sides and one of the reasons given for establishing the Forest was to keep the sheep men and cattlemen apart. George was home-schooled on the ranch and it is reported that his mother had trouble challenging George with enough new books and materials. Soon after George became a teenager, the family moved to the Portland area where he attended public schools and the family operated a butcher shop with beef from the family ranch being sold there. Later, they moved to Whittier, CA where George got to know a person by the name of Richard Nixon. He returned to Portland receiving his B.S. degree in Physics from Reed College in 1932. He distinguished himself through his work at Reed College and was the 5th person to receive a degree from the new department working under Dr. A. A. Knowlton (Knowlton Hall is the name of the present physics building at Reed College). Dr. Knowlton had a keen interest in atmospheric physics and taught weather observation personnel during WWII. George was an athlete at Reed College specializing in gymnastics and wrestling. His senior project examined a method for measuring smoke plume visibility and he spent four years from 1932 to 1936 working in the Forest Service on smoke visibility studies before going to graduate school at the University of California at Berkeley for a year. Probably his early education and the many observations of fires and plumes from fires led to his interest in the interactions of the atmosphere that influence the development of blowup fires.

During 1936, George and Elizabeth were married and shortly after their marriage traveled to Asheville, NC where he began working for the USFS Appalachian Forest Experiment Station. His work in identifying smoke plumes and visibility research continued, but he became more and more interested in factors contributing to fire growth. There are many stories about home fire experiments and other interesting hobbies that George had with mushroom hunting and astronomy. His son gained a Masters from MIT and his daughter married a physicist and now lives on her mother’s ranch in North Dakota. The speakers that follow will be discussing the intricacies and significance of George’s work; his early years were important in cultivating the mind that discovered so many principles about fire that we use today in describing and quantifying fires of all types. Thank you, George!

Editors Note: The following letter written by George likely in the 1980's is a brief personal synopsis of his career. Dr Ward found it in the Reed College achieves while gathering information for the above presentation. A video of the complete session including all speakers is available on line at http://vimeo.com/61394967

LETTER FOUND IN ARCHIVES AT REED COLLEGE, PORTLAND, OR DECEMBER 2012

George M. Byram
3 Baird Lane
Asheville, NC 28804

On that sunny commencement afternoon in June, 1932, I never realized just how short an interval of time a half-century would be. Perhaps this means that at any moment now we can start looking forward to our first reunion in the twenty-first century in the year 2032.

Shortly after graduating from Reed, I started work at the Pacific Northwest Forest Experiment Station with Dr. Richard E. McArdle in the Division of Fire Research. This work was a continuation of visibility investigations I had done for my senior thesis under Dr. A.A. Knowlton. My early years in the Forest Service (1932-1936) were spent on smoke visibility studies and on the design of special instruments for measuring visibility and variables affecting the flammability of forest and spread of fire. An important part of the work of the young personnel in the research branch of the Forest Service was the writing of manuscripts and preparation of their work for publication. Hence I soon had reason to be grateful for the experience of my senior thesis.

During the winter of 1935-36 I attended graduate school at the University of California at Berkeley and returned to work with the Forest Service the following spring. I married Elizabeth Coughlin of Portland in 1936 but our stay in Portland was a very short one. In early October we traveled to Asheville, North Carolina, where two days later I started work with the Southeastern Forest Experiment Station.

Western North Carolina proved to be an interesting and delightful place to live but for a year or two we missed the West. In spite of the scenic mountains, temperate climate, and friendly people, transferred westerners did not always "transplant" immediately.

Our son was born in 1938 and our daughter in 1942. They grew up as southerners for the most part and this was noticeable in both their speech and outlook on life. Apparently children's peers and teachers in school exert an influence that may exceed that of parents.

From 1936 to 1950 most of my work was in vision and visibility research and fire behavior investigations. Prescribed fire is an important tool of forest management in the southern states so a part of this period was spent on the study of low intensity fires and their effect on living trees and other living vegetation. In 1950 I began work on a special type of high intensity fire which causes great damage. Although these fires are not common, their erratic and unpredictable behavior can be a major threat to the safety of fire fighters. Work on these "blowup" fires was to occupy much of my time until my retirement in 1968.

By the late 1950s, the high intensity blowup fire was generally recognized as the major problem in fire control. Consequently, special fire laboratories were designed in which it was felt that fire behavior phenomena could be studied more effectively. The first of these, located near Macon, Georgia, was built by the Georgia Forest Research Council and staffed by the U.S. Forest Service.

I was transferred to the new laboratory at Macon in 1961 and began one of the busiest and most interesting periods of my career. Basic research on energy processes controlling the behavior and spread of high intensity fires was the main responsibility of my research group. The techniques of modeling, which have long been used in such fields as fluid mechanics and aerodynamics, proved to be very effective in studying many of the complex features of fire behavior. An example is the fire tornado, or fire whirlwind, which is one of the most troublesome and dangerous characteristics of high intensity fires.

The laboratory had a considerable number of visitors including occasional groups of school children. Sometimes the younger children would become bored before their visit was over but the sight of a model fire whirlwind would always fascinate them and hold their attention. Children seem to be interested in both fire and rotating objects and the rapidly spinning column of fire (about 3 inches in diameter and 8 or 10 feet in height) combined both of these features. As an additional bonus the fire vortex had some built-in sound effects -- primarily a result of the speed of the upward spiraling hot gasses which travel about 50 feet per second.

Some of the important experiences of the last 50 years were not always related to my work. There comes to mind an incident in 1943 which was a result of my growing interest in the culinary possibilities of the local wild mushrooms. Because of their abundance in this moist climate, I had decided a couple of years earlier to become an expert in mushroom identification. I had diligently studied the appropriate books and references and was quite proud of my "expertise". Then my favorite book failed me when it listed a certain species (Clitocybe dealbata) as edible but did not mention an almost identical twin species with a bad reputation. As a consequence, there was a 10- or 12-hour period where there was no lack of excitement and apprehension in our household.

On the positive side, an incident of this kind has no equal as an educating experience. Wild mushrooms had no place in our diet until the basis of my "expertise" had been questioned, analyzed and considerably enlarged.

Although I retired officially in 1968, I worked part-time (mostly on the preparation of manuscripts for publication) for another two years. In 1970 Elizabeth and I moved back to Asheville where we still live. One of the things we now enjoy most is the ever-changing landscape scenery in wildland areas as well as scenes in those inhabited regions where man's presence has not detracted from nature's original plan. Probably this pleasure resulted from our early interest in photography and landscape painting as well as my early visibility work.

George M Byram – forest fire research pioneer: perspectives of a colleague

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Abstract: George Marsden Byram spent 36 years as a US Forest Service fire researcher, most of them with the Southeastern Forest Experiment Station in Asheville, NC. He was considered a gentleman by those who knew him. All forest fire researchers have been influenced in some way by his work. This paper begins with remembrances of the influence George Byram had on me as a young person and ends with reflections from me and from others who either knew him or knew of his work. In the early 1950s George used case studies of major wildfires to relate atmospheric lapse rates and low-level jet winds to erratic fire behavior and blowup fires. His two chapters in the 1959 Davis textbook on forest fire control and use described the combustion of forest fuels and a criterion for anticipating blowup fires. During the 1960s George's research concentrated on modeling fire whirls, mass fires, and fire spread. For wind-driven fires, he demonstrated two of the mechanisms involved in ignition of unburned fuel. George also introduced the moisture timelag concept and completed the technical development of the Keetch-Byram Drought Index. Three papers by George were published in the early 1970s after he retired; they discussed fire whirls, mass fire scaling laws, and fire modeling with pure heat sources. These papers were the final contributions from a distinguished researcher whose ability to effectively address relevant problems still leads the way for us today.

Introduction

George Marsden Byram was a soft-spoken, modest man and a gentleman in the eyes of all who knew him. He earned the respect of his fellow fire researchers during a productive 36-year career with the US Forest Service and made lasting contributions in nearly every subject matter area of forest fire research. I was fortunate to be among those who worked for and with him at the Southern Forest Fire Laboratory in Macon GA during four of the last seven years of his career. I believe all forest fire researchers have been influenced in some way by George's work, which began in 1932 in the Pacific Northwest and ended in 1968 in Macon.

The story of how George transferred from the Pacific Northwest Forest Experiment Station in Portland OR to work at the Appalachian Forest Experiment Station in Asheville NC is an unusual one. He and other Forest Service fire researchers attending a national meeting in Portland were taking a nightly stroll when they noticed a car in a store window with one of its wheels spinning at constant speed. The car, rumble seat included, was offered to the person who could come up with the closest estimate of the wheel's rpm. George quickly retrieved a stroboscope, measured the rpm, and won the car. A colleague from the Appalachian Station was so impressed he persuaded George to join the research staff in Asheville. Thus in the fall of 1936

George and his new wife, Elizabeth Coughlin, made their way across the country to Western North Carolina.

This paper is a record of the presentation made by the author at a Special Session of the 4th Fire Behavior and Fuels Conference honoring George Byram for the man he was and for the pioneering contributions he made that advanced our understanding of the physical and biological aspects of forest fires. The early years of George's life and career are presented elsewhere in these proceedings; in brief, his work from 1932 to 1950 dealt with atmospheric visibility, human vision, fire danger rating, and fire behavior and effects. This paper describes highlights of George's research from 1950 to 1970 and presents personal reflections from the author and from other Forest Service scientists who either knew George or knew of his work.

George and my early years

George's influence on me began when I was young because he and my dad (Ralph M Nelson Sr) worked at the Appalachian Forest Experiment Station in Asheville NC beginning in 1936, the year after I was born. Our families were good friends and visited occasionally. Sometimes on Saturday mornings my mom would drive over to the Byram's home to visit Elizabeth and take me with her. George was usually there, so he would invite me out to the side yard, show me his grape arbor, and tell me about the various kinds of grapes he was growing. Then he would bring me back inside and show me a few of his paintings. I later learned he was different from most artists in that he painted scientifically – he mixed his paints according to formulas he had derived from the laws of physics. Much of his painting was of landscapes; he occasionally painted a portrait or bowl of fruit. George gave up painting fairly early in his career -- perhaps in the early 1940s; one can speculate that his family (a wife, two children, and eventually three grandchildren) plus his research kept him extremely busy.

My dad admired George's work at the office, so I grew up hearing about projects the two of them were working on -- either together or separately. When I was perhaps age 15 and still at home, my dad showed me a handwritten manuscript by George and asked if I would like to read it – which I did. In addition to some foreign (to me) terminology, the draft included a derivation and several solutions of the diffusion equation for flow of water through wood; I probably understood about 25% of what George had written. Nevertheless, I was duly impressed and my respect for George rose to a higher level. As I thought about all this, there was one thing I was sure of – I wanted to eventually produce reports like the one I had just read. After high school graduation and a 3-year tour in the military, I enrolled in the Forestry School at NC State College to study Wood Science and Technology because the courses in wood drying were being taught in that department. As it turned out, about 50% of my career was devoted to fuel moisture relationships.

During my sophomore year at NC State, George was a big help to me. I was taking calculus and having some trouble. My dad asked George if he would help, so when I was at home during weekdays there were several afternoons when I went to his office for about an hour of tutoring on triple integration, and perhaps a few related topics as well. In any case, George's advice helped because I passed the course with a decent grade.

In June 1963 I began full-time work at the Macon fire lab. George was away from the lab at that time, so except for his tutoring me in 1957, I had little contact with him during the 10 years from 1953 to 1963.

George's research during the 1950s

After several decades of fire exclusion, large wildfires exhibiting extreme behavior were common throughout the South as well as in many other parts of the country where frequent fire had previously kept fuel accumulations in check. In January 1950, George attended a meeting in Ogden UT where fire researchers were urged to address problems associated with large wildfires; by the late 1950s the high intensity blowup fire had become recognized as the major problem in fire control. In response to the call, George (in collaboration with my dad) used case studies of major wildfires in SC as the basis for a 1951 paper on the possible roles of turbulence and atmospheric instability in causing troublesome phenomena such as fire whirlwinds and spotting (Byram and Nelson 1951). This paper reinforced the views of a few earlier researchers who had mentioned instability as a possible cause of erratic wildfire behavior. In 1954, George published more results from his case studies and theoretical work which suggested the low-level jet wind as an important factor in the development of blowup fires (Byram 1954). He identified nine different types of low-level jet wind profiles, presented a table listing the 17 blowup fires he had considered, and for each fire discussed the features of these profiles that might have contributed to the blowup behavior.

Five years later, the 1959 book on forest fire control and use edited by Kenneth P. Davis was published. George's Chapter 3, *Combustion of Forest Fuels*, includes definitions of fire behavior variables such as available fuel, heat yield, and fire intensity. It describes topics ranging from combustion chemistry to fire propagation mechanisms to an empirical equation relating flame length to fire intensity (Byram 1959). In the mid-1960s, George was perplexed to learn that his flame length equation, which had been derived from data taken in a single fuel type, was being used to describe flame length in many different types. The chapter also included George's ideas about how a surface fire could transition to a crown fire. Chapter 3 is as relevant now as it was in 1959 because it provides the foundation for virtually all ensuing fire behavior studies worldwide.

George's Chapter 4 in the Davis book is titled *Forest Fire Behavior*; it discusses major wildfires and the conditions that cause them (Byram 1959). Included is a list of 12 warning signals for anticipating the development of extreme fire behavior. These warning signals are still used by NOAA fire weather forecasters and state fire control organizations. Also in Chapter 4 is a discussion of how the rate of energy release from a wildfire (which George called power of the fire) and rates of energy flow due to atmospheric winds at given elevations above the fire (which he called power of the wind) may be combined into an energy criterion that seems related to the onset of extreme fire behavior. George claimed that when the power of the fire approaches and eventually exceeds the power of the wind to heights at least 300 meters above the fire, the intensity of the fire may have increased to a level such that the fire has become difficult or impossible to control – i.e., the fire has blown up. He used one fire from his case studies, the May 1951 Wood River Valley Fire in RI, to illustrate the application of his equations for power of the fire and power of the wind to data from a real blowup fire. George later referred to the ratio of the power of the fire to the power of the wind as the 'convection number' and designated it with the symbol N_c – use of this terminology continues today. George wasn't content to simply envision and mathematically derive these relationships; he also was quick to communicate these concepts and their practical applications to the fire management community (Fig. 1).

Fig. 1. George speaking at a 1955 national fire research meeting in Baton Rouge LA. He is probably discussing his work on blowup fires.

Personal comments regarding George's N_c > 1 criterion

I know of seven case studies describing major wildfires for which researchers were able to correlate the timing of the fire's maximum intensity (or blowup) with the existence of vertical profiles of N_c with values exceeding unity for considerable heights above the fire: Pungo Fire (Wendel and Storey 1959), Sundance Fire (Anderson 1968, Aronovitch 1989), Hofmann Forest Fire (Ward and Nelson 1972), Air Force Bomb Range Fire (Wade and Ward 1973), Mack Lake Fire (Simard *et al.* 1983), Butte Fire (Aronovitch 1989). Though these results come from only six fires, they constitute evidence in support of George's suggestion that when $N_c > 1$ for elevations above the fire of at least 300 m, erratic and/or blowup behavior will occur.

On the other hand, I know of two published papers describing controlled field burns for which the calculated N_c values did not reflect the observed fire behavior (Sullivan 2007, Morandini and Silvani 2010). In both cases this led the authors to suggest that studies of N_c might be better applied in academic endeavors conducted in the laboratory. These conclusions are questionable because only surface values of N_c were used to test George's claim. Any valid test of his hypothesis must compare the observed fire behavior with N_c as a function of height above the fire.

Convection number N_c has been with us for over 50 years but, to my knowledge, there has been no organized effort by fire research to test it on controlled burns or wildfires. It has been suggested that practical considerations make such studies nearly impossible on going fires, but I doubt the problems are beyond our abilities to investigate and solve with an 'engineering' approach. The time has come for researchers to take N_c off the shelf and study it in an organized global networking effort; this kind of effort also has been advocated for crown fires. If it is thought that study of N_c on a global scale does not merit the required effort and resources, then we should at least include study of N_c as part of a larger overall investigation of surface-to-crown transition and extreme fire behavior. Regarding the use of N_c on going fires, basic questions to be answered would include the following: (a) is it practical to supply the required resources, (b) does our methodology yield an improvement in fire control, and (c) for which climates and land forms does the methodology produce positive results? George provided the spark of interest in 1959 – researchers should at least inquire into the benefits rather than letting the idea die!

George's research during the 1960s

In 1960 Wallace Fons transferred from CA to the new Macon fire lab to continue his rate of spread modeling in the lab's combustion room. His work, under contract with the Office of Civil Defense, was performed under the title 'Project Fire Model'. A year later, George transferred from Asheville to Macon to conduct basic research on energy processes controlling the behavior of high intensity fires. Unfortunately, Wally died unexpectedly in October 1963, and George was the obvious choice to finish the work; the Final Report was published in 1966 (Byram *et al.* 1966). In that report there was an obvious change from Fons' emphasis on radiation to studies of convection in which George was primarily interested. Many white fir cribs were burned in the wind tunnel and combustion room, but the report also presented ethanol pool fire data in three separate figures illustrating increases in fuel ignition distance with increasing wind speed. George considered these increases as due to continuous flame contact (ignition caused by horizontal extension of what appears as solid or continuous flame) and to intermittent flame contact (ignition caused by darting fingers of flame ahead of the combustion zone). The combined effects of these processes constitute part of the mechanism by which new fuel is ignited, causing increases in flame zone depth with increasing wind speed or slope angle -- a process sometimes referred to these days as flame attachment.

In Chapter 4 of the Davis book, George mentioned the possibility of modeling the convective features of wildland fires. Part of this interest involved the modeling of fire whirls, and by 1962 he had completed his theoretical calculations. He also built several Plexiglas fire whirl chambers of varying size and shape for generating and measuring whirl velocities and rotation rates. Bob Martin was at the Southern Forest Fire Lab during the early 1960s and collaborated closely with George in this work; they produced several papers describing this phenomenon between 1962 and 1970 (Byram and Martin 1962, 1963, 1970).

The USDA's Secretary of Agriculture announced in 1965 that George would be heading a new Pioneering Research Unit to study forest fire energy systems. The Southeastern Forest Experiment Station's news release stated that the new leader would be bringing to the project an unusually productive background in the physical sciences as well as a sound knowledge of national and regional fire problems. My thought was that there was no one more qualified for the job than George. Within the new project, business continued as usual (Fig. 2) – no internal announcements, work changes, or celebrations. I suppose at least a month passed before I realized there had been a name change.

Fig. 2. George in his office at the Southern Forest Fire Laboratory, Macon GA, 1965. And yes, he always came to work wearing a tie and jacket.

I believe George's interest in scale modeling of forest fires goes back to 1957. In that year he attended a national meeting requested by Federal Civil Defense authorities for the purpose of stimulating new research that would aid in the control of wartime and peacetime mass fires. In 1960 he and three other US Forest Service fire researchers attended a conference during which the scale modeling of forest and building fires was emphasized. These meetings may have motivated George to develop his scaling laws for modeling the convective behavior of mass fires, and line fires as well. His most extensive paper on the subject was published in 1966 (Byram 1966). Approximately 2 years later, Forman Williams of the University of California San Diego and Richard Corlett of the University of Washington produced expanded versions of his 1966 paper; both of their analyses confirmed George's work.

Early in the scale modeling work, George bought a copy of the Langhaar book on dimensional analysis for every scientist in his project, and for a few months taught us the subject in his office two times a week; counting George, there were usually four of us present (five during the summer). He never taught down to us during the course (or any other time). He assigned homework problems and when we would discuss them in the next class he would say, 'I had trouble with this problem', or 'I wasn't able to get that one – did anybody finish it'? I didn't know whether to believe him or not. Because of the cost in effort and time George spent with us, I can only believe he was planning a major scale modeling effort for the future. Unfortunately, the application of George's scaling laws to experiments with wind-driven fires never materialized. I'm not sure why because in the late summer of 1967 I left Macon to attend the University of Washington for additional training (with George's blessing) and remained there until the spring of 1970. As it turned out, George retired in 1968 -- a year after I left Macon.

George made two important contributions to fire danger rating in the 1960s with his introduction of the timelag concept (Byram 1963) and his technical development of the Keetch-Byram Drought Index (Keetch and Byram 1968). He presented his timelag paper at an international symposium on humidity and moisture, and later submitted it for publication in the Proceedings. It was rejected because it lacked originality -- the derivation and solutions of the diffusion equation had been known for many years. That afternoon in his office, George smiled, chuckled, and commented to me that the reviewers had no idea that the paper was about an application of diffusion theory to a practical problem. None of this bothered him – he didn't worry about counting publications.

Three papers by George were published in the early 1970s (he had written them prior to his retirement in 1968). First, there was a fire whirl paper with Bob Martin (Byram and Martin 1970). The second dealt with experimental verification of one of the scaling laws George had published in 1966 (Byram and Nelson 1970). In the third, George showed that for purposes of modeling convection above a steadily burning fire, the reaction zone and its associated complexities due to combustion can be replaced by a pure heat source of equal strength (e.g. one or more hot screens) (Byram and Nelson 1974). These papers were the final contributions from a distinguished researcher whose leadership and ability to solve problems continue to lead the way for us today.

My remembrances and those from others who knew George or his work

What was it like to be a member of George's research project? In his project everyone was treated fairly and equally. When he asked me to do a study, he made sure I knew what he wanted and that I was properly prepared; then he left me alone – except once in a while when we would meet by chance and he would ask how things were going. George spent significant time as an advisor to co-workers, research colleagues in other Forest Service units around the nation, and sometimes to researchers in places like Australia and England. He was always willing to help – except in rare cases when I would find his office door closed, but I knew he was at work. The message was clear – please do not disturb! Even when his door was open there were times when I, as a younger scientist, was hesitant to interrupt his train of thought with what might have been an insignificant question. The truth is that I was in awe of him, and I probably was not the only person around who felt that way.

My wife Sally and I were visiting the Byrams one evening in the early 1990s; they had moved from their home to an apartment in Asheville. I was working at the time and had thought of possibly publishing George's derivation of the convection number (I had a copy of the derivation). I mentioned to him that he should be the senior author of the article because the concept was his and he had done all the original work -- case studies and conversations with fire control people. George politely declined my offer and urged me to go ahead with the project. This is yet another example of George's unselfishness in thinking of others rather than himself.

Sally and I also remember a tense night in June 1987 -- the eve of leaving Macon for our transfer to Missoula MT. George and Elizabeth drove 250 miles from Asheville to Macon to take our family of five out to dinner. George's age then was 78; he had been retired for 19 years. We had a warm visit after dinner, and they gave us a nice parting gift. I often wonder whether George regarded his working with my dad early in his career, and with me at the close, as something special. I most certainly felt that way! In 1992 they moved from Asheville to Dunedin FL to be close to their daughter Irene and her family. It was there that George passed away on April 12, 1996.

Earlier I mentioned George's gentlemanly demeanor and unassuming manner. I want to share some comments made to me by fellow researchers after they learned of George's passing (researcher's affiliation: MFSL, Missoula Fire Sciences Laboratory; SFFL, Southern Forest Fire Laboratory):

1. Pat Andrews, MFSL: 'If you've been involved with fire, you know of George Byram.'
2. Dale Wade, SFFL: 'His work can only grow in significance over time.'
3. Bill Frandsen, MFSL: 'He was and still is a grand gentleman in my eyes. I am happy to have had my few moments with him.'
4. Darold Ward, SFFL and MFSL: 'I feel privileged to have known George, certainly not the mentor and close friend he was to you, but he was and is a dear friend to all in fire research for sure.'
5. Jack Cohen, SFFL and MFSL: 'I never had the opportunity to meet George but wish I had. It is testimonial that so many of us continue to utilize George's work.'
6. Dick Rothermel, MFSL: 'I remember him fondly from our trip to England when he showed Hal and I how to relax and listen to the bell chimes in King's Cathedral rather than rushing to another fire conference.'

Finally, I quote part of the letter written to George in 1968 by the Director of the Southeastern Forest Experiment Station, Tom McClintock, shortly after he learned of George's imminent retirement:

> *You have provided the kind of informed and imaginative leadership in a difficult and complex field of science which cannot be matched or replaced. The unique blending of mathematics and physics which you have used so skillfully to explore the basic laws and reactions of fire not only gave us badly needed fundamental knowledge, but has been a major determinant in establishing forest fire research on a solid scientific foundation.*'

I cannot think of a better way to describe the scientific gifts we were given by George Byram. It was a pleasure and privilege to participate in the tribute to George during the 4th Fire Behavior and Fuels Conference. Indeed, he was one of the great forest fire research pioneers.

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Learning from those who came before us: closing remarks to the George M. Byram special session tribute

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Abstract. This paper constituents the closing comments made at the special session 'Standing on the Shoulders of a Giant: A Tribute to George M. Byram (1909-1996) – Pioneering Scientist in Forest Fire Research' held on February 20, 2013, at the International Association of Wildland Fire's 4th Fire Behavior and Fuels Conference in Raleigh, North Carolina.

Additional keywords: fire behavior, forest fire research.

Introduction

This special tribute session has been more than simply paying homage to or a demonstration of respect of George Byram (Fig. 1). In keeping with the theme of this conference, we have much to learn from fire research pioneers like Byram, as we look to the future.

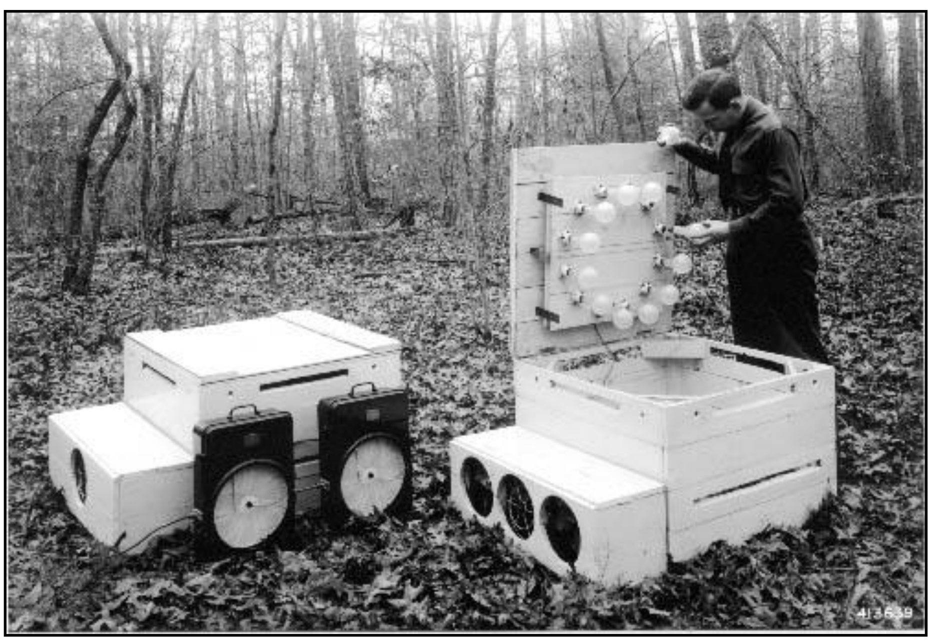

Fig. 1. George Byram examining one of two artificial sun instrument boxes utilized in the fuel moisture study of Byram and Jemison (1943).

Special session significance

One individual attending the special session later on described it as the highlight of his professional career to date (M.G. Cruz, CSIRO Ecosystem Sciences and Climate Adaptation Flagship, pers. comm., 2013). The stories of Byram's contributions, accomplishments and efforts, including mentorship, as related to us by Dale Wade, Darold Ward, Ralph Nelson Jr. (Fig. 2) can certainly serve as sources of inspiration for us all as evident by the following sentiments:

- '*He was without ego or self-promoting agenda*' – Dale Wade
- '*Many principles about fire that we use today in describing and quantifying fires of all types are owed to him*' – Darold Ward
- '*I think all forest fire researchers have been influenced in some way by his work*' – Ralph Nelson

Fig. 2. Speakers at the special session tribute to George M. Byram. From left to right: Marty Alexander, Dale Wade, Darold Ward, and Ralph Nelson, Jr. Photo by Wesley G. Page, USU.

Video recording available

For those that missed it, the entire special session tribute to George M. Byram was videotaped by Darold Ward and can be viewed at http://vimeo.com/61394967. Thanks Darold for your efforts in this regard!

Acknowledgments

I would especially like to thank the International Association of Wildland Fire and the Joint Fire Science Program for supporting my attendance at the special tribute session to George M.

Byram. A very special thanks to Ralph Nelson Jr. and those 'brothers from different mothers' the DW Boys, Dale Wade and Darold Ward, for their willingness to participate in this event. Without them there simply would not have been an event.

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Proceedings of 4th Fire Behavior and Fuels Conference, February 18-22, 2013, Raleigh, North Carolina, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Ground measurements of fuel and fuel consumption from experimental and operational prescribed fires at Eglin Air Force Base, Florida

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Abstract: Ground-level measurements of fuel loading, fuel consumption, and fuel moisture content were collected on nine research burns conducted at Eglin Air Force Base, Florida in November, 2012. A grass or grass-shrub fuelbed dominated eight of the research blocks; the ninth was a managed longleaf pine (*Pinus palustrus*) forest. Fuel loading ranged from 1.7 Mg ha^{-1} on a sparsely vegetated grass site to 19.9 Mg ha^{-1} on the managed longleaf pine site. Fuel consumption followed suit and was lowest on the sparsely vegetated site (1.1 Mg ha^{-1}) and highest on the forested site (6.7 Mg ha^{-1}). A fuelbed selected from the fuelbed library of the Fuel Characteristic Classification System (FCCS) matched well with the forested site. Consume 3.0 and FOFEM 5.9 predicted total fuel consumption to within 0.5 Mg ha^{-1} of the measured total consumption in 4 of the 9 blocks randomly selected for comparison. This preliminary data analysis is part of the Joint Fire Science Program-supported project 'A Data Set for Fire and Smoke Model Development and Evaluation—the RxCADRE Project'. The entire dataset will be available in a globally accessible repository for testing and evaluation of fire and fuel models in 2014.

Additional keywords: fuel loading, fire effects

Introduction

The availability of an integrated, quality-assured fuels, fire, fire effects, and atmospheric parameter dataset for the development and evaluation of fuels, fire behavior, emissions, and fire effects models is limited (Cruz and Alexander 2010; Alexander and Cruz 2012). To develop such a dataset, the Joint Fire Science Program (JFSP) generously supported this study: 'A Data Set for Fire and Smoke Model Development and Evaluation – the RxCADRE Project' (JFSP 2012). The study focused on 6 disciplines: fuel characteristics and consumption, meteorology, fire behavior, fire mapping, emissions, and fire effects. This paper presents preliminary ground-based measurements of fuel loading, fuel moisture content, and fuel consumption, collected on nine research burns conducted at Eglin Air Force Base (Florida) as part of the this study. It also presents a simple comparison of the Fuel Characteristic Classification System (FCCS) (Ottmar *et al.* 2007), Consume v. 3.0 (Prichard *et al.* 2007), and the First Order Fire Effects Model v. 5.9 (FOFEM) Reinhardt *et al.* 1997) predictions with the measured data as an example of how this dataset can be used to evaluate current fire and fuel tools.

Methods

Ground-level measurements of fuel loading, consumption, and moisture content were taken from six 100x200-m (2 ha) replicate experimental blocks (S3, S4, S5, S7, S8, S9) and three 200-400 ha operational blocks (L1G, L2G, L2F) both before and after prescribed burning at Eglin Air Force Base in November 2012 (Fig. 1). A grass or grass-shrub fuelbed dominated eight of the research blocks while one block was a longleaf pine (*Pinus palustrus*) forest. Twenty-five pre- and twenty-five post-burn clip plots (1 m^{-2}) were established on the outside of each experimental burn block, and thirty pre- and thirty post-burn clip plots (1 m^{-2}) were established along 3 grid lines within the operational blocks L1G, L2G, and L2F. In addition, nine pre- and post-burn clip plots (0.25 m^{-2}) were established at each of three highly-instrumented plots (HIPS) located within blocks L1G and L2G. Twelve pre- and post-burn clip plots (0.25 m^{-2}) were established at the HIPS in L2F to account for the increased variability of the fuels in a forested site (Fig. 2). Fuel from within the clip plots was collected and categorized into 5 fuelbed categories (shrubs, grasses, down-and-dead wood, litter, and duff), dried in an oven, then weighed to determine pre- and post-burn loading. Consumption was calculated by subtracting the average preburn loading from average postburn loading, by fuelbed category, for each set of plots. Five to ten 6 L plastic bags of fuel moisture content samples representing shrubs (stems and leaves), grasses, small and large woody material, litter and duff, were collected immediately before each burn.

We assessed the usefulness of this dataset in evaluating fire models by comparing 1) measured fuel loading with the best fit fuelbed from the FCCS fuelbed library and 2) measured fuel consumption with predictions from Consume vs. 3.0 (Prichard *et al.* 2007), and the First Order Fire Effects Model 5.9 (FOFEM) (Reinhardt *et al.* 1997).

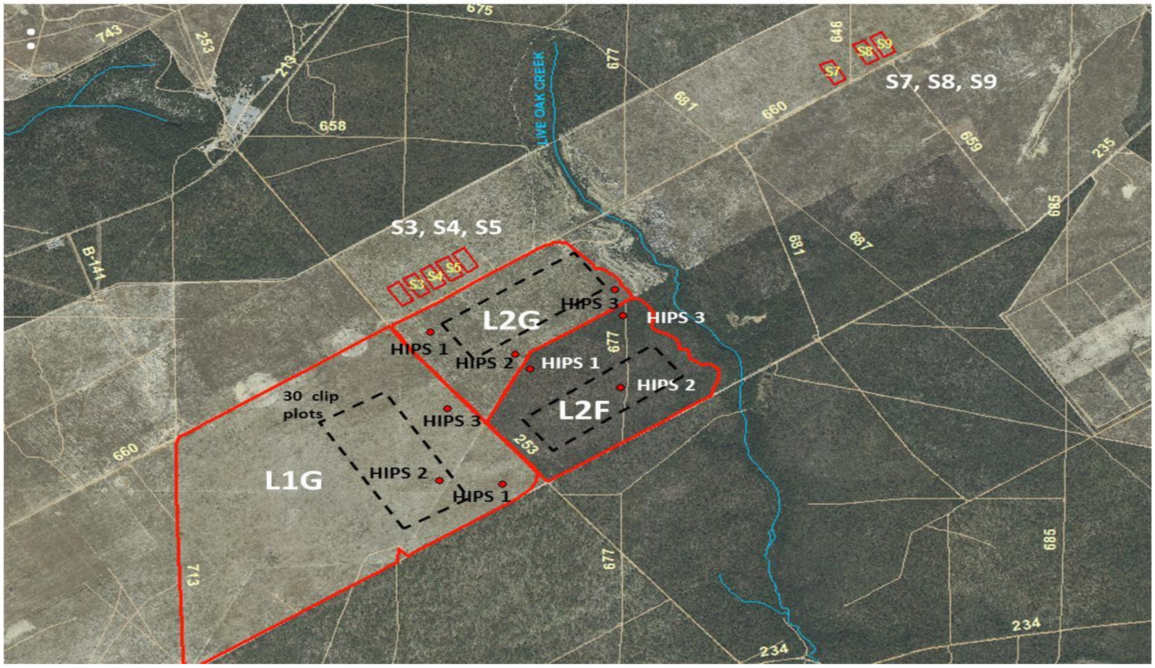


Fig. 1. Small replicate and larger burn blocks established for the November, 2012 RxCADRE research project located on the B70 bombing range at Eglin Air Force Base, Florida.

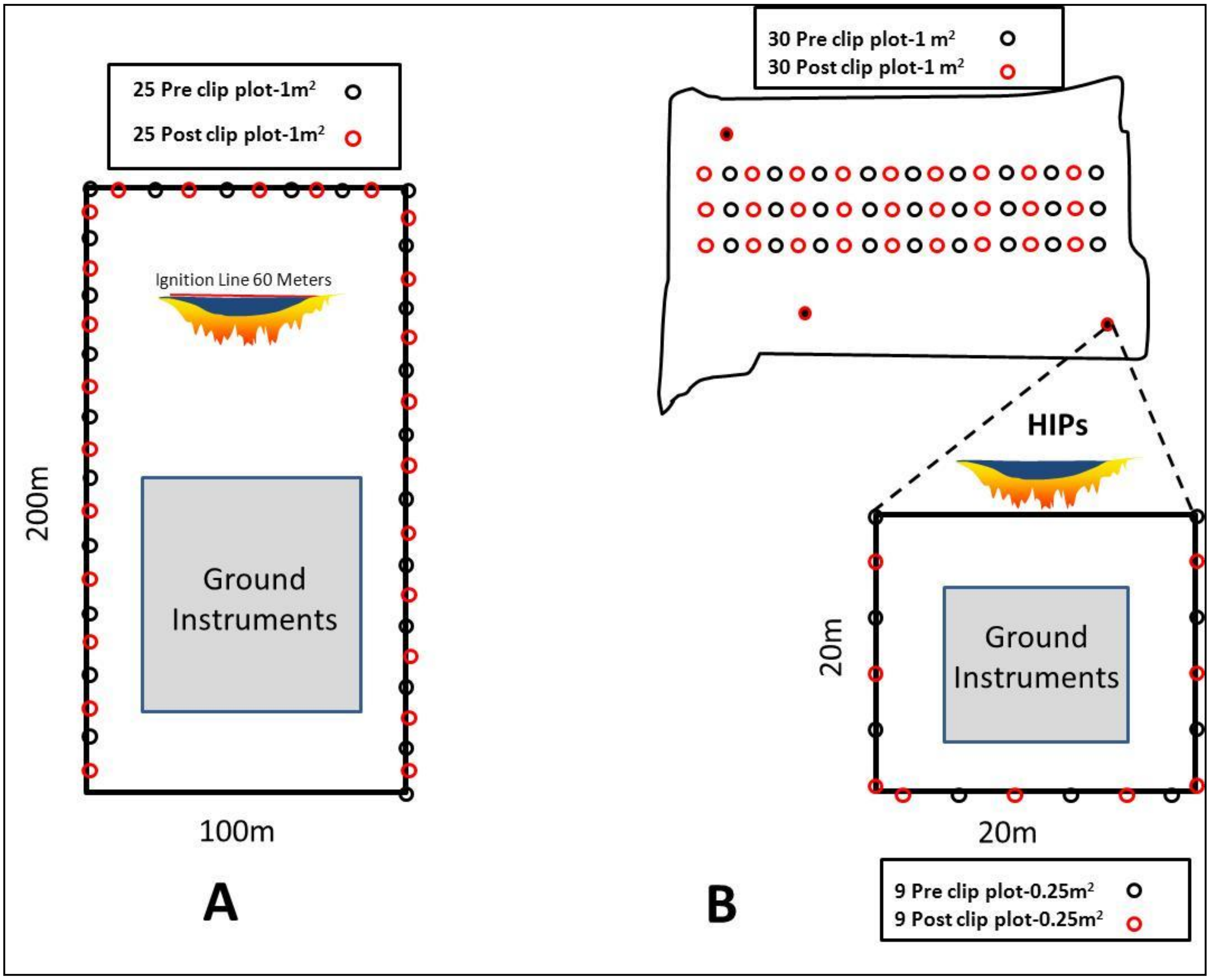


Fig. 2. Plot layout for (A) replicate small experimental burn blocks and, (b) large operational burn blocks.

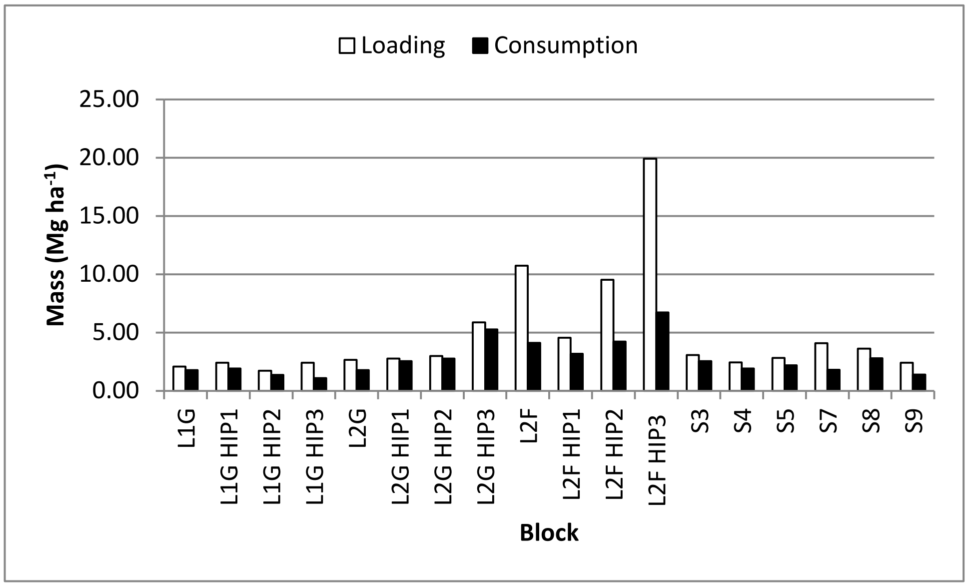
Results and Discussion

Fuel loading ranged from 1.7 Mg ha^{-1} on L1G-HIP2 to 19.9 Mg ha^{-1} on L2F-HIP3 (Fig. 3A). Block L1G was sparsely vegetated because it had been burned recently and treated with herbicide. L2F HIP 3 was more heavily vegetated since it was a forested site and contained more live and dead material than the grass and grass/shrub burn blocks.

Fuel consumption ranged from a low of 1.1 Mg ha^{-1} in L1G-HIP3 to 6.7 Mg ha^{-1} in L2F-HIP3 (Fig. 3A). The lowest fuel consumption corresponded to the block with the lowest loading; and the highest fuel consumption corresponded to the block with the highest fuel loading. Overall, fuel consumption may have been limited because a hard frost had not occurred and the shrub leaves and grasses were not cured. Furthermore, all blocks had been routinely burned every two to three years, reducing the total available fuel.

The day-of-burn fuel moisture content of the live vegetation (shrub, grass and forb) ranged from 108 percent in L2F to 129 percent in S4 (Fig. 3B). The moisture in surface fuels (litter) ranged from 2 percent on S9 to 17 percent on S4. The only block to contain down-and-dead woody material was L2F where the moisture contents were 12, 17, 26, and 40% respectively for the 1-hr, 10-hr, 100-hr, and 1000-hr woody fuel classes.

(A)



(B)

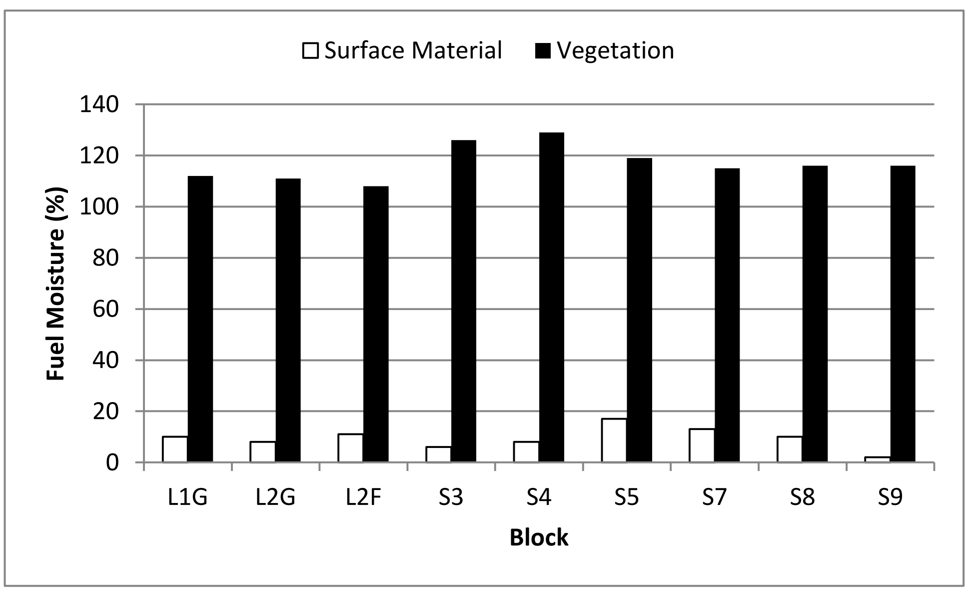


Fig. 3. (A) Measured fuel loading and fuel consumption and (B) measured fuel moisture content.

A search was made of the FCCS fuelbed library to find a fuelbed that closely matched the most complex fuelbed (L2F); fuelbed 191 was selected. This fuelbed is indicative of a longleaf pine forest that is burned every two to three years. It matched closely with data collected before the fire (Fig. 4A). Fuelbed 191 would have provided a reasonable fuelbed to initiate a customization. Additional comparisons will be conducted as we further analyze the data.

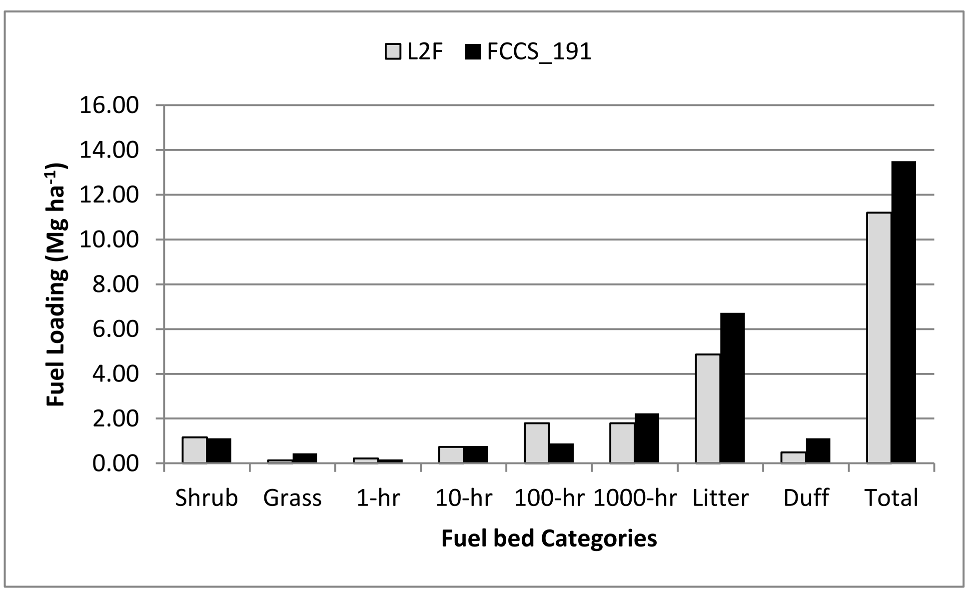
Consume and FOFEM both predicted the measured fuel consumption within 0.5 Mg ha^{-1} in all research blocks with the exception of block L2F (Fig. 4B). Here, Consume was within 0.5 Mg ha^{-1}, however, FOFEM over predicted total consumption by more than 3 Mg ha^{-1}. This is explained in part by the fact that FOFEM assumes all litter is consumed during a prescribed fire. In the case of block L2F, some litter was not consumed. Similar conclusions were reached by Reid *et al*. 2013).

Fuel loading, fuel moisture content, and fuel consumption data are expected to be used by those in other scientific disciplines to evaluate their results within the broader RxCADRE research effort. The data will also help to evaluate fuels, fire behavior, smoke, and fire effects models such as the Wildland-urban interface-Fire Dynamics Simulator (WFDS) (Mell *et al.* 2007), FIRETEC (Linn *et al.* 2002), FlamMap (Finney *et al.* 2006), BehavePlus (Heinsch and Andrews 2010), Consume, FOFEM, BlueSky Playground, CanFIRE, and BORFIRE (de Groot *et al*. 2007; de Groot *et al*. 2009).

Conclusion

This paper offers a preliminary review of a small portion of the ground-level data (fuel loading, moisture content, and fuel consumption) collected during the Joint Fire Science Program-supported RxCADRE field campaign at Eglin Air Force Base in Florida. We also assessed the usefulness of this dataset in evaluating fire models by comparing this data set with fuel loadings from the FCCS fuelbed library and fuel consumption predicted from Consume v. 3.0 and FOFEM v. 5.9. These data are one of several sets that will be available in an open repository in 2014 for the testing and evaluation of fire and fuel models. Further data reduction and analysis will be performed in the upcoming year.

A



B

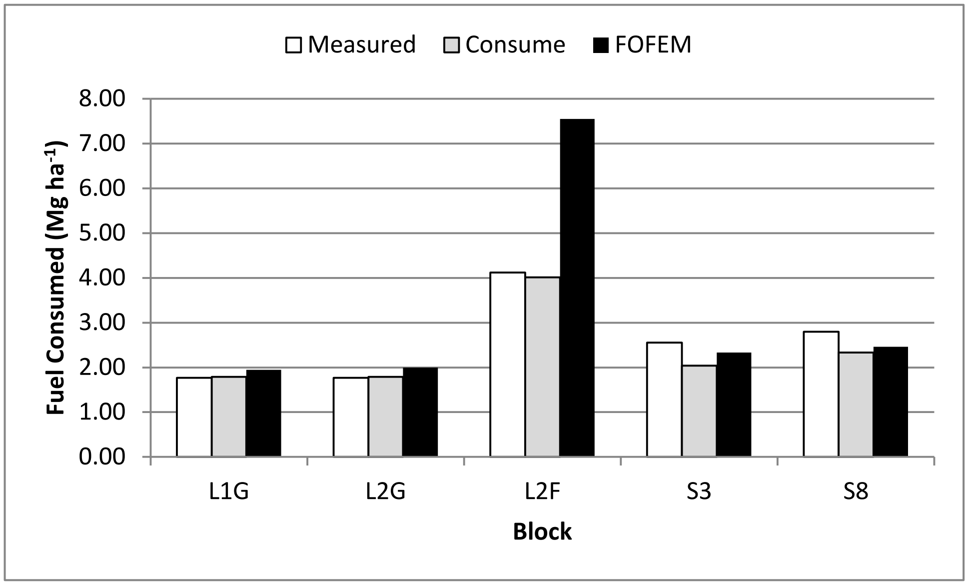


Fig. 4. (A) Measured fuel loading and fuel loading catalogued with FCCS fuelbed 191,and (B) comparison of total fuel consumption as measured and modeled by Consume and FOFEM.

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Relationship of post-fire ground cover to surface fuel loads and consumption in longleaf pine ecosystems

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Abstract: The RxCADRE research team collected multi-scale measurements of pre-, during, and post-fire variables on operational prescribed fires conducted in 2008, 2011, and 2012 in longleaf pine ecosystems in the southeastern USA. Pre- and post-fire surface fuel loads were characterized in alternating pre- and post-fire clip plots systematically established within burn units. Pre- and post-fire surface fuel loads summarized at the plot level were aggregated to estimate absolute consumption (tons/acre) and relative consumption (%) in 28 sample units. Percent cover of green vegetation, non-photosynthetic vegetation (NPV), black char, white ash, and mineral soil were ocularly estimated in plots co-located with the post-fire fuel plots and aggregated to the same 28 sample units. Spearman correlations were calculated between the usually non-normal distributions of ground cover fractions (%) and either surface fuel loads or consumption. There were highly significant correlations between many of these variables, with post-fire white ash cover and exposed mineral soil producing the highest correlations with pre- and post-fire surface fuel loads and consumption. This study provides empirical evidence for the assumption that post-fire white ash is the fire effect most indicative of surface fuel consumption.

Additional keywords: ash, char, fire effects, fuel consumption, prescribed fire

Introduction

Prescribed fires provide opportunities for physical measurements of pre-, active, and post-fire conditions on the ground, making them an important component for advancing fire science (Macholz *et al*. 2010). Because prescribed fire ignitions are planned in advance and often burn under less extreme conditions than wildfires, they simplify safety and logistical constraints. Furthermore, unlike many parts of the West and Alaska, the dense road network throughout the rural South typically allows one to position themselves on a Class 4 or 5 day, so one can select a fire that will provide an opportunity to collect pre-burn fuel and weather data as well as aerial and ground-based fire behavior and downwind smoke data. Some of these fires are likely to escape initial attack thereby providing extended opportunities to collect data.

Prescribed fires do not typically produce as wide a range of fire intensity and severity as wildfires (van Wagtendonk and Lutz 2007), but do exhibit spatial and temporal variability that can be measured to advance understanding of both fine-scale and landscape-level fire dynamics and effects. Lewis *et al*. (2011) accomplished this on the 2004 Taylor Complex wildfires in interior Alaska, and found significant correlations between fuel consumption and post-fire ground cover materials (green vegetation, non-photosynthetic vegetation (NPV), black char, white ash, and exposed mineral soil or rock) measured/estimated on the ground and/or by remote sensing. In that study, the post-fire cover measure most highly correlated to fuel consumption was green vegetation fraction (or the lack thereof), not black char or white ash, the respective products of incomplete and complete combustion (Smith and Hudak 2005). Other studies have shown that abundance and cover of black char and white ash are good indicators of fire severity (Smith *et al*. 2007; Lentile *et al*. 2009). Hudak *et a*l. (2013) found that white ash cover correlates significantly to surface fuel consumption across four very different fuel types, which they argued should be expected given that white ash is the direct result of complete fuel combustion. Our objective in this analysis was to assess if the ocularly estimated fractional cover of white ash and other post-fire surface materials correlates significantly to surface fuel consumption in frequently burned longleaf pine (*Pinus palustris*) stands in the southeastern USA, a much narrower range of surface fuel conditions than were measured by Hudak *et al*. (2013).

The RxCADRE research team (http://www.firelab.org/research-projects/physical-fire/205-rxcadre) destructively sampled fuels and deployed a dense network of instruments to directly or remotely measure fuels, meteorological conditions, fire behavior, combustion products, convection column characteristics, smoke transport and dispersion, and fire effects. While remote sensing of pre- and post-fire fuel and surface cover measures is a goal of the RxCADRE project, remotely sensed measurements will be described in future papers; thus, only the pre- and post-fire surface fuel load and post-fire ground cover measurements are presented in this paper.

Methods

The RxCADRE research team highly instrumented and measured pre-fire, active, and post-fire characteristics on 16 prescribed fires in the southeastern USA in 2008 (n=5), 2011 (n=2), and 2012 (n=9). All of the 2008 and 2011 burn units were forested with longleaf pine dominating the overstory and turkey oak (*Quercus cerris*) and saw palmetto (*Serenoa repens*) frequently occurring in an understory matrix of wiregrass (*Aristida beyrichiana*) and other grasses. One 2012 unit was dominated by longleaf pine while the other eight units were non-forested with a mix of grasses and shrubs.

In March 2008, two units were burned at Eglin Air Force Base (AFB) in northwestern Florida and three units were burned at the Jones Ecological Research Center in southwestern Georgia. Clip plots for destructive sampling of fuels were established in a grid pattern covering a 5 ha sample area randomly positioned within each unit; the 20 pre-fire and 20 post-fire plots (1-m x 1-m) were alternately situated at 20-m intervals along two parallel transects 40 m apart. In February 2011, two units at Eglin AFB were burned, with two widely separated sampling areas in one burn unit and three widely separated sampling areas in the other. One sampling area in the latter case had 20 pre-fire and 20 post-fire plots (1-m x 1-m) alternately situated at 5-m intervals along two parallel transects 30 m apart (similar to the 2008 sampling design). The other four sampling areas each consisted of 20 pre-fire and 20 post-fire clip plots (1-m x 1-m) distributed at 5-m intervals around the periphery of a 40-m x 40-m highly instrumented plot (HIP). In

November 2012, three large units (>200 ha each, comparable in size to the 2008 and 2011 burn units) and six small units (2 ha each) were burned at Eglin AFB. In each of the large units, 30 pre-fire and 30 post-fire clip plots were alternately situated at 50-m intervals along three roughly parallel transects ~100 m apart (similar to the 2008 sampling design). Within each large unit were an additional three sampling areas, each consisting of either 9 (two grass units) or 12 (one forested unit) pre-fire and post-fire clip plots alternately situated at 2.5-m intervals around the periphery of a 20-m x 20-m HIP (similar to the 2011 sampling design). The small units were each surrounded by 25 pre-fire and 25 post-fire clip plots alternately situated at 10-m intervals. Clip plots in the 2012 grass/shrub units were 1-m x 1-m (1 m^2) in size as in 2008 and 2011. Clip plots in the 2012 forested unit were 0.5-m x 0.5-m in size (0.25 m^2). Specific gravities and other sample processing details used to calculate fuel loads are described in Ottmar *et al*. (2003).

Ground cover fractions were estimated ocularly, under the constraint that the fractional cover of green vegetation, NPV, ash, and soil must sum to one. Char fraction was estimated as the combined percentage of residual NPV or exposed mineral soil that was charred.

All plot-level measurements were aggregated to the unit level in this analysis. Because pre- and post-fire clip plot locations must differ, absolute consumption (tons/acre) and relative consumption (%) were only calculable at the unit level. Spearman correlations were used to test the strength of relationships between surface fuel loads or consumption measurements and ground cover fractions (%) because many of the data distributions were non-normal. Data analysis was performed using R statistical software (R Core Team 2012).

Results

Pre-fire fuel loads averaged 5.4 tonnes/ha and post-fire fuel loads 2.0 tonnes/ha across the 28 sampling units (Fig. 1). This translated to a mean consumption of 3.4 tonnes/ha and a mean relative fuel consumption of 67%. (Note that because the sampling design of the pre- and post-fire clip plots limited fuel consumption calculations to the level of the sampling units, there are no measures of variability in Fig. 1c.) Higher pre-fire fuel loads in the forest units generally led to higher fuel consumption by weight and white ash production than in the grass units (Fig. 1). Post-fire ground cover was primarily composed of unburned NPV (mean 53%) and mineral soil (mean 39%) with minor contributions of green vegetation (mean 3%) and white ash (mean 4%). Slightly less than half (mean 48%) of residual NPV was charred.

All post-fire ground cover fractions were significantly correlated to pre- and post-fire fuel loads, except green vegetation and post-fire fuel load (Table 1). All ground cover fractions were significantly correlated with consumption, but only soil cover was significantly correlated with percent consumption. Percent exposed mineral soil was the ground cover material most highly correlated with the fuel variables overall, although white ash cover—the first order fire effect that directly results from complete fuel combustion—was indeed the post-fire ground cover material most highly correlated to consumption (Table 1). Sorting the 28 sampling units by consumption helps to visualize the highly significant relationship between consumption and pre-fire fuel load (Spearman's $\hat{\rho}$ = 0.84, P < 0.001) and white ash cover ($\hat{\rho}$ = 0.76, P < 0.001) but weakly significant relationship with post-fire fuel load ($\hat{\rho}$ = 0.41, P = 0.032). However, post-fire fuel load was strongly correlated to relative fuel consumption ($\hat{\rho}$ = 0.86, P < 0.001).

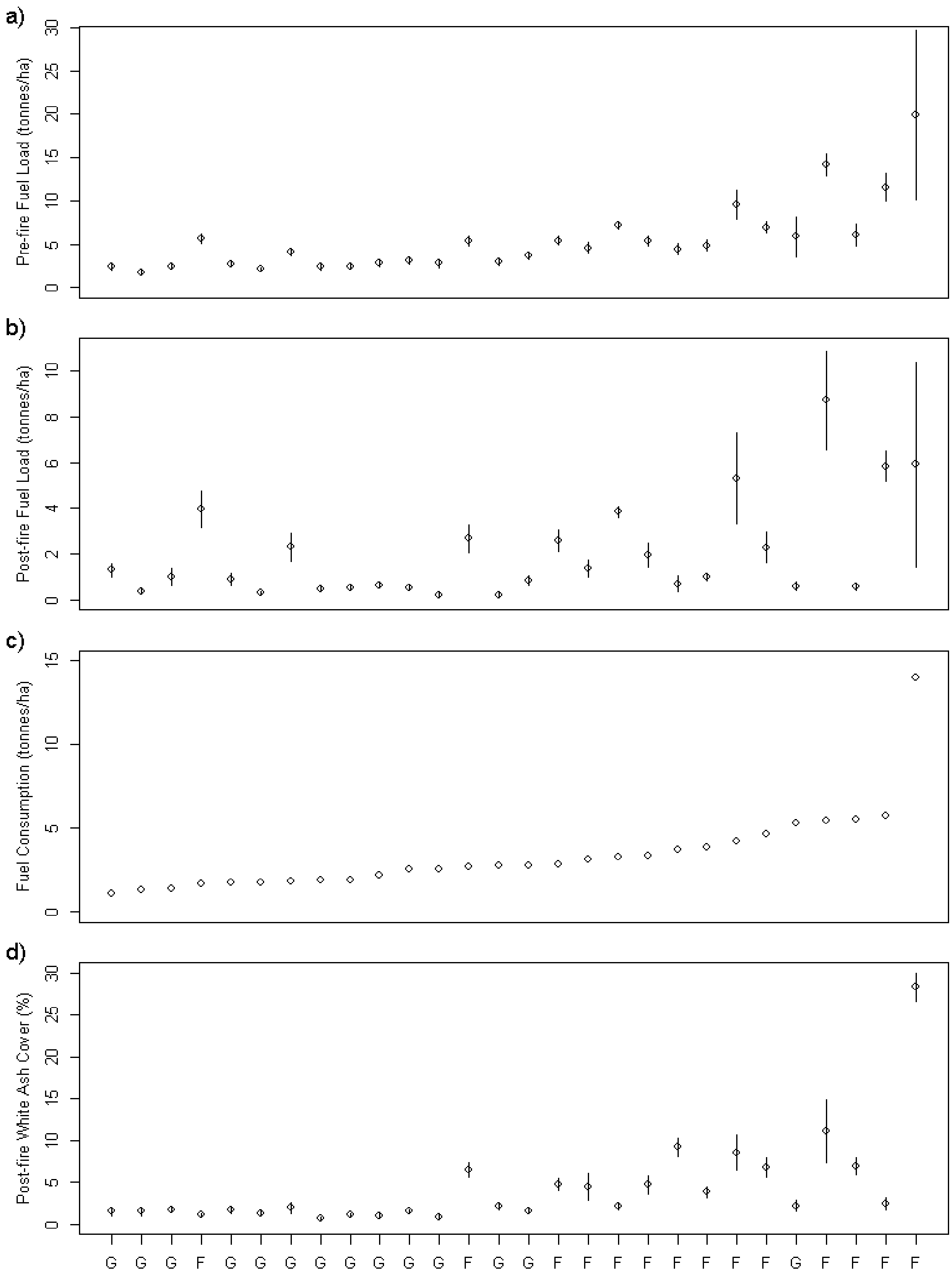

Fig. 1. Mean a) pre-fire fuel load, b) post-fire fuel load, c) fuel consumption, and d) post-fire white ash cover for 28 sampling units; F = forest (n = 14) and G = grass (n = 14). Standard error

bars are shown except in c), since fuel consumption is calculated at the sample unit level. The order of the sampling units is sorted from left to right by increased fuel consumption.

Table 1. Spearman ($\hat{\rho}$) correlations between surface fuel loadings or consumption versus post-fire ground cover fractions.

Significant correlations are indicated as follows: ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$.

	Green (%)	NPV (%)	Char (%)	Ash (%)	Soil (%)
Pre-fire Fuel (tonnes/ha)	-0.39*	0.62***	0.67***	0.74***	-0.78***
Post-fire Fuel (tonnes/ha)	-0.10	0.55**	0.44*	0.58**	-0.77***
Consumption (tonnes/ha)	-0.44*	0.41*	0.57**	0.76***	-0.52**
Consumption (%)	-0.22	-0.38	-0.12	-0.21	0.53**

Discussion

These results show that white ash cover is the ground cover material most highly correlated to fuel consumption. This is an intuitive finding that corroborates the main conclusion of Hudak *et al*. (2013), but over a narrow range of fuel conditions in a single fuel type. Furthermore, Hudak *et al*. (2013) had only the five 2008 burn units in longleaf pine from which to calculate Spearman correlations between the same fuel and ground cover variables as presented here. The large number of sampling units (n = 28) included here show that white ash and other post-fire ground cover fractions may be stronger indicators of absolute consumption than relative consumption. This result is useful for making retrospective estimates of biomass consumption upon which emissions estimates are based (Jenkins *et al*. 1998), especially in wildfire situations where pre-fire fuel loads are more often unknown. This research on prescribed fires points to the value in making both pre-fire and post-fire measurements towards a more quantitative understanding of the relationship between fuel consumption and fire effects.

Conclusion

This paper provides a preliminary assessment of surface fuel consumption in longleaf pine ecosystems and its influence on ground cover fractions estimated immediately post-fire. The main conclusion is that white ash cover measured immediately post-fire is a strong indicator of surface fuel consumption, justifying the quantification of white ash cover in retrospective assessments of fuel consumption and fire severity. These and other data collected by the RxCADRE project team will be uploaded into an open repository that will become publicly available in 2014 for testing and evaluation of fuel, fire, and fire effects models.

Acknowledgements

This research was primarily funded by the Joint Fire Science Program, with additional support from the Pacific Northwest and Rocky Mountain Research Stations of the U.S. Forest Service. We thank Joe Restaino and Jon Dvorak for much of the fuels data collection and reduction, along with Eva Strand, Donovan Birch, and Ben Hornsby. We also thank Kevin Hiers and Brett Williams for outstanding logistical support at Eglin Air Force Base or the Jones Ecological Research Center. We appreciate Dale Wade's critical review for improving this paper.

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Linking ground, airborne, and satellite measurements of fire power

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Abstract: An ongoing challenge in fire measurement is obtaining quantitative and validated measurements of fire power (kW m^{-2}) and energy (kJ m^{-2}) across a range of spatial and temporal scales. Our approach to measurement has been hierarchical, where characterization of the fire heat budget at high temporal resolution and small spatial extent from instruments deployed near the ground is used to calibrate and evaluate measurements of fire radiation obtained at moderate temporal resolution (~5 min sampling rate) and extent (~500 ha) from sensors flown on manned aircraft. In turn, we have obtained coincident satellite measurements of fire radiated power from NASA's MODIS (Moderate-Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) sensors that compare well with coincident airborne and ground-based estimates. In the November 2012 RxCADRE field campaign, MODIS and VIIRS fire retrievals, along with coincident ground and airborne (WASP, Wildfire Airborne Sensor Program) measurements, were obtained through coordination of ignition operations with satellite overpass. As well, RxCADRE burns in 2008 and 2011 and burns from two other projects involving ground and airborne fire power measurements also coincided with MODIS retrievals. We have begun to evaluate the ground, airborne, and satellite retrievals and find that fire power estimates have overlapping error intervals. An addition to the RxCADRE 2012 campaign were Unmanned Aircraft Systems that obtained near continuous imagery from developing fires from which we can extract spatial information and, in combination with ground radiometer (dual-band) data, obtain independent estimates of fire power. As described in other talks in this special session ("A data set for fire and smoke model development and evaluation—the RxCADRE project"), the RxCADRE project focuses on prescribed fires to allow for a high level of control on fire characteristics and to develop improved methods and understanding that can ultimately be applied to wildfires.

Additional keywords: dual-band radiometry, fire radiative flux density, fire radiative energy density, WASP, MODIS, VIIRS.

Assessing canopy fuels across heterogeneous landscapes using LiDAR

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Extended Abstract:

Additional keywords: Crown bulk density, Crown fuel weight, pitch pine, Crown fires, LiDAR.

Introduction

LiDAR (Light Detection and Ranging) systems are indispensable for estimating 3-dimensional structure of forest canopies. LiDAR data provide significant advantages over biometric, inventory-based approaches to quantifying canopy fuels, including the ability to conduct rapid, landscape-scale assessments at high resolution, and an accurate quantification of damaged, non-uniform crowns (Skowronski *et al*. 2007, 2011). However, for a truly accurate determination of canopy fuels, it is essential to calibrate LiDAR signals against destructive harvest data, preferably with concurrent LiDAR acquisitions and sequential harvesting of trees to quantify fuels in 1-meter layers. This crucial step is frequently omitted from studies which have generated canopy fuel assessments using LiDAR technology. We are improving estimates of canopy fuel loading in pitch pine (*Pinus rigida* Mill.) stands for wildland fire managers in the New Jersey Pinelands by integrating sequential tree harvests with repeated upward-profiling LiDAR sampling in 20 m x 20 m plots. We then use wide-ranging Airborne Laser Scanning (ALS) data to scale canopy fuel estimates across a heterogeneous landscape consisting of stands of various age, structure, and wildfire history. Here we report on: 1) the calibration of LiDAR data with biometric data derived from sequential harvests to quantify crown fuel weight (CFW) and canopy bulk density (CBD) in 1-meter height bins, 2) the comparison of profiling LiDAR and scanning ALS data in pitch pine stands of varying structure, and 3) the initial validation of LiDAR-derived estimates of canopy fuels in the Pinelands.

Study Site

Sites are located in the Pinelands National Reserve in southern New Jersey, USA. The Pinelands is the largest continuous forested landscape on the Northeastern coastal plain, and covers ca.

23% of New Jersey. Uplands consist of oak- and pine-dominated forests that have a higher frequency of severe wildfires than most forests in the northeastern United States. Pitch pine-dominated stands are of major concern to wildland fire managers in the Pinelands because of their propensity to crown during wildfires, and their proximity to WUI areas along the eastern boundary of the Pinelands National Reserve. Harvested stands were dominated by pitch pine, with scattered oaks (*Quercus* spp.) and an understory of scrub oaks, huckleberry (*Gaylussacia* spp.) and blueberry (*Vaccinium* spp.).

Methods

We used a three-tiered approach: 1) sequential destructive sampling of pitch pine in 20 x 20 meter plots to quantify foliage and live and dead 1-, 10-, 100- and 1000-hr fuels in the canopy in 1-meter layers combined with simultaneous sampling with an upward sensing backpack mounted LiDAR system to develop calibrated CFW and CBD height profiles in 1-meter layers, 2) downward sensing scanning LiDAR data combined with the recently-determined relationships between upward sensing and downward sensing systems to scale estimates over a large, heterogeneous landscape, and 3) a second set of independent, randomly located plots within the scanning LiDAR acquisition to evaluate model predictions of CFW and CBD height profiles in pitch pine-dominated stands in the Pinelands of New Jersey. Finally, we are producing high-resolution maps to assist suppression activities and to guide fuel reduction treatments, and digital datasets for modeling purposes using Wildland-Urban Interface Fire Dynamics Simulator (WFDS) and other models (Mell *et al*. 2009, Parsons *et al*. 2011).

Results and Discussion

Five 20 x 20 m plots were harvested from 2010 to 2012, ranging in total live tree biomass from 67 to 108 Mg ha^{-1}. Crown fuel weight (CFW; kg m^{-2}) ranged from 0.83 to 1.16 kg m^{-2}, and maximum canopy bulk density (CBD; kg m^{-3}) ranged from 0.15 to 0.23 kg m^{-3}. Allometric relationships between parabolic bole volume, calculated from height and DBH measurements, and available fuels, needle mass, and 1-hour and 10-hour fuels were highly significant; linear regression equations explained between 89% and 91% of the variation in fuel mass. Regression coefficients calculated for the relationship between parabolic bole volume and maximum CBD or its height using biometric data were 0.81 and 0.72, respectively. Relationships between upward-sensing profiling LiDAR returns and available fuels, needle mass, and 1-hour and 10- hour fuels in the canopy were also highly significant, and with linear regression equations accounting for > 90% of the variation in crown fuel weight or maximum CBD. Across all comparisons, the poorest predictions were for 1000-hr fuels and dead needle mass.

Previous research has demonstrated that relationships between upward sensing profiling LiDAR and downward sensing scanning LiDAR are highly significant in pitch pine – dominated stands, facilitating the scaling of crown fuel estimates across the landscape (Skowronski *et al*. 2011). They obtained equivalent 1-meter height bin estimates of CBD using upward sensing profiling LiDAR and downward scanning ALS data in 20m x 20m plots, with correlation coefficients of 0.83 and 0.82 for each system, respectively. Initial analyses of data from validation plots indicate that biometric and LiDAR-derived estimates of CFW and maximum CBD are not significantly different. For example, CFW estimates were 1.15 ± 0.27 vs. 1.22 ± 0.28 kg m^{-2} (n = 17 plots, paired-sample T = 0.22, ns) and maximum CBD estimates were 0.22 ± 0.08 vs. 0.22 ± 0.08 kg m^{-3} (n = 17 plots, paired-sample T = 0.59, ns) for biometric and LiDAR-derived estimates, respectively.

The results of our project will assist the New Jersey Forest Fire Service and federal wildland fire managers because highly accurate canopy fuel maps can now be produced for large forested areas in the Pinelands, and for areas in and around wildland-urban interface. Our results can also be used to evaluate the effectiveness of prescribed burns and mechanical canopy fuel reduction treatments (Clark *et al*. 2009, Skowronski *et al*. 2011). In addition, we can now generate highly accurate estimates of crown bulk density (CBD) and other canopy fuel characteristics, which are appropriate for current fire behavior models such as the FVS-Fire and Fuels Extension, and for the next-generation of fire behavior models such as WFDS, which require high resolution canopy fuel loading information (e.g., Parsons *et al*. 2011).

Conclusions

The use of LiDAR to assess canopy fuels has advantages over allometric, plot-based approaches because: 1) large, landscape-scale inventories can be accomplished in a systematic manner, 2) accurate canopy fuels maps are limited by data-processing time, not by field crews, access and scheduling, and 3) damaged, non-uniform crowns can be quantified accurately. Although time consuming, the evaluation of LiDAR signals against destructively harvested data, preferably with sequential harvesting and concurrent LiDAR data collections, provides highly accurate information on canopy fuel characteristics. This research provides important, useful information for wildland fire managers, and will improve their decision-making during wildfire suppression activities, and for evaluating the effectiveness of hazardous fuel reduction treatments. In addition, high resolution canopy fuels information will be essential for the next generation of fire behavior models.

Acknowledgements

The Joint Fire Sciences Program (JFSP #10-01-02-14: A Validated Framework for Assessing Canopy Fuels Across Heterogeneous Landscapes Using LiDAR) and the USDA Forest Service NRS-06 provided funding for this research.

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Fire-atmosphere interactions during low-intensity prescribed fires in the New Jersey Pine Barrens

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Abstract: Of particular concern to fire and air-quality management communities, particularly in the eastern portion of the U.S., are the behavior and air-quality impacts of low-intensity prescribed fires for fuels management. For example, smoke from prescribed fires, which often occur in wildland-urban interface (WUI) areas in the eastern U.S., can linger in an area for relatively long periods of time and have an adverse effect on human health. Smoke from wildland fires can also reduce visibility over roads and highways in the vicinity, and for some distance downwind of these fires. Planning for, and tactical management of low-intensity prescribed fires can be enhanced with models and decision support tools developed with a fundamental understanding of how the atmosphere interacts with these types of fires and the smoke they generate. As with the observations that have been carried out during more intense wildland fire field experiments such as the International Crown Fire Modeling Experiment (ICFME) and the FireFlux grass fire experiment, observations of the atmospheric environment and fire-atmosphere interactions during low-intensity prescribed fires provide critical data for evaluating new and existing modeling systems appropriate for simulating the behavior and impacts of low-intensity wildland fires. The observations also enhance our fundamental understanding of how atmospheric turbulent circulations can affect the spread of these fires and local smoke dispersion. This paper describes and presents some initial observations of the fire-atmosphere interactions that occurred during two low-intensity prescribed fires carried out in the New Jersey Pine Barrens. We specifically focus on the atmospheric turbulence regimes that were present in the fire environments. The observational results set the foundation for subsequent analyses of how forest vegetation and ambient and fire-generated atmospheric turbulence affect local transport and diffusion of smoke from low-intensity wildland fires.

Effect of peat moisture content on smouldering fire propagation

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Abstract: Smouldering combustion affects live and dead organic material stored in peatlands (e.g. peat, humus, duff) and forest soil layers. In soil organic layers, smouldering happens when a surface fire transfers heat downward. This kind of fire slowly self-propagates, consuming the organic mantel, converting it to char or ash. Such fires are difficult to extinguish and can abruptly transition to a flame front (Putzeys *et al.* 2007). The consequences can be important to the ecosystem, as peat fires can either kill resident flora and fauna directly, especially tree roots which typically results in death through either thermal cell mortality, or indirectly through removal of supporting material for plants. When a large quantity of organic material is consumed, air quality is detrimentally impacted and substantial amounts of carbon are released.
Factors such as oxygen availability, moisture content, bulk density and mineral content all play a role in the behavior of smouldering. Of these, moisture content is the main factor affecting ignition and propagation of smouldering fires (Frandsen 1987; Rein 2013) since the energy required to vaporize water content of peat decreases the energy available to maintain combustion (Rein 2013). The 50% probability of smouldering ignition was established at peat moisture content of 100-125% (oven dry weight basis) (Frandsen, 1997; Rein *et al.* 2008). However, once ignited a self-sustained smouldering front is able to dry and propagate through organic layers above this limit (Reardon *et al.* 2007).

In peatland ecosystems moisture content of the organic layers is heterogeneously distributed. Our research focuses on understanding how the moisture variation affects lateral propagation of smouldering fire. We performed burning experiments to record the horizontal propagation of a smouldering front through a commercial sphagnum peat (insulated trays of 20x20x5cm). The ignition method followed Rein *et al.* (2008). Peats under six different moisture content treatments were tested (0%, 25%, 50%, 75%, 100% and a heterogeneous mix of 0% and 200%). Data was collected with an infrared camera, thermocouples and weighing scales, from which temperatures at the front, spread rates and mass consumption were calculated.

The smouldering front in dry peat (0% moisture content) maintained temperatures over 400^{o}C during the whole burn (Fig. 1). Smouldering in peat with 100% moisture content reached initial temperatures of 400^{o}C and then slowly decreased as the front moved further from the igniter. Forward spread rates were 9.8±2.1 cm h^{-1} in dry peat, but remained between 6.0 cm h^{-1} and 2.8 cm h^{-1} for all other moisture treatments. The mass loss rate for dry peat reached 1.7±0.2g min^{-1} m^{-2}, during the first half of the experiment. For the other moisture treatments, the maximum rates of consumption were below 0.9 g min^{-1} m^{-2}.

We observed self-sustained propagation in burns with peat at 200% moisture content. Smouldering fronts moved at a mean rate of 6.6±0.1 cm h^{-1}. We recorded low peak temperatures of 202±85°C at the front due to heat losses in vaporizing the water from the peat. These temperatures were the lowest recorded in our experiments for a self-sustained propagation. Experiments with heterogeneous distributions allow us to study the behavior of smouldering propagation in more realistic scenarios where the water is not homogeneously distributed.

The data presented (Fig 1.) shows the smouldering behavior for a range of peat moisture contents. It is being used to parameterize and validate smouldering fire models following previous work described in Belcher *et al.* (2010). We are carrying out a series of experiments to look at the effect of spatial distributions of moisture content on smouldering propagation.

Peat moisture %	Velocity **cm/h**	Max. Front Temp **°C**	Mass consumed **%**	Max. mass loss rate **g/min/m²**	Burn duration **min**	Replicates **num.**
0	9.8 ± 2.1	436 ± 33	93.7 ± 2.1	1.65 ± 0.17	295 ± 37	9
25	3.9 ± 0.7	413 ± 36	95.5 ± 1.04	0.90 ± 0.05	400 ± 5	3
50	3.5 ± 0.9	438 ± 28	89.3 ± 2.9	0.87 ± 0.01	390 ± 17	2
75	2.8 ± 0.7	378 ± 24	82.4	0.79	460	1
100	2.8 ± 0.5	202 ± 85	84.3 ± 4.9	0.77 ± 0.01	445 ± 44	4
0/200	6.6 ± 0.1	207 ± 33	-	-	-	2

Fig.1. Median (±median absolute deviation) parameter estimates of smouldering fire propagation for peat under different moisture contents.

Additional keywords: peatland, heterogeneity, spatial distribution, mass loss rate, spread rate, peat fire.

Acknowledgment

This study is funded by the Earth and Natural Sciences Doctoral Studies Programme (PRTLI-5) from the Higher Education Authority of Ireland, under the Programme for Research in Third-Level Institutions and co-funded under the European Regional Development Fund.

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Synthesizing knowledge on crown fire behavior in conifer forests: we could use your help!

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Abstract. This poster paper presentation provides a summary of the types of information sought from field practitioners regarding the Joint Fire Science Program synthesis project 'Crown fire behavior characteristics and prediction in conifer forests: a state-of-knowledge synthesis.'

Additional keywords: crowning, free-burning wildland fires, wildfires.

Introduction

The Joint Fire Science Program (JSFP) is supporting a project aimed at synthesizing the currently available information on crown fire behavior in conifer forests (e.g. the onset of crowning, type of crown fire and the associated spread rate and fireline intensity). The present paper outlines a description of items being solicited by the project investigators at this time.

Needs of project investigators

In addition to summarizing the existing scientific and technical literature on the subject, we are actively seeking assistance from individuals in the form of field observations of crown fires and related experiences as well as still pictures (Fig. 1) and video footage; for example, do you have a favourite YouTube presentation (e.g. http://www.youtube.com/watch?v=KKpBqdf16rE)? We are looking for firsthand experiences of rare or perhaps unusual observations like independent crown fire runs or specific cases of conditional crown fire activity and crown fire cessation as well as instances of long-distance spotting (>2 km) from active crown fires along with the associated environmental conditions: What was happening climatically? What were the fuel types? Was there anything out of the ordinary? Did suppression play a role?

We are interested in hearing from you as to your opinions on the subject of crown fires and any specific questions and/or research needs/knowledge gaps or areas in fire behavior training that you would like to see addressed in this crown fire behavior synthesis project. For example, when implementing mastication fuel treatments how much material can be left onsite or how long after a mastication treatment is the potential risk of crown fire alleviated? Are there gaps in knowledge pertaining to crown fire such as the desire for better assessment methods for assessing crown fire risk in a particular conifer forest stand type? Finally, we would really like to hear your general thoughts and experiences pertaining to crown fire. The project team members that are in attendance would particularly like to hear about situations that are unique to the southern United States in regards to crown fire behavior in conifer forests.

For more information

The completion date for this JFSP project was June 30, 2013. To obtain further information on the deliverables associated with the JFSP 09-S-03-1 synthesis project 'Crown fire behavior characteristics and prediction in conifer forests: a state-of-knowledge synthesis', visit the project website (http://www.fs.fed.us/wwetac/projects/alexander.html) or alternatively the JFSP website (http://www.firescience.gov/).

Fig. 1. Crowning associated with the Jackpine Fire in the Willmore Wilderness Park, Alberta, Canada, at 4:29 pm MDT on July 4, 2006. Photo by Emile Desnoyers, Alberta Environment and Sustainable Resource Development.

Acknowledgment

The support of David L. Peterson, USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, Fire and Environmental Research Applications Team, Seattle, WA, in the project is duly noted.

Proceedings of 4th Fire Behavior and Fuels Conference, February 18 – 22, 2013, Raleigh, North Carolina, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Predicting litter and live herb fuel consumption during prescribed fires in native and old-field upland pine communities of the southeastern United States

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Abstract: The ability to predict fuel consumption during fires is essential for a wide range of applications, including estimation of fire effects and fire emissions. This project identified predictors of fuel consumption for the dominant fuel bed components (litter (<0.6-cm diameter dead material) and live herbs) during 217 prescribed fires in native longleaf pine (*Pinus palustris* Mill.) and old-field loblolly pine (*Pinus taeda* L.) – shortleaf pine (*Pinus echinata* Mill.) communities in the southeastern United States. Additionally, these data were used to validate the First Order Fire Effects Model (FOFEM) fuel consumption computer model using custom and default fuel loads. Regression models using empirical data suggested that litter and live herb fuel consumption can be predicted by inputting prefire litter and live herb fuel loads, litter and live herb fuel moisture, litter fuelbed bulk density, season of burn, years since last fire, days since last rain ≥0.64 cm, relative humidity, energy release component (obtained from the National Fire Danger Rating System), community type, pine and hardwood basal areas, and the Keetch–Byram drought index. FOFEM's prediction of fuel consumption for litter, live herbs, and duff combined using default fuel loads was 1.5 times the measured fuel consumption (where duff fuel load was zero). Refinement of FOFEM's fuel load and consumption calculations in the studied community types using the newly collected data and suggestions for model improvement would provide more accurate air quality inventories and assist in protecting our ability to utilize prescribed fire.

Large wildfire growth and dry slots in the United States

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Abstract: Recognizing dark bands (dry slots) in satellite water vapor imagery reveals surface and near-surface drying and winds that can adversely affect fire behavior and firefighter safety. A review of the literature regarding mid- to upper-atmosphere influences on wildland fire behavior is undertaken from the perspective of a wildland fire supervisor in order to stress the influence of these events and the value of understanding dry slots in the literature. Weather forecasts are a crucial facet of wildland fire management. The first Standard Firefighting Order deals specifically with weather conditions and forecasts while three of the 18 Watch Out Situations deal with local weather. Surfacing mid- to upper-troposphere weather is responsible for dry intrusions manifesting themselves as dry slots in satellite water vapor imagery (WVI). When a dry slot passes over a fire, the usual result is abrupt surface drying and strong, gusty winds which markedly increase fire behavior. Dry slots are particularly well documented in Australia and are therefore routinely forecasted during bushfire season. However, the indicators, occurrences, and influences of dry slots on fire weather and fire behavior in the United States are rarely recognized and documented regarding their negative influence on firefighter safety. To increase the awareness and appreciation of this dangerous meteorological phenomenon, several wildland fires in the U.S. where a dry slot resulted in extreme and unusual fire behavior and rapid fire growth are examined.

Introduction

There are a several good reasons for reviewing the research on mesoscale and synoptic meteorology of wildand fires in the United States influenced by dry slots. Virtually all authors correctly identified the upper air influences on these fires, but few actually referred to the sources and signatures as dry slots; this is a focus area that needs attention nationally in operational wildland fire weather meteorology. Next, the actual verification of WVI features and signatures is good, however, the verbiage to consistently identify them as dry slots is somewhat lacking, albeit there is recent improvement here. There are more than 30 synonymous terms for dry slots used in the U. S. Lastly, Charney (2007) and Charney & Keyser (2010) state the importance of researching '*atmospheric conditions aloft'* for establishing '*more accurate fire weather and fire behavior predictions, particularly for periods of extreme and erratic fire behavior'*. They emphasize the importance of being able to predict such structures as dry slots hours or, better yet, days in advance of the event and advocate additional work to '*develop and implement indices and diagnostics into operational fire weather and fire behavior forecasting that sense these conditions and communicate to other forecasters and the operational users of fire weather* *prediction, when and where the potential exists for extreme fire behavior'*, a suggestion I fully agree with.

Below I describe dry slots, dry intrusions, and upper air influences on wildland fires (See Fig. 1), then discuss 'fighting fire by the rules' in wildland fire engagement, how critical high nighttime temperatures trigger extreme fire behavior, the Campbell Prediction System, trigger points, and the '*alignment of forces*' principle, followed by a critical review of pertinent literature on meteorological conditions related to observed fire behavior. Then common meteorological, climatological, and physiological mechanisms and traits regarding the wildfires I examined in the literature are discussed. The final section ties the facts presented into take-home messages, including potential implications of the results for real-time fire-weather forecasting and future research.

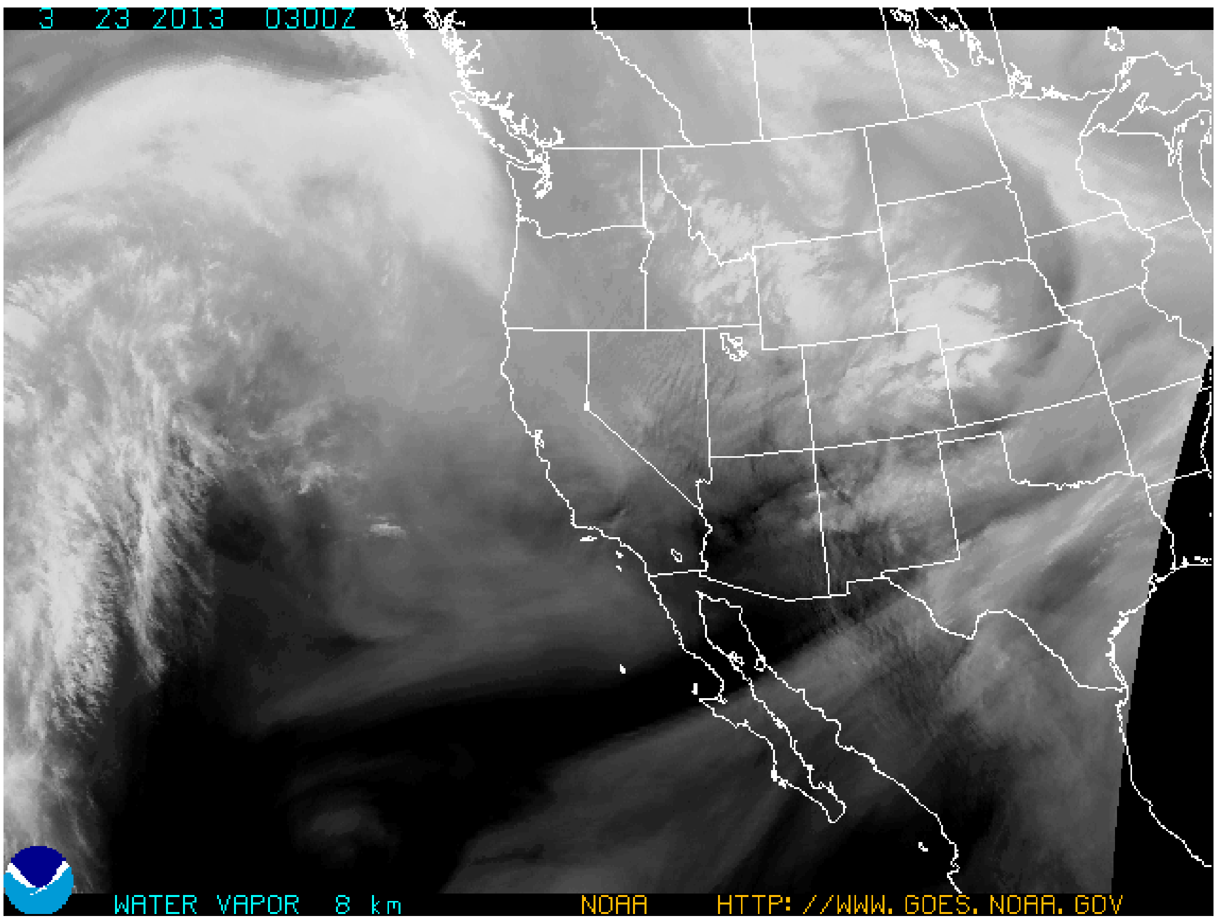

Fig. 1. GOES 8 km WVI for 23 March 2013 at 03Z (2100 MDT) indicating dry slots and dry intrusions (the darker bands) advecting into the Southwest and central United States (NOAA, NESDIS, OSPO Geostationary satellite image archives).

Dry slots and dry intrusions

Dry Slots show up as dark bands or filaments of very dry air in satellite WVI between 4 km and 6 km, and the term applies mainly to the darkest ones (Weldon and Holmes 1991) (Fig. 1). Dry slots tend to be associated with middle tropospheric thermal troughs (e.g. Weldon and Holmes 1991). The vertical structure of dry slots indicates that the genesis of this dry, high-momentum air is in the mid- to upper-troposphere and/or the lower-stratosphere (Charney 2007) and they manifest themselves quite distinctly in the WVI (Weldon and Holmes 1991). If the dark area has a well-defined definite boundary, the very dry air most likely extends to the lowest altitudes adjacent to the distinct boundary (Weldon and Holmes 1991). Commonly, the dark zones of the dry slot category are vertically deep with dry air extending downward to near the surface (Weldon and Holmes 1991).

Dry slots can be inferred from skew-T soundings; however, they are best visible via satellite WVI. Identifying dry slots can provide fire weather forecasters with beneficial nowcasting and forecasting advice for verifying National Weather Predictions (NWP) as well as Fire Weather predictions. Fireline supervisors and fire managers can view satellite imagery while on the firelines using laptops and other personal wireless devices. It is recommended that dry slots be corroborated with atmospheric sounding data to verify they are well developed and producing or about to produce dry, windy, unstable conditions.[1]

Dry slots and their effects may be inferred from fire weather forecasts; however, they can best be seen with satellite imagery, particularly WVI. I have been involved with numerous wildland fires where the humidity dropped like a rock, and have examined archived Incident Reviews (Wildland Fire Lessons Learned Center 2012-13) where fire behavior was, in fact, influenced by very low relative humidity's and dew points, and gusty winds. In the vast majority of cases, dry slots were found to be a causal mechanism and indicator.

According to Browning (1997), '*a dry intrusion is a coherent region of air descending from near tropopause-level, often with a clear signature in satellite imagery, especially water vapor, and is quite distinguishable as a 'dark zone' (emphasis added).* Some parts of dry intrusions are considered to have high potential vorticity and therefore, rapid cyclogenesis may be expected when approaching a low-level baroclinic zone. Note that the identification of dry intrusions will provide a forecaster with additional nowcasting evidence that is especially helpful when issuing severe weather warnings. Browning (1997) added that the identification of dry intrusions can form a basis for methodology to validate NWP models. Because dry intrusions are associated with high potential vorticity, they thus also serve as a useful guide for verifying NWP models in situations of potentially severe weather (1997).

Causes – contributing factors – precursors – indicators – outcomes

The causes, contributing factors, precursors, indicators, and outcomes of dry slots are addressed by many researchers as follows: Dry slots are basically columns of high, fast moving, dry air that descend rapidly to or near the Earth's surface affecting surface drying and intensifying surface winds (Mills 2010).[2] Dry slots are not accurately predicted by current computer models. They are most likely to occur in mid-afternoon, especially on hot days (Mills 2006; Miretzky 2009).

[1] Wachter, Brent (2012-2013) personal communications
[2] Werth, Paul (2012-2013) personal communications

Out of a total of 232 'abrupt drying events', Mills found 70% occurred with troughs, dry cold front passages, cool changes, and/or were co-located with jet streams. An additional 20% to 30% occurred overnight, or in the early morning (Mills 2006, 2009). Different types of dry slots are associated with other weather patterns such as pre-frontal, post-frontal, the breakdown of upper level ridges, foehn winds, low-level jet entrance and exit regions, and in advance of tropical storms (e.g. Mills 2006).

Dry intrusions and dry slots are often evident in WVI almost a full day before seen in infrared or visible imagery (e.g. Muller and Fuelberg 1990). They form during tropospheric jet stream induced gravity waves and are influenced by topographic (mountain-wave breaking and lee trough circulations) rather than coastal stimuli (Mills 2006). Dry slots always reflect a comparatively dry middle and upper troposphere.[3] Generally, the darker the dry slot, the lower the humidity (e.g. Weldon and Holmes 1991) and this generally applies to the color-enhanced imagery as well, with the exception that the brownish color is drier than the black or the yellowish to orange version. Dry slots almost always indicate descending dry air and/or horizontal dry air advection (e.g. James and Clark 2003) and air parcels in the dry intrusion originate at high tropospheric, or even stratospheric levels and then descend in the region upstream of a developing cyclone (e.g. James and Clark 2003). Each water vapor image is unique (Weldon and Holmes 1991) and satellite imagery will reveal structures not detected by conventional data (e.g. Muller and Fuelberg 1990).

Grumm et al. (2004) discovered that the strongest wind gusts were confined to the region of the dry slot. They also noted that strong low-level wind gusts progressed eastward along with the dry slot. Moreover, a secondary dry slot was often noted to the west and appeared to be associated with gusty winds and influenced by the leading dry slot. They also noted that the growing dry slot and the expanding area of strong gusty winds were coincident as the cyclone moved northward and the surface front advanced eastward.

Surfacing dry slots almost always result in a Haines Index[4] value of 5 or 6.[5] An RH drop caused by surfacing dry slots is almost always lower than the forecast RH; sometimes surprisingly lower. Dry slots are responsible for abrupt decreases in RH, dew point, and ultimately fuel moisture (e.g. Mills 2008*a*, 2008*b*, 2009) and strong, gusty winds (Mills 2005*b*). They can cause rapid, sustained increases in fire behavior (e.g. Mills 2005*b*).

It is the development of a deep, statically neutral boundary layer that contributes to the link between mid-tropospheric dry slots and the surface (e.g. Mills 2008*a*, *2008b*). Thus the source of the extremely dry air associated with the abrupt and rapid surface drying is a band of mid- to upper-tropospheric dry air associated with identifiable dark (dry) features in the WVI (e.g. Mills 2005*a*, 2008a, Charney 2007). Miretzky (2009) looked at Northeastern U.S. wildfires affected by subsidence and found that 'reservoirs' of dry air typically formed just above the Planetary Boundary Layer (PBL). I used WVI to verify that these reservoirs were, in fact, dry slots, and that they did influence the same fires.

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[3] Werth, Paul (2012-2013)
[4] This is a fire weather index based on the stability and moisture content of the lower atmosphere that measures the potential for existing fires to become large (Haines 1988*a*). The ratings range from 2 (moist stable lower atmosphere) to 6 (dry unstable lower atmosphere). A Haines Index of 6 is conducive of extreme fire behaviour and very rapid perimeter growth.
[5] Werth, Paul (2012-2013)

Fighting fire by the rules

On the fireline, firefighters and fireline supervisors are expected to follow the Ten Standard Fire Orders, as well as recognize, heed and then mitigate the 18 Watch Out Situations. The Ten Standard Firefighting Orders are fundamental rules of engagement for all wildland firefighters, the first of which deals specifically with weather conditions and forecasts (NWCG 2010). The 18 Watch Out Situations complement the Ten Standard Orders. Firefighters face severe, sometimes fatal consequences if they any of these situations are violated, but is not as unusual as one would like, for fire managers to fail to recognize one or more, or fail to heed their warnings and mitigate them (Schoeffler 2012). To help others learn from such mistakes, many are critiqued by the *Wildland Fire Lessons Learned Center* (2013). As a generally accepted practice, fireline supervisors use clouds as indicators to predict fire weather, especially the winds. In this paper, I propose using dry slots as a new WVI indicator (Schoeffler 2012).

Weather related standard fire orders:

1) Keep informed on fire weather conditions and forecasts.
3) Base all actions on current and expected fire behavior.
10) Fight fire aggressively, having provided for safety first.

Weather related watch out situations:

4) Unfamiliar with weather and local factors influencing fire behavior.
5) Uninformed on strategy, tactics, and hazards.
14) Weather is getting hotter and drier.
15) Wind increases and/or changes direction.

Almost all wildland fire injuries, burn-overs, fire shelter deployments, and fatalities are the result of not strictly following one or more of the Ten Standard Orders and/or failing to recognize and heed one or more of the 18 Watch Out Situations (Wildland Fire Lessons Learned Center 2013). Predicted fire behavior is often underestimated and/or unheeded resulting in tragic results. Fireline supervisors base their strategy and tactics on accurate fire weather forecasting; dry slot forecasting would provide more accurate and timely real-time fire weather predictions of abrupt surface drying and related wind events affecting fire weather and ultimately erratic fire behavior (Schoeffler 2012). I thus strongly recommend utilizing the Australian Bureau of Meteorology '*dry slot'* fire weather nowcasting and forecasting on a regular basis, as these signature patterns also occur in the United States (Schoeffler 2012).

The literature reveals quite a gamut of terms regarding dry slots, e.g. *dark bands, filaments, streamers, tongues of dry air*, and the like. The 'dry slot' term is utilized extensively in the South and Southeast regions of the United States National Weather Service, and the Southwestern Region is utilizing it more often, but usage appears to be scattered elsewhere (Schoeffler 2012).

Fireline supervisors generally have a basic understanding of subsidence, dry air intrusions, and dry slots from their fire weather training, but not a working knowledge. Currently, the best that fireline supervisors can do on the fireline is view WVI from a laptop or from a mobile device (Schoeffler 2012). Forecasting these events and broadcasting them to the fireline would be much more reliable if accomplished by trained and experienced meteorologists (Mills 2006). This would give fireline supervisors timely and important information allowing them to more safely and aggressively carry out their assigned wildland firefighting tasks. This information would enable them to anticipate expected fire behavior on a real time basis so they could more efficiently change tactics or disengage and move to safety if need be. In a nutshell, it would increase their situational awareness and enhance their options (Mills 2006).

Key to blow-up conditions in the Southwest?

This is the title of a 1962 research paper by Robert Bates. He postulated that nighttime temperatures above 7°C (45°F) portend blow-up conditions; and when they rise above 10°C (50°F) blow-up conditions will exist. He established these temperature thresholds (81°F (27°C) in the semi-deserts and 11°C (52°F) in the pines) from his analysis of wildland fires in the Southwest. He concluded that the day *following* the highest nighttime temperature generally revealed the most extreme fire behavior. Through experience and research, I have found this principle to be accurate nationally.

The alignment of forces principle and trigger points

The Campbell Prediction System (Campbell 1995) talks about '*reading a wildland fire'* by heeding the '*alignment of forces'* of wind, slope, and preheating that cause variations in fire behavior. I added RH to the list based on experience and research. When these forces align, the fire is going to be at its maximum fireline intensity. With experience, one should be able to more accurately predict the fire signature that will result and take appropriate suppression and/or evasive action (Campbell, 1995). A wildland fire 'trigger point' is a preplanned, easily recognized condition(s) indicating that the present tactics are about to become unsafe and that it is time to disengage from the fire and move to safety (Greenlee 2003).

Dry slots correspond quite well with the alignment principle as a primary causal factor and indicator of unexpected fire behavior in the fires listed below. I infuse literature that focuses on mid- to upper-atmospheric influences, dry slots, dry intrusions, and surface to near-surface drying into the discussion of each fire.

- Mann Gulch Fire of 5 August 1949; Helena National Forest (N.F.) in Montana
- Mack Lake Fire of 5 May1980; Northern Michigan, Huron N.F.
- Willis Gulch Fire of 26-27 July 1988; Boise N.F. in Idaho
- Lowman Fire of 29 July 1989; Boise N.F. in Idaho.
- Awbrey Hall Fire of 4 August 1990; near Bend in Central Oregon.
- Double Trouble State Park Fire (DTSP) of 2 June 2002; East-Central New Jersey.

- Texas and Oklahoma wildfires of 1 January 2006.
- Lower North Fork Prescribed Burn Escape on 26 March 2012; near Conifer, Colorado.

In every case, a dry slot and/or dry air intrusion advected over, or proximate to the fire area causing very low relative humidities, low dew points, and strong winds, to align resulting in unusual, often extreme, and/or erratic fire behavior and rapid fire growth. These dry slots typically coincided with atmospheric instability resulting in a Haines Index of 5 or 6 (Brotak *et al.* 1977; Saltenberger and Barker 1993; Werth and Ochoa 1993; Zimet *et al*. 2003, 2007; Prevede, 2007; Miretzky 2009; and Bass *et al*. 2012). The following wildland fire mesoscale and synoptic weather discussions are restated strictly from the individual fire case study authors in order to retain, as possible, the authors' original intent.

Mann Gulch Fire – Helena N.F. near Helena, Montana, 5 August 1949

Mesoscale and Synoptic Weather

A record-setting heat wave gripped the entire Western U.S. in early August 1949, and over the western United States, the afternoon RH pattern revealed a tongue of very dry air extending from the Great Basin into the Northern Rockies (Figs. 2 and 3); surface RH ranged from 10%-20% within this area when the Mann Gulch blowup overran and killed thirteen firefighters, twelve of them smokejumpers. The weather pattern at the fire site was dominated by: 1) an upper level high pressure ridge, 2) a surface heat low (thermal trough) and, 3) very dry near-surface air (Werth 2007). In Helena, approximately 32km (20mi) north, the temperature was in the 30's C (90's F), the RH dropped from a morning high of 40% to a mid-day 24%, the winds were 2-3ms^{-1} (5-8mih^{-1}) in the morning and increased to 7ms^{-1} (15mih^{-1}) by mid-day; conditions likely similar to those at the lightning-caused fire site (although Fig 2 suggests the RH was about 10% higher at Helena). Helena also reported 13+ ms^{-1} (30+ mih^{-1}) winds in the afternoon, as well as downdrafts[6] calculated at 18-22 ms^{-1} (40 – 50 mih^{-1} (Rothermel 1993; Werth 2007; Alexander, Ackerman, and Baxter 2009). Werth confidently concluded that the Mann Gulch Fire weather was a classic case of the 'Breakdown of the Upper Ridge' (Werth 2007).

[6] There is credible evidence these downdrafts arose from thunderstorms in the area even though not officially addressed in the final investigative report, Board of Inquiry (Rothermel 1993; Werth 2007; Wildland Fire Lessons Learned Center 2013).

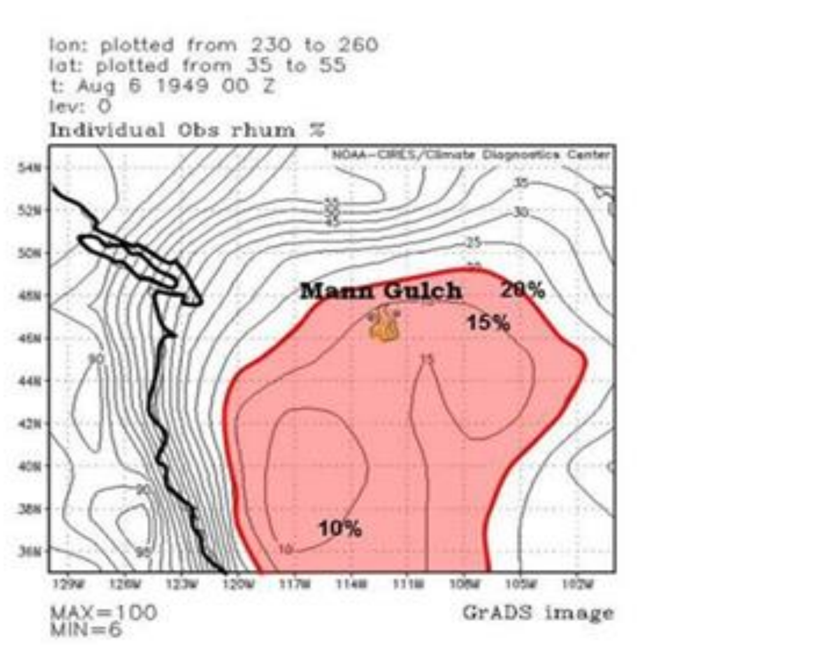

Fig. 2. (Afternoon RH map 6 August 1949) indicating very low RH at the Mann Gulch Fire site (from Werth 2007).

The fire was estimated at about 20-24ha (50-60ac) in size upon initial attack at 1600 MDT. Fire behavior increased with single tree and group torching, spot-fires, and intense fire whirls overrunning and killing the firefighters as they attempted to flee (Werth 2007) as the fire intensely burned 1,200 ha (3,000 ac) of grass and open timber within a bowl in ten minutes!

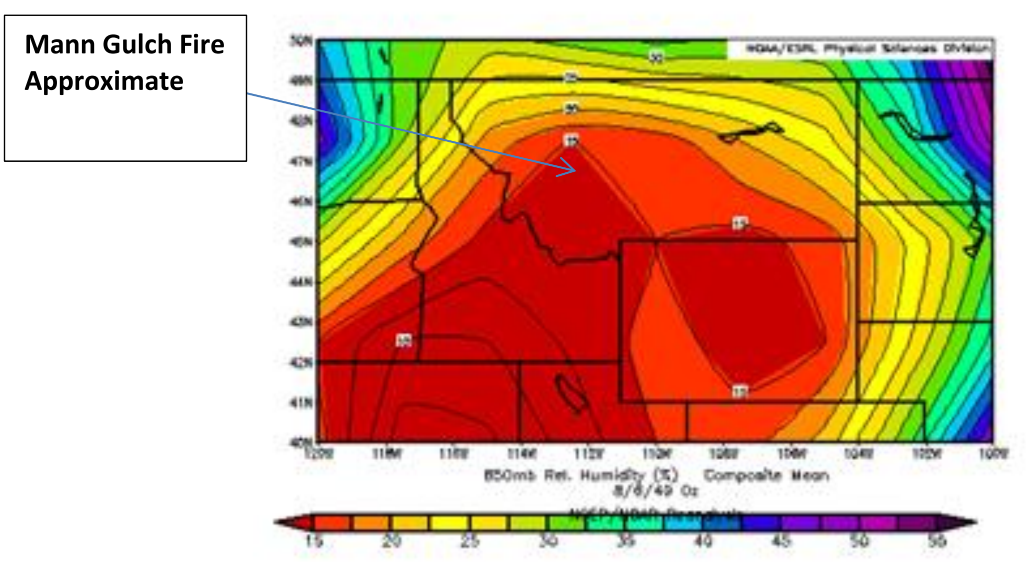

Fig. 3. NCEP/NCAR Reanalysis profile indicating the 850 mb RH at 0Z (1800 MDT) for 6 August 1949 – showing the *tongue of very dry air* mentioned by Werth (2007). The Mann Gulch Fire is located approximately at latitude 47° N, longitude 112° W indicated by arrow.

Mack Lake Fire, 5 May 1980, Huron N.F.

The Mack Lake Fire was the result of an escaped prescribed (RX) burn on the Huron N.F near Mio, Michigan in the northeast portion of the lower peninsula of Michigan. The U.S. Forest Service intended to burn only 11ha (27ac) that day to prepare for replanting Jack Pine in the area, part of a wildlife project for the Kirtland's Warbler, an endangered bird (Simard *et al.* 1983). Even though rated as a 'Very High' fire danger day, forest personnel ignited the RX burn at 1030 EDT on 5 May 1980.[7] By 1215 EDT, the fire had spotted across State Highway 33 and was declared a wildfire. During the first three and one-half hours, the fire advanced 12km (7.5mi) within six hours, killed an Agency tractor plow operator, destroyed 44 homes and buildings and burned 8,093ha (20,000) acres (Simard *et al*. 1983).

Unusually intense fire behavior

There was distinct evidence of very intense fire behavior in the form of Horizontal Roll Vortices (HRV's) after the fire passed through various timbered areas when 'crown streets' of unburned trees were left behind as evidence of this phenomenon. HRV's occur from very intense burning in moderate terrain under light winds. They often begin as a vertical fire whirl, bifurcate, and bend over horizontally and 'roll' paralleling the fire perimeter, both inside and outside the firelines and therefore pose a very real hazard to firefighters (Simard *et al*. 1983; Haines *1988b*; Haines and Lyon 1990; Werth *et al*. 2011).

Mesoscale and synoptic weather

On May 5th, the 1300 EDT RH over Mio dropped to its lowest point (19%) and the 500-millibar chart displayed a high pressure ridge over the Northern Rockies. A closed low enveloped eastern Canada with divergent centers over Newfoundland and Hudson Bay (not shown). It was during this time of lowest humidities, highest temperatures, and highest wind speeds that the Mack Lake Fire made its significant run (Simard, *et al*. 1983). This is also fairly well documented in a case study of several Alberta, Canada wildfires that occurred at the same time (Alexander et al (1983) and under the same weather conditions influencing their intense fire behavior and large fire growths.

The Mack Lake fire was influenced by a developing upper-level front deep within a shortwave trough in the fire area. Subsidence, in the form of a fully developed dry air intrusion,

[7] One just has to wonder why the Prescribed Fire Managers ignored both the weather forecast and the 'very high' fire danger and lit the fire anyway.

injected dry air from the middle and upper-troposphere downward along sloping isentropes adiabatically warming and further drying it along its path (Zimet *et al*. 2007). The organized subsidence was also the mechanism for downwind advection of high momentum air from within the frontal zone downward into the fire environment. The authors concluded that upper-frontal processes, characteristic of northwesterly synoptic-scale flow, were most likely a causal factor in the May 5th wildfire spread under such synoptic-scale conditions (Zimet *et al*. 2007) In Fig. 4, a dry slot is inferred down through the middle of the RH contours and this also would very likely have shown up as a dry slot on WVI.[8]

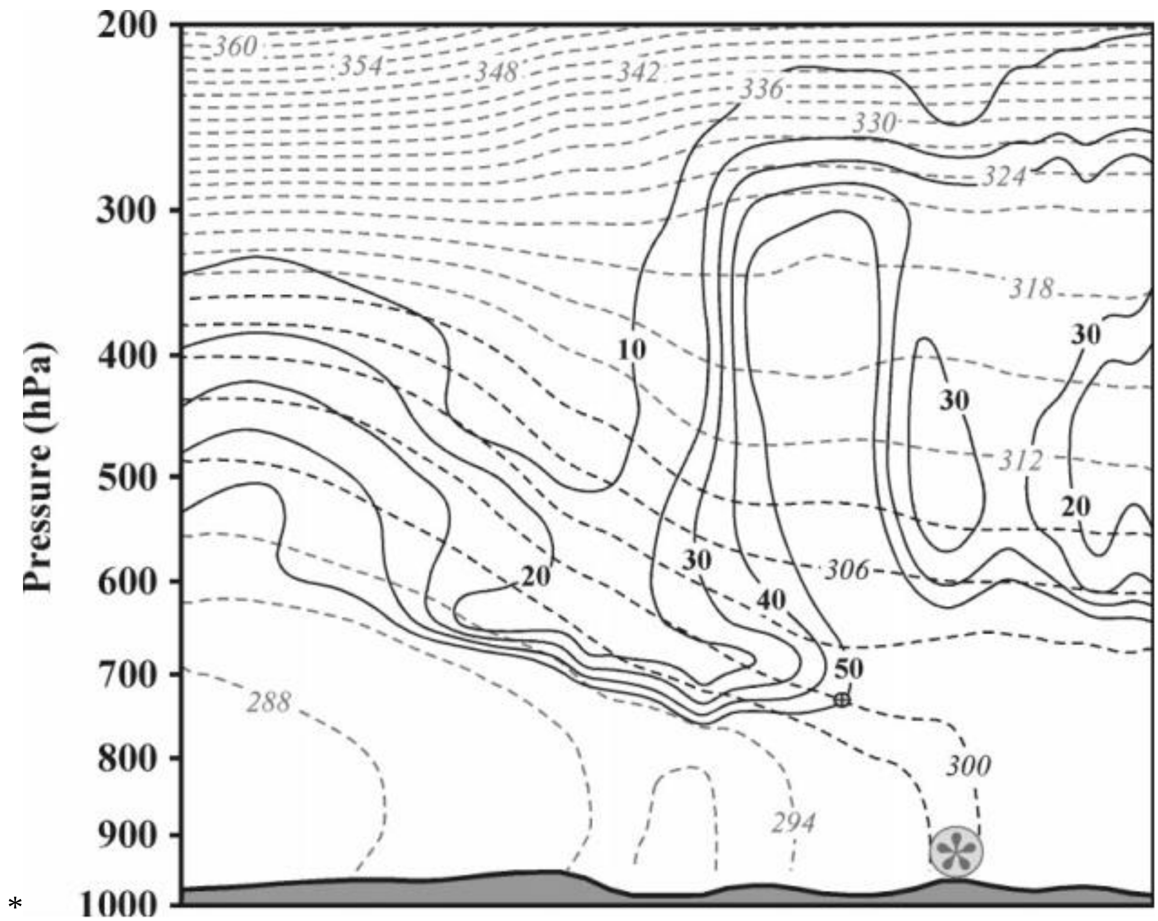

Fig. 4. Vertical cross-section of Mack Lake Fire relative humidity valid at 18Z (1400 EDT), 5 May 1980. RH (solid black lines) labeled in percent and contoured every 10% between 10% and 50%. Small gray circle with a + represents the location of the 750 mb air parcel mentioned later in the text. The asterisk within the circle indicates the approximate location of the Mack Lake Fire (from Zimet *et al*. 2007.

[8] Unfortunately, only infrared and visible satellite imagery were available in the NOAA, GIBBS archive for 5 May 1980. Moreover, the angle and quality of the infrared image were too poor to render a good image for publication.

Willis Gulch Fire, Boise NF – 26 July 1988 - Boise NF, Idaho

This human-caused fire started on the Boise N. F. in west-central Idaho about 21Z (1500 MDT) spreading rapidly up Willis Gulch and into the mountains south of the south fork of the Payette River. Idaho was experiencing drought conditions during the 1987-1988 fire seasons with rainfall and snowpack levels well below normal (Werth and Ochoa 1993). Temperatures during the Willis Gulch Fire ranged from 35°C to 39°C (95ºF to 102ºF). The RH was very low, ranging from10% to 15% with a corresponding Haines Index of 5 (Werth and Ochoa 1993).

Mesoscale and synoptic weather

The Willis Gulch Fire was influenced by: 1) a closed high centered in the Four Corners area where Arizona, New Mexico, Utah and Colorado meet, 2) a weak trough at 500-mb near the Nevada-California border, as well as a circulation center near Reno, 3) a thermal trough at the surface extending from central California into western Oregon and eastern Washington and, 4) a weak cold front near the northwest tip of Washington associated with development taking place in the Gulf of Alaska. The airmass over the fire was very dry and unstable below 500-mb. The high temperature at Lowman, Idaho was 39°C (102°F) with a minimum RH of 14%. Surface winds were light from the southwest at 2-3ms^{-1} (4-7 mih^{-1}) (Werth and Ochoa 1993). The Willis Gulch Fire had its most intense fire runs when several factors aligned. On July 26, 1988, the fire experienced high temperatures, low humidities, extended drought, high Haines Index, and a dry slot advecting through Idaho and the fire area hours prior to the intense fire behavior (Werth and Ochoa 1993). The alignment of the high values on the Werth and Ochoa Haines Index map and the WVI dry slot for both the 1988 Willis Gulch Fire and the 1989 Lowman Fire virtually match - almost to the day (not shown).

Lowman Fire - Boise N.F., 29 July 1989 - Boise NF, Idaho

Mesoscale and synoptic weather

The July 29th weather at the lightning-ignited Lowman Fire site was hot and dry throughout the day. Maximum temperatures ranged from 32°C to 35°C (90°F to 95°F), and a minimum RH of 8%. The inversion that kept the fire quiet finally broke at approximately 1100 LST, and this caused the air to rapidly warm and dry, which radically increased fire behavior (Werth and Ochoa 1990). The Haines Index was 6 throughout Idaho. The satellite WVI indicated a dry intrusion that extended from southern California, through Nevada, and into Idaho and Montana over the Lowman Fire area at 15Z (0900 MDT) (See Fig. 7 in Werth and Ochoa 1990). The fire experienced a blow-up described as a 'fire storm'[9] on July 29th with the fire moving at 1.5kmh^{-1} (.93 mih^{-1}) (Werth and Ochoa 1993).

At the time of intense fire behavior on the Lowman Fire, on site weather was dominated by: (1) a low pressure 'thermal trough' in the valleys of California, (2) a Pacific Northwest coast upper-low moving into the area, (3) the thermal trough shifting eastward across Idaho and Nevada, (4) in response, an area of surface low pressure moving into the Oregon-Washington border area, (5) the northern range of the thermal trough 'linking up' with the warm front accompanied by the surface low that also approached the area and, (6) the Intermountain region low pressure area which had thermal trough characteristics, with the warmest temperatures in the trough's center and the highest thickness values directly over the fire area (Werth and Ochoa 1990). On 29 July 1999, the fire experienced erratic fire behavior due to high temperatures, low RH, Haines Index of 6, persistent drought, and coincident alignment of a dry air intrusion as the causal factors. Moreover, the high Haines Index value aligns with the dry slot in the WVI (Werth and Ochoa 1993) (See Figs. 6 and 7 in Werth and Ochoa 1990).

Awbrey Hall Fire, Central Oregon near Bend – 4 August 1990

Mesoscale and synoptic weather

At the time of the Awbrey Hall Fire, the weather pattern at the fire site was dominated by: (1) an intense long-wave ridge over western North America, (2) an upper ridge axis over central Oregon (not shown), (3) subsidence high pressure at the surface from east of the Cascades, and (4) a weak surface thermal trough to the west (Saltenberger and Barker 1993). RAWS observations taken near Bend the afternoon of August 4th reported a temperature of 35°C (95ºF) and a RH of 15%. Northerly afternoon surface winds at this site remained less than 4ms^{-1} (8 mih^{-1} during the night of August 4th and 5th (Saltenberger and Barker 1993). The authors also stated that nearly every upper air station in the region reported extremely low humidity aloft (Fig. 5).

[9] Violent convection caused by a large, continuous area of intense fire characterized by destructively violent surface indrafts, near and beyond the fire perimeter, and sometimes by tornado-like firewhirls (NWCG 2012).

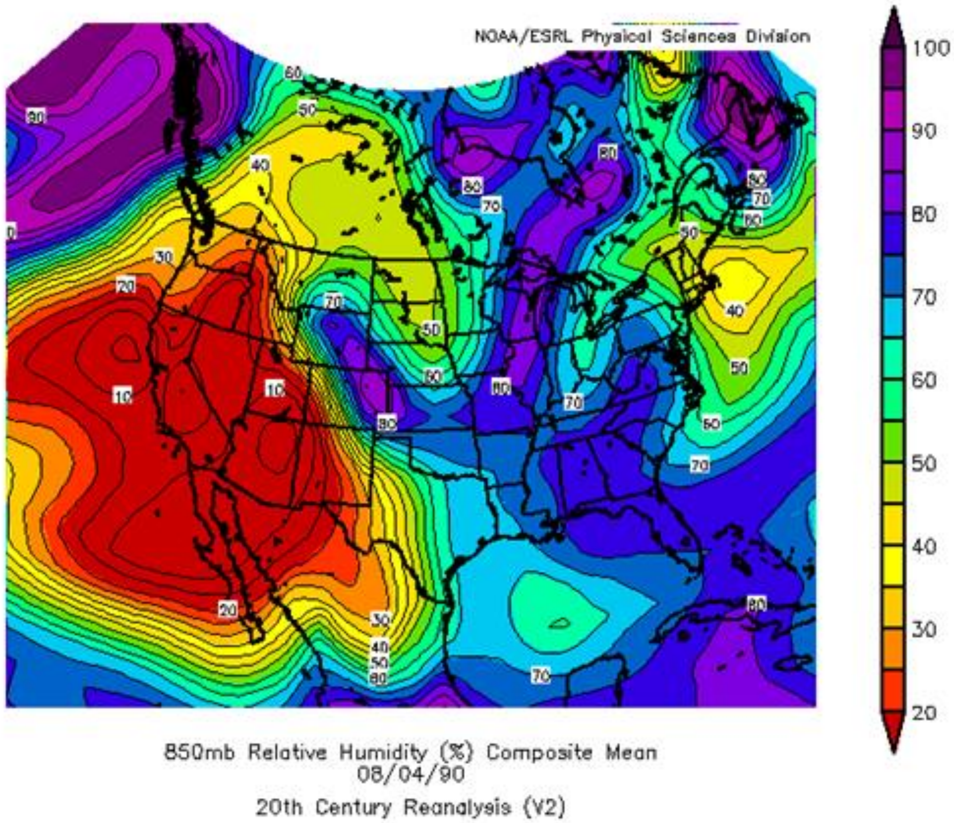

Fig. 5. 20th Century Reanalysis image for 4 August 1990 indicating low 850 mb relative humidity in the Awbrey Hall Fire area of central Oregon; NOAA/ESRL 20th Century Reanalysis (2013).

The authors displayed a GOES WVI that revealed a dry intrusion throughout the West and the Awbrey Hall fire area on 5 August 1990 at 0301Z (2001 PDT) (See Fig. 6 in Saltenberger and Barker 1993). This dry intrusion referred to can be inferred in Fig. 5 throughout the very low RH area in the West and into the Pacific Northwest and the fire area. The authors also noted a fast-moving high-level shortwave impulse pushing northeast along the Oregon coast at 45 kn (50 mih^{-1}) during the evening of 4 August affecting the fire weather. According to Weldon and Holmes (1991) darkening in the dry slot behind the shortwave implies increasing subsidence behind it (See Fig. 5 Saltenberger and Barker 1993)

It is noteworthy that the Awbrey Hall Fire exhibited very unusual, extreme fire behavior resulting in plume domination[10], with equally unusual peak fire intensity between 2100-2400 PDT (Saltenberger and Barker 1993). Overall, Oregon was enduring atmospheric instability with a Haines of 5 and 6 (not shown). The WVI indicated a dry slot 3-6 hours after erratic and unusual fire behavior (See Fig. 6 Saltenberger and Barker 1993). The authors' conclusion was that erratic

[10] Plume domination is when the power of the fire is greater than the power of the wind (Byram 1959). This is mostly a daytime occurrence and hence it is very unusual for this to occur at night.

and unusual fire behavior was due to very low RH, high nighttime temperatures, strong winds, and a moderate to high Haines Index, all in alignment as a dry intrusion (in the signature of a large dry slot) passed over fire area.

Double Trouble Fire, 2 June 2002 – Double Trouble State Park (DTSP), NJ

Mesoscale and synoptic weather

This human-caused wildland fire began 2 June 2002 under moderate drought conditions and had some reasonably complicated weather influences.[11] At the time of the DTSP Fire the weather pattern at the fire site was dominated by: (1) deep upper tropospheric subsidence under the right exit region of a jet streak drying out the atmospheric column, (2) mid-level sinking behind a second lower-level and accelerating jet streak entrance region further transporting dry air toward the surface and (3) the development of a convective boundary layer, (4) rightward directed ageostrophic flow directed towards eastern Pennsylvania (PA) and northern New Jersey (NJ) at 15Z (1100 EDT) (not shown), (5) Directly under the right exit region is a second jet streak at ~850 – 750 hPa whose entrance region is parallel to the leading edge of a mid-level warm pool just to the southwest (not shown) and is crossing eastern PA under the right exit region of the mid-level jet (not shown), (6) This elevated warm band has been transported eastward from the western High Plains over the previous 24- 36 hour period (not shown). Therefore, the likely inferences are that a cluster of circulations are delivering a favorable atmosphere for intense fire weather over central NJ as depicted in Fig. 6 (Charney and Keyser 2010). The Palmer Drought Severity Index for the week prior to the fire indicated a severe long-term drought in central and southern NJ. The local Forestry officials reported anomalous freezing temperatures also, thus ‘freeze-drying’ any moisture from the live and dead fuels, a process known as sublimation (Charney and Keyser 2010).

[11] See also Kaplan et al. (2008) and Charney and Keyser (2010) link below for further detailed explanations and images and the respective authors’ complex fire weather research papers on the DTSP Wildfire.

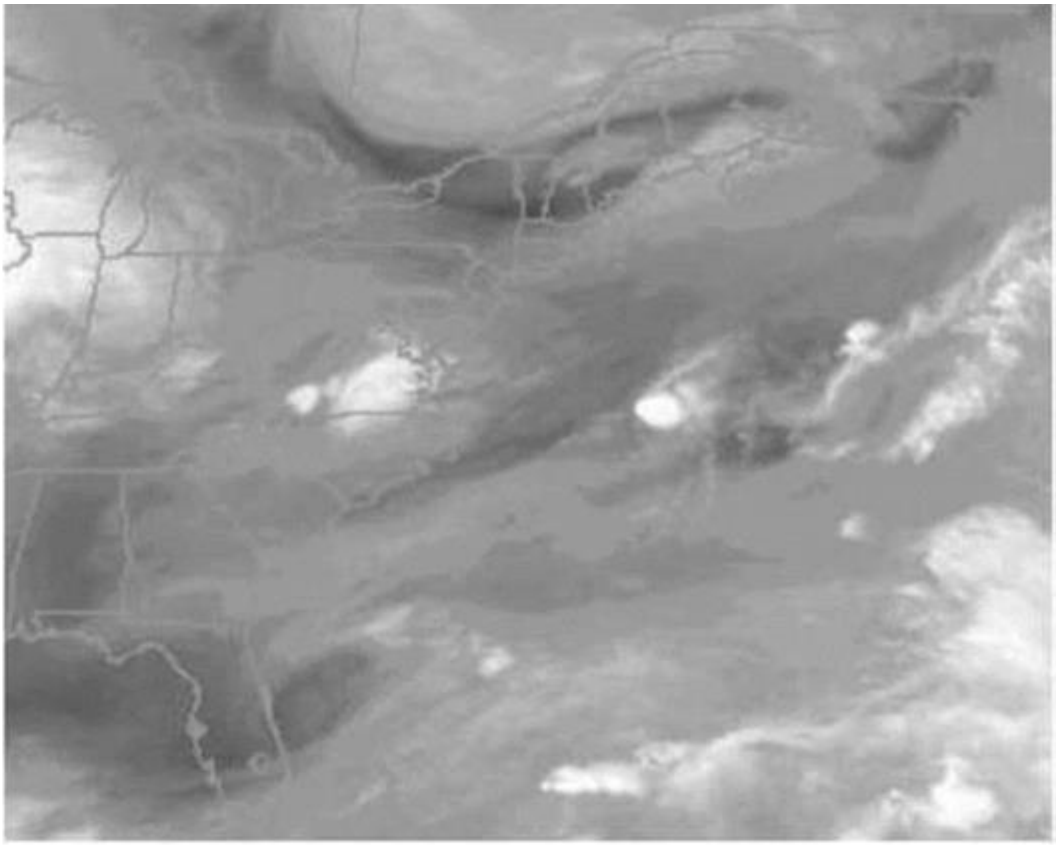

Fig. 6. GOES WVI valid at 1215Z (0800 EDT), 2 June 2002 with a dark dry slot approaching the DTSP fire area, Courtesy Charney and Keyser (2010).

During the late morning and early afternoon hours of 2 June, the DTSP weather observations indicated a precipitous surface RH decrease together with a wind speed increase in the wildfire vicinity. The surface drying and wind speed increase were theorized to be the result of descending dry, high-momentum air of middle troposphere origin occurring coincidence with a deepening mixed layer (Charney and Keyser 2010). The authors dealt with this premise and used a high-resolution mesoscale model simulation (MM5[12]) to document the structure and development of the PBL and lower-tropospheric features coupled with the entrance of surfaced dry, high-momentum air coincident with the sudden and dramatic wildfire growth (Charney and Keyser 2010).

[12] PSU and NCAR mesoscale model designed to simulate or predict mesoscale atmospheric circulation

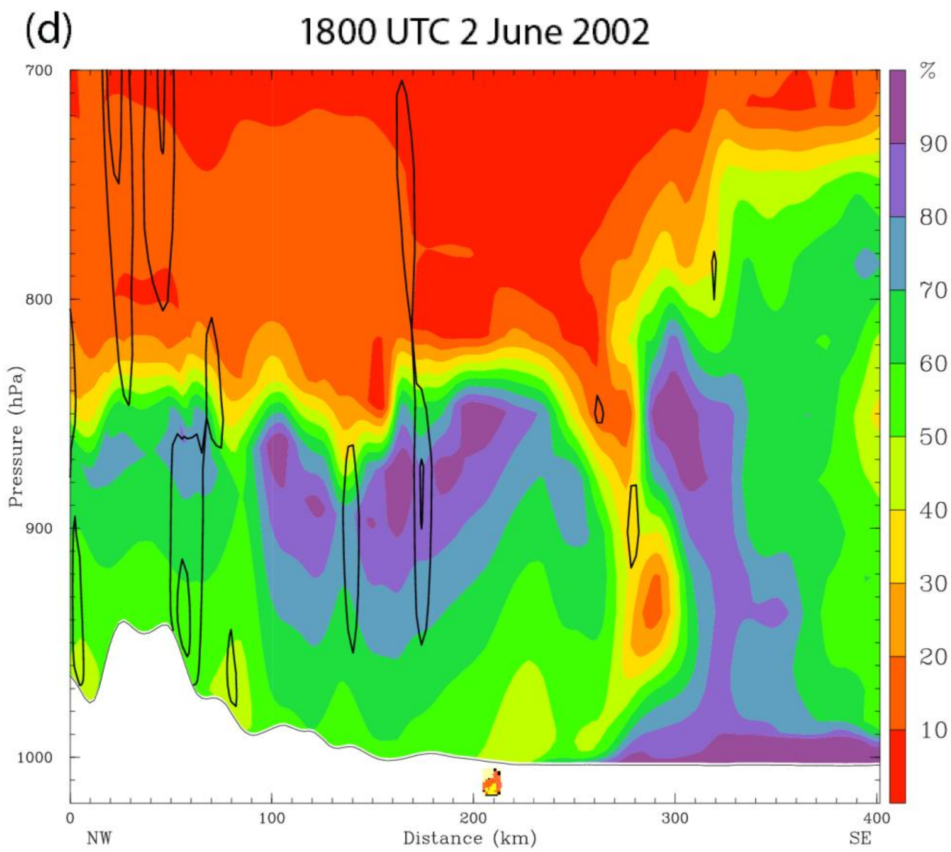

Fig.7. 2 June 2002 18Z (1400 EDT) north-west–south-east-oriented vertical cross-section passing through the DTSP fire location of simulated relative humidity and pressure-coordinate vertical velocity Courtesy of Charney and Keyser 2010.

For a comprehensive account of the complex DTSP wildfire mesoscale and synoptic weather events and images see Kaplan, *et al.* (2008) and Charney and Keyser (2010).

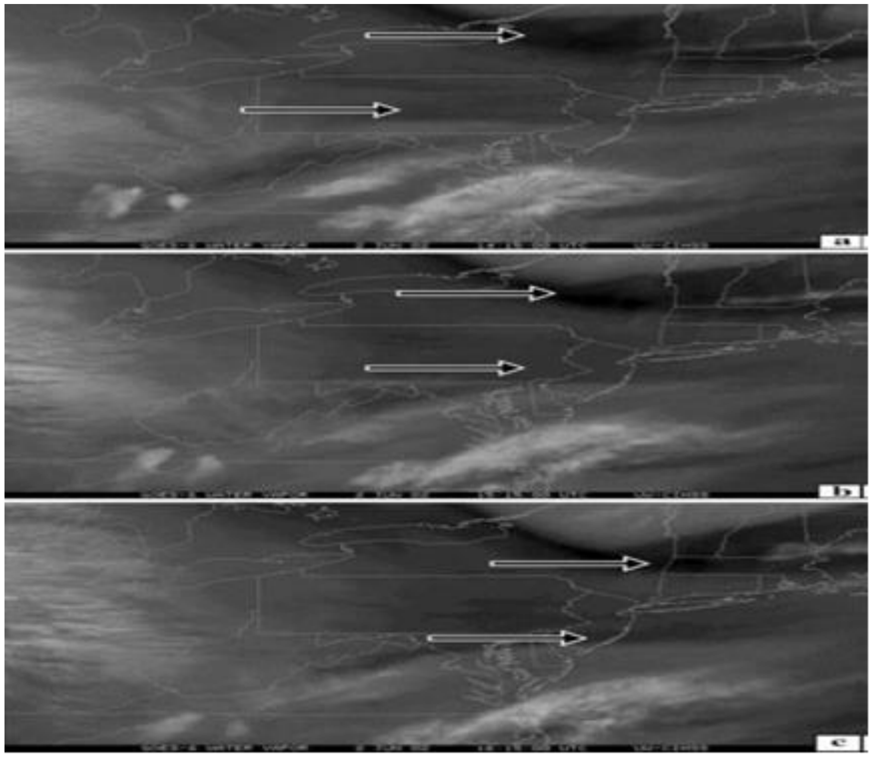

Fig. 8. GOES satellite WVI valid at (a) 1415Z (1015 EDT), (b) 1515Z (1115 EDT), and (c) 1615Z (1215 EDT), 2 June 2002. The arrows indicate the changing location of the dry tongues (Courtesy of Kaplan et al. 2008).

Charney and Keyser (2010) suggested that this fire weather was the result of a dry slot phenomenon. WVI for 1215 UTC (0800 EDT) 2 June 2002 (Fig. 6) and 0015 UTC (2000 EDT) 3 June 2002 (not shown) delineated a '*ribbon of dry air*' that advanced south-eastward during that period of time (emphasis added). And the '*ribbon of dry air'* coincided closely with the jet streak axis at 1200 UTC (0800 EDT) (Fig. 6) 2 June 2002 and 0000 UTC (2000) 3 June 2002 (emphasis added). Furthermore, WVI suggested that dry air in the middle-to-upper troposphere moved over southern New England during the previous days and set the stage for the DTSP wildfire By 18 UTC (1400 EDT), the surface RH was at its lowest, the PBL depth at its maximum value, and the winds continued to increase into the night. This adverse fire weather caused the fire to escape containment lines and the DTSP wildfire was declared a 'major fire.'

On 2 June 2002, at 1915Z (1515 EDT) the temperature was 24°C (75ºF), and the RH 62%. At 21Z (1700 EDT) the temperature rose 11°C (20°F). By 1800 EDT (22Z) the RH fell sharply to less than 10% - An anomalously sheer drop of over 50% in 4 hours. From 21Z (1700 EDT) to 02Z (2200 EDT), the temperature stayed unusually high at around 26°C (80ºF). The winds shifted from the northwest to west-northwest, strengthening and gusting (Kaplan *et al*. 2008).

Therefore, the signature that the authors refer to as a '*ribbon of dry ai*r' is a dry slot - clearly visible on GOES satellite WVI that coincided and aligned with rapidly lowered RH values and strong winds on the surface, which appeared about 1600 and lasted throughout the fire's maximum intensities (Charney and Keyser 2010).

Texas and Oklahoma Wildfires, January 1, 2006

Mesoscale and synoptic weather

At the time of the human-caused TX and OK wildfires, the weather pattern at the fire sites was dominated by: (1) surface pressure gradients tightening over the Southern Plains as cyclogenesis originated along a surface front over southeast Colorado and southwest Kansas helping to accentuate a dryline across central Oklahoma and Texas (Fig. 9), (2) strong westerly winds, (3) a very dry boundary layer over the region, (not shown), (4) and the breakdown of a weak inversion, which allowed for regional deep mixing of the boundary layer (Lindley at al. *2006b*).

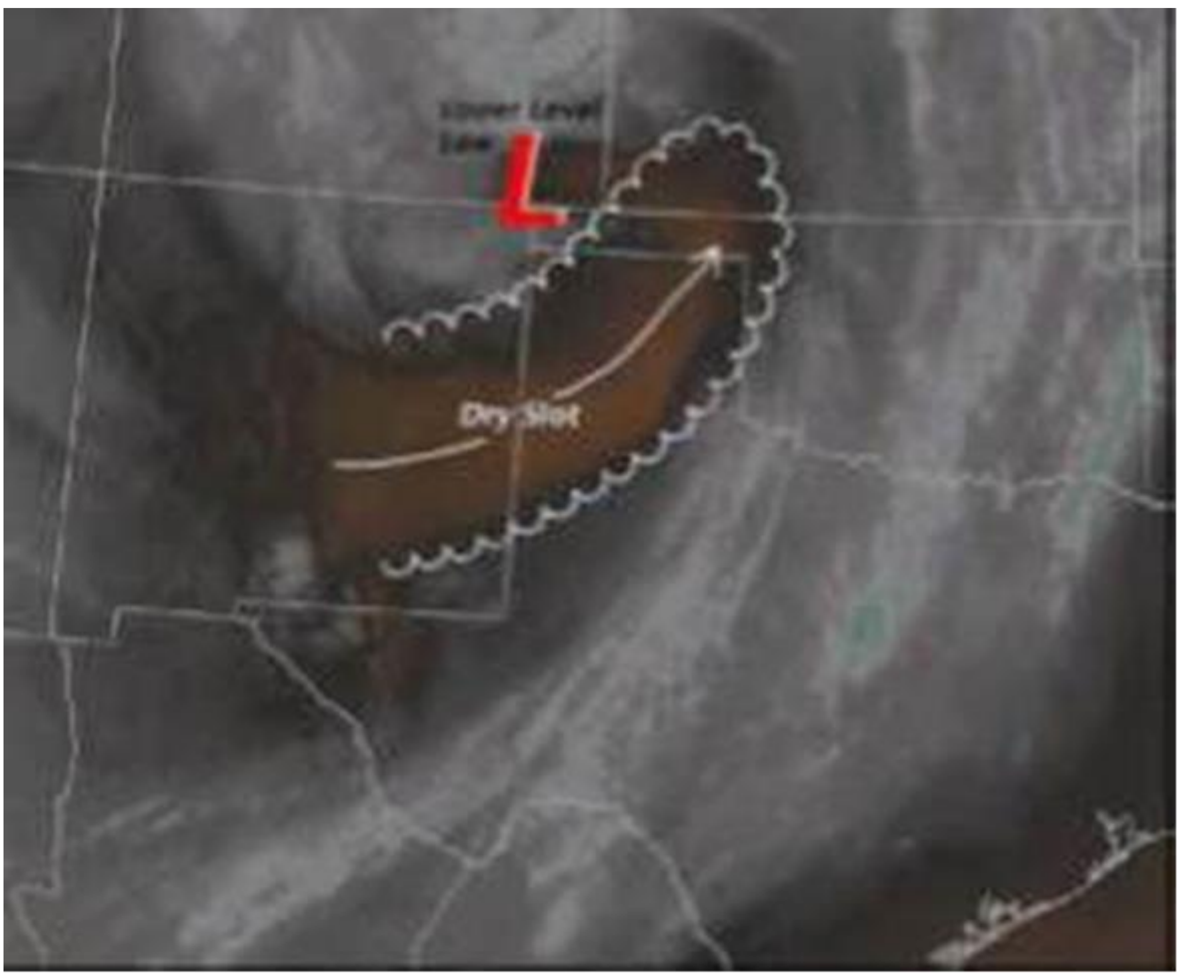

Fig.9. GOES-East water vapor channel satellite WVI from approximately 16Z (1100 CDT), 1 January 2006 revealing a midlevel cyclone centered over far southeast Colorado with a pronounced dry slot across eastern New Mexico into the Texas and Oklahoma Panhandles. Courtesy of Lindley *et al. 2006b*.

Mesoscale weather included low surface dewpoint depressions from (10°C (18°F)) to23°C (40°F) over west Texas (not shown), 65 to 75kn (74 to 86mih^{-1}) () mid-level winds upstream at El Paso, Texas and Albuquerque, New Mexico, respectively at the 500 hPa level (not shown). By late morning, 20kn (23mih^{-1}) westerly surface winds had strengthened the downslope trajectories over the higher terrain, which allowed surface temperatures to warm rapidly, and eventually reach record-breaking levels. This very dry air and the strong winds aloft were readily mixed to the surface, which greatly enhanced the fire weather hazard. According to several NOAA/NWS meteorologists, very poor weather forecast modeling resulting in drastically and unfortunately grossly overestimated near-surface moisture and underestimated low-level wind speeds' that resulted in wildland fire agencies and personnel receiving poor fire weather information to base tactics and strategy on. In fact, one forecast completely missed an approaching cold front that had a dangerous wind shift (Lindley *et al.* 2006*a*; Lindley *et al. 2006b*). All this contributed to radically increased fire behavior on several wildfires with varying consequences (Lindley *et al*.2006). On 1 January 2006, there were a total of 143 fires that burned 122,850ha (303,570ac) and damaged or destroyed 115 structures (TFS 2007); two communities were virtually wiped out (Lindley *et al*. (2006*b*).

In conclusion, a dynamic dry slot passed over eastern New Mexico and northwest Texas resulting in very low RH's and dew points, critically low fuel moistures, and strong, gusty winds that aligned regularly, which produced very erratic fire behavior throughout this particular fire event (Fig. 9).

Lower North Fork Prescribed (RX) Fire Escape, Colorado State Forestry, near Conifer, CO on 26 March 2012

This tragic fire occurred near Conifer, Colorado, and was the result of the Lower North Fork prescribed (RX) burn days earlier on 22 March 2012. The entire project was only 20ha (50ac). From 23-26 March 2012, the CO State Forestry resources were mopping up, patrolling, and securing the RX burn[13].

On 23 March 2012, the West was dominated by a ridge of high pressure from New Mexico, northward into Colorado, eastern Wyoming and the Black Hills of South Dakota, as a new trough of low pressure began to take shape off the Pacific Northwest Coast (See Fig. 12 Bass *et al*. 2012). This shift in the pattern resulted in a significant air mass change across Colorado. Temperatures increased 9 to 12°C (15 to 20°F) with Denver, CO setting an all-time March high of 24°C (76°F). Local RAWS within 8-21km (5-13mi) of the fire site indicated a steady decrease in RH with single digit values by 1400 MDT (not shown) Bass *et al*. (2012).

From 24-25 March 2012 the upper ridge that extended across Colorado on the 23rd had shifted into The Plains as an upper trough and associated surface front migrated east into California and Nevada by the end of the 25th (Fig. 13 in Bass *et al*. 2012).The RH dropped into the single digits on the afternoons of the 24th and 25th. The manually-calculated Haines 5-6,

[13] A key aggravating causal factor was the deep, smouldering mechanically-treated, (masticated) fuel bed.

indicated an unstable air mass. On March 26th the upper ridge shifted east into the High Plains as an upper air trough and associated cold front migrated into Utah early in the day.

As most operational fire weather forecasters know, this was the classic '*Break Down of the Upper Ridge*' recognized as a critical fire weather pattern. This produced strong, gusty winds, warm temperatures, low RH's, enhanced vertical lift, i.e. Haines 6, and an ultimate increase in fire behavior. The nearest RAWS from midnight to 0800 MDT, indicated critical high nighttime temperatures (9 to 10°C) (48 to 50°F), poor RH recovery (23% to 28%), south-southwest winds from 3 to 5 ms^{-1} (8 to 11 mi/h^{-1}), with gusts from 9 to 11ms^{-1} (20 to 24 mi/h).

Once the forecasted Red Flag conditions manifested themselves during the afternoon of the 26th, RX/fire personnel patrolling and securing the burn experienced massive '*surface-borne ember [showers] in strong winds near the ground surface that spotted a few feet downwind, ignited new spot [fires], which then repeated the process in a 'leapfrog' fashion*.' On the 26th at 1645 MDT, satellite visible imagery detected a noticeable smoke column from the RX project area and a very conspicuous smoke column by 1732 MDT (Fig. 24 Bass *et al*. 2012) which indicated an obvious fire behavior increase.

On March 26th, there was a clearly visible dry slot in the WVI (Fig. 10) and fire weather forecasts noticeably called for very high winds and exceptionally low RH's (Bass *et al*. 2012). The RX Burn module had a total of three spot fires due to extremely low RH and very strong winds (Red Flag) beginning about 1315 MDT. They could only suppress two of the three spot fires. The third spot fire "*exceeded the capacity for control by ground forces resulting in an escape and subsequent conversion to a wildfire at 1430"* (emphasis added) (Bass *et al*. 2012). See the Lower North Fork Prescribed Fire – Prescribed Fire Review for complete mesoscale and synoptic weather and fire behavior details which can be accessed at http://dnr.state.co.us/SiteCollectionDocuments/Review.pdf

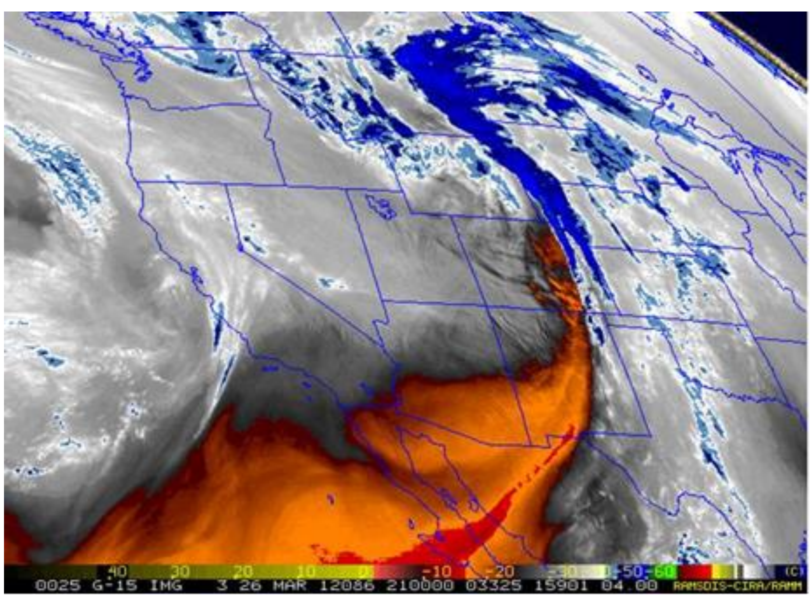

Fig. 10. A 6-KM WVI at 21Z (0900 MDT) on Monday, 26 March 2012 just west of the Lower North Fork RX burn unit. Mid-level dry air indicated by dark and orange enhancement Courtesy of CO State University Cooperative Institute for Research in the Atmosphere (CIRA).

Australian dry slot theory becomes a reality

Now I will briefly discuss Australian dry slot forecasting, since they ostensibly are the ones that came up with the idea for utilizing it in their wildland (bush) fire weather forecasting. The genesis of Bureau of Meteorology (BoM) dry slot theory emerged as Dr. Graham Mills studied two mid-tropospheric drying events during Australia's catastrophic 2003 bush fires (Fig. 11) along with a number of water vapor drying events from four weather stations over four years (Mills 2005*a*). Mills utilized the seminal works of American researchers Werth and Ochoa (1993), Charney *et al*. (2003), Zimet *et al*. (2003), and Zimet *et al*. (2007) who examined surface drying and enhanced fire activity from mid-tropospheric induced low relative humidity associated with the 1988 Willis Gulch wildfire and the 1989 Lowman wildfire in Idaho, the 2002 New Jersey DTSP wildfire, and the 1980 Mack Lake Fire respectively. Mills (2005b) hypothesized that the Australian 2003 Canberra and 2005 Eyre Peninsula bush fires were subject to abrupt surface drying and strong, gusty winds. He later observed satellite WVI and noted that dark bands or dry slots coincided with decreased humidities and dew points, trough/dry cold frontal passages, and gusty winds (drying events) as they passed over the bushfire areas. And from this his 'dry slot theory' was developed. Mills (2006) cautioned that when there is a going fire, '*the dry slot is potentially one of the triggers to set the fire going uncontrollably. Suddenly, the fuel is drying out more quickly, the wind is stronger and gustier, and the fire can take off expl*osively' (emphasis added).

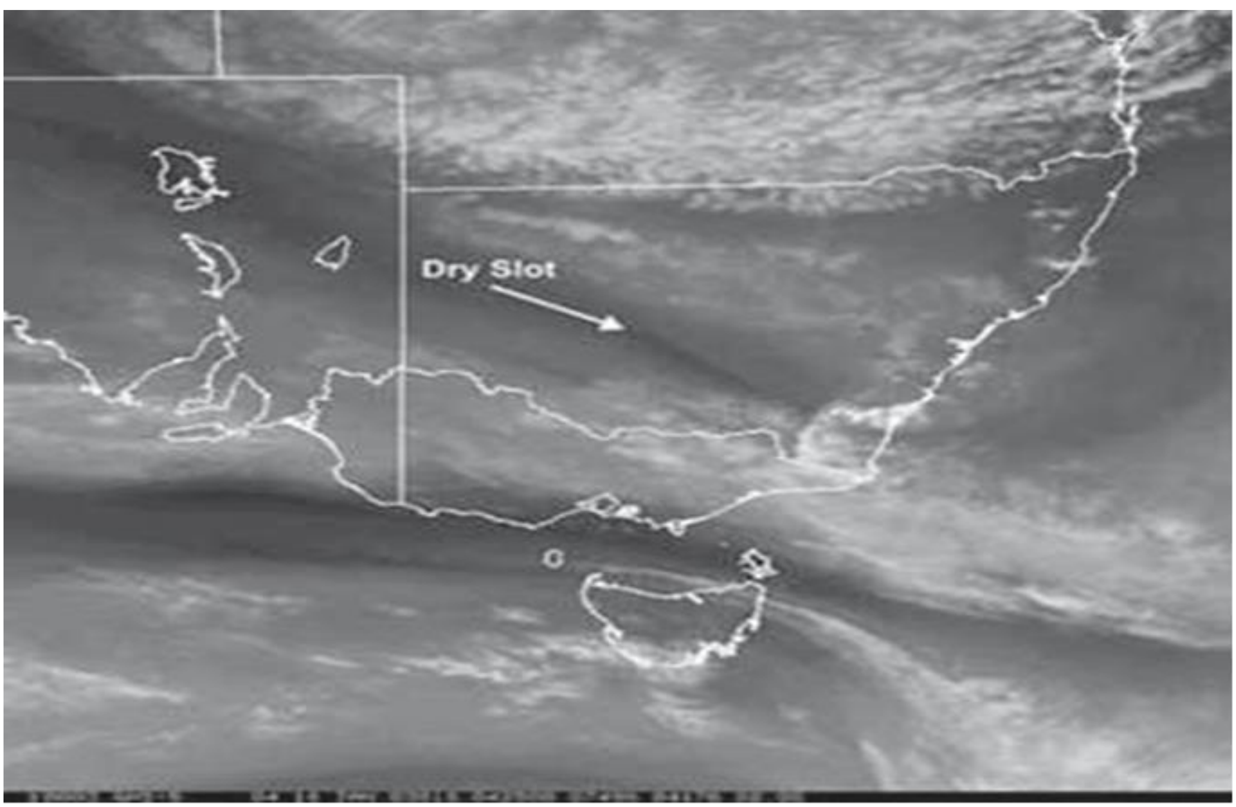

Fig. 11. Dry slot extending across New South Wales. WVI -18 January 2003 at 18Z (1400 EST) Courtesy of Japan Meteorological Agency and Australia BoM.

Mills (2006) stated that one has several hours of warning if one can see a dry slot moving toward an ongoing fire. Fire agencies can then be given a warning that the fire behavior may soon become more explosive. The dry air aloft has long been the bane of experienced fire managers, but little was understood about its behavior and where it originated. They didn't really know where the dry air aloft was except that it was '*up there somewhere*' (Mills 2006); now they know exactly where the dry air comes from and what sort of explosive impact it can have on a bushfire. There is an expectation that fire weather forecasters will monitor WVI for dry slots of various forms (Mills 2005*b*). But there is also an obligation on fire managers to seek such information, or at least notify the BoM of on-going fire activity, even if they are not of sufficient intensity to require special fire weather forecasts (Mills 2005*b*). The Australians also advise that skill and care are needed when interpreting water vapor images and only qualified staff should be using them.

Common meteorological, climatological, and physiological mechanisms and traits regarding all the examined wildfires

The fires reviewed and examined above had many, if not most, of these factors in common:

(1) Record and/or near record warm to high temperatures preceding the fire events,
(2) Springtime fires had early depletion of snowpack and/or early snowmelt,
(3) Air mass changes, e.g. Breakdown of the Upper Ridge,
(4) Satellite WVI revealed dry slots and/or dry intrusions prior to, during, and even after drying events, strong winds, and extreme fire behavior and/or large fire growth,
(5) Rapidly changing weather factors, e.g. high temperatures, low to anomalously low RH's,
(6) Subsidence,
(7) Decreased cloud cover which led to strong vertical mixing between the surface air masses and aloft, which allowed for stronger winds to surface,
(8) Troughs, including Thermal troughs, and ridges,
(9) Dry cold fronts,
(10) Pre-frontal and/or post-frontal conditions, e.g. above average temperatures, falling RH's and dew points, strong and gusty winds, unstable atmosphere, i.e. high Haines Index, and poor overnight RH recovery,
(11) Alignment of Forces, e.g. wind, slope, RH, and preheating,
(12) High nighttime temperatures, and
(13) Recent to prolonged drought and low soil moistures.

Future research

The definite connection between dry air aloft and dry slots influencing large wildland fire growth warrants further research. Previous work suggests there are very strong associations to high Haines Index, high potential vorticity (PV), stratospheric intrusions, subsidence, jet streaks, high ozone events, and other mechanism which warrant further research.

Summary and conclusions

This review of selected United States wildland fires clearly suggests that dry slots are in fact responsible for many fire blowups and associated rapid wildland fire growth. The effects of dry slots on fire weather can be found in the literature despite the myriad of synonyms used to describe this phenomenon.

The dry slot theory originally proposed to explain this phenomenon in Australia by Graham Mills (205a, 205b) has been shown in the literature, and more importantly in the field, to verify that dry slots are indeed responsible for dramatic abrupt near-surface decreases in dew points and RH's that enhance surface drying which in turn decreases fuel moisture and increases wind gustiness resulting blow-up fire behavior and rapid fire growth. The formation and movement of dry slots can now be tracked using WVI and fire managers given a several hour warning before they reach a going fire, or move into an area where fire danger is already extreme. Grumm *et al*. (2004) proposed using WVI to identify dry slot signatures over a region of anomalously high winds because they may be a useful short-term forecast tool in diagnosing similar wind events. WVI has proven to be a valuable tool for observing the ridge developments, particularly the role of the upstream ridge where clouds are absent (Weldon and Holmes 1991). These researchers found that WVI was very useful in comparing atmospheric behavior with weather model output thereby allowing fire weather forecasts to be confirmed, modified, or significantly changed before passed on to fire managers. I quote Forest Service researcher J. J. Charney (2007) and Charney and Keyser (2010) to underscore the point regarding atmospheric conditions aloft and utilizing new indices and diagnostics for operation wildland fire forecasting:

> '*Atmospheric conditions aloft are becoming increasingly recognized as important factors in producing more accurate fire weather and fire behavior predictions, particularly for periods of extreme and erratic fire behavior. The atmospheric structures that contribute to these conditions are, in many cases, predictable hours or even days in advance of the event. The task is to develop and implement indices and diagnostics into the operational fire weather and fire behavior forecasting that sense these conditions and communicate to the forecasters and the operational users of fire weather prediction when and where the potential exists for extreme fire behavior.' '…[research is] leading to the better understanding, improved diagnosis, and enhanced prediction of fire–atmosphere interactions. These advances provide a pathway for the formulation and design of a new generation of fire-weather indices and diagnostics capable of identifying specific locations where meteorological conditions are anticipated to be conducive to erratic fire behavior and rapid fire growth*

The utility of WVI to forecast dry slots and other dangerous fire weather phenomena has been amply shown. It is time for this tool to be routinely incorporated in fire weather forecasts – I firmly believe that it will save lives and reduce fire damage!

Acknowledgements

The author gratefully acknowledges the valuable encouragement and constructive criticism supplied by those that have most assisted in my dry slot research: Dale Wade, Research Forester (retired) for his helpful feedback, suggestions, and editing which undoubtedly improved the quality of this paper. Dr. Graham Mills, Australian BoM (retired) initially sparked my interest in the subject and guided me toward U.S. wildfires affected by dry slots. John F. Saltenberger, U.S. Fish and Wildlife Service meteorologist in the Northwest Interagency Coordination Center, Predictive Services Program in Portland, Oregon recognized the importance of dry slots and has been a stalwart advocate from the beginning. J. Brent Wachter, NOAA NWS meteorologist and Incident Meteorologist (IMET) in Albuquerque, NM has continued to educate me in the research involved in operational meteorology. Paul Werth, Weather Research and Consulting Services, LLC of Battle Ground, Washington; meteorologist and researcher has continually assisted with dry slot insight and information, data, and images from the Mann Gulch Fire and many NOAA Reanalysis searches. Nicole Petersen, meteorologist, Rutgers University who has given very valuable advice and guidance on mid- and upper-air influences.

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Turbulence and energy fluxes during prescribed fires in the New Jersey Pinelands

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Additional keywords: Eddy covariance, forest energy balance, Sensible and latent heat, fuel consumption.

Introduction

Smoke emission models require a number of assumptions regarding turbulent transfer of gasses and particulates within and above the forest canopy. Some of these assumptions as well as model predictions can be evaluated using micrometeorological measurements made during fires (Seto *et al*. 2013). However, it is important that eddy covariance measurements quantify momentum, heat, and water vapor exchange correctly, because instruments are likely operating well beyond their performance thresholds within the fire environment. One solution is to evaluate forest energy balance terms during fires, similar to the approach employed to ensure the accuracy of longer-term carbon and water flux measurements above forests. Stand energy balance can be approximated as:

$$R_{net} - G - \Delta S_{air} - \Delta S_{bio} = H + \lambda E \qquad (1)$$

Where, R_{net} = net radiation, G = soil heat flux, ΔS_{air} = heat storage in the canopy air space, ΔS_{bio} = heat storage in aboveground biomass, H = sensible heat flux, and λE = latent heat flux. Fuel combustion adds a second source of H and λE, but these terms have rarely been evaluated together during fires. We first evaluated long-term energy balance closure in three upland forest stands in the New Jersey Pinelands using eddy covariance and standard meteorological measurements (Clark *et al*. 2012). We then compared energy exchange measurements to energy release calculated from fuel consumption estimates during four operational prescribed fires conducted in the Pine Barrens of New Jersey from 2006-2012.

Study Sites

Sites were located in the Pinelands National Reserve in southern New Jersey, USA. The Pinelands is the largest continuous forested landscape on the Northeastern coastal plain, and covers ca. 23% of New Jersey. Uplands consist of oak- and pine-dominated forests that have a higher frequency of severe wildfires than most forests in the northeastern United States. Eddy flux towers were located in pitch pine (*Pinus rigida* Mill.), mixed, and oak-dominated stands. Understory vegetation consisted of scrub oaks, huckleberry (*Gaylussacia* spp.) and blueberry (*Vaccinium* spp.).

Methods

In each experiment, at least one above-canopy eddy covariance tower was operating within the burn block during the prescribed fire, and two other "control" towers were operating simultaneously in unburned stands. A complete description of the instrumentation is in Clark *et al*. (2012). Fuel consumption was quantified using pre- and post-burn sampling of the understory and forest floor in 1.0 m^2 plots located throughout each burn block (Clark *et al*. 2009, 2010). Fuel moisture was sampled throughout the day during each prescribed burn.

Results and Discussion

Pre-fire, sensible and latent heat fluxes accounted for an average of 97 ± 5% of available energy at each stand, calculated from net radiation and heat storage in the canopy air space, biomass and soil in Equation 1(Clark *et al*. 2012). During prescribed fires, instantaneous vertical windspeed and air temperature measured at 10 Hz four meters above the canopy were enhanced up to 2.4 and 11.6 times ambient conditions in control stands, respectively. 10 Hz upward vertical windspeed velocity and air temperature were positively correlated during each fire, with the correlation highest at the hottest burn at a mixed stand in 2011 ($r^2 = 0.48$, $p < 0.0001$). During the prescribed fires at the mixed and pine stands, the sum of latent and sensible heat fluxes above the canopy was 4.8 and 5 times greater than available energy. Half-hourly sensible heat flux peaked at 3128 and 1675 W m^{-2}, and water vapor flux at 443 and 483 W m^{-2}, respectively. Energy release during these fires calculated from the 'excess' H and λE flux after correction for available energy was 7,827 and 8,346 kJ m^{-2}. Instantaneous heat storage in the canopy air space was large but short in duration, and soil heat storage was relatively minor due to only partial burning of the litter layer and not the deeper organic layer of the forest floor.

Fuel consumption on the forest floor and in the understory ranged between 5.1 and 9.8 metric tons ha^{-1}, representing 44 to 53% of pre-burn loadings. Corresponding heat of combustion values calculated from fuel consumption data and measured fuel moisture contents ranged between 4,155 and 10,079 kJ m^{-2}. Energy exchange measurements totaled ca. 78% and 85% of the estimated energy release calculated from fuel consumption measurements at the mixed and pine stands, and were dominated by increased H and secondarily by λE.

Although our values compare reasonably well, a number of potential errors can affect data quality during 'fireflux' experiments. For example, it is possible that the eddy covariance measurements sample only a limited portion of the plume, 10 Hz data may underestimate instantaneous fluxes during enhanced turbulent transfer occurring in fires, smoke occasionally interfered with the sonic anemometer sensors, and the LiCor LI-7000 used to sample water vapor may not accurately sample such large fluctuations in H_20 concentrations. In addition, filters used by the LiCor LI-7000 had to be changed frequently because of loading by smoke particulates. Quantifying consumption using pre- and post-burn field plots also is not without error. For example, the coefficient of variation for consumption of fine and 1-hour fuels on the forest floor represented 23 to 32% of the mean values. In addition, char particles < 2 mm diameter that were produced from litter during the prescribed fire were not sampled, because we sifted samples through 2 mm mesh size screens to remove sand and fine-grained organic matter.

Conclusions

Landscape-scale tower networks are valuable for evaluating energy fluxes during prescribed fires. A large majority of the estimated energy released from complex fuel beds during combustion was measured as 'excess' H and λE above the canopy. Despite some sampling limitations, simultaneous quantification of fluxes and fuel consumption during fires can provide essential information for evaluating predictive plume dispersion and fire behavior models.

Acknowledgements

The Joint Fire Sciences Program (JFSP #09-1-04-1: Development of Modeling Tools for Predicting Smoke Dispersion from Low-intensity Fires) and the USDA Forest Service NRS-06 provided funding for this research.

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Strategic budget planning for managing wildland fire in the National Park Service

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Extended abstract:

Introduction

As a result of the need for an updated analysis of the wildland fire workload within the National Park Service (NPS), coupled with projected declines in wildland fire operating budgets over the next several years, the NPS completed development of a workload analysis for strategic budget planning. The Planning Data System (PDS) workload analysis is intended to assist agency leadership in the allocation of limited funding given a selected management philosophy.

The PDS analysis outputs will serve a key role in balancing our investments between regions and between parks, by providing a framework for decision making to achieve cost efficiencies. Regardless of whether projected budget declines materialize in the future, the new workload analysis will be relied upon to prioritize current and future NPS investments in wildland fire management activities.

Methods

The system uses mathematical processes to find dissimilarities between the workloads by analyzing the following different program attributes: (a) number of wildfires; (b) frequency of large wildfires; (c) amount of area within each park that should be treated annually that is within the Asset Protection Zone – lands proximal to park infrastructure, park boundaries, and wildland-urban interface – in order to increase fire protection capabilities; (d) amount of area within each park outside of the Asset Protection Zone that should burn annually (either from wildfire or prescribed fire) in order to maintain the historical fire regime; and (e) the total number of active days in the analysis period. The system provided a method to stratify NPS park units with similar wildland fire workloads into sets or 'bands'. Each band was examined in detail to characterize the workload and then elicit expert opinion to ascertain the minimum level of staffing necessary to manage both the program and the workload.

Upon completion of these analyses, a modified Delphi method was used to elicit expert knowledge about the relationship between workload and staffing levels. For the purposes of this analysis, the unit used for staffing levels was measured in terms of the full-time equivalent FTE. FTE is a unit of measurement that defines an employed person in a way that makes workloads comparable across various contexts. For this analysis, one (1) FTE means that the person is a full-time worker. Two rounds of anonymous feedback were given by the PDS development team to estimate the number of FTE that would be needed to manage the workload in each of twelve 'bands' that were produced in the stratification process. Each band had at least one park and all parks that met the criterion for permanent staffing were included in the banding process. To quantify the relationship between the expert opinion FTE estimates and the actual historical workload for each park over the analysis period, a series of stepwise regressions were created to find the best fit between the expert opinion FTE and program attributes that define the workload for all parks within each band.

These efforts produced a specific level of minimum core (permanent) staffing for each park given projected budget levels. Operational (seasonal) staffing levels for preparedness and fuels management were derived through an identical process.

Components of the analysis

The primary component of the PDS analysis is the calculation of the number of Full Time Equivalents (FTE) for each park with a wildland fire workload. The analysis examines the wildfire and fuels management workload at each park, providing three primary outputs:

The minimum number of core FTE for each park to manage the program, provided the workload meets the entry threshold of >7 wildfires per year

The minimum number of preparedness funded operational FTE to manage the workload from unplanned ignitions

The recommended minimum number of fuels-funded operational FTE, if the park were performing the volume of fuels treatments suggested by the PDS analysis

FTE for each of the three outputs are subsequently converted to actual funding amounts. The PDS analysis is expected to be used to determine minimum staffing levels at the seven regional offices as well as the NPS Fire Management Program Center at the National Interagency Fire Center in Boise, which is the 2nd component of the analysis. The staffing level for "central offices" was primarily based on an FTE cap that was commensurate with the projected reduction in FTE for the entire NPS wildland fire organization.

The 3rd component is the engine analysis which answers the question of whether the wildfire workload – in terms of frequency and magnitude of unplanned ignitions – at a park necessitates the use of a wildland fire engine for initial response, and if so, how many. The 4th component is the aviation support analysis, which examines initial response workload to ascertain the frequency and magnitude of helicopter support needs and whether that workload warrants placement of a helicopter, given limited funding and the need to prioritize allocations. Both the engine analysis and aviation support analysis were based on geospatial data analysis.

The 5th component evaluated the need for mobile tactical teams (e.g. fuels modules, wildland fire modules, etc.). A suite of options was developed for leadership to consider regarding which parks and specific types of workload would benefit most from mobile tactical teams.

Application

Staffing distribution and funding levels suggested by the system have been integrated into a framework for workforce management which is being used by agency leadership to meet projected budget declines over the next three years, starting in FY2014, which begins October 1, 2013. By 2016, the wildland fire budget for the NPS is projected to decrease approximately 32% from the FY2010 level, based on pre-sequester projections.

This FY2016 projected budget level ($47,196,330) was used in combination with a management philosophy that emphasizes preparedness capabilities to distribute FTE between the parks, central offices, and the two Interagency Hotshot Crews, for a total of approximately 515 FTE. In the event that there is a shift in program emphasis (e.g. between preparedness and fuels management) and/or budget projections decline more dramatically or the NPS realizes unexpected budget increases, the analysis can be modified by using an updated management philosophy and revised numbers of FTE.

Future improvements

The utility of workload analyses for strategic budget planning is dependent upon the careful selection of workload descriptors as well as the quality of input data. There are many potential sources of error in this data and efforts have been made to filter and/or correct data that are questionable.

However, additional work is indicated in reviewing the data quality of the individual fire reports, as well as improving future fire reporting procedures, especially related to fire location and fire type definition. Discussions are also underway to modify the extent of the Asset Protection Zone, based on evolution of wildland-urban interface data sources and fire behavior risk modeling processes. The workload analysis will be utilized for transitioning park organizations in FY2014, and is expected to be refined in the future; it will remain adaptive to fluctuating budget levels as well as departmental and agency investment priorities.

Oak woodlands and forests fire consortium: a regional view of fire science sharing

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Abstract: The Joint Fire Science Program established 14 regional fire science knowledge exchange consortia to improve the delivery of fire science information and communication among fire managers and researchers. Consortia were developed regionally to ensure that fire science information is tailored to meet regional needs. In this paper, emphasis was placed on the Oak Woodlands and Forests Fire Consortium to provide an inside view of how one regional consortium is organized and its experiences in sharing fire science through various social media, conference, and workshop-based fire science events.

Additional keywords: Information Sharing, Joint Fire Science Program, Regional Consortia, , Social Media

Introduction

In 1998 the U.S. Congress appropriated funding to create the Joint Fire Science Program (JFSP) and provide a more flexible funding authority to support fuels treatment research with the goal of reducing severe wildfires (Joint Fire Science Program 1998). Congress supplied JFSP with four issues to direct research funding: 1) fuels inventory and mapping, 2) evaluation of fuels treatments, 3) scheduling of fuels treatments, and 4) monitoring and evaluation of fuels treatments. Additionally, Congress stated that JFSP should focus on ensuring products from funded research are in a format that can be readily used in project planning, land and resource management, and project implementation. The overall goal of JFSP has been to accelerate the awareness, understanding, and adoption of wildland fire science information by federal, tribal, state, local, and private stakeholders within ecologically similar regions (Joint Fire Science Program 2013a). To meet this goal JFSP spent approximately $125 million between 1998 and 2007 on fuels and fire management research (Wright 2010).

When JFSP underwent a 10 year review, one of the recommendations was to improve the sharing of fire science by developing a two-way communication process between scientists and managers (LeQuire 2011). In response, JFSP has dedicated about 25% of its funding to develop regional fire science consortia. In 2009 JFSP solicited proposals to develop consortia for the purpose of improving information exchange between managers and researchers. Initially eight consortia were selected for development and included: Alaska, the Appalachians, California, the Great Basin, the Lake States, the South, the Southern Rockies, and the Southwest (Fig. 1, Table 1). The initial consortia were so effective that in 2010 JFSP issued a second solicitation for proposals to establish additional regional consortia to serve and provide geographic coverage for most of the United States (LeQuire 2011). The solicitation resulted in the development of six additional consortia: Great Plains, Northern Rockies, Northwest, Oak Woodlands & Forests, Pacific, and Tallgrass Prairie and Oak Savanna (Fig. 1, Table 1).

Regional consortia follow six guiding principles outlined by JFSP:

1) Inclusive: be inclusive, make sure all relevant partners have the opportunity to be involved,
2) Impartial: serve as a neutral science partner,
3) End-user driven: be customer driven, both in how they are structured and how they function,
4) Collaborative: operate collaboratively, fostering joint management and science communication,
5) Innovative: be innovative, pursuing new and creative ways to disseminate knowledge, and
6) Facilitative: facilitate the flow of fire science information, dialogue of new science findings, and needs of resource managers and policymakers.

One benefit of the regional structure is that consortia can focus on highlighting regional fire issues, needs and priorities. With the tremendous volume of fire science available, managers often do not have time to search and identify research relevant to their needs (Wright 2010). Consortia act as a filter identifying products relevant to regional issues and develop programs to promote distribution of information. In other words, consortia are brokers of fire information and help break down some of the communication barriers that limit effective fire science communications.

Although each consortium is different, all offer similar core services. For example, each consortium has developed a webpage to serve as a central information and contact point. Consortia utilize social media such as Facebook and Twitter to rapidly disseminate news about fire science and current fire events. Consortia organize and host webinars which enable fire science to be shared with a large group of viewers at no cost to the participants. Additionally, webinars can be recorded and archived online for fire professionals to view at their convenience. Other common products of consortia are newsletters that highlight current and future events in each region. Consortia have also developed and assisted other groups in developing fire workshops, special sessions, and conferences. The true power of the regional consortia effort is that all activities address regional fire science needs that have been communicated to the consortia through interactions with managers within their region.

Fig. 1. Current geography of the Joint Fire Science Program Knowledge Exchange Consortia (Joint Fire Science Program 2013b).

Table 1. The 14 Joint Fire Science Program regional consortia short and full names with web addresses.

Consortia Short Name	Consortia Full Name	Web Site Address
Alaska	Alaska Fire Science Consortium	www.frames.gov/partner-sites/afsc/home
Appalachians	Consortium of Appalachian Fire Managers and Scientists	www.cafms.org
California	California Fire Science Consortium	www.cafiresci.org
Great Basin	Great Basin Fire Science Delivery	www.gbfiresci.org
Lake States	Lake States Fire Science Consortium	lakestatesfiresci.net
South	Southern Fire Exchange	southernfireexchange.org
Southern Rockies	Southern Rockies Fire Science Network	www.frames.gov/partner-sites/srfsn/home

Southwest	Southwest Fire Science Consortium	swfireconsortium.org
Great Plains	Great Plains Fire Science Exchange	gpfirescience.missouristate.edu
Northern Rockies	Northern Rockies Fire Science Network	nrfirescience.org
Northwest	Northwest Fire Science Consortium	www.nwfirescience.org
Oak Woodlands	Oak Woodlands and Forests Fire Consortium	www.oakfirescience.com
Pacific	Pacific Fire Exchange	www.pacificfireexchange.org
Tallgrass	Tallgrass Prairie and Oak Savanna Fire Science Consortium	www.tposfirescience.org
JFSP	Joint Fire Science Program	www.firescience.gov

The Oak Woodlands & Forests Fire Consortium: an inside view of fire science delivery

The Oak Woodlands & Forests Fire (Oak Woodlands) Consortium formed in 2012 to provide fire science information to managers in portions of 10 states (Fig. 1): Alabama, Arkansas, Illinois, Indiana, Kansas, Kentucky, Missouri, Oklahoma, Tennessee, and Texas (Grabner *et al*. 2012). This region is nearly 1 million ha in area and encompasses the following ecoregions: Cross Timbers, southern tallgrass prairie, Ouachita Mountains, Ozark Highlands, and the Interior Low Plateau (The Nature Conservancy 1999). This region is unified by the historical dominance of oak woodlands and forests and historically fire was an important disturbance that affected vegetation development (Stambaugh 2010). Currently in this region, oaks and many other species remain important both ecologically and economically, but fire has been eliminated from much of the landscape due to fire suppression, land use changes, agriculture, and urbanization.

The purpose of the Oak Woodlands Consortium is to promote the dissemination of fire information across a section of the interior U.S. and serve the fire information needs of natural resource managers working in mixed hardwood and pine communities such as woodlands, forests, savannas, and barrens. The Consortium aims to promote fire information sharing and work towards establishing partnerships among fire professionals. The Consortium will enable researchers and managers to share their combined experiences studying and managing fire. Based on end-user input, the Oak Woodlands Consortium fire science delivery and outreach utilizes a mix of web-based applications, face-to-face interactions, social media, publications, and meetings.

The Oak Woodlands Consortium is currently administered by the University of Missouri and led by Michael Stambaugh and consortium coordinator Joseph Marschall. To ensure the Oak Woodlands Consortium meets its mission and purpose, the Consortium installed a two-tiered governing structure comprised of a governing board and advisory board. The ten member governing board is comprised of researchers and managers whose task is to help determine the activities the Consortium will undertake each year. Governing board members are from across the Oak Woodlands Consortium region to ensure that regional concerns are represented on the board. The roles of the governing board members are to confirm fiscally responsible decision making and budget execution, provide annual oversight and priority setting, and ensure that annual reporting and planning requirements are completed in a timely manner. The advisory board consists of eight members with at least one member from: Texas, Tribal Lands, Arkansas, Missouri, Illinois, Tennessee, Kentucky, and Indiana. The advisory board's role is to develop recommendations for fire science information and technical assistance needs, science delivery opportunities, ideas for possible new research, and objective evaluation of Consortium activities and progress towards meeting the overall purpose of the Consortium. The governing and advisory boards guide the Consortium in developing programs to address the following regional fire science information needs that were identified from surveys of managers and researchers.

Priority information needs identified for the Consortium region are:

Game species and prescribed fire: Managers are interested in information about fire effects on species that are harvested for food, recreation, and fur. Information on both habitat and species life history responses to prescribed fire is needed. Game species include wild turkey, quail, white tailed deer, elk, and others.

Prescribed fire effects on exotic species: This topic addresses the effects of prescribed fire on exotic species such as Japanese stiltgrass (*Microstegium vimineum)*, sericea lespedeza (*Lespedeza cuneata)*, spotted knapweed (*Centaurea stoebe)*, and exotic honeysuckles (*Lonicera* spp).

Applying prescribed fire during different seasons and its effects: This information relates to varying seasonality of prescribed fire and the effects on woody and herbaceous vegetation. The topic includes native species diversity, effects on trees and shrubs, graminoid and forb diversity, and fuel consumption.

Comparing effects of prescribed fires with different fire intensities: In the Oak Woodlands region, low-intensity prescribed fires often do not meet ecological objectives. This information covers the effects of prescribed fires with different intensities and the operational considerations of how managers can meet land management objectives when using prescribed fire with higher intensities.

Vegetation structure and prescribed fire: This information focuses on using fire to develop desired forest stem density, canopy diversity, and canopy layering. Experts in the use of prescribed fire contribute their experiences and methods for using fire to alter forest stand structure.

Timber management and prescribed fire: The topic of prescribed fire effects on timber quality is an important issue in the Oak Woodlands region. This information addresses land management for multiple objectives and includes questions such as: Can we manage large landscapes with prescribed fire and maintain high quality timber? What is the economic devaluation caused by prescribed fire?

Ground flora diversity and prescribed fire: Managers are interested in information on how fire can be applied to enhance plant diversity, with emphasis on the effects of fire frequency, seasonality, and intensity.

Climate change and fire: This topic addresses the current state of knowledge on how climate change is expected to influence the Oak Woodlands region and how this will affect fire management and fire effects.

Using prescribed fire to manage fuel loads: This information aims at understanding the effectiveness of prescribed fire for reducing fuel loads. Emphasis is placed on using prescribed fire on sites that have elevated fuel loads due to timber management or natural disturbances such as ice storms, tornados, or insects and disease.

Reptile and amphibian responses to prescribed fire: Concerns exist regarding the potential negative effects of fire on reptiles and amphibian communities (particularly with growing season burns). New research projects on this subject are underway throughout the Oak Woodlands region. This topic is of interest to managers who are charged with increasing species diversity as a management objective.

Sharing fire science information

The Oak Woodlands Consortium disseminates fire science through many different outlets. The following are fire science information delivery methods that have been used and advantages and disadvantages the Consortium has realized with each.

A. Web-based methods

1. Website

The Oak Woodlands Consortium website (www.oakfirescience.com) is intended to serve as a central depository and 'go-to' place for regional fire science information. The website identifies important regionally applicable fire science publications, a calendar of regional fire science events, information regarding upcoming fire science activities supported by the Oak Woodlands Consortium, and links to various fire science organizations. Media on the website includes captured videos of regional fire science presentations. Advantages of using a website include instant access anytime and anywhere given the ubiquity of internet capable technology. The major disadvantage to using a website for information sharing has been the absence of interaction with the user since websites are a passive information exchange resource. The effectiveness of a website is related to how it is designed and a lot of time and expense can go into website development, modification, and updating at the expense of other information sharing activities.

During the first eight months after the website was launched (April 20 - December 21, 2012), monthly averages for the following categories were observed:

Number of visits/Month: 281
Number of unique visitors/Month: 143
Number of new visitors/Month: 114
Number of returning visitors/Month: 166
Average visit duration: 3 minutes and 30 seconds.

2. Facebook and Twitter

The Oak Woodlands Consortium utilizes social networking sites Facebook and Twitter to rapidly disseminate fire news and information and also to facilitate communication between the Consortium and the fire management 'audience'. Current fire news and research articles relevant to the region, upcoming meetings and workshops, and webinar announcements are posted to Facebook and Twitter as soon as the information is available. Both sites are also excellent sources of information, as other fire organizations, including the other regional consortia, post fire news as well. Building the audience is a critical aspect of successful use of Facebook and Twitter, and the Consortium is constantly seeking new methods for expanding the social media 'reach'. As of 4/9/2013, 123 people 'like' the Oak Woodlands and Forests Fire Consortium Facebook page and 138 people 'follow' Oak Woodlands Consortium on Twitter, at @oakfirescience. These numbers have been steadily climbing since accounts were established in May of 2012. The total number of people actually reached through these media is actually higher, as other users share or re-tweet posts by Oak Woodlands Consortium. The biggest disadvantage to using both Facebook and Twitter is that someone must be constantly adding or updating postings. If users do not see new Facebook and Twitter posts, the pages become stale and the Consortium risks losing followers.

3. Webinars

Web conferencing (i.e., webinars) is an effective method of fire science delivery primarily due to remote access. Many other consortia and agencies are utilizing webinars to share scientific information. Webinars hosted by the Oak Woodlands Consortium have been attended by scientists, policymakers, fire practitioners, land managers, students from universities, government agencies, private industry, and non-governmental organizations. Attendance in our first four webinars ranged from 32 to 100 participants with the majority being land managers and fire practitioners. For consistency, webinars are provided using the same service (i.e., AdobeConnect®) and are scheduled at the same time on the same day of the week. We have found that advertising is important to webinar attendance and the Oak Woodlands Consortium has found it effective to advertise webinars twice; once two weeks prior and again one day prior to the webinar date. Participants are encouraged to be active by entering names, affiliations, and questions in a dialogue box that all participants can view. Webinars are recorded and posted on the Oak Woodlands Consortium website within about one week. This enables managers who were unable to attend the original webinar to access the presentation at their convenience. Disadvantages of utilizing webinars include potential for technological problems during the presentation and lack of user familiarity with a somewhat recent technological service.

4. Newsletters

The Oak Woodlands Consortium publishes quarterly newsletters. The newsletter is an effective manner to keep our customer base engaged and updated. The newsletter is distributed electronically as a PDF document which can also be printed; additionally newsletters are posted on the Oak Woodlands Consortium website. It is perceived that a 'ready to print' booklet layout format aids in cohesiveness and ease of reading. Most JFSP fire science consortia distribute newsletters, though the frequency of distribution ranges widely. Advantages to using newsletters are that they provide a summary of Consortium activities, highlight timely regional events or research, provide a mechanism for highlighting managers and researchers in our region, and provide an avenue for advertising upcoming events.

Newsletters are consistently composed of four components:

1) Perspective Feature: This is the cover of the newsletter and is usually a melding of seasonally relevant fire science and humanistic perspectives.
2) Fire Science Research Brief: This provides a summary of a regionally applicable scientific journal article, with a strong focus on management implications. Articles are chosen to be summarized based on regional fire science needs identified by fire practitioners and researchers.
3) Spotlight: This section introduces a regional fire science consumer and highlights regional fire cultures: alternating between a fire practitioner and fire research scientist. Three questions are asked in each issue: two are general questions that remain the same issue to issue; the third is person specific and reflects either a timely or agency perspective issue.
4) Upcoming Events/Calendar: This section provides information about upcoming regional and national events as well as links to additional information.

B. Non-web-based methods

1. Workshops

The Consortium has sponsored three workshops as part of larger conferences and has developed one independent field-based workshop since its inception in February 2012. Attendance at workshop presentations has ranged from over 30 to 100. The workshops the Oak Woodlands Consortium has sponsored have been very successful at reaching managers because the Consortium targeted conferences that tend to focus on issues relevant to diverse natural resource managers. There appear to be some disadvantages to utilizing workshops as forums of science delivery. First, information sharing is passive; speakers present their information, attendees listen, and there is often limited time for questions and discussion at the end of each presentation. Second, interaction with presenters is limited to those in attendance. To overcome this limitation the Oak Woodlands Consortium records presentations and archives them on the Consortium website.

In the fall of 2012 the Consortium organized a '*Timber Quality and Prescribed Fire Workshop*', which included a half-day of talks and full-day field tour of research sites. This workshop was attended by 150 people with almost everyone attending the field portion of the workshop. The workshop was very successful in getting managers and researchers to interact. The disadvantages to presenting information through field tours are primarily related to the costs to the Consortium and participants and the abilities of managers to travel. In an effort to provide the workshop information to a wider audience than just those who could attend, the Oak Woodlands Consortium recorded presentations and archived them on the Consortium website.

2. Conference Presentations

The Oak Woodlands Consortium has given oral and poster presentations at 10 different conferences since February 2012. This is an effective way to introduce the Consortium to the fire and natural resources management community at large. Oral presentations provide a mechanism to reach a large number of individuals quickly, but there is often limited opportunity for conversations about fire science delivery and needs given the short amount of time for questions at the end of the presentation. Poster presentations at conferences are an excellent way to introduce the Consortium to potential end-users and learn about fire science needs from managers and researchers.

3. Attending Regional Fire Meetings

In the first year of activity, the Oak Woodlands Consortium has travelled to eight regional fire meetings and events. This has aided in increasing awareness of fire science resources available through the Oak Woodlands Consortium and has helped consortia leaders better understand the different needs and resources within the region. The types of regional meetings the Consortium has attended include state prescribed fire council meetings and regional fire and land manager meetings.

C. Capturing talks and workshops

A hallmark of the Oak Woodlands Consortium's fire science dissemination efforts is the capturing, archiving, and sharing of otherwise ephemeral fire science presentations. Frequently, regionally important fire-related topics are presented to small groups or events not sponsored by the Consortium. Talks are recorded, with the presenters' permission, and saved as videos. Videos are shared via Vimeo®, a video sharing social network website. For the time period of April 20 to December 31, 2012, 395 video views occurred from the United States, and 25 views from 12 other countries: Sweden, Canada, Portugal, United Kingdom, South Korea, Spain, Italy, Serbia, Mexico, Netherlands, Germany, and India. A total of 422 video plays, 4,303 video loads (counted each time the video loads on any page), and 1,294 embeds (video posted on website outside of Vimeo®) occurred during this time period. There are many advantages to recording and posting these ephemeral talks, one of which is that local, national, and international communities are able to easily access fire science that was in the past only available to individuals in attendance. The biggest disadvantage to this type of information sharing is that a representative from the Consortium needs to be at all recorded talks to ensure the presentation is recorded correctly. Also, a considerable amount of video post-processing is required to prepare for sharing through Vimeo®.

I. Future directions and efforts

In addition to maintaining the above-mentioned activities, future Consortium activities will grow and adapt to new fire science information needs and directions. One example of new efforts includes engaging public groups and preparing fire science materials to serve general fire interests. These efforts include support of the eXtension Prescribed Fire Community of Practice (www.extension.org/prescribed_fire), which is an online service dedicated to providing information on prescribed fire management and use and is part of the Cooperative Extension System. In addition, the Consortium will host public fire science meetings and forums, and develop fire science materials geared toward general audiences.

Future Consortium efforts and directions will also include improving and expanding existing commitments as they relate to our regional fire information needs. In particular, efforts will be focused on organizing regional conferences and providing opportunities for face-to-face 'conviction' interactions among fire scientists and managers. Increased efforts will focus on publication and distribution of regionally relevant fire science syntheses such as factsheets. In addition, an online database of regional fire demonstration sites is under construction.

Conclusions

JFSP has funded 14 regional fire science consortia to improve the delivery of fire science information to fire and land managers. Due to their regional nature, each consortium has identified different fire science information needs and developed different ways of sharing information. JFSP encourages regional consortia to share information with each other and to learn from each other's successes and failures. The Oak Woodlands Consortium, established in February of 2012, has made significant progress towards reaching and networking fire managers and researchers through a dedicated website; Facebook; Twitter; attending and presenting at international, national, and regional conferences; attending regional fire and land management meetings; hosting webinars; and preparing quarterly newsletters. The Oak Woodlands Consortium efforts have been to fulfill the mission of providing fire science information to resource managers, landowners, and the public about the use, application, and effects of fire.

Acknowledgements

We thank Alan Long, Timothy Swedberg, Marcia Kelly Nelson, and Karl Anderson for providing helpful comments on drafts of this manuscript. Funding in support of the Oak Woodlands & Forests Fire Consortium is provided by the Joint Fire Science Program. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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Fuel treatment effectiveness over 10 years in California forests

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Abstract: Longevity of fuel treatment effectiveness to alter potential fire behavior is a crucial question for managers preparing plans for fuel hazard reduction, prescribed burning, fire management, forest thinning, and other land management activities. Results from this study will help to reduce uncertainty associated with plan prioritization and maintenance activities. From 2001 to 2006, permanent plots were established in areas planned for hazardous fuel reduction treatments across 14 National Forests in California. Treatments included prescribed fire and mechanical methods. After treatment, plots were re-measured at various intervals up to 10 years post-treatment. Very few empirically based studies exist with data beyond the first couple of years past treatment, and none span the breadth of California's coniferous forests. With the data gathered, this research aimed to meet three main objectives: 1) Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior by measuring effects of treatments on canopy characteristics and surface fuel loads over time, and modeling potential fire behavior with custom fuel models; 2) Quantify the uncertainty associated with the use of standard and custom fuel models; and 3) Assess prescribed fire effects on carbon stocks and validate modeled outputs. Data collection continues.

Additional keywords: fuel loading, forest stand characteristics, fire behavior modeling, custom fuel models, carbon

Drought-year tree mortality following a lightning fire in the Ouachita Mountains, AR

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Abstract: In 2011, a severe drought resulted in extreme fire danger throughout the southern United States. The Ouachita Mountains of southwestern Arkansas experienced the highest number of lightning-ignited fires since at least 1971. Most fires were contained with full suppression, but one lightning ignition occurred in a remote and rugged area of the Ouachita National Forest. In the interest of ensuring fire fighter safety given the rugged terrain and extreme heat, and restoring the natural role of fire to the landscape, Forest staff decided to manage the fire with less-than-full suppression. Given the hot, dry conditions, however, there was concern that overstory tree mortality might exceed the Forests' desired future condition for forest structure. We generated 50 random points within the 729 hectare containment area and determined tree mortality in 10-meter radius plots. One-year post-burn, overstory tree mortality on the High Peak Wildfire was not significant and is consistent with the Forest's desired future condition for forest structure. This information suggests that limited suppression is a viable option even under severe drought conditions. This is welcome news given the long-term weather outlook for the Ouachita region which forecasts hotter and drier conditions over the coming decades.

Additional keywords: ecosystem restoration, less-than-full suppression, loblolly pine plantation, pine-oak forest

Introduction

The summer of 2011 was exceedingly hot and dry in the Ouachita Mountains of southwestern Arkansas, U.S.A. resulting in a record number of lightning fires. Most were extinguished using full suppression, but one fire, the High Peak Wildfire, occurred in a particularly remote and rugged area of the Ouachita National Forest. In the interest of ensuring fire fighter safety given the rugged terrain and extreme heat, and restoring the natural role of fire to the landscape, Forest staff decided to manage the fire with less-than-full suppression. They designated a 729 hectare containment area where the fire burned from 29 July to 11 August 2011. In spite of low relative humidity (daily low averages = 27), high temperatures (daily high averages = 40 °C (104°F)) and high KBDI (Keech Byram Drought Index; daily high averages = 704), fire intensity on the High Peak Wildfire was low with mostly backing or flanking fire and flame lengths of 0.2 to 0.6 m

(0.7 to 2 ft). However, literature and anecdotal experience suggested that fires burning during this extreme drought may completely consume the long-unburned forest floor which could result in overstory tree mortality that would exceed the Forests' desired future condition for forest structure (Varner *et al*. 2007).

Methods

We generated 50 random points within the 729 ha (1801 acres) containment area and established 10 m radius plots directly after the fire (Fig. 1) in all areas that had burned (32 plots). Due to time constraints, only two plots were established in unburned areas. Plots were located in one of three community types: pine plantation, hardwood, and pine-oak forest. On each plot, we identified and measured all dead and live trees over 2.5 cm (1 in) DBH and determined scorch height, percent of live crown scorched, and char height for live trees. Since we were unable to collect pre-burn data, we used immediate post-burn conditions to reconstruct the pre-burn composition of live versus dead trees. Trees with scorched leaves were considered "live" while trees with clear signs of death prior to the fire were considered "dead". Overstory and sapling trees are defined as trees > 15cm (6 in) DBH and ≤ 15 cm DBH respectively. Plots were re-measured one-year post-burn to determine mortality and changes in tree composition (Fig. 2).

Fig 1. Immediate post-burn of a burned plot on the High Peak Wildfire, Arkansas, 2011.

Fig 2. One-year post-burn of a burned plot on the High Peak Wildfire, Arkansas, 2012.

We also collected data on six 15.3 m (50 ft) Brown's transects (Brown 1974) that were measured pre-burn and immediately post-burn. We tallied dead and down woody fuel that bisected the transect and sampled depth (to the nearest 0.25 cm (0.1 in)) of litter and duff using a ruler at 10 points along each Brown's transect pre- and post-burn. Additionally, we collected data on flame length and rate of spread during the fire. This information was not associated with the 10 m radius plots mentioned above.

We used the t-test and Mann-Whitney Rank Sum test (SigmaStat 3.0) to test for differences in tree mortality pre-burn and post-burn between burned and unburned plots, and between overstory and sapling trees.

Results

Pine plantations were dominated by loblolly pine (*Pinus taeda*). Hardwood and mixed pine-oak plots were dominated by shortleaf pine (*P. echinata*), white oak (*Quercus alba*), northern red oak (*Quercus rubra*), blackgum (*Nyssa sylvatica*), and hickory (*Carya* asp.). Prominent members of the sapling layer in all communities were red maple (*Acer rubrum*), blackgum, sweetgum (*Liquidambar styraciflua*), hickory, shortleaf pine, hophornbeam (*Ostrya virginiana*), winged elm (*Ulmus alata*), and white oak.

Overall tree mortality in burned plots was 51% (966 stems ha^{-1}; $p<0.001$). In burned plots, overstory tree density was insignificantly reduced (5%, $p=0.573$) (Fig. 3), while sapling tree density was significantly reduced (64%, $p<0.001$) (Fig. 4). In unburned areas, neither overstory nor sapling tree densities were significantly reduced ($p=0.293$ and $p=0.667$ respectively). In the sapling layer, mortality was highest for red maple (reduced from 232 to 41 stems ha^{-1}), blackgum (178 to 50 stems ha^{-1}), oak (172 to 66 stems ha^{-1}), hickory (143 to 57 stems ha^{-1}), sweetgum (110 to 51 stems ha^{-1}), shortleaf pine (82 to 24 stems ha^{-1}), and winged elm (91 to 54 stems ha^{-1}). Litter was reduced nearly 100% from 6075 kg ha^{-1} to 471 kg ha^{-1} (2.71 to 0.21 tons $acre^{-1}$) or 3.7

cm to 0.3 cm (1.46 to 0.12 in). Duff was reduced from 5828 kg ha^{-1} to 3250 kg ha^{-1} (2.60 to 1.45 tons $acre^{-1}$) or 11.2 cm to 6.4 cm (0.44 to 0.25 in).

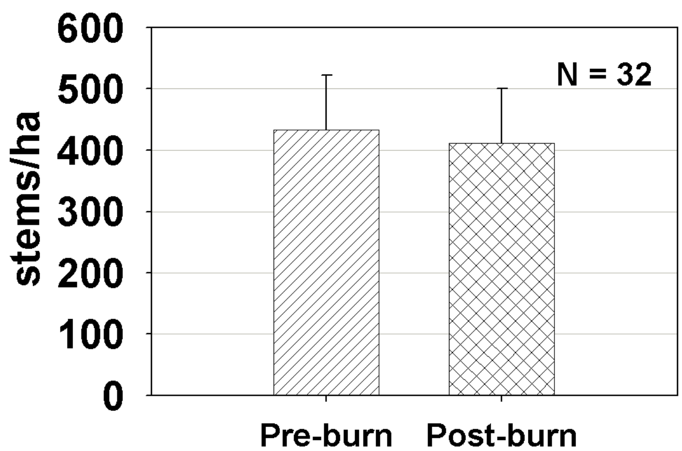

Fig. 3. Change in live overstory density (trees >15cm DBH) between pre- and post-burn on High Peak Wildfire, Arkansas, 2012. Error bars represent ±2 Standard Error.

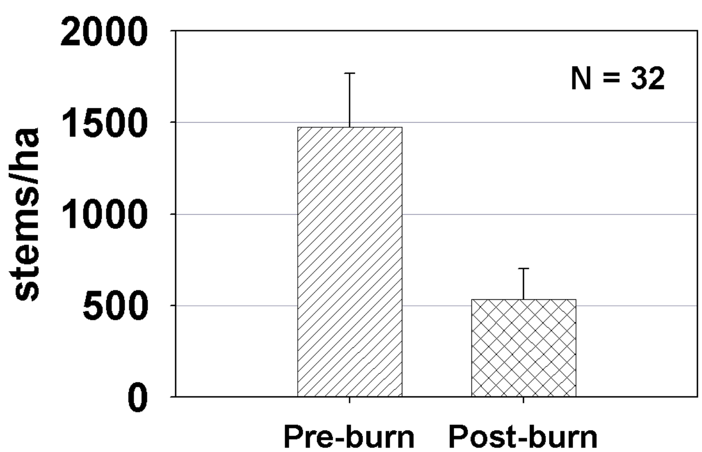

Fig. 4. Change in live sapling density (trees <15cm DBH) between pre- and post-burn on High Peak Wildfire, Arkansas, 2012. Error bars represent ±2 Standard Error.

Discussion

Overstory tree mortality one year after the High Peak Wildfire was not significant. There are several reasons why expected mortality did not occur. First, fire behavior on the High Peak Wildfire was very low throughout the burn and the topography was such that there were very few opportunities for a potentially destructive head fire. Second, the duff layer in the Ouachita

Mountains is very thin. There was enough wind associated with the fire to carry it over the leaf litter at ten to 40 m h^{-1} (0.5 to 2 ch h^{-1}) consuming nearly 100% of the litter but very little duff. The residence time was short and any effects on the feeder roots of the trees were not fatal. Additionally, due to the drought, any feeder roots would have moved lower in the soil horizon to avoid desiccation.

Significant mortality of sapling sized trees was an expected and welcome outcome of the High Peak Wildfire. The increased sunlight that will reach the forest floor will increase the diversity of forbs and grasses and create better wildlife habitat. The lack of significant mortality in the control plots, in spite of the small sample size, indicates that mortality in burned plots was most likely due to fire.

The High Peak Wildfire did not create overstory mortality that was beyond the Forest's desired future condition for forest structure. With the long-term outlook for the Ouachita region including hotter and drier conditions in the coming decades, using less-than-full suppression techniques will not only reduce firefighter risk exposure, but also produce ecosystem restoration benefits without undue overstory tree mortality. We plan to re-measure plots 2 and 5 years after the burn to determine any lag mortality and expand this study to other areas if managers continue to use less-than-full suppression techniques.

Acknowledgements

We thank the Ouachita National Forest for supporting this project. Dale Wade provided a thorough critique which greatly improved this paper. We would not have had the opportunity to do this project without the willingness of Ben Rowland to attempt a new form of fire management and his ability to manage the fire as Strategic Operational Planner. Randy Carter, Mike Melnechuk, and Justus Beggs provided excellent fire effects monitoring during the burn. Erica Taecker, Lisa Picconi, Jennifer Vrbicky, Mike Thompson, Mollie Wright, and Idun Guenther assisted with data collection. We thank the Caddo/Womble fire crew for their efforts. Thanks to Jennifer Lecker for creating BARC imagery.

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Human cognition for wildfire decision making

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Abstract:
Though better land and forest stewardship seem crucial to the prevention of wildfires, the fighting of such fires also matters. How wildfire managers, who are assigned the duty of responding to wildfires once they break out, react to and engage in the wildfire fighting task, and thus impact the outcomes resulting from a wildfire, matters. To understand their task better, wildfire fighting will be divided into two parts—the managerial decisions and actions required for allocating resources (equipment and firefighters) and then the fire-line labor of battling the blaze itself. This latter labor has been scrutinized extensively in the classic study (Weick, 1993) of the Mann Gulch wildfire, which was quite recently reanalyzed by Whiteman and Cooper (2011). The general focus of my recent research efforts have centered on the managerial decisions and actions that precede the firefighting labor. These managerial acts set up the daily work of the wildfire fighters; hence, they are the vital and important precursors that decide which firefighting outcomes will or will not be realized.

The traditional approach for examining managerial decisions with risk relied upon expected utility theory. However, concerted efforts since the 1970s (spearheaded by Kahneman and Tversky (1979 and their development of prospect theory) have revealed the weaknesses of utility theory. Prospect theory focuses attention on the role of human cognitive biases in human decision making. Prospect theory (PT), being a descriptive model of decision making and not a prescriptive one as utility theory is, intends to show how humans actually make decisions. It has been tested inside a number of real-life situations, but never in a wildfire fighting context until 2011 when Wilson et al. (2011) published a survey study using scenarios that uncovered the cognitive biases exhibited by a sample of 206 wildfire managers from the USDA Forest Service. In light of this, the important question becomes—do these biases exhibit themselves in actual decision-making for allocating resources to a real wildfire? And, if the biases are present as prospect theory predicts, do they influence the outcomes realized from the wildfire fighting effort?

Opposed to PT, especially for wildland firefighting, is naturalistic decision making (Lipshitz et al., 2001,), which contends that humans can make sound decisions without biases. Generally, naturalistic decision-making (NDM) denies expert bias (Kahneman and Klein, 2009). To address these questions in a rigorous manner, my current research agenda looks at the first one—the presence of bias in wildfire decision-making. To ascertain the presence of human cognitive biases in wildfire decision-making, I have been analyzing in detail the daily resource allocation decisions for the 2011 Las Conchas fire in New Mexico. Prior to answering the questions about possible decision bias, one should entertain an even more fundamental question. Does the extant literature on wildland fires recognize that human cognitive biases may be present in risk assessments and decision making?

To answer that question, I am now examining two literature bases—wildfire management and wildfire prevention. Before comparing and contrasting these literatures, I first focus on the major differences between PT and NDM and discuss the roots and assumptions of each theory in order to propose a conceptual basis for contending that the two decision making models can be combined. By combining them, I am not arguing for an integrated model, which seems highly difficult to do; instead, the emphasis falls on their complementarity, which offers a more useful method for analyzing wildfire decision making.

Additional Keywords: Wildfires, decision making, prospect theory

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Vegetation fire behavior prediction on the basis of vegetation fuel maps in GIS

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Abstract:
Successful management of vegetation fires is impossible without their behavior prediction, which includes fire spread over the area, fire development, and effects. The paper considers an experience in creation and use of the information database developed during the elaboration of the Russian fire behavior prediction system.

Reliable fire behavior prediction should be based on a comprehensive description of fuel complex (especially primary fire carriers), on maximum account of local topography and weather conditions. For this vegetation fuel classification and methods of their mapping are developed in Russia as well as a method of making an information database for vegetation fire behavior prediction on the basis of the vegetation fuel maps in GIS.

On the example of the Chunsky Forest Office and the nature reserve “Stolby” of the Krasnoyarsk region an information database in GIS for plain and mountain conditions was made to predict active fire behavior. Retrospective performance tests of the software for active fire behavior prediction are presented.

Additional Keywords: Fire growth model, information database, forest types, primary fire carriers, Krasnoyarsk region

Introduction

Fire behavior prediction (FBP) systems were created long ago and are being developed further in the USA and Canada (Anderson 1982; Finney and Ryan 1995; Finney 2000; Ryan *et al*. 2006; Forestry Canada 1992). Russia has no such a system yet. There are only “Guidelines for forest fire detection and suppression” from 1995, which actually reproduce similar guidelines dating back to 1976 and include “approximate indices of forest fire development and spread”. Moreover, the data are provided only for seven forest types in the European Russia and for four forest types in the Far East. The vast area of Siberia including the Krasnoyarsk Krai with hundreds of forest types is left uncovered. Anecdotal evidence suggests that mere adoption of available international fire behavior and fire danger rating systems cannot resolve problems in the countries with differing environments (natural, economic, political, and historical) (Sofronova and Volokitina 1996; Volokitina and Sofronov 2001a, 2002; Volokitina *et al*. 2006; Sofronova *et al*. 2007).

Fire behavior prediction is realized through mathematical modeling. Application of any model is possible only if an information database is available for it. Therefore, a most important element of all national FBP systems is development of methods and technologies for information database creation. The main part of the information databases is data about vegetation fuels (VF) on the landscape.

Background

Three methodical approaches can be distinguished to study the nature of wildland fires and create information databases for fire behavior prediction: 1) selective, 2) standard, and 3) individual. A *selective method* implies that fuel curing and burning of some categories of vegetation plots (biogeocenoses) are empirically studied in relation with dynamic external factors: weather conditions and phenological periods. This method was used in different regions of the former USSR in 60’s – 80’s of the 20th century. Loads of forest fuels and the rate of fuel curing were studied in different forest types. However, there are so many forest types by the geographical location, density, tree composition and age that it is next to impossible to study all of them.

An approximately similar way was chosen by Canada in development of the Canadian FBP system. Sixteen categories of the vegetation plots are distinguished for Canada as standard vegetation fuel complexes called “fuel types” (Forestry Canada 1992). However, the list of fuel types does not cover the whole variety of Canadian forests.

A *standard method* is used in the US National FBP system “BEHAVE”. The method implies that all vegetation (forest and non-forest) is divided into pyrological types – “fuel models”. The US vegetation was first divided into 13 fuel models (Anderson 1982), and recently its number was increased to 40 fuel models (Scott and Burgan 2005).

The standard method’s advantage is that each plot obtains pyrological description needed for fire behavior prediction. However, this method is rough since the diversity of vegetation ecosystems is high.

An *individual method* is being developed at the Forest Fire Science Laboratory of the Sukachev Institute of Forest SB RAS. The idea of this method is providing individual pyrological descriptions for vegetation plots from a set of standard elements. The technique was created to provide such descriptions for any vegetation plot on the basis of available forest inventory descriptions or airborne images and this way to compile an information database for fire behavior prediction (Volokitina and Sofronov 2001b; Volokitina and Sofronov 2002; Catalogue 2009).

Fire growth model selection

Sullivan (2009) conducted an extended analysis of fire growth models. Only one Russian model by Grishin (1992) was mentioned in the analysis, although there are a number of others. We will briefly review them to give grounds for the selection of a fire growth model for the Russian FBP system.

In Russia, mathematical models are divided into three kinds: 1) analytical, 2) experimental-statistical, and 3) mixed experimental-analytical (Dorrer and Kurbatsky 1978). According to Sullivan (2009) they are 1) physical, 2) empirical, and 3) quasi-empirical – respectively.

Physical models consider processes on a fundamental level. They analyze burning of a VF layer on the basis of heat transfer and mass transfer laws and gas dynamics involving a large number of physiochemical VF characteristics (specific heat, elementary composition, ash content, compactness, surface area-to-volume ratio, moisture content, etc.) and environmental characteristics (air temperature, humidity, wind direction and speed, slope steepness, etc.). An example of this from the Russian literature is an air-thermo-chemical model of a forest fire developed by Grishin (1992). It contains a few dozen of equations and boundary conditions describing three-dimensional processes of heat and mass transfer, phase and chemical transformations during burning, and so on. Current vegetation monitoring techniques make it virtually impossible to parameterize the model precluding its general application in wildland fire management.

Most simple are *empirical models*. They are based on data obtained during experimental fires on specific plot categories (e.g., a certain forest type). As a result, dependence between fire spread rate and intensity upon variable factors (wind, fire weather index, etc.) is established in the mode of an empirical formula, which serves as a model.

One example of a model of this type, which has seen widespread use beyond the domain of its experimental base, is the Canadian Forest Fire Behavior Prediction system (Forestry Canada 1992). It is based on empirical formulae and tables covering 16 standard VF complexes (fuel types), which, unfortunately, do not reflect the whole variety of Canadian vegetation.

Russian examples of such models include those by Vonsky (1957), Amosov (1964), Korovin (1969). In spite of their simplicity, such models can give satisfactory results but only for the fires on areas from which experimental data were obtained and generalized. Since there are numerous plot categories, multiple fire experiments on all categories are next to impossible to carry out. Therefore, an information database cannot be completed, which limits the application of these types of models.

In contrast to empirical models, *quasi-empirical models* include empirically derived physical and chemical properties of the fuels thereby extending their potential application to many vegetation types. Among quasi-empirical models, Rothermel’s (1972) model is perhaps the most widely used. The model predicts rate of spread at the head of the fire assuming the fire is burning upslope with the wind. To predict for other locations on the fire perimeter the slope and wind are reduced accordingly. Rothermel’s model is the basis for the United State’s National Fire Danger Rating System (Deeming *et al*. 1978), the BEHAVE-Plus (Andrews *et al*. 2005), and FARSITE (Finney 1998) models. Development of the US FBP System using Rothermel’s model became possible owing to creation of an information database through derivation of standard characteristics of vegetation, i.e. through its division into pyrological types – “fuel models”. There are identifiers helping to choose a fuel model for each plot. For boreal forests (which dominate in Russia) there are no fuel models. The advantage of the standard method is that each plot obtains pyrological characteristics necessary for fire behavior prediction. However, the characteristics are rather rough because the number of fuel models is limited and the diversity of the vegetation cover is huge in terms of fire science.

Among Russian quasi-empirical models, there are models by Telitsin (1973), Konev (1984), Gusev (2005), Dorrer (2008) and others. Telitsin’s mathematical model (1973) contains a simple formula for frontal surface fire spread rate (V):

$$\mathbf{V = 1.6\cdot10^4 \cdot \delta /\ \rho\cdot (15 + w)^2 \cdot (1 - \cos \alpha)^2}$$

The formula infers that the frontal fire spread rate (V) is directly proportional to the depth of the layer consumed (δ, m) and inversely proportional to the layer compactness (ρ, kg / m^2) and the squared moisture content (w, %). The fire spread rate is also much dependent upon the angle of the flame (α, degrees). The flame angle is, in its turn, influenced by the wind and slope steepness. There are theoretical formulae to calculate coefficients of wind and slope direct impact on the fire spread rate. It should be noted that the depth of the consumed layer and its moisture content are variable values depending upon the layer structure and specific conditions of moistening and drying. Special programs are needed to calculate these values, i.e. this model lacks an information database.

Konev (1984) suggests two models:

1) one of the analytical type considers a complex heat-mass exchange between the burning zone and the initial matter;
2) another one of the experimental-analytical type is simple: no-wind-no-slope fire spread rate is multiplied by the coefficient reflecting burning conditions. The burning conditions include impact by wind speed and direction (in relation to the fire edge) as well as slope steepness. The regularities were obtained both analytically and by generalization of published experimental data. A constant no-wind-no-slope fire spread rate is attributed to some types of primary fire carriers in spite of the fact that it actually differs considerably with drying of the fire carrier layer.

Gusev's mathematical model (2005) is a modified Rothermel model (1972). The modifications were as follows: subclasses of forest fuels were introduced, approximations for a number of characteristics were changed, etc. According to Gusev, application of this model in practice is limited because of its complexity. Therefore, Gusev suggested a simplified model. The formula for frontal surface fire spread rate (v) under no-slope conditions is:

$$v = \exp\,(a_1 + a_2U + a_3M + a_4U^2 + a_5M^2 + a_6UM),$$

where U – wind speed under the forest canopy, m/s; M – moisture content of surface fuel fire carriers, 0,01· % ; $a_1 \, . \, . \, . \, . \, . \; a_6$ – coefficients which are constant for given surface fuels.
Rear and flank fire spread rate (v_r) is calculated by an empirical formula:

$$v_r = v \exp\,[\,\mathrm{A}\,(\cos^4 \alpha/2 - 1)],$$

where $A = 0{,}974\ U^{\,0{,}1466}$ – empirical coefficient; α – angle between the fire spread direction and wind direction.

Gusev also suggests mathematical models assessing moisture content of surface fuels in rainless periods, interception (retention) of precipitation by stand canopy, wind speed in the forest, parameters of a convection column, travel distance of burning particles, parameters of a spot fire, potential for a surface fire to crown, etc. Nonetheless, the system of models does not take into account: retention of solar radiation by the forest canopy (a most important factor of VF drying); well-known regularities of precipitation distribution under the forest canopy; probable number of burning particles capable to start ignitions; duration of a fire edge contact with a fire barrier as a most important factor assessing the possibility for a fire to get over a barrier; presence of oxygen in the convection flow when assessing the possibility of involvement of the canopy in fire propagation, etc.

All of Gusev's models have coefficients related to special features of specific kinds of stands. The information database has a selective character and includes only pine stands with lichen, green moss, and grass cover, which are found in the central taiga and forest-steppe zones of the European part of Russia.

Dorrer's mathematical model (2008) describes forest fire spread as a running wave in a heterogeneous and anisotropic medium. On the basis of the methods of Hamilton's mechanics, a geometrical theory was developed of propagation of flat forest fire fronts; formulae were given for calculations of fire contours, fire perimeters and areas; numerical algorithms were developed for fire front graphical representation both of an imitation type and based on the method of flexible (mobile) grids. In essence, this is a whole complex system modeling forest fire propagation and suppression including a number of subsidiary mathematical models (for instance, models of spatial structure of forest fuel layers, dynamics of fuel moisture content, etc.) The system took 30 years to develop. The results were published in a monograph (Dorrer, 2008). The issue of a wide information database provision for this system was not sufficiently developed.

Creation of a VF information database was developed theoretically and practically only for the model developed at the Sukachev Institute of Forest (Sofronov 1967; Sofronov and Volokitina 1990; Volokitina and Sofronov 2002). In this model an individual method was applied as the main method to pyrologically characterize vegetation plots. The individual characteristics in this method are composed of standard elements, which reflect information about components of the VF complex, about conditions of moistening, drying and burning of a plot. All this is shown in the fine-scale VF maps and in the pyrological descriptions enclosed with them. Methods and a technology were developed for making such maps based on forest inventory data or in the process of forest inventory. The proposed mathematical model for surface fire growth prediction is very simple:

$$\mathbf{Vx = V_o \cdot Kw \cdot Kr \cdot K\varphi,}$$

where $\mathbf{V_o}$ **–** no-wind-no-slope spread rate, m/minute;
Kw – variable wind coefficient;
Kr – variable relative humidity coefficient;
Kφ – variable slope coefficient.

No-wind-no-slope spread rate shows the capacity of fire to spread over the given fuel under "standard" combination of dynamic external factors (wind – 0 m/s, slope – 0°, and relative humidity – 40%). On the basis of experimental data and fire observations, the no-wind-no-slope spread rate was determined for each type of a primary fire carrier depending upon the fire weather index or "drought index" in Russian terminology (Sofronov and Volokitina 1990). Relative influence of wind, slope, and humidity (i.e. variable coefficients Kw, Kr, Kφ) on fire spread rate was established during experimental prescribed burns and fire experiments (Sofronov 1964; Sofronov 1967).

Analysis of experimental data and observation on active fires allowed the determination of no-wind-no-slope fire spread rate (m/ min) for each type of a primary fire carrier depending upon the drought level (related to fire weather index), surface combustion heat (mJ/m^2), consumable fuel load (kg/m^2) and other characteristics (Sofronov and Volokitina 1990; Volokitina and Sofronov 2002).

Knowing the no-wind-no-slope spread rate and taking into account the relative impact of the aforementioned factors on spread rate, it is possible to calculate the actual spread rate under any value of these factors. This allows prediction of surface fire growth and its development into crown fires. This model of fire growth was chosen as a foundation for Russian FBP program software applicable in plain and mountain conditions.

A proposed principle scheme of fire behavior prediction is shown in Figure 1. The information database, which is aimed to provide the mathematical model with input data, consists of: 1) vegetation fuel maps (VF maps); 2) pyrological description of plots enclosed with the maps; 3) tables characterizing properties of various VF. The pyrological description contains characteristics of a VF complex on each plot including its seasonal dynamics as well as description of VF moistening, drying and burning on each plot.

Information database creation

For more than 30 years, the Sukachev Institute of Forest SB RAS has been developing a theoretical approach, conducted experimental studies in different regions of Russia and developed practical recommendations to provide the selected model with the information database (Sofronov and Volokitina 1990; Volokitina *et al*. 1995; Volokitina *et al.* 1996).

First of all, the VF classification by Kurbatsky (1962) was given further development. The VF groups, distinguished by Kurbatsky, were divided into VF types (Sofronov and Volokitina 1985; Volokitina and Sofronov 1996, 2002). Primary focus was on the classification of the first VF group, which includes hygroscopic surface fuels (fine vegetation remnants, mosses, and lichens). This layer load and moisture content predetermine the possibility of ignition. This layer serves as a carrier of the flame combustion under surface fires. Therefore, it is called a primary fire carrier (PFC). To classify the PFC and obtain PFC characteristics, over 800 fire experiments were carried out in a flammability sample cylinder (the idea of which was developed from G.C.

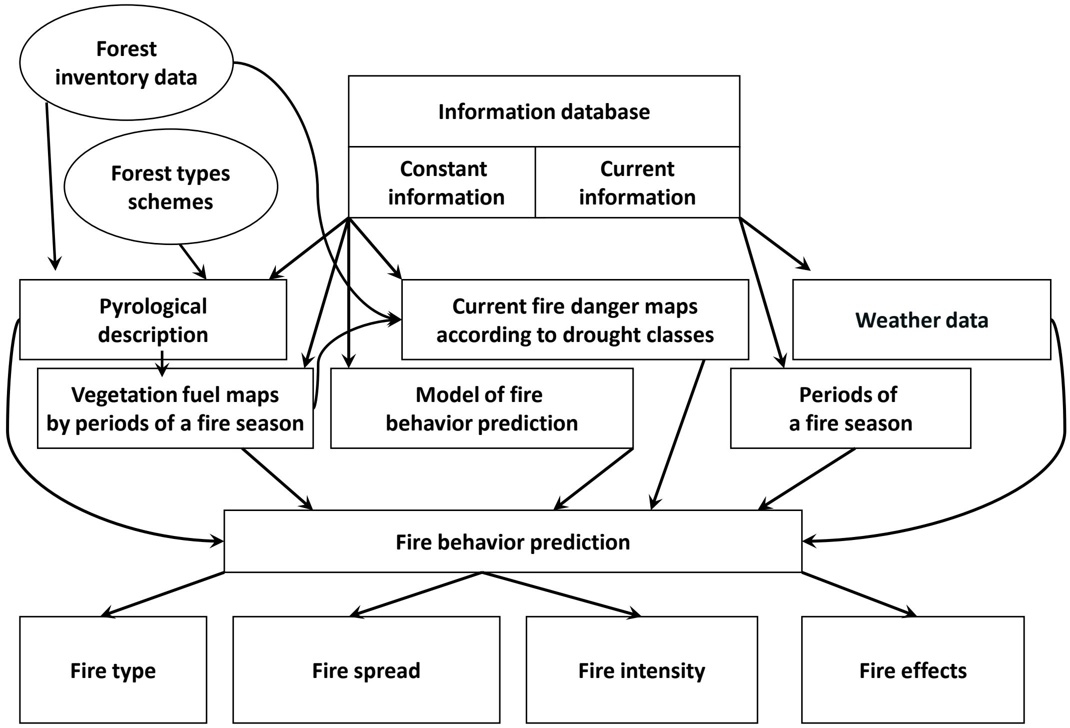

Fig. 1. Principle scheme of fire behavior prediction

Wright (1967) under different types of surface fuels and weather conditions including 24-hour ignitions and taking of more than 3,000 surface fuel samples (Fig. 2). The studies were conducted in different regions of Russia: Belomorsko-Kuloysky plateau in the Archangelsk oblast, Lake Baikal basin in the Buryatia Republic, the Irkutsk oblast, Priangariye and Evenkia in the Krasnoyarsk krai. The obtained results were compared with the published data about curing of different surface fuels in different regions of Russia. As a result, the major classification criterion was determined for dividing the primary fire carriers into types – rate of fuel curing (Volokitina and Sofronov 2002; Volokitina *et al*. 2002).

The PFC group was divided into the following subgroups: 1) *moss group* with dominant mosses or lichens having no expressed seasonal changes, and 2) *litter group* with dominant vegetation remnants (litter, cured grass) having well-expressed seasonal dynamics. Each subgroup was divided into five types (including subtypes) depending upon the drought level (related to fire weather index) at which a PFC layer becomes ready to ignite if drying conditions are standard: horizontal surface in a moderately closed forest stand. If drying conditions deviate from standard, corrections for non-standard conditions were developed. PFC drying rate under standard conditions depends upon the structure of the layer and the soil moisture regime. Consequently, the PFC classification “automatically” takes into account not only the fuel structure but also the moisture regime of an underlying substrate.

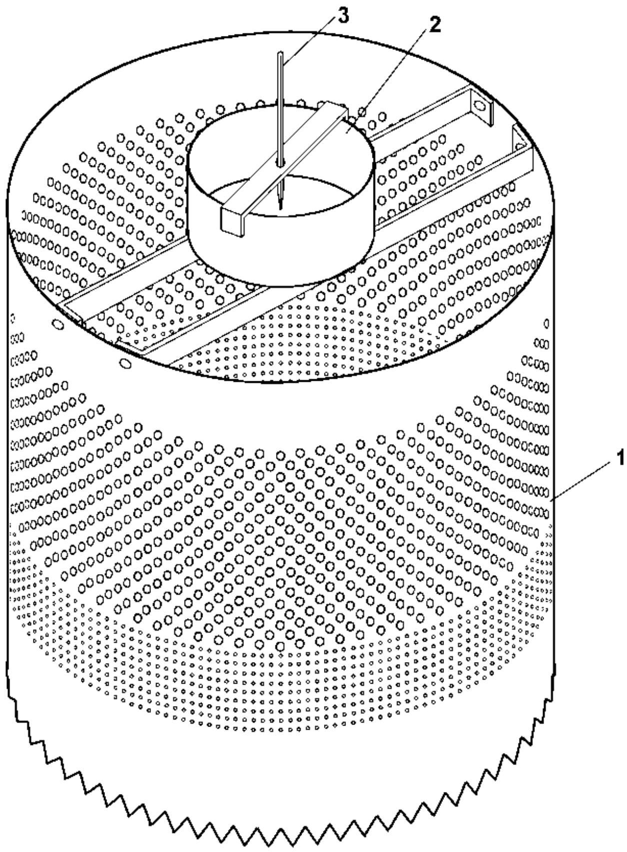

Fig. 2. Flammability sample cylinder.
1 – cylinder, 2 – water vessel (heat accumulator), 3 – thermometer. Size: 70 × 70 cm

The PFC layer structure in the litter subgroup changes within a fire season, with green grass producing the largest impact on drying and burning conditions of the layer in summer. As a result, one PCF type can transform into another one in the litter subgroup.

Special identifiers were elaborated to determine PFC types both by descriptions of vegetation, relief, soil, and by direct observation *in situ*. On the example of the Krasnoyarsk Priangarie, the area was divided into 12 ecosystem categories and characteristics were attributed to each PFC type for deciphering space images (Volokitina 1990).

Owing to observations in different regions of Russia, it was defined more precisely how forest inventory characteristics of a tree stand and relief influence PFC moistening and drying. As a result, a technique was developed to assess a critical class of drought (CCD); at which a plot becomes ready to burn) for each plot depending upon the PFC type, canopy closure, and relief. Fire experiments in natural conditions allowed studying the burning of the main PFC types in relation to the drought level including dynamics of the consumable fuel load (kg/m^2) and amount of the energy release from a unit of area (kJ/m^2), dynamics of fire intensity (kW/m^2) and value of the no-wind-no-slope fire spread rate (m/min) (Sofronov and Volokitina 1990; Volokitina and Sofronov 2002).

A simple method and a relatively cheap technology were developed for making fine-scale VF maps (Volokitina *et al*. 1995; Volokitina 1996). The idea of the method is to maximally use forest inventory data during VF mapping. That is an uncolored forest inventory scheme of forest stands or a digital layer of forest inventory plots in GIS is taken as a base for the VF map. Pyrological description of the forest inventory plots is made on the basis of the available forest inventory data.

Forest inventory data have no information about PFC types and their seasonal dynamics. Therefore, a technique was developed for identifying PFC types through the description of forest types indicated in the forest inventory data. This pyrological description of forest types should be preliminarily made using available schemes describing forest types of a given area and an identifier of PFC types. Usually forest type descriptions lack information about litter and duff, therefore they should be supplemented with descriptions in the natural conditions. Finally, a table is made showing PFC types by periods of a fire season for each forest type used during forest inventory.

More accurate is the assessment of the PFC types by a specially developed identifier in the process of forest inventory when PFC types are identified and marked by a forest inventory specialist. This method was tested during forest inventory of the State Nature Reserve “Stolby” in 2007-2008.

Thus, the most important and labor-consuming stage in the technology of the VF maps creation is pyrological description of forest inventory plots. It can be complete or abridged. An abridged version of the pyrological description of a forest inventory plot necessary for predicting surface fire spread rate, intensity and postfire tree mortality should contain the following data: 1. Number of a forest inventory plot. 2. Dominant tree species. 3. Forest type. 4. Tree diameters of dominant tree species. 5. Relative tree density (generalized for all storeys). 6. Slope aspect and steepness. 7. PFC type for spring (autumn) and summer. 8. Critical class of drought (CCD) for spring (autumn) and summer.

The Russian FBP system is being developed very slowly because of the absence of funds for testing available scientific elaborations on test areas, first of all, for creation of information databases. The situation moved off dead center recently owing to the State Contract of the Institute of Forest with the Forestry Agency of the Krasnoyarsk Krai and owing to the Agreement of the Institute of Forest with the Institute of Space Research and the Central Airbase of Avialesookhrana. As a result, since 2008, computer software in GIS started being developed for VF maps creation and for fire behavior prediction (Catalogue 2009).

Two objects were chosen. The first is the Chunsky Forest Office area of about 1 million ha in the basin of the Angara River. The second object is the State Nature Reserve “Stolby” of about 50,000 ha located in the mountain area near the city of Krasnoyarsk. VF maps for the Chunsky Forest Office area were made using the computer software in GIS and the data from the previous forest inventory. In the Reserve “Stolby”, the data for digital VF maps in GIS were obtained in the process of forest inventory. For each of the two objects, a set of forest inventory information was bought in the Federal State Unitary Enterprise “ROSLESINFORG”.

A table of PFC types for each forest types was preliminarily made based on the scheme of forest types. Using an earlier created technology a computer program was developed for calculation of pyrological characteristics of forest inventory plots on the basis of which VF maps were created in GIS. Thus, an information database was created in the mode of VF maps for the Chunsky Forest Office area.

An abridged version of the program for VF maps creation was applied for the Nature Reserve "Stolby" since the PFC types were identified directly in each forest inventory plot during ground forest inventory using a specially developed identifier. VF maps for the Nature Reserve "Stolby" were also made in GIS. The developed computer software can be used for VF maps creation in other forest offices after introducing pyrological description of forest types used in their areas.

Then a program for fire behavior and fire effects prediction was developed. The program is realized on the basis of ERSI ArcView GIS 3.2 using an object-oriented language Avenue (Fig. 3). The program can be installed on a personal computer under operational system Windows (SE, 2000, XP) and does not require advanced efficiency from the personal computer (Catalogue… 2009).

The basis of the developed FBP program is the application of VF maps. A table is automatically made with burning indices for given seasonal and weather conditions on the basis of the pyrological description. Then one can interactively observe the dynamics of fire growth as time series of vector fire edge contours from the given contours of initial fire areas. The main statistical and dynamic characteristics are calculated for each fire contour at a given time (burnt area, fire perimeter, rate of their changes for an interval). The program also calculates the necessary resources for fire suppression, tree mortality by species (Voynov and Sofronov 1976; Volokitina *et al*. 2005), and crown fire development taking into account pyrological characteristics of vegetation on each plot.

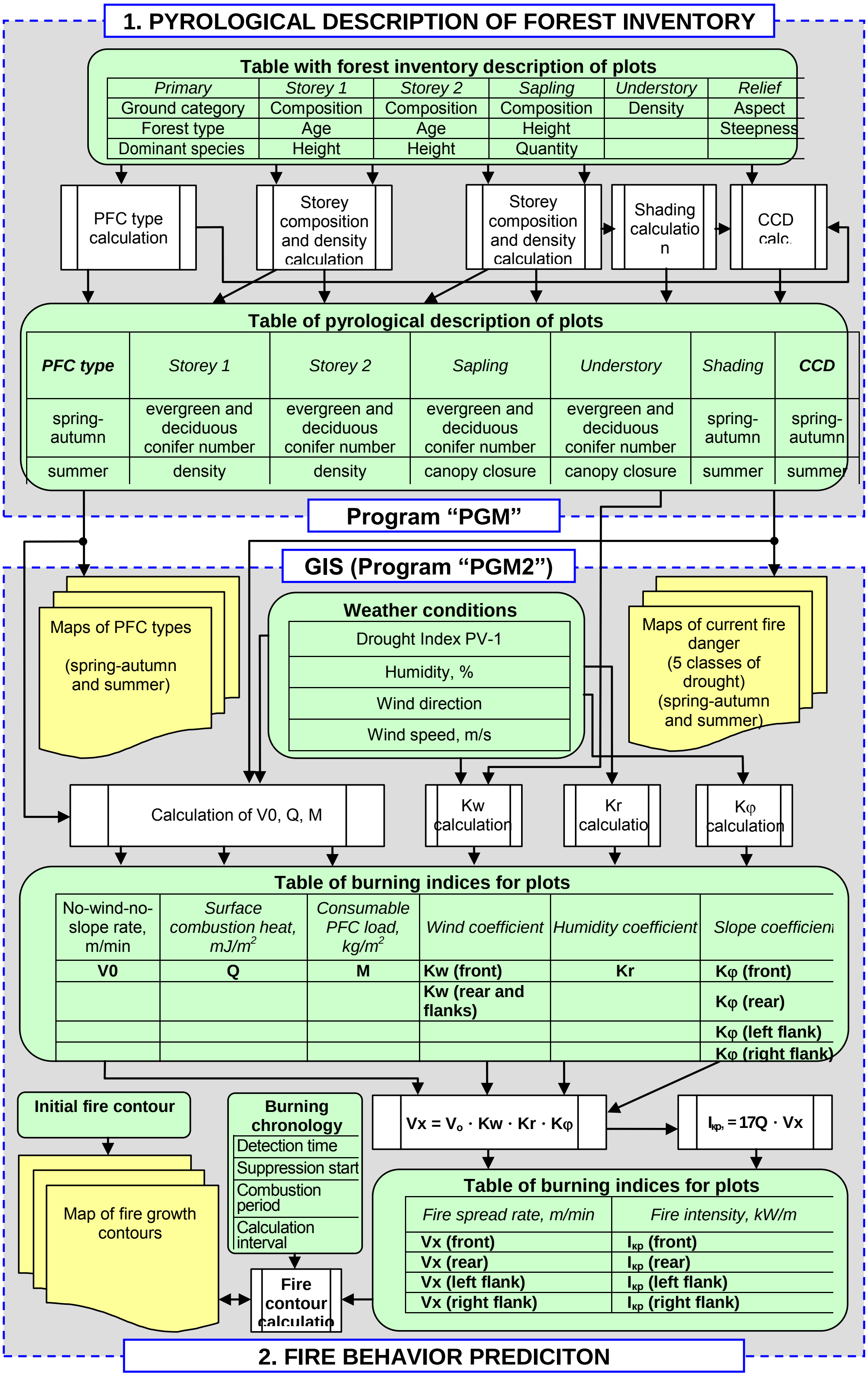
1. PYROLOGICAL DESCRIPTION OF FOREST INVENTORY
Table with forest inventory description of plots
Primary
Ground category
Forest type
Dominant species
Storey 1
Composition
Age
Height
Storey 2
Composition
Age
Height
Sapling
Composition
Height
Quantity
Understory
Density
Relief
Aspect
Steepness
PFC type calculation
Storey composition and density calculation
Storey composition and density calculation
Shading calculation
CCD calc.
Table of pyrological description of plots
PFC type
Storey 1
Storey 2
Sapling
Understory
Shading
CCD
spring-autumn
evergreen and deciduous conifer number
summer
density
canopy closure
Program "PGM"
GIS (Program "PGM2")
Maps of PFC types (spring-autumn and summer)
Weather conditions
Drought Index PV-1
Humidity, %
Wind direction
Wind speed, m/s
Maps of current fire danger (5 classes of drought) (spring-autumn and summer)
Calculation of V0, Q, M
Kw calculation
Kr calculation
Kφ calculation
Table of burning indices for plots
No-wind-no-slope rate, m/min
Surface combustion heat, mJ/m2
Consumable PFC load, kg/m2
Wind coefficient
Humidity coefficient
Slope coefficient
V0
Q
M
Kw (front)
Kr
Kφ (front)
Kw (rear and flanks)
Kφ (rear)
Kφ (left flank)
Kφ (right flank)
Initial fire contour
Burning chronology
Detection time
Suppression start
Combustion period
Calculation interval
Vx = Vo · Kw · Kr · Kφ
Iкр = 17Q · Vx
Map of fire growth contours
Fire contour calculation
Table of burning indices for plots
Fire spread rate, m/min
Fire intensity, kW/m
Vx (front)
Iкр (front)
Vx (rear)
Iкр (rear)
Vx (left flank)
Iкр (left flank)
Vx (right flank)
Iкр (right flank)
2. FIRE BEHAVIOR PREDICITON

Fig. 3. Control-flow chart for programs "PGM" and "PGM2"

Performance test

The most accurate test of the FBP program performance can be done during experimental fires. However, the experimental fires are not only difficult and expensive to carry out but also they are limited in number and do not provide statistical confidence for various natural conditions in which wildland fires can occur.

Performance tests on active fires can be more objective only under active collaboration with fire fighting services and under good provision of the research with equipment. In 2009, such a performance test was not organized because of absence of fires during field observations. Therefore, a third performance method was applied – a retrospective one.

Fuel curing prediction implies finding of plots on the VF map (numbers of the forest inventory units and plots are marked) and assessment of the critical classes of drought (i.e. drought classes at which fire propagation over a plot is possible) on the basis of the enclosed pyrological description of plots. If the drought class of the current day is lower than the critical class of drought indicated for a given plot, then this plot cannot burn. If the drought class of the current day is higher than the critical class of drought indicated for a given plot, then the plot is ready to burn. If the drought class and the critical class of drought coincide, the plot is in a transitional state, which can be defined more precisely directly on a fire (fire spreads over the plot – the plot and similar plots are ready to burn, fire does not spread over the plot – the plot and similar plots are not ready to burn).

For a retrospective performance test, data (location, duration) about 125 forest fires for 2006-2009 were taken in the Chunsky Forest Office. Numbers of forest inventory plots where fires were active were established by the fire contours enclosed with the reports about forest fires. The pyrological description enclosed with the VF map was used to determine the critical classes of drought for a given period of a fire season for each plot. Fire weather index (drought index PV-1) was calculated for May – September 2006-2009 using weather data from the weather station in the Chunoyar Aviabase. On the basis of the fire weather index, a drought class (DC) was defined for each day according to the following scale: 1st DC – up to 300, 2nd DC – 301-1,000; 3rd DC – 1,001-3,000; 4th DC – 3,001-10,000; 5th DC – over 10,000 units.

By comparing the drought classes for the days when fires were active with the critical classes of drought of the plots where fires were active, it was established that 117 out of 125 fires were active in the plots absolutely ready to burn and only 8 fires were active in the plots which were in a transitional state, i.e. among burning plots there were no plots which were not ready to burn according to the prediction. Thus, the accuracy of the fuel curing assessment on plots according to the VF map turned out to be almost 100%.

It was more complicated to test the accuracy of the fire growth prediction because the fire record data give information only about the final contour of a burnt area after the fire was suppressed and the fire origin location is not always accurately fixed. Therefore, only 26 out of 125 fires were chosen for a retrospective FBP performance test.

The computer FBP software was used to simulate historical fire growth and to compare it with the actual fire growth. The testing results showed an overall good performance of the model and the program using VF maps and proved that it is useful to simulate the behavior of occurring fires and the results of their suppression under different calculations of fire fighting resources

(Table 1). Figure 4 shows an example of the fire growth simulation versus actual fire propagation.

Table 1. Characteristics of the fire #10 (June 13-15, 2009) calculated in the program "PGM2"

Fire characteristics	Time from the simulation start, hours		
	1	2	3
Burnt area, ha	16	31	46
Fire perimeter, m	1430	2050	2540
Rate of fire perimeter growth, m/hour	620	540	550
Rate of burnt area growth, ha/hour	12.7	16.6	15.9
Average frontal spread rate, m/hour	94	80	65
Average fire edge intensity, kW/m	280	270	240
Assessment of fire intensity	Moderate	Moderate	Moderate
ASSESSMENT OF RESOURCES FOR FIRE SUPPRESSION			
Optimum suppression rate, m/hour	280	240	200
Minimum width of a fire barrier, m	12	11	9
Suppression duration, hours/ burnt area after suppression, ha (depending upon the number of people and bulldozers)			
Suppression without bulldozers			
Large expenditures on suppression – additional calculation needed	-	-	-
Suppression with bulldozers			
7 people/ 1 bulldozer	6 / 50	6 / 50	10 / 130
10 people/ 2 bulldozers	3 / 35	3 / 35	5 / 90
15 people/ 2 bulldozers	2 / 30	2 / 30	2.5 / 75
20 people / 3 bulldozers	1.2 / 28	1.2 / 28	2 / 70

TREE MORTALITY PREDICTION

Forest inventory		Crown fire	Tree mortality by species, %					
unit	plot	possibility	spruce	pine	larch	birch	aspen	total
89	16	yes	-	100	-	100	65	88
89	19	no	-	36	6	38	-	27
90	16	yes	-	100	-	100	63	87
90	17	no	-	36	5	37	-	26
90	18	no	67	-	-	32	-	33

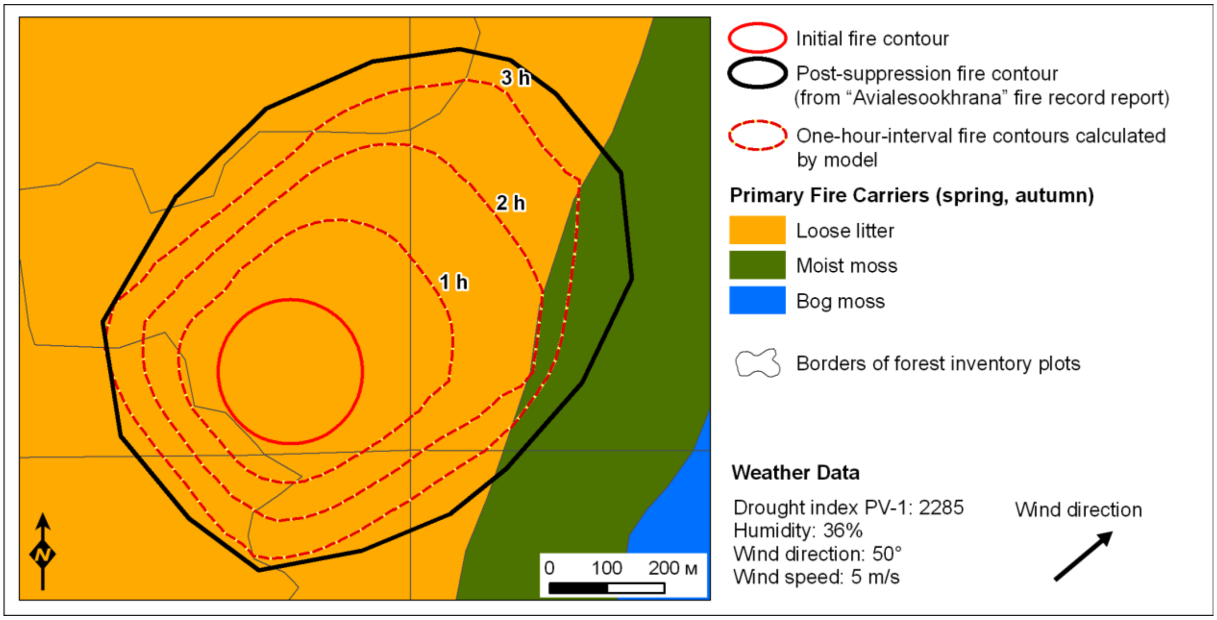

Fig. 4. Simulation of fire # 10 detected June 13, 2009 (5 ha of area burnt) and suppressed June 15, 2009 (total burnt area 60 ha) in the forest inventory unit # 89 of the Novokhaysk Ranger District

It is planned to supplement the program with the prediction of crown fire development on the basis of fire intensity prediction for PFC types in relation to weather conditions and taking into account a rich Canadian experience in this issue (Alexander 2006; Cruz and Alexander 2010). Fire barriers impact on fire spread is also under consideration.

Summary

Examples of information databases in GIS were created for fire behavior and fire effects prediction in plain and mountain conditions. Retrospective tests of the elaborated programs carried out using data about past fires in the Chunsky Forest Office area and in the Nature Reserve "Stolby" showed overall good performance. This should speed up the creation of the Russian fire behavior and fire effects system. The limiting factor is lack of funds for performance tests of the developed programs and technologies including tests on active fires in collaboration with local forest office fire protection.

Acknowledgements

We are thankful to the Forestry Agency of the Krasnoyarsk krai (Krasnoyarsk, State Contract #82, 2008-2010), the Institute of Space Research and the Central Aviabase "Avialesookhrana" (Moscow, Agreement # 1263/10, 2009) for financial assistance.

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Fine fuel dynamics following selection-harvest in *Sequoia sempervirens*

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Abstract: Fire has increasingly become more frequent and damaging in the coast redwood (*Sequoia sempervirens*) forests of the Santa Cruz Mountains in California, leading to concerns regarding impacts of post-harvest logging slash on escalated fire hazard in the highly-managed forests there. Therefore, we quantified changes to surface fuels and potential fire behavior for three years following a selection harvest that employed two types of yarding (cable and tractor) and was followed by a lop-and-scatter treatment. We also simulated fire behavior with custom fuel models with NEXUS (v. 2.0).

In the first year following harvest, surface fuel loading significantly increased in 1-hr (<0.64 cm diameter), 10-hr (0.64-2.54 cm), and 100-hr (2.54-7.62 cm) timelag surface fuels. Increases to all fuel categories were linearly correlated to the amount of volume removed during the harvest. All fuel categories returned to pre-harvest levels by the second year following harvest. Like fuel dynamics, simulated flame lengths and rates of spread significantly increased in the year immediately following harvest, but returned to pre-harvest levels by the second year. Thus, fire hazard is indeed slightly elevated in the first year following a selection harvest in this forest type, but the effect is relatively short-lived.

Additional Keywords: Coast redwood, logging slash, fire behavior modeling, Santa Cruz Mountains, Swanton Pacific Ranch

Introduction

Sequoia sempervirens (hereafter, redwood), the native range of which consists largely of a narrow band extending ~800 km along the central and northern coasts of California (Roy 1966) is a vastly important species by most ecological and economic metrics. The species, which includes the tallest trees in the world, can live in excess of 2000 years, providing a menagerie of critical ecosystem functions. Valued for their aesthetics and lumber quality, they are also extremely valuable commercially and are therefore heavily managed throughout their range.

Fire is the principal natural disturbance agent in redwood forests. The extent of fire's influence is largely determined by latitude and proximity to the coast (Veirs 1980), which has led to a wide range of documented fire return intervals. In the moister, northern portion of the species' natural range, fire is extremely infrequent, occurring on some sites only every 500 years (Agee 1993); in the drier, southern portions of its range, however, fire return intervals have been documented from 6-29 years (Jacobs et al. 1985, Stuart 1987, Finney and Martin 1989, 1993, Brown and Swetnam 1994). Historically, fires in redwood forests were of low to moderate severity, with few stand-replacing fire events (Veirs 1980, Agee 1993). These fires eliminated understory species while having little residual effect on overstory redwood trees greater than 20 cm DBH (Finney and Martin 1991) due to the species' thick bark, which insulates the cambium from lethal temperatures (Finney and Martin 1989).

The redwood forests in the Santa Cruz Mountains in the southern portion of the species' range are heavily managed for timber. While thinning is a common method for reducing fuel continuity and subsequent fire hazard in many coniferous forests, residual logging slash can potentially increase surface fuel loading and subsequent intensity of wildfire on harvested sites if not properly treated. To ameliorate elevated post-harvest slash in the Santa Cruz Mountains, state regulations require that following any harvest there, all downed wood greater than 10.2 cm diameter be lopped and scattered to a depth of less than 0.61 m (per California Forest Practice Rule 14 CCR § 957.4).

Interestingly, many residing in the Santa Cruz Mountains where evidence of previous fire is readily apparent have largely discounted the potential for fire, commonly referring to redwood stands there as the "asbestos forest". However, recent high-severity events in the region, including the 2008 Bonny Doon Fire (210 ha), the 2008 Summit Fire (1730 ha) and the 2009 Lockheed Fire (3,163 ha), have caused many to question this paradigm and whether the current lop-and-scatter regulations are adequate to protect the post-harvest forest and nearby residential communities. However, because literature on changes in fuel loading in redwood forests is minimal, the extent and length of time of any elevated fire hazard is uncertain.

Therefore, to help elucidate the impact of harvesting on fine fuel dynamics and potential fire behavior, we examined changes to fine fuel surface loading (i.e., dead and down wood <7.62 cm diameter) for three years following a single-tree selection harvest in a redwood forest in the Santa Cruz Mountains so as to determine (1) if the harvest significantly changed surface fuel loading, (2) the temporal extent of any changes, (3) factors that influenced any changes, and (4) subsequent changes to potential fire behavior following the harvest.

Methods

Study Site

The study site was located in the Santa Cruz Mountains near Aptos, California on the Valencia tract (Latitude: 37°01'16" N, Longitude: 121° 51' 31" W), which is owned and actively managed by California Polytechnic State University, San Luis Obispo. Valencia is mostly a second growth redwood forest that originated after the site was clearcut for rebuilding efforts following the 1906 San Francisco earthquake. The site is in a maritime, Mediterranean climate with cool, rainy winters and dry summers that are moderated by a coastal fog belt. The land is considered to have good site quality for tree growth and has nearly 100% tree coverage. The forest there is actively managed under a Nonindustrial Timber Management Plan (NTMP) regulated by the State of California (Culver et al. 2001). As part of the NTMP, Valencia was selectively harvested by either tractor or cable yarding methods, with the objective of creating uneven aged stands with old growth characteristics (Piirto et al. 1997).

Surface Fuel Loading

Fuel loading data was collected using a modified planar intercept method per Brown et al. (1982) immediately before and for 3 consecutive years following the selection harvest on 31 permanent 0.80 ha Continuous Forest Inventory (CFI) plots at the site (17 of which were cable-yarded and 14 of which were tractor-yarded). At each plot, two perpendicular transects were utilized, the first was positioned directly downslope from plot center with the direction of the second perpendicular transect decided by coin toss. Counts of 1-hour and 10-hour timelag fuels (i.e., woody surface fuels <0.635 cm and 0.635 cm to 2.54 cm diameter, respectively) were sampled along each transect to a distance of 1.54 meters from plot center. Counts of 100-hour timelag fuels (i.e., woody surface fuels 2.54 cm to 7.62 cm) were recorded to a distance of 3.048 meters from plot center. Counts for each size class were then converted to a Mg ha^{-1} basis for each plot.

As part of the CFI protocol, every tree >15.24 cm diameter at breast height in every plot was numbered and annually measured for total tree volume (m^3) per locally developed volume equations (S. Gill, unpublished data). Total plot volume was the sum of all individual tree volumes within a given plot. Volume removed during the harvest for each plot was calculated as the aggregate per-tree volume measured immediately preceding the harvest minus the volume of the specific trees removed and was expressed in m^3 ha^{-1}.

Data Analysis

To determine if the harvest significantly changed fine fuel loads through time, each of the three fine fuel categories was analyzed with a 1-way ANOVA via a general linear models procedures within Minitab statistical software (v. 16.1.1; Minitab, Inc. 2010). In each ANOVA analysis, the dependent variable was surface fuel loading for a given timelag fuel category and the independent variables were year (pre-harvest and for 3 consecutive years post-harvest), yarding method (cable-yarded and tractor-yarded), and the interaction of year and yarding method. For all statistical tests in this study, α=0.10 for establishing significance. If $p<0.10$ for year in any of the three ANOVA analyses, then a subsequent Tukey's pairwise analysis was performed to determine how each year significantly varied from others.

To determine if volume was significantly correlated to changes to fine fuels, a linear regression analysis was performed for each of the three surface fuel categories. For each regression, change in fuel loading (measured as post-harvest loading minus pre-harvest loading) was the dependent variable and change in volume (measured as pre-harvest volume minus post-harvest volume) was the independent variable.

Fire Behavior Simulations

Custom surface fuel models were created within BehavePlus (v. 5.0.5; Andrews 2007) for each of the four years (pre-harvest and 3 post-harvest years). Based on an examination of mean fuel loads for each of the three timelag fuel categories in each of the four years, the pre-harvest custom fuel model was initialized per the standard model for low load compact conifer litter (TL1; Scott and Burgan 2006) as were the custom fuel models developed for years 2 and 3 following harvest; the first-year post-harvest fuel model was initialized per the standard model for low load activity fuel (SB1; Scott and Burgan 2006).

Weather scenarios were created for average (50th percentile) and extreme (97th percentile) conditions. Historical weather data (1988 through 1992) from the nearby Corralitos remote automated weather station were imported into FireFamilyPlus climatology software (v. 4.1; Rocky Mountain Research Station Fire Sciences Lab and Systems for Environmental Management 2009). Confining the data to August and September, the months in which most large fires in redwood occur (Gripp 1976), moistures for each of the surface fuel categories were then calculated for the two weather scenarios.

Fire behavior simulations for both weather scenarios were completed within NEXUS software (v.2; Scott and Reinhardt 2001) across a range of open wind speeds. Table 1 shows all inputs utilized in the fire behavior simulations. Surface fuel moistures were set per FireFamilyPlus calculations described above. Crown Base Height was set at 10 m based on CFI data. Crown Bulk Density was set at 0.15 based on casual observation and comparison with values in Scott and Reinhardt (2005). Foliar moistures were set per values in Philpot and Mutch (1971) for *Pseudotsuga menziessii*, a species commonly associated with redwood. Wind adjustment factor was set at 0.3 per common procedure when working in partially sheltered stands. Slope was input as the mean slope across all plots.

Table 1. Inputs used for fire behavior simulations at Valencia Creek study site.

	Weather Scenario	
Fire Behavior Input	Average (50^{th} percentile)	Extreme (97^{th} percentile)
1-hr fuel moisture (%)	7	4
10-hr fuel moisture (%)	14	7
100-hr fuel moisture (%)	16	14
Canopy Base Height (m)	10	10
Crown Bulk Density (kg m^{-3})	0.15	0.15
Foliar Moisture (%)	120	80
Wind Adjustment Factor	0.3	0.3
Slope (%)	42	42

Results

Table 2 displays ANOVA results for the impact of year (pre-harvest and 3 post-harvest years) and yarding method on surface fuel loading for three timelag fuel categories. Year significantly varied in all three categories. Yarding significantly varied for only the smallest category. The Year × Yarding interaction was not significant for any fine fuel category.

Table 2. Statistical significance (α=0.10) for variables potentially influencing surface fuel loads at the Valencia study site as determined by 1-way ANOVA analysis. "Y" represents statistical significance and "N" represents no statistical significance. Year includes a pre-harvest year and three consecutive post-harvest years. Yarding includes a cable-yarding and a tractor-yarding technique.

	Timelag Surface Fuel Category		
Source	1-hr (<0.64 cm)	10-hr (0.64 cm to 2.54 cm)	100-hr (2.5 cm to 7.62 cm)
Year	Y	Y	Y
Yarding	Y	N	N
Year × Yarding	N	N	N

Figure 1 illustrates significant differences in mean fuel loading between years for each of the three surface fuel categories. For each, there was a significant increase in the first year following harvest. For the 1-hr and 10-hr categories, loading returned to pre-harvest levels within 2 years; for the larger 100-hr category, loading did not necessarily return to pre-harvest levels, but was significantly reduced from the initial post-harvest year.

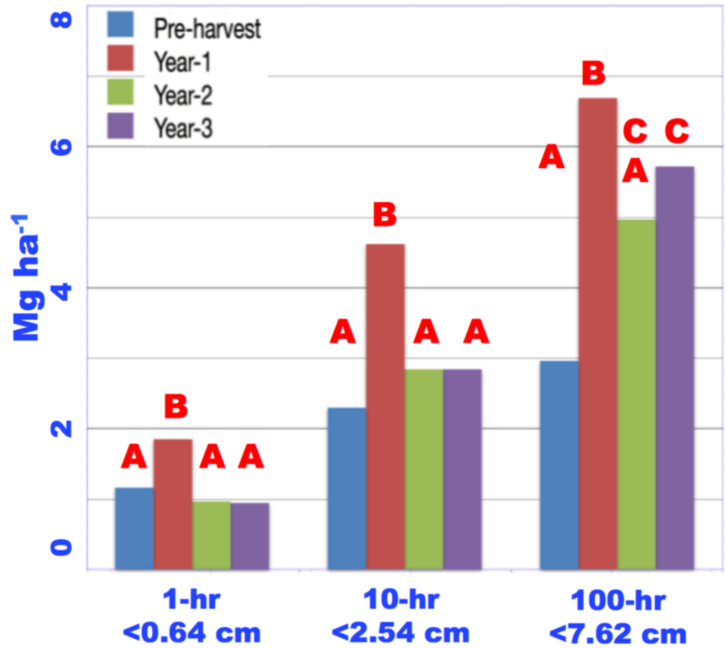

Figure 1. Tukey's pairwise comparisons between years for 1-hr, 10-hr, and 100-hr timelag surface fuels (<0.64 cm, 0.64 cm to 2.54 cm, and 2.54 cm to 7.62 cm diameters, respectively). For each specific fuel category, differing letters represent significant differences between years (α=0.10).

Figure 2 illustrates the relationship of volume removed and the first year change in fuel loading following harvest, which was statistically significant for each of the fuel categories.

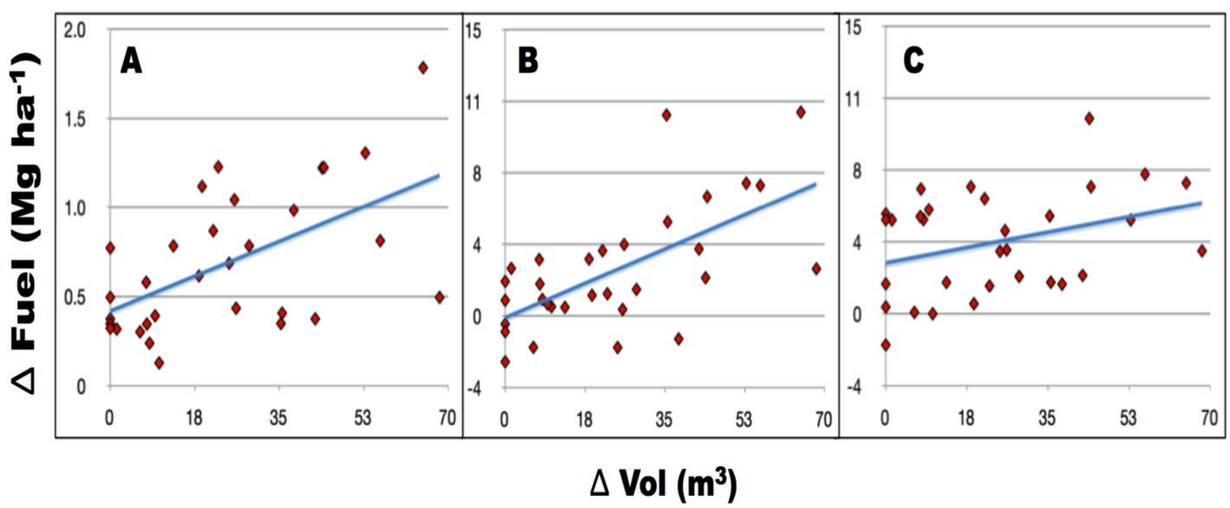

Figure 2. Linear regression of first-year change in 1-hr (A), 10-hr (B), and 100-hr (C) timelag surface fuel categories as influenced by the amount of volume extracted during a selection harvest at the study site. All regressions were statistically significant (α=0.10).

Figures 3 and 4 illustrate simulated rates of spread and flame lengths, respectfully, for each year under average (A) and extreme (B) weather scenarios.

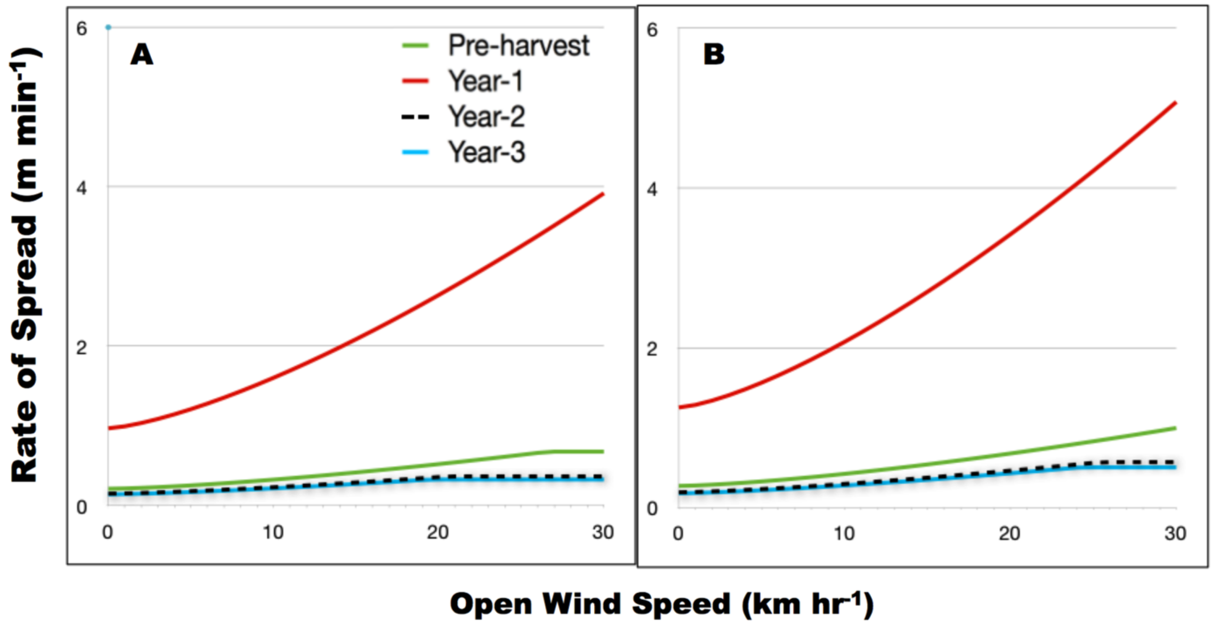

Figure 3. Rate of spread simulated by NEXUS under 50th percentile (A) and 97th percentile (B) weather scenarios. Weather scenarios were calculated per analysis of historical weather data at the Corralitos remote automated weather station, which was located within 10 km of the study site.

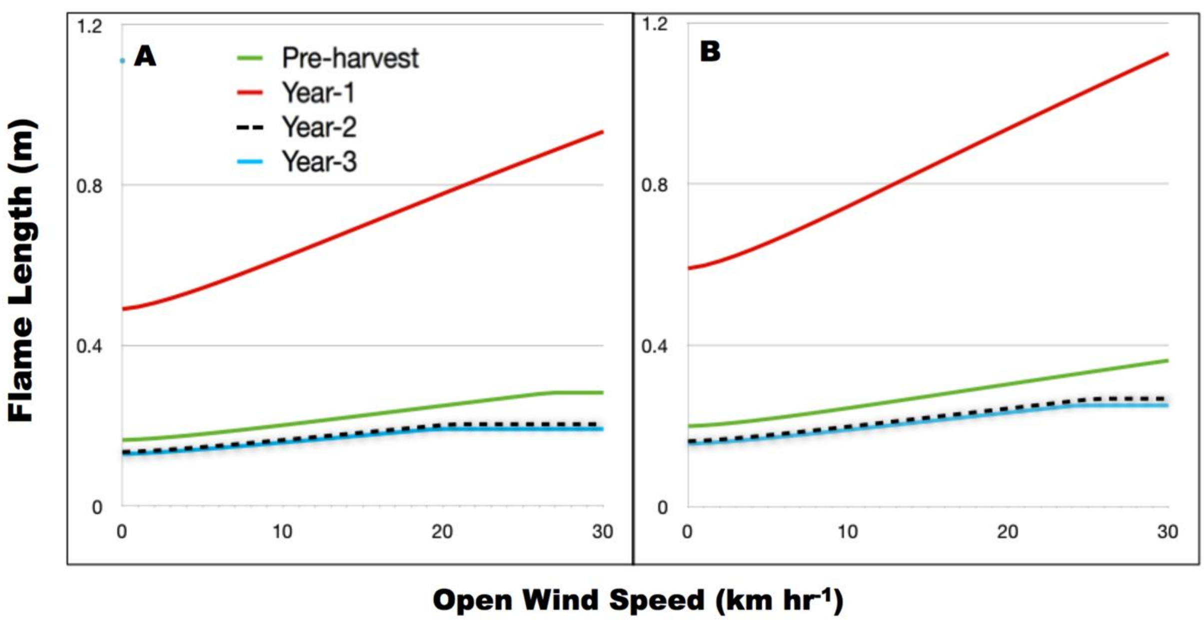

Figure 4. Flame length simulated by NEXUS under 50th percentile (A) and 97th percentile (B) weather scenarios.

Discussion

It was not surprising that fuel loading significantly varied between years for any of the three categories (Table 2) since elevated logging slash is inherent to harvesting operations. However, the return to pre-harvest levels within two years was more rapid than expected. Much slower rates of slash decomposition have been documented in many similar ecosystems including *Pseudotsuga menziessii* in the Pacific Northwest (Edmonds et al. 1986, Preston et al. 2012) and mixed conifer forests in the Sierra Nevada Mountains (Wagener and Offord 1972). We postulate that this rapid return to pre-harvest levels was related to the relatively small additions of new fuels (due to the low volumes extracted during the harvest) and to the cool and moist climate at the study site, which would facilitate rapid decomposition.

The significant relationship between volume extracted and first year increases in fuel loading is encouraging. While certainly not all of the increases in fuel loading can be explained by extracted volume alone (all R^2<42%), development of such predictive equations might be able to better assist local forest managers in planning for post-harvest slash remediation in future harvests. Future analyses might better account for differences in slope and aspect, which will further influence the local microenvironment and subsequent decomposition rates.

As expected, changes to potential fire behavior (Figures 3-4) followed patterns of surface fuel dynamics. Like surface fuel loading, simulated rates of spread and flame length increased in the first year following harvest, but returned to pre-harvest fire behavior by the second year following harvest. While calibrating simulations, fire behavior in the second and third year was more similar to first year results when the custom fuel models were initiated from a slash/blowdown model instead of the timber litter model. However, we chose to initiate second and third year custom fuel models from the standard low load compact timber litter model because we deemed that the statistical return to pre-harvest fuel loading in years 2 and 3 warranted such an action. It should be noted that while fire behavior outputs were commonly more than double the pre-harvest levels, the practical difference is minute. For example, post-harvest flame length was triple that of pre-harvest flame length at the 10 km hr^{-1} open wind speed in the extreme weather scenario (Figure 4b) which could give reason for pause; however, the total actual difference was less than 0.5 meters, which would have minimal impact on fire effects experienced at the site.

There were only slight differences in fire behavior outputs between average and extreme weather scenarios, which was somewhat surprising (Figures 3 and 4). We attribute the lack of change to there only being slight variation in calculated fuel moistures (7% vs. 4%) for the 1-hr fuel categories; within the fire spread equation that is the basis for the fire behavior simulations here, fine fuels have a much greater impact on wildland fire spread than do coarser fuels. Apparently, average conditions significantly dry out fine surface fuels by August and September at the study site. This might not hold in other parts of the redwood range, particularly in lower-elevation sites closer to the coast, which would experience lower temperatures and increased moistures from marine fog (Dagley & O'Hara, 2003).

Of interest, fire behavior simulated in this study was substantially more benign than actual behavior observed in recent fires in the local area. During the 2006 Summit Fire and the 2009 Lockheed fire, there was substantial crowning in portions of the redwood forest, which was not demonstrated here. This is partially explained by limitations in the current fire spread equations that drive today's simulations. First, observation of those fires revealed that wind/topography interactions caused horizontal roll vortices on ridgetops, which led to high-severity crown fires on the lee side of slopes; this type of phenomenon is presently unable to be modeled. Second, fully consumed crowns were observed at the boundary of redwood forests and highly-volatile shrublands when fire intensity from the shrubs was sufficient to initiate crowning at the edge of the redwood forest, but not enough to sustain active crowning as the fire moved deeper into the interior of the forest; this transition of fire behavior at the boundaries of fuel types is presently difficult to simulate.

Fire behavior simulations in this study, however, do align in parts with observed fire behavior. For example, no crowning was simulated here, which was due low surface fuel loading coupled with a high crown base height, the combination of which effectively prohibited fire intensities sufficient enough to initiate passive torching. Indeed, NEXUS outputs revealed that exceedingly high wind speeds would be required to initiate a crown fire from within these stands (Torching Index exceeded 1000 for all scenarios), but Crown Bulk Density was sufficient to sustain a crown fire at relatively low wind speeds (Crowning Index = 37) if a high-intensity fire moved into the forest from adjacent vegetation. This phenomenon was observed on both wildfires; while crown scorch from surface fire was readily apparent within the burned forest, total involvement of the canopy was mostly observed at the boundaries of the forest and where wind/topography interactions caused the aforementioned roll vortices.

Conclusion

In conclusion, while there is indeed an increased fuel load and subsequently elevated fire hazard, the effects are relatively short-lived, apparently returning to a pre-harvest equilibrium within two years. Thus, the current lop-and-scatter regulation on slash disposal seems to be adequate in this forest type for this type of harvesting operation.

Acknowledgements

The project was funded in part by the California State University Agricultural Research Initiative (ARI) and the McIntire-Stennis Cooperative Forestry Research Program under the Cooperative State Research, Education, and Extension Service. The authors are grateful for the unwavering support offered by M.L. Dicus throughout this research.

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Mathematical modeling of crown forest fires with firebreaks

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Abstract:
Forest fires are extremely complex and destructive natural phenomena that depend on availability of fuel, along with meteorological and other conditions. The theoretical investigation of the problems of forest fire initiation and spread was carried out in this study. The mathematical model of forest fire was based on an analysis of experimental data, using concepts and methods from reactive media mechanics. The research was based on numerical solution of three-dimensional Reynolds equations. The boundary-value problem is solved numerically using the method of splitting according to physical processes. A discrete analogue for the system of equations was obtained by means of the control volume method. The developed numerical model of forest fire initiation and spread would make it possible to obtain a detailed picture of the variation in the velocity, temperature, and chemical species concentration fields with time. The results of calculation give an opportunity to evaluate critical condition of the forest fire spread, which allows the application of the given model for prediction of forest fires development. It overestimates the rate and contour of crown forest fire spread that depends on crown properties: bulk density, moisture content of forest fuel and etc.

Additional Keywords: Forest fire, combustion, control volume, firebreak

Introduction

Analysis of the characteristics of forest fires reveals their dependence on the specific conditions under which the experiments were conducted, and their insufficient accuracy, which results from the fact that under actual conditions it is impossible to control the meteorological situation and the homogeneity of forest fuel layer. For this reason the physical modeling of forest fires must be combined with mathematical experiments using numerical methods and computers. The object of study in this case is not nature, but a mathematical model of a forest fire, which usually consists of a set of partial differential equations with appropriate initial and boundary conditions. The deduction of a system of equations, and boundary and initial conditions, and the subsequent solution of the corresponding mathematical problem is usually called mathematical modeling of forest fires. Mathematical modeling possesses a number of advantages over physical experimentation, for example, ecological safety and greater economic efficiency. One of the objectives of this study is the improvement of knowledge on the fundamental physical mechanisms that control forest fires initiation and spread. Considering that, natural investigations of these problems are simply impossible, which means methods of mathematical modeling are urgent. The first explanation of forest fires initiation processes was given by Van Wagner (1977). Crown fire initiation and hazard have been studied and modeled later by other scientists(Xanthopoulos 1990; Rothermel 1991; Albini et al. 1995; Alexander 1998; Cruz and others 2002; Scott and Reinhardt 2001). The complete discussion of the problem of crown forest fires is provided by Konev (1977) and coworkers at Tomsk University (Grishin 1997, 1998; Perminov 1995, 1998). In particular, a mathematical model of forest fires was obtained by Grishin (1997) based on an analysis of known and original experimental data (Konev 1977), and using concepts and methods from reactive media mechanics. The physical two-phase models used by Morvan & Dupuy (2001, 2004) may be considered as a continuation and extension of the formulation proposed in (Grishin 1997). The investigation of crown fires has been limited mainly to cases studied of forest fires initiation as the result of transition of surface fires into crown forest fires and surface forest fires spread. The present mathematical model and results of calculation are used to understand and predict crown forest fires behavior. It gives an opportunity to evaluate critical condition of the forest fire spread, which allows applying the given model for prediction of these fires behavior.

Physical and mathematical formulation

The basic assumptions adopted during the deduction of equations, and boundary and initial conditions: 1) the forest represents a multi-phase, multistoried, spatially heterogeneous medium; 2) in the fire zone the forest is a porous-dispersed, two-temperature, single-velocity, reactive medium; 3) the forest canopy is supposed to be non - deformed medium (trunks, large branches, small twigs and needles), affects only the magnitude of the force of resistance in the equation of conservation of momentum in the gas phase, i.e., the medium is assumed to be quasi-solid (almost non-deformable during wind gusts); 4) let there be a so-called “ventilated” forest massif, in which the volume of fractions of condensed forest fuel phases, consisting of dry organic matter, water in liquid state, solid pyrolysis products, and ash, can be neglected compared to the volume fraction of gas phase (components of air and gaseous pyrolysis products); 5) the flow has a developed turbulent nature and molecular transfer is neglected; 6) gaseous phase density doesn’t depend on the pressure because of the low velocities of the flow in comparison with the velocity of the sound. Let the coordinate reference point $x_1, x_2, x_3 = 0$ be situated at the centre of the forest fire source at the height of the roughness level, axis $0x_1$ directed parallel to the Earth’s surface to the right in the direction of the unperturbed wind speed, axis $0x_2$ directed perpendicular to $0x_1$ and axis $0x_3$ directed upward (Fig. 1).

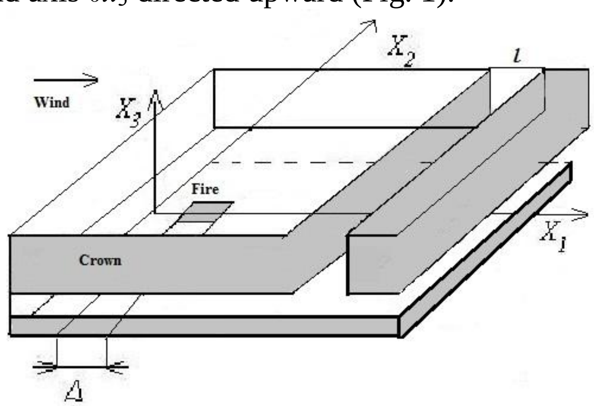

Figure 1.

Because of the horizontal sizes of forest massif more than height of forest, system of equations of general mathematical model of forest fire (Grishin 1997) was integrated between the limits from height of the roughness level - 0 to *h*. The problem formulated above is reduced to a solution of the following system of equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho v_j)=\dot{m}-(\dot{c}^- - \dot{c}^+)/h,\ j=1,2,\ i=1,2; \quad (1)$$

$$\rho\frac{dv_i}{dt}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}(-\rho\overline{v_i'v_j'})-\rho s c_d v_i\,|\vec{v}\,|-\rho g_i-\dot{m}v_i+(\tau_i^- - \tau_i^+)/h; \quad (2)$$

$$\rho c_p\frac{dT}{dt}=\frac{\partial}{\partial x_j}(-\rho c_p\overline{v_j' T'})+q_5R_5-\alpha_v(T-T_s)+(q_T^- - q_T^+)/h+k_g(cU_R-4\sigma T^4)\,; \quad (3)$$

$$\rho\frac{dc_\alpha}{dt}=\frac{\partial}{\partial x_j}(-\rho\overline{v_j' c_\alpha'})+R_{5\alpha}-\dot{m}c_\alpha+(J_\alpha^- - J_\alpha^+)/h, \alpha=1,5; \quad (4)$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_j}\right)-kcU_R+4k_S\sigma T_S^4+4k_g\sigma T^4+(q_R^- - q_R^+)/h=0, k=k_g+k_S; \quad (5)$$

$$\sum_{i=1}^{4}\rho_i c_{pi}\varphi_i\frac{\partial T_S}{\partial t}=q_3R_3-q_2R_2+k_s(cU_R-4\sigma T_S^4)+\alpha_V(T-T_S); \quad (6)$$

$$\rho_1\frac{\partial\varphi_1}{\partial t}=-R_1,\rho_2\frac{\partial\varphi_2}{\partial t}=-R_2,\rho_3\frac{\partial\varphi_3}{\partial t}=\alpha_C R_1-\frac{M_C}{M_1}R_3,\rho_4\frac{\partial\varphi_4}{\partial t}=0; \quad (7)$$

$$\sum_{\alpha=1}^{5}c_\alpha=1, p_e=\rho RT\sum_{\alpha=1}^{5}\frac{c_\alpha}{M_\alpha},\vec{v}=(v_1,v_2,v_3),\vec{g}=(0,0,g).$$

This system of equations must be solved taking into account the initial and boundary conditions:

$$t=0:\ v_1=0,\ v_2=0, v_3=0,\ T=T_e,\ c_\alpha=c_{\alpha e},\ T_s=T_e,\ \varphi_1=\varphi_{ie}; \quad (8)$$

$$x_1=-x_{1e}: v_1=V_e, v_2=0, v_3=0, T=T_e, c_\alpha=c_{\alpha e}, -\frac{c}{3k}\frac{\partial U_R}{\partial x_1}+\frac{cU_R}{2}=0; \quad (9)$$

$$x_1=x_{1e}:\frac{\partial v_1}{\partial x_1}=0,\frac{\partial v_2}{\partial x_1}=0,\frac{\partial v_3}{\partial x_1}=0,\frac{\partial c_\alpha}{\partial x_1}=0,\frac{\partial T}{\partial x_1}=0,\ \frac{c}{3k}\frac{\partial U_R}{\partial x_1}+\frac{cU_R}{2}=0; \quad (10)$$

$$x_2=-x_{2e}:\frac{\partial v_1}{\partial x_2}=0,\frac{\partial v_2}{\partial x_2}=0,\frac{\partial v_3}{\partial x_2}=0,\frac{\partial c_\alpha}{\partial x_2}=0,\frac{\partial T}{\partial x_2}=0,-\frac{c}{3k}\frac{\partial U_R}{\partial x_2}+\frac{cU_R}{2}=0; \quad (11)$$

$$x_2=x_{2e}:\frac{\partial v_1}{\partial x_2}=0,\frac{\partial v_2}{\partial x_2}=0,\frac{\partial v_3}{\partial x_2}=0,\frac{\partial c_\alpha}{\partial x_2}=0,\frac{\partial T}{\partial x_2}=0,\frac{c}{3k}\frac{\partial U_R}{\partial x_2}+\frac{cU_R}{2}=0. \quad (12)$$

The values of functions in the source of ignition are written using the formulas:

$$T = T_S = \begin{cases} T_e + \frac{t}{t_0}(T_0 - T_e), t \le t_0 \\ T_e + (T_0 - T_e)\exp\left(-k_0(t/t_0 - 1)\right), t > t_0 \end{cases}, \rho v_3 = h_0 \dot{m}, |x_1| \le \Delta_x, |x_2| \le \Delta_y, \quad (13)$$

Here and above $\frac{\mathrm{d}}{\mathrm{d}t}$ is the symbol of the total (substantial) derivative; α_V is the coefficient of phase exchange; ρ - density of gas – dispersed phase, t is time; v_i - the velocity components; T, T_S, - temperatures of gas and solid phases, U_R - density of radiation energy, k - coefficient of radiation attenuation, p - pressure; c_p – constant pressure specific heat of the gas phase, c_{pi}, ρ_i, φ_i – specific heat, density and volume of fraction of condensed phase (1 – dry organic substance, 2 – moisture, 3 – condensed pyrolysis products, 4 – mineral part of forest fuel), R_i – the mass rates of chemical reactions, q_i – thermal effects of chemical reactions; k_g , k_S - radiation absorption coefficients for gas and condensed phases, c - speed of light; T_e - the ambient temperature; c_α - mass concentrations of α - component of gas - dispersed medium, index α=1,2,3, where 1 corresponds to the density of oxygen, 2 - to carbon monoxide CO, 3 - to carbon dioxide and inert components of air, 4,5 – soot and ash; R – universal gas constant; M_α , M_C, and M molecular mass of α -components of the gas phase, carbon and air mixture; g is the gravity acceleration; c_d is an empirical coefficient of the resistance of the vegetation, s is the specific surface of the forest fuel in the given forest stratum, t_0 – the time formation of an ignition source, T_0 – temperature of combustion, k_0 – empirical coefficient. In system of equations (1)-(7) are introduced the next designations:

$$\dot{c} = \rho v_3, \tau_i = -\rho \overline{v_i' v_3'}, J_\alpha = -\rho \overline{v_3' c_\alpha'}, J_T = -\rho \overline{v_3' T'}$$

Upper indexes "+" and "-" designate values of functions at $x_3=h$ and $x_3=0$ correspondingly. It is assumed that heat and mass exchange of fire front and boundary layer of atmosphere are governed by Newton law ($\alpha = 300\ W/m^2K$) and written using the formulas:

$$(q_T^- - q_T^+)/h = -\alpha(T - T_e)/h,$$
$$(J_\alpha^- - J_\alpha^+)/h = -\alpha(c - c_{\alpha e})/hc_p$$

To define source terms, which characterize inflow (outflow of mass) in a volume unit of the gas-dispersed phase, the following formulae were used for the rate of formulation of the gas-dispersed mixture $\dot{m}$, outflow of oxygen R_{51}, changing carbon monoxide R_{52}.

$$\dot{m} = (1-\alpha_c)R_1 + R_2 + \frac{M_c}{M_1}R_3, R_{51} = -R_3 - \frac{M_1}{2M_2}R_5,$$

$$R_{52} = \nu_g(1-\alpha_c)R_1 - R_5, R_{53} = 0, R_{54} = \alpha_4 R_1, R_{55} = \frac{\alpha_5 \nu_3}{\nu_3 + \nu_{3*}}R_3.$$

Here ν_g – mass fraction of gas combustible products of pyrolysis, α_4 and α_5 – empirical constants. Reaction rates of these various contributions (pyrolysis, evaporation, combustion of coke and volatile combustible products of pyrolysis) are approximated by Arrhenius laws whose parameters (pre-exponential constant k_i and activation energy E_i) are evaluated using data for mathematical models.

$$R_1 = k_1\rho_1\varphi_1 \exp\left(-\frac{E_1}{RT_s}\right), R_2 = k_2\rho_2\varphi_2 T_s^{-0.5} \exp\left(-\frac{E_2}{RT_s}\right),$$

$$R_3 = k_3\rho\varphi_3 s_\sigma c_1 \exp\left(-\frac{E_3}{RT_s}\right), R_5 = k_5 M_2 \left(\frac{c_1 M}{M_1}\right)^{0.25} \frac{c_2 M}{M_2} T^{-2.25} \exp\left(-\frac{E_5}{RT}\right).$$

The initial values for volume of fractions of condensed phases are determined using the expressions:

$$\varphi_{1e} = \frac{d(1-\nu_z)}{\rho_1}, \varphi_{2e} = \frac{Wd}{\rho_2}, \varphi_{3e} = \frac{\alpha_c \varphi_{1e}\rho_1}{\rho_3}$$

where d -bulk density for surface layer, ν_z – coefficient of ashes of forest fuel, W – forest fuel moisture content. It is supposed that the optical properties of a medium are independent of radiation wavelength (the assumption that the medium is “grey”), and the so-called diffusion approximation for radiation flux density were used for a mathematical description of radiation transport during forest fires. To close the system (1)–(7), the components of the tensor of turbulent stresses, and the turbulent heat and mass fluxes are determined using the local-equilibrium model of turbulence (Grishin 1997). The system of equations (1)–(7) contains terms associated with turbulent diffusion, thermal conduction, and convection, and needs to be closed. The components of the tensor of turbulent stresses $\rho\overline{v_i' v_j'}$, as well as the turbulent fluxes of heat and mass $\overline{\rho v_j' c_p T'}$, $\overline{\rho v_j' c_\alpha'}$ are written in terms of the gradients of the average flow properties:

$$-\rho\overline{v_i' v_j'} = \mu_t\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) - \frac{2}{3}K\delta_{ij}, \; -\rho\overline{v_j c_p T'} = \lambda_t \frac{\partial T}{\partial x_j}, \; -\rho\overline{v_j c_\alpha'} = \rho D_t \frac{\partial c_\alpha}{\partial x_j},$$

$$\lambda_t = \mu_t c_p / \mathrm{Pr}_t, \rho D_t = \mu_t / Sc_t, \mu_t = c_\mu \rho K^2 / \varepsilon,$$

where μ_t, λ_t, D_t are the coefficients of turbulent viscosity, thermal conductivity, and diffusion, respectively; Pr_t, Sc_t are the turbulent Prandtl and Schmidt numbers, which were assumed to be equal to 1. In dimensional form, the coefficient of dynamic turbulent viscosity is determined using local equilibrium model of turbulence. The system of equations (1)–(7) must be solved taking into account the initial and boundary conditions. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different type of forest; such as, pine forest (Grishin 1997).

Numerical method and results

The boundary-value problem (1)–(13) is solved numerically using the method of splitting according to physical processes (Perminov 1995). In the first stage, the hydrodynamic pattern of flow and distribution of scalar functions was calculated. The system of ordinary differential equations of chemical kinetics obtained as a result of splitting was then integrated. A discrete analogue was obtained by means of the control volume method using the SIMPLE like algorithm (Patankar 1981). The accuracy of the program was checked by the method of inserted analytical solutions. Analytical expressions for the unknown functions were substituted in (1)–(7) and the closure of the equations were calculated. This was then treated as the source in each equation. Next, with the aid of the algorithm described above, the values of the functions used were inferred with an accuracy of not less than 1%. The effect of the dimensions of the control volumes on the solution was studied by diminishing them. The time step was selected automatically. Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. The distribution of basic functions shows that the process of crown forest fire initiation goes through the next stages. The first stage is related to increasing maximum temperature in the fire source. At this process stage the fire source a thermal wind is formed a zone of heated forest fire pyrolysis products, which are mixed with air, float up and penetrate into the crowns of trees. As a result, forest fuels in the tree crowns are heated, moisture evaporates and gaseous and dispersed pyrolysis products are generated. Ignition of gaseous pyrolysis products of the ground cover occurs at the next stage, and that of gaseous pyrolysis products in the forest canopy occurs at the last stage. As a result of the heating of forest fuel elements of crown, moisture evaporates, and pyrolysis occurs accompanied by the release of gaseous products, which then ignite and burn away in the forest canopy. At the moment of ignition the gas combustible products of pyrolysis burns away, and the concentration of oxygen is rapidly reduced. The temperatures of both phases reach a maximum value at the point of ignition. The ignition processes is of a gas - phase nature. The distribution of temperature, concentrations of gas products of pyrolysis and oxygen in the forest fire front are presented in the Figure 2. It is seen that the combustion wave looks like as a soliton. The oxygen concentration drops to near zero in front of a fire. It is consumed in the combustion of the pyrolysis products, the concentration of which reaches a maximum before the maximum temperature is reached

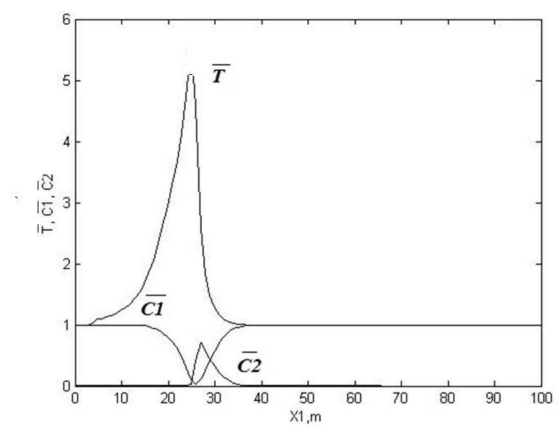

Figure 2.

The distribution of temperature $\bar{T}\,(\bar{T} = T/T_e, T_e = 300K)$, concentrations of gas products of pyrolysis $\bar{c}_2(\bar{c}_2 = c_2/c_{1e}, c_{1e} = 0.23)$ and oxygen $\bar{c}_1(\bar{c}_1 = c_1/c_{1e})$ in forest fire front.

Figures 3 - 4 present the distribution of isolines for temperature $\bar{T}\,(\bar{T} = T/T_e, T_e = 300K)$ (1- 1.5, 2 - 2., 3 – 2.6, 4 – 3, 5 – 3.5, 6 – 4.) for gas phase, concentrations of oxygen $\bar{c}_1$ (1 – 0.1, 2 – 0.5, 3 – 0.6, 4 – 0.7, 5 – 0.8, 6 – 0.9) and volatile combustible products of pyrolysis $\bar{c}_2$ (1 – 1., 2- 0.1, 3 – 0.05, 4 – 0.01) ($\bar{c}_\alpha = c_\alpha / c_{1e}, c_{1e} = 0.23$) for wind velocity V_e= 5 m/s (Fig.3) and V_e= 10 m/s (Fig.4) at h=10 m. The distribution of isotherms of combustion temperature shows the moving of forest fire front with time. Figure 3 shows that with the increase of wind speed up to 10 m/s increases the rate of fire spread to 5 m/sec. Ignition of forest due to spotting is one of the most difficult aspects to understand the behavior of fires. The phenomenon of spotting fires comprises three sequential mechanisms: generation, transport and ignition of recipient fuel. The present mathematical model and resulting calculations are used to illustrate the formation of large fires by combining small combustion sources arising from the transfer of firebrands. In order to understand these mechanisms, many calculation experiments have been performed.

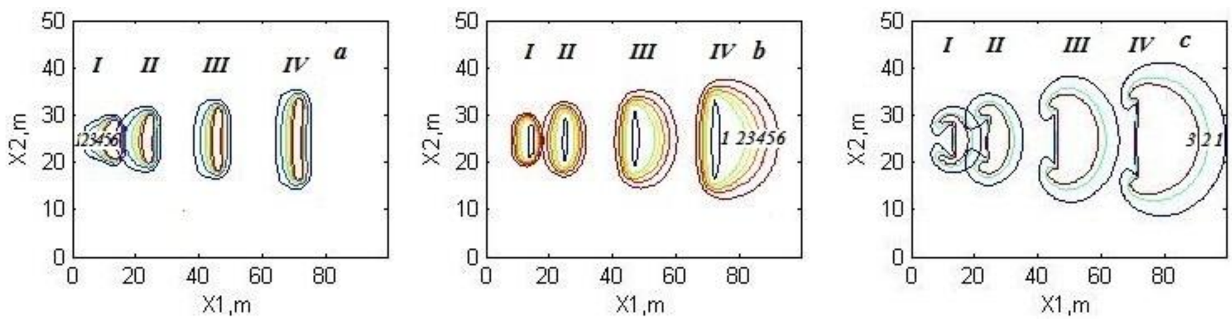

Figure 3.
The distribution of a) temperature for gas phase, b) concentration of oxygen and c) volatile combustible products of pyrolysis; V_e= 5 m/s, at different instants of time: I - t=3 sec., II - t=6 sec, III - t=12 sec., IV - t= 20 sec.

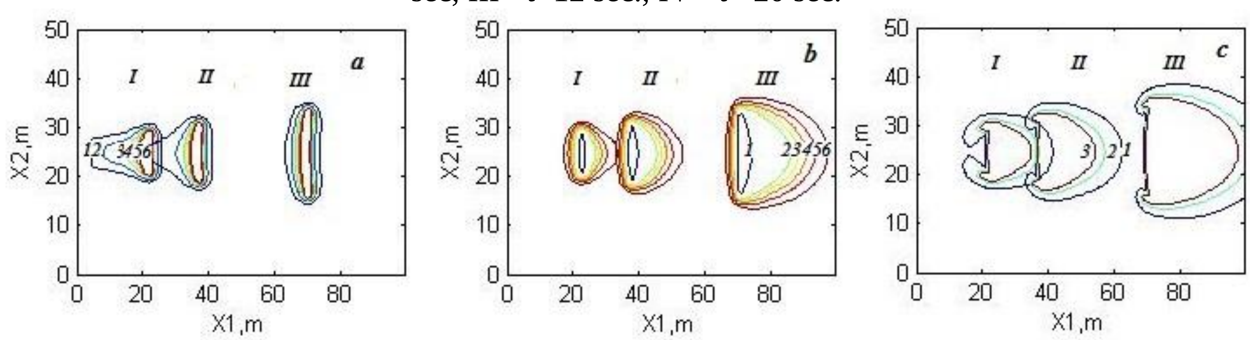

Figure 4.
The distribution of a) temperature for gas phase, b) concentrations of oxygen and c) volatile combustible products of pyrolysis; V_e= 10 m/s, at different instants of time: I - t=3 sec., II - t=6 sec, III - t=12 sec.

It is important to study the interaction of forest fire front with firebreak of finite size (glade) (Figure 5. a) temperature $\overline{T}$ for gas phase, b) oxygen $\bar{c}_1$, c) volatile combustible products of pyrolysis $\bar{c}_2$ concentrations). The distance between forest fire source and glade equals 84 m. Figures 5(a, b,c) show the results of numerical simulation of a forest fire spreading around the glade under the action of wind blowing through it at a speed 5 m/s in the direction of the Ox_1-axis. Initially, the source of the fire has the shape of a rectangular. Then isotherms are deformed under the action of wind and the contour of forest fire is look as crescent. When the fire (isotherms II in Figure 5 a) moves around the forest glade it is divided in two parts. But after that two fire fronts were joined in united fire (isotherms VI in Figure.5 a). Figures 5 (b, c) present the distribution of concentration of oxygen and volatile combustible products of pyrolysis $\bar{c}_2$ for this case.

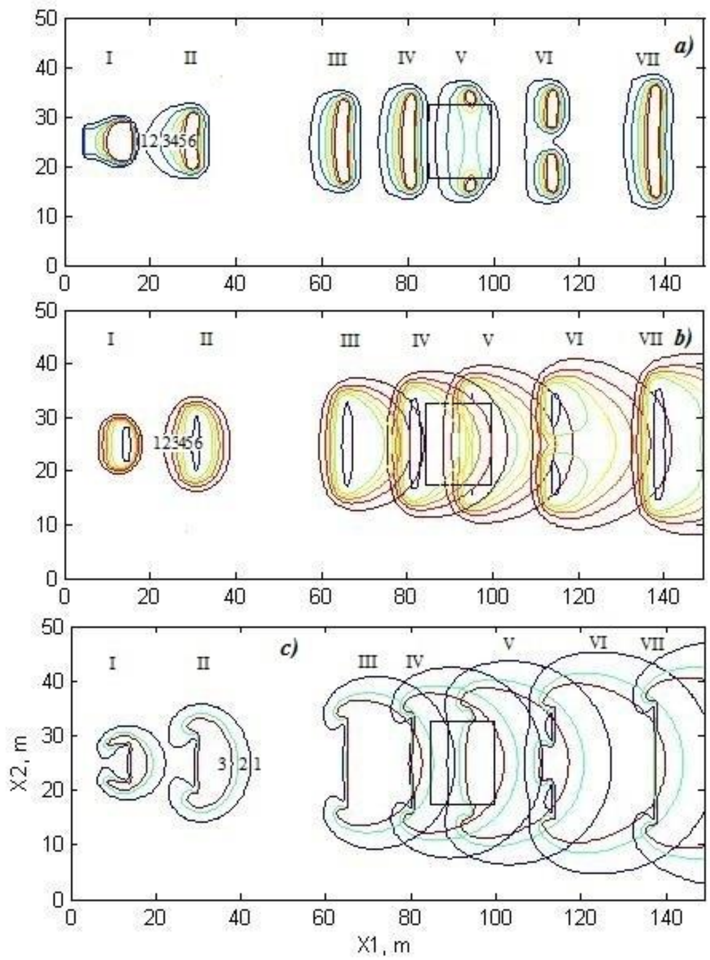

Figure 5.
I – t=3 s, II – 7 s, III - 12 s, IV - 18 s, V - 24 s, VI – 32 s, VII - 38 s; V_e=5m/s.

If the distance between the initial forest fire source and glade is decreased to 74 m the crown forest fire does not spread around the glade and the forest fire is burned away before this clearing (Figure 6. a) temperature $\overline{T}$ for gas phase, b) oxygen $\bar{c}_1$, c) volatile combustible products of pyrolysis $\bar{c}_2$ concentrations). It is interesting to study the influence of wind velocity, moisture content and bulk of forest combustible materials on the size of the fire breaks, which will ensure a non spread of forest fires. If the firebreak has infinite size these results are presented in the Figure 7. Of course the sizes of safe distance (firebreak) depends not only of wind velocity, but type and quality of forest combustible materials, its moisture, height of trees and others conditions. This model allows studying an influence all these main factors.

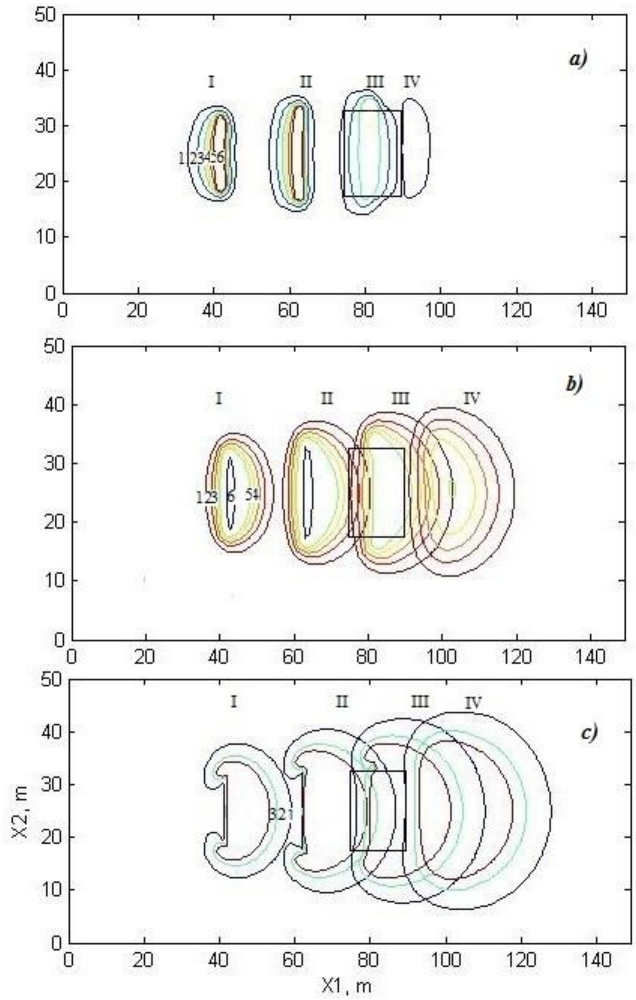

Figure 6.

I – t=3 s, II – 7 s, III - 12 s, IV - 18 s, V - 24 s, VI – 32 s, VII - 38 s; V=5m/s.

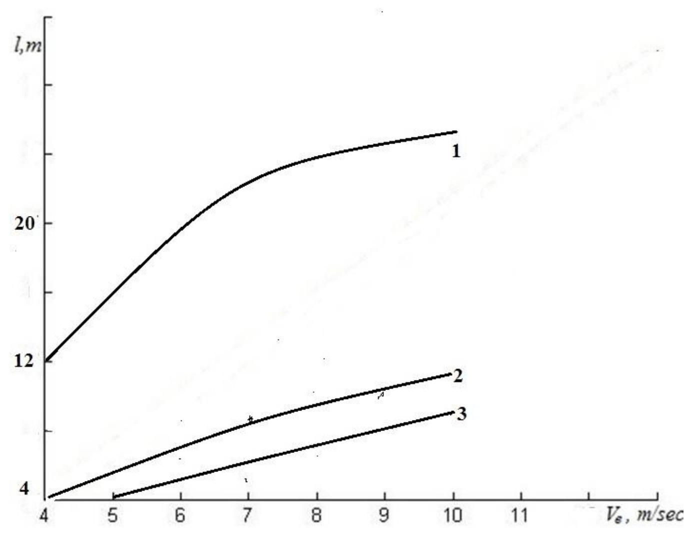

Figure 7.

The effect of wind speed on the size of firebreaks: 1-d=0.2 , w=0.4; 2 – d=0.2, w=0.6; 3 – d=0.4, w=0.6.

Conclusion

Results of calculation give an opportunity to describe the different conditions of the forest fire spread taking account different weather conditions and state of forest combustible materials, which allows application of the given model for predicting and preventing fires. It overestimates the rate of crown forest fire spread that depends on crown properties: bulk density, moisture content of forest fuel, wind velocity and etc. The model proposed here gives a detailed picture of the change in the temperature and component concentration fields with time, and determine as well as the influence of different conditions on the crown forest fire spreading for the different cases of inhomogeneous of distribution of forest combustible materials. The results of calculation of the rate of crown forest fire agree with the laws of physics and experimental data (Konev E.V. 1977; Grishin A.M. 1997).

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Unsteady phenomena affecting the propagation of surface fires

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Abstract:
Wind flow is certainly one of the most important factors affecting the behaviour of wildfires. However its effect upon the propagation of the fire front is not yet understood. The relationship between the rate of spread (ROS) and the wind speed velocity appears in the literature through a power law relation with an exponent varying between 0.5 and 1.5. Some experimental results related also some contra intuitive phenomena, such as a decrease of the ROS as the wind speed exceeds a certain value.

We have explored this problem using numerical simulations of surface fires through homogeneous vegetation layer. The numerical results have been analysed in terms of rate of spread, fire line intensity, Byram's convection number. Two regimes of fire propagation (plume dominated and wind driven) have been clearly identified. We also proposed a detailed analysis of the unsteady behaviour of fire intensity signals (average value, standard deviation, power spectrum analysis) and the consequences in terms of predictability of fire behaviour (see Figure 1). A set of numerical simulations was also carried out in adding a sinusoidal variation of the inlet wind velocity.

Additional Keywords: Wildfire behaviour, modelling, wind effect

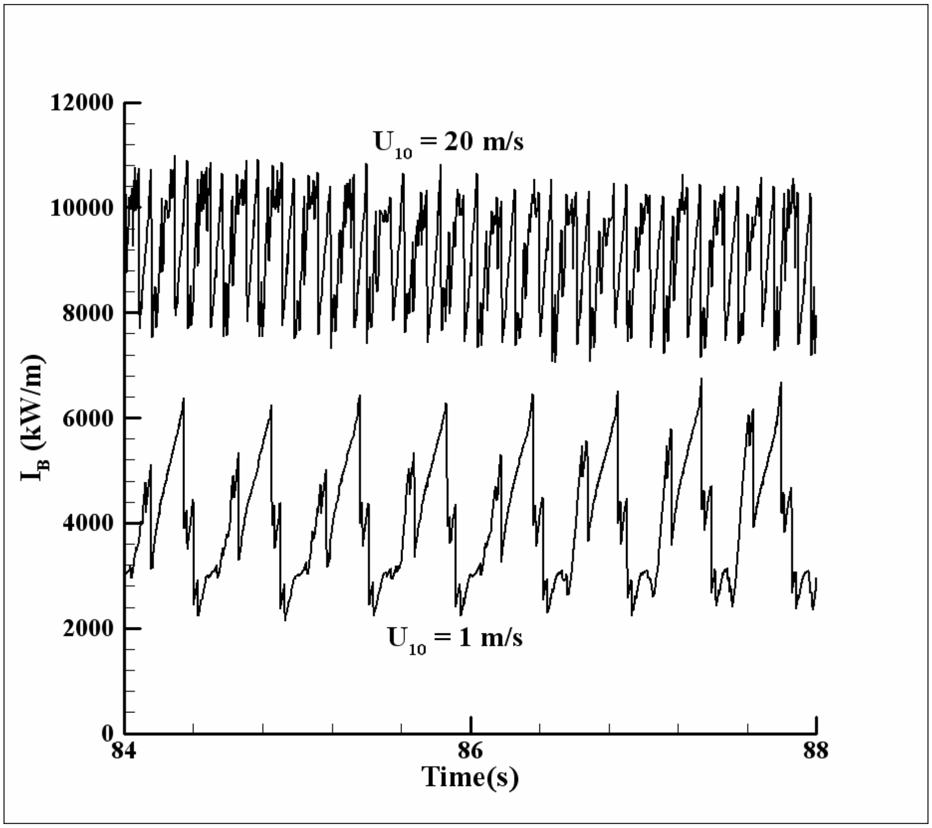

Figure 1: Time history of the fireline intensity for two wind conditions (U_{10} = 1 and 20 m/s).

Combustion chemistry and pyrolysis kinetics of forest fuels in wildfire modeling

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Abstract: Chemical processes play the major role in the combustion of forest fuels (FF) and in the emergence and spread of forest fires. Knowing the kinetics and the mechanism of FF pyrolysis, as well as of the kinetics and the mechanism of oxidation of pyrolysis products in flame is a necessary condition for developing an adequate model of FF combustion and a model of the emergence and spread of forest fires. This paper is dedicated to the study of the kinetics of oxidative pyrolysis of Siberian pine needles by the method of thermogravimetric analysis. Based on the analysis of experimental data, the kinetic parameters of this process were found, using three methods. To evaluate the quality of solving the problem of finding the parameters from the experimental data, dependences of mass loss and the mass loss rate on time were calculated and compared with experimental data. An experimental study of the fire spread through a pine needles bed was conducted under laboratory conditions, modeling ground fire. The fire spread rate depending on the wind velocity was measured.

Additional Keywords: Forest fire; thermogravimetric analysis; fire spread through a forest fuel bed; pine needle

Introduction

Chemical processes play the major role in the combustion of forest fuels (FF) and in the emergence and spread of forest fires. An important aspect of developing the physical and mathematical model of the emergence and spread of forest fires is knowing the quantitative characteristics of the physical and chemical processes taking place during ignition and combustion of forest fuels (FF), such as the kinetics and the mechanism of FF pyrolysis, the composition of the pyrolysis products, and the kinetics and the mechanism of these products' oxidation in flame. Good knowledge of the parameters of these processes allows computer simulation forecasts to be more exact and reliable. The major chemical stages during FF combustion are the following. 1.FF pyrolysis with volatile products formed (such as CO, CO_2, CH_4, light hydrocarbons – C_2H_2, C_2H_4, C_2H_6, C_3H_6 - and tar) and condensed char;

2.Heterogeneous reactions of char oxidation; 3.Gas-phase reactions of oxidation of volatile pyrolysis products.

Developing forest fires models is essentially slow down by the lack of experimental data on the kinetics and mechanism of the most essential chemical stages of FF combustion. In literature, there are numerous studies dedicated to investigating the kinetics and the mechanism of FF pyrolysis and pyrolysis of their components in inert and oxidative media (Grishin *et al.* 1991; Safi *et al.* 2004; Statheropoulos *et al.* 1997; Leoni *et al.* 2001; Senneca 2007; Haykiri-Acma and Yaman 2007; Leoni *et al.* 2003; Saddawi *et al.* 2010; Font *et al.* 2009; Liu *et al.* 2002; Schemel *et al.* 2008). However, there are few data on the pyrolysis kinetics of Siberian pine FF. There are quite a number of papers on the experimental studies and modeling of FF combustion and on forest fire spread, including the papers on the spread of ground forest or steppe fires (Tihay *et al.* 2008; Dupuy *et al.* 2003; Mell *et al.* 2009; Zhou *et al.* 2005; Webwr 1991; Porterie *et al.* 2000; Morvan and Dupuy 2004; Morandini *et al.* 2001; Balbi *et al.* 2007; Simeoni *et al.* 2003; Grishin 1992; Zhou and Mahalingam 2001; Leroy *et al.* 2008; Leroy *et al.* 2007). This paper is dedicated to the study of the kinetics of oxidative pyrolysis of Siberian pine needles, to finding the kinetic parameters of this processes, as well to the experimental study of the fire spread through a pine needles bed under laboratory conditions for the purpose of further application of these data to modeling of this process.

The experimental technique

Thermogravimetric analysis

Thermal decomposition at a low heating rate was conducted in a synchronous TG/DSC analyzer STA 409 PC (Netzsch) at different heating rates (10, 20, 30, 40 and 50 K/min) in oxidative (helium / 21% oxygen) media. The sample weight was 4 mg.

Measuring the fire spread through a pine needles bed

The experiments were conducted in a chamber (Fig. 1) 70 cm long, 15 cm wide and 30 cm high. Inside the chamber a bed of pine needles was placed in the center, 8 cm wide and 34 mm long. The quantity of pine needles was about 0.07 g/cm^2. The pine needles were placed on an asbestos board 10 mm thick into a space restricted by chamotte (fire-proof clay) plates 18 mm high, as shown in Fig. 2. Air was delivered into the combustion chamber from an air blower producing 110 (liters of air)/s. On the way of the air blow was a slide gate, with fine adjustment of the gate

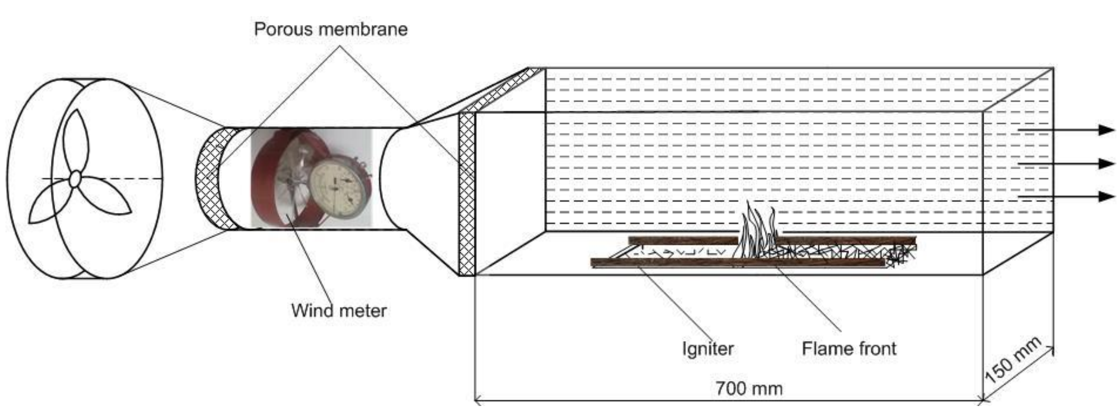

Fig. 1. A chamber for measuring the fire spread rate through a pine needles bed.

Fig. 2. The photo of a board with a pine needles bed.

Fig. 3. A photo of the fire spread process

movement. Then air passed through a porous filter to form uniform air-flow. The air-flow rate was controlled with a calibrated anemometer. Pine needles were ignited with nichrome wire 0.4 mm in diameter, heated with electric current to a glowing state. The igniting wire was placed in the middle of the pine needle bed 10 mm above the board surface. To prevent sagging of the wire during heating, it was pulled with a spring. The side walls of the combustion chamber were made from transparent glass 4 mm thick, with the video recording of the pine needles ignition and combustion process, with the given air flow rate, imitating the wind velocity above the needles bed. The wind velocity varied from 0.10 m/s to 1.5 m/s, with spacing of 0.1 – 0.2 m/s. The fire-spread velocity was determined based on the video recording of the combustion process. A photo of the combustion process is shown in Fig.3. Pine needles litter was taken from under pine forest trees, then the needles were separated from leaves and twigs, so that only needles were in the litter. The needles thus obtained were then dried at the temperature of 60 °C during 24 hours in a cabinet dryer. After the experiment, the unburned residue was weighed.

The results of kinetic analysis of thermogravimetric data
To find the kinetic data, several methods were used.

Method 1 (“Iterations method”)
To obtain the kinetic parameters of FF pyrolysis, a software program developed by the authors was used, the algorithm of which was based on an assumption that the model of this process should include two independent stages – first-order reactions. In processing, it is considered that each stage proceeds in its own temperature range and that the temperature ranges of individual stages do not overlap. As each stage proceeds, condensed reaction products are formed. For each stage, dependence is calculated of the relative mass loss, during which the value of the conditionally non-reacting residue remaining after the stage is taken into account.

The main part of this algorithm is finding the activation energy and the pre-exponent by the iteration method. The iteration algorithm of calculating the activation energy is based on a modified dichotomy method (the method of half division of the parameter search area). First an assumption is made on determination of the maximum and minimum values of the activation energy (E_{min} и E_{max}), then, from these values the average geometric value is found E_{test}. The value E_{test} obtained is used to estimate the species consumption and further to calculate the pre-exponential factor. Then, based on the activation energy and the pre-exponential factor, deviation of the experimental data from the computational ones (obtained by the algorithm described above) is calculated. Based on the analysis of deviation between the experimental and computational data, a conclusion is made regarding either the necessity of iterating the entire procedure of computation (with a changed value E_{test}), or its termination. The computation data for rate constants are shown on Table 1.

Table 1. Rate constants of oxidative pyrolysis of Siberian pine needles, obtained by three methods

	lgk_0, k_0 (1/min)	E_a, kJ/mol
Method 1, stage 1	10.02	120.48
Method 1, stage 2	8.09	117.75
Method 2, stage 1	7.083	99.27
Method 2, stage 2	8.09	133.52
Method 3, stage 1	9.83	118.41
Method 3, stage 2	15.49	219.24

To evaluate the quality of solving a reverse problem for the parameters obtained, a direct problem is solved in accordance with a system of equations, then the mass of the solid phase species is evaluated, which is compared with the experimental data. It is to be emphasized that in solving the direct problem, computation is conducted in assumption of two consecutive reactions, with the characteristic temperature range overlapping. To evaluate the quality of the solution of the reverse problem, solution of the direct problem is obtained in accordance with the available system of equations.

$$\frac{dm_1}{dt} = -R_1; R_1 = m_1 k_1 \exp\left(-\frac{E_1}{RT}\right)$$

$$\frac{dm_2}{dt} = -R_2 + \alpha_1 R_1; R_2 = m_2 k_2 \exp\left(-\frac{E_2}{RT}\right)$$

$$\frac{dm_3}{dt} = +\alpha_2 R_2$$

Here R_i – reaction rates of different stages, α_1 – the ratio of char output to consumption of the initial substance for a pyrolysis reaction, α_2 - the ratio of ash output to char consumption for a char oxidation reaction. Them the mass of the solid-phase substance is evaluated

$$m_{эксп} = m_1 + m_2 + m_3$$

(here m_1, m_2, m_3 – masses of the initial substance, char and ash), which is compared with the experimental data. These data allow us to evaluate how adequately the fitted parameters describe the experimental curves TG and DTG.

Shown in Fig.4 (left) are the results of TG analysis for pine needle pyrolysis in an oxidative medium (20% O_2). In this figure, the blue curve represents experimental data, and the red line shows solution of the direct kinetic problem, with fitted kinetic parameters. It can be seen from the figure that pyrolysis occurs in two stages, having different temperature ranges. Shown in Fig 4 (right) are the dependences of the mass loss rate (DTG) relating to the experimental data and to

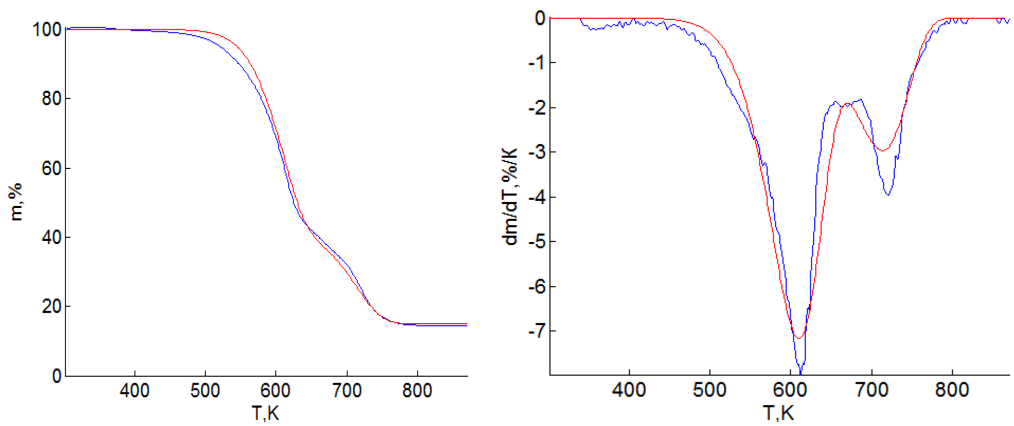

Fig. 4. Comparison of experimental data with the results of fitting (selecting) kinetic constants of pine needles in an oxidative medium (20% O_2)

the data obtained from solution of the direct kinetic problem. It can be seen from these figures that the fitted kinetic parameters ensure satisfactory agreement between the experimental and computed data.

Method 2 (approximation with a formula obtained from an analytical solution for two consecutive reactions)

The oxidative pyrolysis process is viewed as two first-order consecutive reactions:

$$A \rightarrow \alpha_1 B \rightarrow \alpha_2 C,$$

where A – the initial substance, B – the intermediate condensed reaction product (char), C – the end product of the reaction (ash) with reaction rate constants for both stages: $k_1=A_1\cdot\exp(-E_1/RT)$, $k_2=A_2\cdot\exp(-E_2/RT)$.

The analytical approximated solution of this system is described by the following equations (Warnatz *et al.* 2001): $A=A_0\cdot\exp(-k_1\cdot x)$, $B=B_0(k_1/(k_1-k_2)\ \{\exp(-k_2\cdot x)-\exp(-k_1\cdot x)\}$. The resulting change of mass is expressed by the function: f(x)=A+B+C. Dependence f(x) is fitted to the experimental dependence TG, % from x, min, with the procedure of non-linear regression analysis (we used the SigmaPlot package, but the Origin software and other codes have similar possibilities), leading to finding both the kinetic parameters of stages A_1, A_2, E_1, E_2 and the fraction of forming the intermediate product α_1 and the fraction of forming ash α_2. The kinetic parameters are shown in Table 1. To evaluate the quality of solving the reverse problem for the parameters obtained, solution of a direct problem is found for A, B and C, their sum and a derivative of this sum by time are obtained. Comparison of these values with the experimental data (Fig. 5) demonstrates their satisfactory agreement.

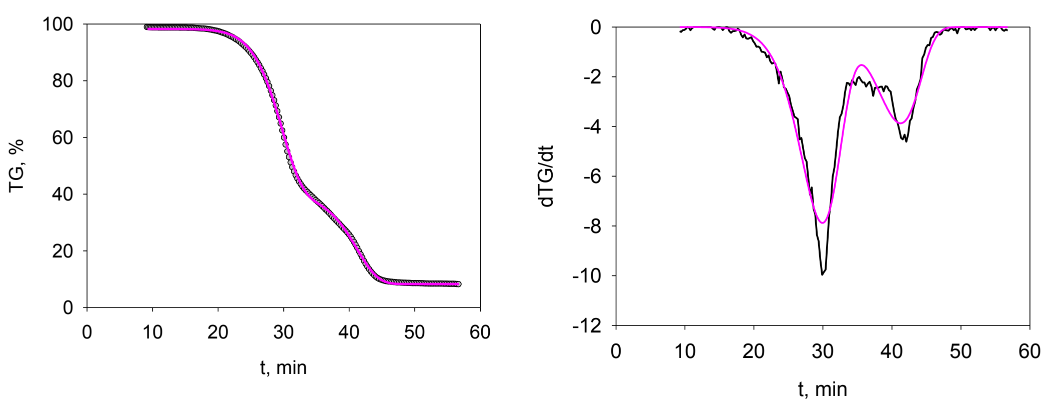

Fig. 5. Profiles of mass loss (left) and of mass loss rate (right) of a sample – a pine needle in oxidative medium as a function of time. The heating rate is 10 K/min. The dark curve indicates the experimental data, the colored curve represents modeling data.

Method 3. Kinetic analysis of FF pyrolysis using the multi-component devolatilization
Another method was also applied, used by (Orfao *et al.* 1999), who studied thermal decomposition behavior of cellulose, xylan (representative of hemicellulose) and lignin under nitrogen and air by TGA. In this method, the mass loss process of forest fuels is modeled by four

parallel reactions, nominally corresponding to the decomposition of three main components of biomass (hemicellulose, cellulose and lignin) and char oxidation (Chen *et al.* 2006; Momoh *et al.* 1996; Senneca *et al.* 2002).

The overall conversion rate of forest fuel in helium/oxygen is described by the sum of the conversion rates of four pseudo reactions,

$$\frac{d\alpha}{dT} = \sum_{i=1}^{4} c_i \frac{d\alpha_i}{dT} \tag{1}$$

where c_i is the proportion of pseudo reaction i and $\sum_i r_i = 1$. The conversion α is defined as

$$\alpha = \frac{m_0 - m}{m_0 - m_\infty} \tag{2}$$

Here m is sample weight recorded by TGA, and m_0 the initial weight of sample, m_∞ the final weight of sample. Therefore the mass loss rate of sample can be expressed as

$$\frac{dm}{dT} = -(m_0 - m_\infty)\sum_{i=1}^{4} c_i \frac{d\alpha_i}{dT} \tag{3}$$

For each pseudo reaction, it is often that an irreversible first-order reaction models is assumed. That is, the conversion rate is described by

$$\frac{d\alpha_i}{dT} = \frac{A_i}{\beta}\exp(-\frac{E_i}{RT})(1-\alpha_i)^{n_i} \tag{4}$$

The simultaneous determination of the kinetic parameters for each reaction, and therefore determination of Eq(3), was performed by minimizing the S_{DTG} coefficient of the experimental data (T , $d\alpha / dT$),

$$S_{DTG} = \sum_j S_j = \sum_j \sum_k [(dm/dT)^{\exp} - (dm/dT)^{simu}]^2 \tag{5}$$

where the superscripts of "*exp*" and "*simu*" are the experimental and simulated values. j is the number of experimental curves and k is the number of data points of each experimental curve. The minimization of S_{DTG} was carried out with the Levenberg–Marquardt non-linear fitting algorithm by Matlab software.

One parameter, Dev, is proposed to evaluate the deviation between the experimental and calculated curves as follows,

$$Dev = \frac{\sqrt{S_{DTG}/(jk)}}{\max[-(dm_j/dT)^{\exp}]} \tag{6}$$

This parameter can reflect the matching performance of the experimental and simulated curves. The results of calculating the reaction rate constants of all four reactions are shown in Table 2.

Table 2. The results of calculating the reaction rate constants of all four reactions.

Reaction	Fraction of the stage	lgk_0, k_0 (1/min)	E, kJ/mol	Deviation
1	0.35	15.65	184.22	2,25 %
2	0.1	8.97	99.79	
3	0.27	5.4	74.03	
4(char)	0.23	15.49	219.24	

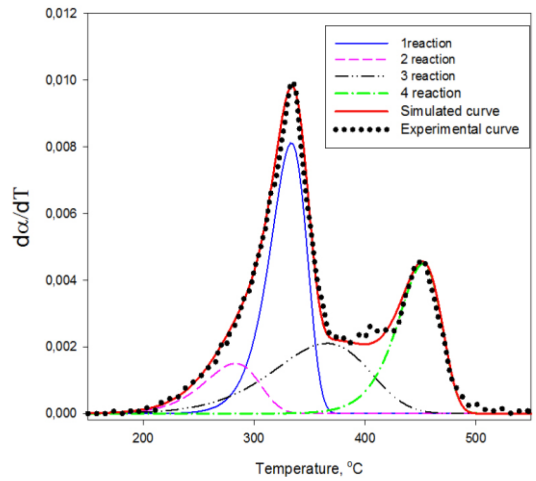

Fig. 6. Comparison of experimental data and of modeling results of the pine needles mass loss rate with constants of a multi-component reaction mechanism fitted with method 3.

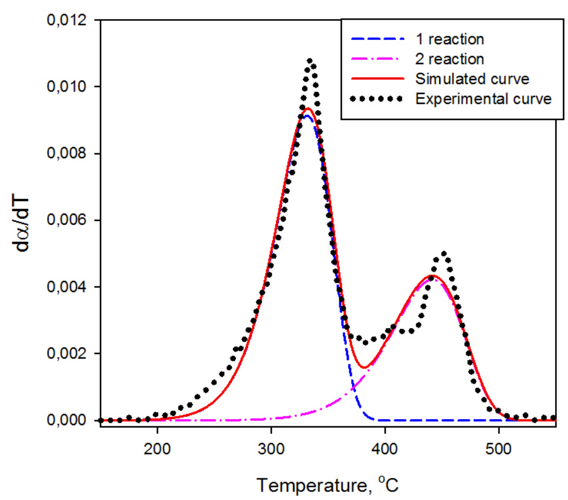

Fig. 7. Comparison of experimental data and of modeling results of the pine needles mass loss rate with constants of a two-stage reaction mechanism fitted with method 3

The results of modeling the mass loss and the mass loss rate for pine needles using mechanism with four parallel reactions are compared with the experimental data in Fig. 6. This figure also demonstrates the contribution of each reaction to the simulated curve. Reactions 1, 2 and 3 are responsible for pyrolysis of cellulose, hemicellulose and lignin, accordingly, while reaction 4 is responsible for char oxidation. The reaction rate constant for char oxidation during oxidative pyrolysis of pine needles is also shown in Table 1. In fire modeling, the use of a kinetic mechanism consisting of four reactions is less convenient than the use of a mechanism consisting of two reactions. Therefore an effective constant of oxidative pyrolysis of pine needles was obtained from the results of analyzing the experimental data shown above and conducted in assumption of two reactions. The results of calculating the first stage reaction rate constant are shown in Table 1, while the results of modeling the mass loss rate of the pine needles with the mechanism consisting of two parallel reactions are compared with the experimental data in Fig.7.

Results of the experiment on fire spread through a pine needles bed

Shown in Fig. 8 are the results of measuring the dependence of the velocity of fire spread through a pine needles bed on wind velocity without a slant (circles) and with a 10° slant of the board (squares). Fig. 9 demonstrates the results of measuring the fraction of burnt-out pine needles depending on wind velocity without a slant (circles) and with a 10° slant of the board (squares).

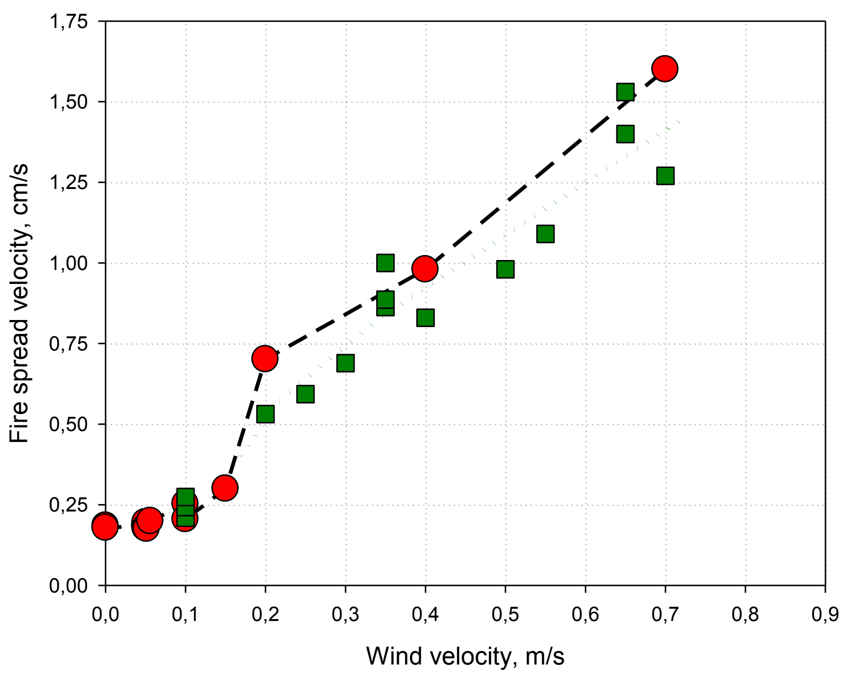

Fig. 8. Dependences of the fire spread velocity through a pine needles bed on wind velocity in experiments without a slant (circles) and with a 10° slant of the board (squares)

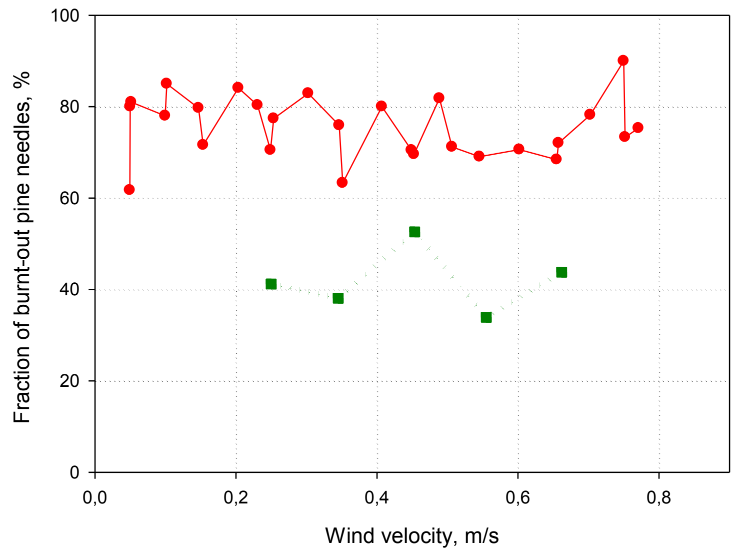

Fig. 9. Dependences of the fraction of burnt-out pine needles on wind velocity in experiments without a slant (circles) and with a 10° slant of the board (squares)

Discussion of results and conclusion

Shown in Fig. 10 in Arrhenius coordinates analysis of the rate constants of the first stage of the pine needles pyrolysis obtained by three methods showed the first and the third method to produce close results.

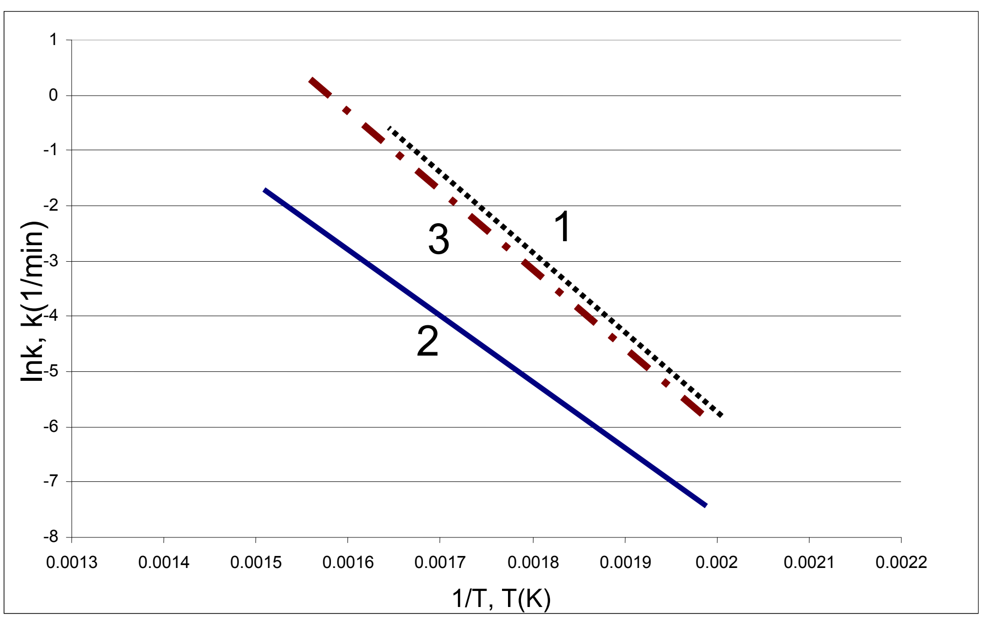

Fig. 10. Rate constants of the first stage of the pine needles pyrolysis obtained by three methods in Arrhenius coordinates; 1, 2 and 3 correspond to methods 1, 2 and 3, accordingly.

The data for the rate constant of the first pyrolysis stage obtained by the method 2 differ from the methods 1 and 3 by an order of magnitude. Therefore we recommend data obtained by methods 1 and 3 for modeling ground fire. As for the rate constants of the second stage of pine needles pyrolysis in oxidative medium (char oxidation reactions with air oxygen), considerable spread in activation energies obtained by three methods should be noted, although the absolute values of the rate constant at the temperature 670 K differ by an order of magnitude. The experimental data on the fire spread velocity through a pine needles bed and the data on the rate constants of pine needles pyrolysis may be used in modeling ground fire spread.

Acknowledgment
This work was supported by RFBR under grant #13-03-91164 and by by the NNSF of China under Grant 51120165001 and 51176179.

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The impact of external velocity field on the behavior on landscape fire

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Abstract:
This paper describes factors that influence the dynamics of the spread of ground fires, such as the wind blow through woodland and topography of the underlying surface. In this paper, we provide a numerical simulation of the dynamics of ground fire spread to different vegetation types and varying degrees of air-flow through the forest. The relief affects the front of the fire. The front of fire on the rise expands while on the way down, it narrows. Obstacle shaped gully promotes the flow of oxygen in the combustion of the pyrolysis products of the active flame due to a vortex that leads to active fading and as a result, a lower concentration.

Additional Keywords: Fire control, numerical simulation, forest fire, landscape fire

Introduction

An important component of firefighting is the prediction of fire propagation. This paper addresses issues related to the influence of topography on the dynamics of a fire. With the growth of human activity, the number of forest fires is increasing, so fire-fighting procedures should be improved.

Model description

The basis of the calculations is a physic-mathematical model (Kataeva 2009; Maslennikov 2012) and Harlow scheme was used for computations (Babkin 2006). The most commonly used method, the Geer method, is used for modeling physical and chemical processes (Kataeva 2008). In this study we used the first-order accurate scheme that is connected, on the one hand, with the need to minimize the computation time and, on the other hand using them ensures the stability of and conservativity (Maslennikov 2012). Furthermore, algorithm of placement data in memory was used to reduce the computation time (Romanov 2012). In contrast to previous work which assumes a constant angle of inclination of the underlying surface (Kataeva 2010), in this paper relief is represented as a broken line with varying inclines (Maslennikov et al. 2012).

Results and analysis

We obtained the temperature distribution of the gas and condensed phases of oxygen concentrations of volatile pyrolysis products and the velocity field for the different geometry of the terrain on the moments of fire and varying air flow through the forest. The results are in good agreement with published data on fire behavior on an inclined surface, namely the wind speed increases with height, so that the fire front is tilted in the direction of propagation, as the development proceeds.

Table 1 shows estimates of the propagation velocity of fire on different areas. Segment 50 - 105 m - corresponds to the windward slope in the case of fire spreading over the hill and leeward for the propagation of across the ravine. Segment lot is 105 - 145 m - corresponds to the spread of the plain for all the cases. Segment 145 - 200 m - corresponds to the downhill fire from the hill and climb out of the ravine.

Table 1

The velocity of fire propagation at areas with different terrain.

Coordinates of segment, м	Velocity of fire propagating through the area with a hill, m / s	Velocity of fire propagating through plain terrain	Velocity of fire propagating through the area with a ravine, m / s
50-105	3,44	3,22	2,61
105-145	3,25		3,00
145-200	2,72		3,67

Table 1 shows that the velocity of fire in areas without inclination approximately equal on the plateau of the hill. It is slightly higher due to the effects of flow. The highest speed of fire is observed at the outlet of the ravine, which is associated with a high angle flame envelope.

Acknowledgements

This work was supported by RFBR 13-03-91164-NNSF_A "Experimental study of the kinetics and mechanism of thermal decomposition of combustible forest materials and processes flame spread upon the layer" and the Ministry of Education and Science of the Russian Federation within the framework of the contract № 02.G25.31.0006 from 12.02.2013, the (Government of the Russian Federation dated April 9, 2010 number 218).

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Fuel Treatment Effectiveness in Reducing Fire Intensity and Spread Rate – An Experimental Overview

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Additional Keywords: Prescribed fire, fire behavior, field experiment

Introduction

Fuel treatments represent a significant component of the wildfire mitigation strategy in the United States. However, the lack of research aimed at quantifying the explicit effectiveness of fuel treatments in reducing wildfire intensity and spread rate limits our ability to make educated decisions about the type and placement of these treatments. As part of a larger project designed to address this knowledge gap, an experiment was conducted in the New Jersey Pine Barrens.

This experiment, the first in a set of two, both of which aim to compare bounding levels of fuel treatment, was focused on evaluating fire behavior in an untreated block of forest. The evaluation was carried out via the observation and measurement of an operational prescribed burn. Within the larger framework of the study, this experiment was designed from the outset to provide information that is easily translatable to fire modeling applications. By simulating these experiments, as well as other similar hypothetical cases, this project will serve as a proof of concept that such models can be an effective tool for studying fire behavior and eventually informing management policy and decisions.

Study Site

The experiment was conducted in the Pinelands National Reserve in southern New Jersey, USA. The Pinelands is the largest continuous forested landscape on the Northeastern coastal plain, and covers about 23% of New Jersey. The climate is cool temperate, with mean monthly temperatures of 0.3 in January and 24.3 °C in July. The terrain consists of plains, low-angle slopes and wetlands, with a maximum elevation of 62.5 m. Uplands consist of oak- and pine-dominated forests that have a higher frequency of severe wildfires than most forests in the northeastern United States. The Pinelands are the focus of an active fuels management program by the New Jersey Forest Fire Service and federal wildland fire managers. The stand was approximately 15 acres, and was predominantly Pitch pine (*Pinus rigida* Mill.) with scattered oaks (*Quercus* spp.). Understory vegetation consisted of scrub oaks, huckleberry (*Gaylussacia* spp.) and blueberry (*Vaccinium* spp.).

Methods

Data related to the fire-environment were collected by a combination of 4 overstory (12.5 m) and 12 (6.5 m) understory measurement towers. 8 thermocouples and a sonic anemometer were positioned on each overstory tower, with one tower being positioned outside of the burn area to monitor ambient conditions. The understory towers supported 5 thermocouples, a vertically oriented flow sensor, and a vertically oriented dual-band radiometer. Additionally, 3 Fire Behavior Packages recorded temperature, vertical and horizontal flow, total heat flux, and both hemispherical and narrow angle radiative heat flux at a height of ca. 1 m. Fire spread was also monitored using the RIT WASP multi-spectral airborne imaging equipment. This provides a time series of georeferenced still aerial imagery in the spectral ranges of 1.0-1.7 μm, 3.0-5.0 μm, 8.0-9.2 μm, and visible, at an accuracy of less than 1 m. Lastly, visual observation was supplemented by the strategic placement of 14 visible spectrum cameras, intended to captured details of local fire spread and flame heights.

Data on the fuel loading within the plot were obtained through a combination of field sampling and remote sensing. In the field, 3 clip plots, 1 m^2 in area, were taken at each of the 12 understory tower locations both pre- and post-burn. This provided information on the distribution of surface and shrub fuels amongst various classes (foliage and live and dead 1-hour, 10-hour and 100-hour fuels), as well as the relative consumption of each class. Pre- and post-fire 3D canopy structure was assessed via airborne Light Detection and Ranging (LiDAR). Data were collected at 400 kHz and the resulting pulse density was ca. 5.12 points m^{-2}. Processing will result in outputs of typical LiDAR derived parameters such as mean and max height and canopy height profiles at ca. 10 m x 10m x 1 m resolution. LiDAR outputs will be calibrated to profiles of CBD from an upward-sensing LiDAR unit in twelve 20 x 20 meter plots within the burn area. This unit has been previously calibrated to represent profiles of CBD using equations developed through destructive harvest by Clark et al. (2013).

Results and Discussion

The fire was ignited by drip torch along a road, starting at the northern tip of the block, at approximately 11:53 am EST on 5 March 2013. Ambient temperature during the burn was ca. 6 to 7 °C, with a relative humidity of 40%. Winds were predominantly from the northwest and did not exceed a magnitude of 7 m s^{-1}, with mean values in the range of only about 1.6 m s^{-1}, measured at 12.5 m by the sonic anemometers. While a portion of the fire behavior data remains to be processed, a preliminary assessment can be made. Video footage confirmed observations that the fire was predominantly a surface fire, with some torching of crowns. Using simplified assumptions, an initial estimate of spread rate was 0.19 m s^{-1}, which falls within the range reported for other surfaces fires with low wind by Morandini and Silvani. Additionally, measurements of integral radiant flux correspond to the range for high intensity surface to brush fires reported by Frankman et al. . Canopy architecture and fuel consumption data from the

LiDAR is also in the processing stage at this time. However, the clip plot data shows that the majority of fuel mass consumed was fine and 1hr fuels on the forest floor, and 1hr fuels in the shrub layer.

Conclusions

The eventual availability of additional data, particularly aerial IR imagery, will serve to provide a much more complete picture of the fire timeline, as well as detailed information about local spread rates. LiDAR data will yield more information about the 3D distribution of consumption throughout the block, and can be tied to fire behavior data to calculate fire intensities. The importance of this experiment can be evaluated when seen in the context of the additional experimental and numerical aspects of the project. This presentation of preliminary data shows the detailed manner in which the fire was documented and measured. Such detail will provide an excellent platform for comparison to the second planned experiment, and to the results of numerical simulation. In turn, detailed comparisons will yield valuable insights into the effectiveness of prescribed fire treatment measures in modifying fire behavior. In a broader context this experiment provided detailed data useful for understanding fire behavior and validating models.

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Wildfires and ways to combat them

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Abstract:
Currently known and widely used in practice, the following are basic ways to combat forest fires of varying intensity (Grishin *et al*., 2007):

1. Rebounding up through the front bottom of the forest fire.
2. Burying the edge of a forest fire ground.
3. Laying mineralized bands tractor plow.
4. Clearing fire breaks of forest fuel.
5. Extinguishing with water using portable backpack forest sprayers.
6. Extinguishing by aircraft.

This report summarizes the development of the Department of Physical and Computational Mechanics together with the Institute for Applied Mathematics and Mechanics on methods and devices of localization and extinguishing forest, steppe, and peat fires.

This report also addresses issues associated with the development of highly efficient and rapid localizing and extinguishing of the hearth burning in peat, based on the idea of introducing the inert gas in the center of the combustion or the surrounding area of this focus under pressure. Thus, there is a displacement of the air and then peat replacement by an inert gas that does not support combustion.

Additional Keywords: Wildfire, prediction, fire hazard, anthropogenic pressure, pyrolysis.

Introduction

The urgency of the study of natural fires and how to combat them is beyond doubt, because in the future, as predicted by climate experts, in most countries there will be warmer and drier summers. For example, in July and August 2010, due to heat and lack of rainfall, Russia experienced a difficult situation with forest fires. The area burned, according to the Federal State Statistics Service of the Russian Federation, amounted to 1,962,333 hectares.

Summer 2012 showed that the situation with firefighting abroad is not better. For example, in the United States the largest fire in its recorded history took place in Colorado. Also in 2012, similar situations occurred in Greece, Croatia, Portugal and France.

The situation in Russia in 2010 and international situations from 2012 show the shortcomings of existing forest monitoring systems and the low efficiency of the methods used contain and extinguish wildfires.

The development of the Department of Physical and Computational Mechanics together with the Institute for Applied Mathematics and Mechanics on methods and devices of localization and extinguishes forest, steppe and peat fires:

- The method of localization ground fires (Grishin *et al*., 2009);
- Device for localization and extinguishing ground fire (Grishin *et al*., 2001);
- Consignment cord charge for containment and extinguishing of forest fires (Grishin *et al*., 2007);
- Disintegrator front of ground forest fire with extinguishing patron (Grishin *et al*., 1998);
- The combined method of localization and extinguishing ground forest and grassland fires (Grishin *et al*., 2012);
- The method of localization and extinguish of peat fires.

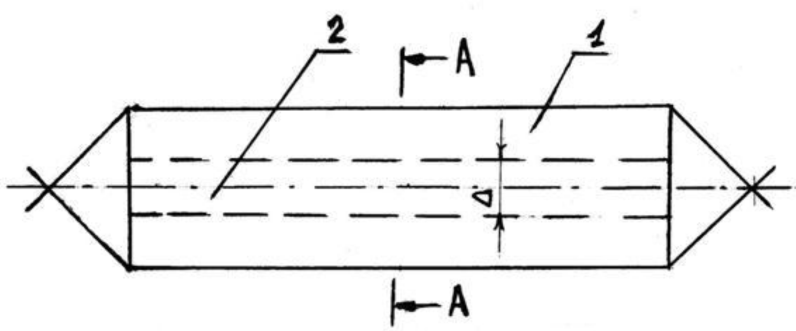
All of these methods divided into three groups: 1 – physics and mechanical, 2 - chemicals 3 - localization and stewing using shock waves produced during blasting explosive charges, and powder charges.

Methods, which belong to the first group (for example, the method of "entanglement" front by the water pumps, aircraft etc.), is not found wide application in practice, because they have high cost of implementation.

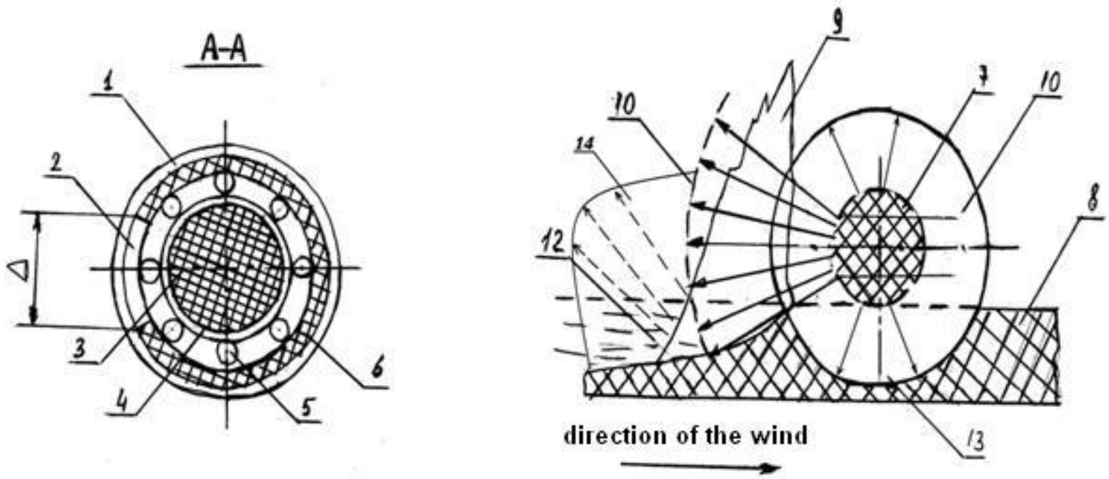
Annealing of forest fuels in front of a fire, which widely used in practice, should be include to the chemical group, which reffered in the books of Grishin (1992, 1999). Low efficiency and environmental friendliness of these methods are the main reason for their rare use in practice.

More effective ways to contain and extinguish with explosive and shock waves (third group), which are formed in blasting hose charge type PZHV-20 and ES-1p. When they are undermining, the efficiency of formation of mineralized bands is high.

Blasting ways to deal with forest fires are mainly related to passive, as their action is directed in advance to create mineralized bands. Method that uses an overhead rope charge containing explosive cartridges supposed as part of this approach to localization and extinguishing forest fires (pic. 1-2).



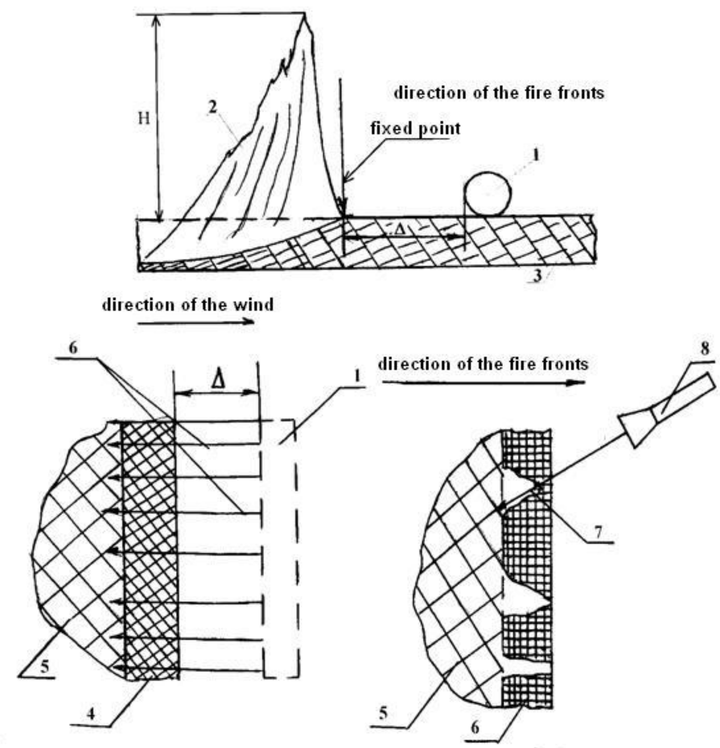
Pic. 1. General view of the surface-rope charge



1 - external elastic shell, 2 - slot 3 - chuck explosive, 4 - paper cup, 5 - зower thread, 6 - sheath, 7 - charge at the time of the explosion, 8 - ground cover, 9 - the flame, 10 - range action of a jet, 11 - the scope of the shock wave, 12 - burned area on the underlying surface, 13 - mineralized groove

Pic. 2. The scheme of the action of the explosion products

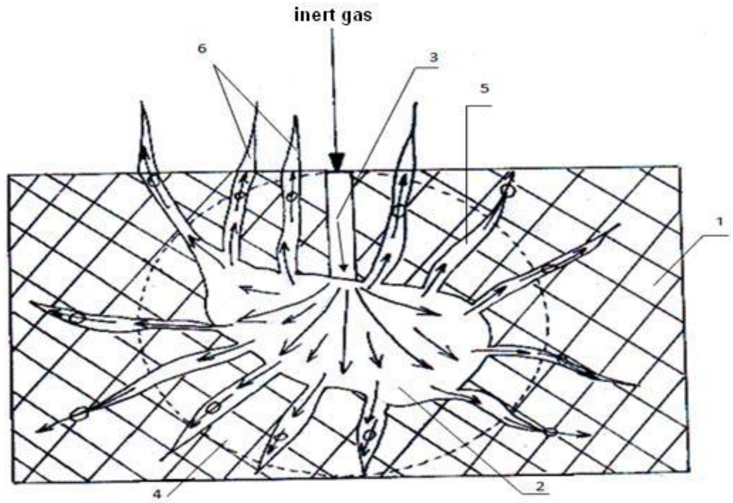
In addition, in 2011, proposed and patented a combined way to contain and extinguish the grassroots forest and grassland fires, which consists in the fact that the front of the fire place on the basis of the invoice charge hose, then it undermines and thus create mineralized barrage streak (pic. 3).



1 – an explosive charge 2 - the flame, 3 - pall, 4 - pyrolysis zone 5 - the burned area, 6 - Shock Wave, 7 - remaining pockets of fire, 8 - disintegrator
Pic 3. Scheme of the method

Current knowledge gained in the study of peat fires propagation mechanisms of this phenomenon, ways to deal with and recommendations has been and remains inadequate for solving practical problems in the operational prevention and extinguishing peat fires in Russia, and for the improvement of modern methods and devices of fire extinguishing.

The report examines the issue associated with the development of highly efficient and rapid way to localize and extinguish the hearth burning in the peat, based on the idea of supplying an inert gas or burning in the hearth surrounding this focus area under pressure (pic. 4). Thus, the displacement of air from the pores of peat and it replacing with an inert gas which does not support combustion.



1 - peat layer 2 - burning hearth 3 – feed to supply of inert gas, 4 - the area adjacent to the combustion hearth, 5 - pores in the layer of peat 6 - combustion of peat, ⟶ - the direction of the inert gas; —⊖⟶ - air direction
Pic 4.Scheme of supplying an inert gas

Conclusion

Current knowledge on the fight against wildfires remains quite small. Requires constant updating and upgrading of the existing arrangements for fire works of varying intensity.

Many areas remain poorly studied, a variety of natural conditions make it extremely difficult to analyze the response of natural systems of various type in the technological impact. Despite the negative impact of peat fires so far not been investigated in detail the reasons for burial burning, and there are no devices and techniques that enable it to be quickly put out the huge costs as multifocal fire on the moor.

Acknowledgements
This work is supported by the Russian Foundation for Basic Research (project № 11-01 00228-a).

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A global mechanism for the thermal degradation of peat

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Abstract:
Investigations were performed in order to improve the energetic characterization of peats with different geological origin, hydrology, and botanical composition. Special attention was focused on the effects of thermal treatment of peat degradation in oxidative atmosphere and its kinetics. Experiments were carried out by thermogravimetry.

Starting with dehydration step between 300 and 423K, the main thermal decomposition process under air showed two distinct degradation zones, corresponding to devolatilisation step between 473 and 650K and combustion step between 650 and 773K. Based on the experimental results, the kinetic parameters for boreal peats pyrolysis and combustion reactions were calculated using a three-steps model. The kinetic triplet of each reaction was calculated using Hybrid Kinetic Method. Our results show a good correlation between experiments and simulations with a three-step model.

Additional Keywords: Peat, thermal degradation, kinetics

Nomenclature listing

M	Mass of the sample (g)	*R*	Gas constant = 8.314 $J.mol^{-1}.K^{-1}$
Δm	Mass loss (%)	*f(α)*	Kinetic model reaction
ΔH	Reaction enthalpy ($kJ.kg^{-1}$)	*A*	Pre-exponential factor (s^{-1})
T	Temperature (*K*)	*E*	Activation energy ($kJ.\ mol^{-1}$)
T	Time (min)	*UK 1*	Sample 1 from United Kingdom
Α	degree of conversion	*RU2*	Sample 2 from Russia
□	Heating rate ($K.min^{-1}$)	*RU3*	Sample 3 from Russia

Introduction

Peatlands represent 3% of the terrestrial biosphere. Some 85% of these are located in northern, boreal and arctic zones and although they occupy a small terrestrial area, they store approximately 33% of all terrestrial soil carbon (Lappalainen, 1987), (Charman, 2002). The organic component of peat deposits has a fairly constant anhydrous, ash-free calorific value around 20 MJ/kg, which is interesting as an energy source (Clarke & Trinnaman, 2010).

Taking into account the annual growth of peat (1 to 20 mm thick each year) and the possibility of producing biomass on cut-over peatlands, it was recently stated that peat could be classified as a biomass fuel (Tolonen, 2000) and in November 2000 the European Parliament, added peat to the list of renewable energy sources. An interesting survey of fuel peat utilization and resources show the large potentiality across the world (Clarke & Trinnaman, 2010) and thus justifying scientific studies on peat as an energy source.

Thermal properties and reaction kinetics are important to be determined when talking with using peat as an energy source. These properties influence the choice of combustion technique. Many studies have been reported for the thermal and kinetic behavior of peats in pyrolysis conditions (Sutcu, 2007), (Sheppard and Forgeron, 1987) but only a few experiments were monitored under air atmosphere (Rydin et al., 2006). This paper proposes a kinetic study of thermal degradation of peat in oxidative atmosphere towards energetic application. The use of TGA and DSC as complementary techniques provides details about the process and reaction kinetics. The kinetic scheme and its associated parameters were determined using TGA which is a high-precision method for the study of degradation under well-defined conditions in the kinetic regime. After a presentation of the material and methods used to carry out this study, the results section is devoted to the kinetic study.

Material and Methods

Peat characteristics

Because of large resources and big peatland areas in Northern Europe, peats from United Kingdom and Russia were selected for this study.

Samples from two deposits of bog peat collected in Edinburgh area (United Kingdom) – named UK 1 – , in Tomsk (Russia) – RU 2 – and one deposit of fen peat from Tomsk – RU 3 – were compared.

The decomposition degree was determined according to state standard of Russia and the ultimate analysis was performed at the Laboratoire Centrale d'Analyse, which is a CNRS laboratory.

Table 1: Peats characteristics

	UK 1	RU 2	RU 3
Degree of decomposition	42	20	10.5
Depth (m)	0.1	0.3	0.4
C content (%)	53.3	44.8	43.1
O content (%)	38.9	45.8	41.6
H content (%)	5.5	5.7	5.6
N content (%)	1.1	0.5	1.2
Mineral matters (%)	1.0	3.0	8.4

The composition of UK 1 sample is characteristic of a peat with a high degree of decomposition (Rydin et al., 2006). On the contrary, Russian samples present a composition close to biomass.

Thermal investigation

The heat flow *vs.* temperature (emitted or absorbed) was recorded thanks to a power compensated DSC (Perkin Elmer®, Pyris® 1) equipped with an exhaust cover onto the measuring cell in order to work at ambient pressure. Samples around 5.0 mg ± 0.1 mg were placed in an open aluminum crucible and an empty crucible was used as a reference.

The mass loss *vs.* temperature was recorded thanks to a TGA (Perkin Elmer®, TGA 6). Samples around 10.000 mg ± 0.005 mg were placed in an open platinum crucible.

Both experimental devices were used with the following conditions: investigation in the range 300 – 900 K, 30 $mL.min^{-1}$ dry air as sweeping gas, crushed and sieved samples in order to obtain a thermally thin sample. To perform kinetic analysis on TGA curves, multi-rate linear non-isothermal experiments were lead at 10, 20 and 30 $K.min^{-1}$.

Kinetic modeling

Kinetic analyses are traditionally expected to produce an adequate kinetic description of the process in terms of the reaction model and the Arrhenius parameters. As we used TGA records the conversion degree is defined as:

$$\alpha = \frac{m_0 - m}{m_0 - m_\infty} \quad (1)$$

The transformation rate for a solid-state reaction is generally assumed as:

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \quad (2)$$

where $f(\alpha)$ is the reaction model and $k(T)$ the rate constant (Arrhenius law) giving:

$$\frac{d\alpha}{dt} = A\, e^{-E_a/RT} f(\alpha) \quad (3)$$

For non-isothermal conditions, $d\alpha/dt$ in Eq. (2) is replaced with $\beta^*(d\alpha/dT)$. In this case, three parameters: A, E and $f(\alpha)$, must be determined to describe the reaction rate. In order to determine this triplet, various methods have been worked out. These methods can be categorized as: (i) isoconversional and (ii) model fitting methods.

In order to obtain a reliable kinetic description of the investigated process, we use an approach that combines the accuracy of isoconversional methods (Pratap et al., 2007), (Leroy et al., 2010) with model-fitting methods (Vyazovkin & Wight, 1997), (Chrissafis, 2009).This approach named Hybrid Kinetic Method was developed in earlier works (Cancellieri et al., 2005). It is based on two-step, the first one use isoconversional methods to provide $E(\alpha)$ and the reaction model. The second step requires these initiation data to be injected in a model fitting method to obtain the pre-exponential factor and n^{th}-order. We feel that such an approach gives the highest probability of selecting the most accurate kinetic triplet (A, E, and model).

Results and Discussion

Thermal events

It is important to notice that the literature is very poor in studies concerning the thermal degradation characteristics and kinetics of peat under oxidizing environment (Chen et al., 2011). Moreover, there are only a few DSC studies in the literature (Aho et al., 1989) concerning the thermal decomposition of peat which is preferably followed by TGA (Rydin et al., 2006), (Sutcu, 2007), (Aho et al., 1989).

The following figures present only plots obtained with □=20 K.min^{-1} but the same phenomena were recorded for other heating rates (Cancellieri et al., 2012). All experiments were performed three times.

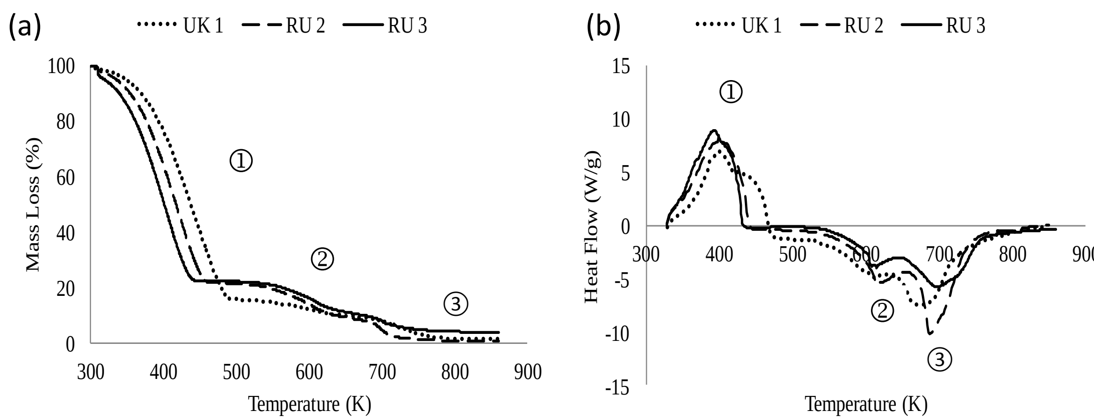


Fig.1: TGA (a) and DSC curves (b) of peat samples (not dried) obtained with a linear heating rate of 20 K.min^{-1} under air atmosphere.

Each thermogram is characterized by an endothermic peak around 373K ($\Delta H_{ENDO\ 1}$), assigned to the dehydration process. This step is visualized in TGA by a first mass loss (Δm_1) approximately at 80% in the temperature range from 300 to 500 K.

At higher temperature, two lower mass losses are visualized (Δm_2, Δm_3). Whereas experiments performed by DSC show two overlapped exothermic peaks ($\Delta H_{EXO\ 2}$, $\Delta H_{EXO\ 3}$).

In the temperature range 500-650 K the peat is pyrolysed contributing to the formation of char. In the same time, gases emissions are visualized in TGA by a mass loss around 10% (② in fig. 1a). Both char and gases do react with the oxygen. This oxidative process is recorded in DSC as the first exothermic peak (② in fig. 1b).

In the temperature range 650-900 K the char forms ashes. TGA plots show a mass loss around 10% (③ in fig. 1a) and a second exothermic peak is recorded in DSC (③ in fig. 1b). This third process is known as glowing combustion.

The same phenomena were observed and recorded by other authors (Rein, 2009), (Usup et al., 2004), (Chen et al., 2011).

According to these observations, thermal degradation of peat fuels displays three thermal events (see figure 2).

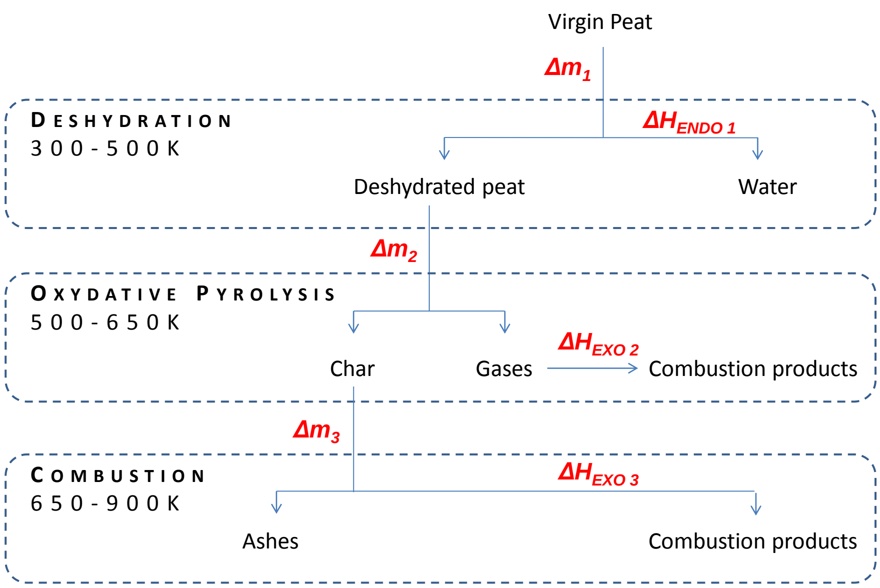


Fig.2: Thermal degradation of a peat fuels

Firstly, virgin fuels were studied but in these conditions of high moisture content, pyrolysis and combustion processes are concealed by this dehydration phenomenon. So, in order to focus on oxidative pyrolysis and combustion processes, samples were oven-dried for 24 hours at 333 K. Dry samples were then kept to the desiccator to preserve samples from ambient air humidity. The moisture content coming from self-rehydration was about 4% for all the samples before the testing. TGA and DSC curves obtained from oven-dried peat samples at □□= 20 K.min^{-1} are presented in figure 3.

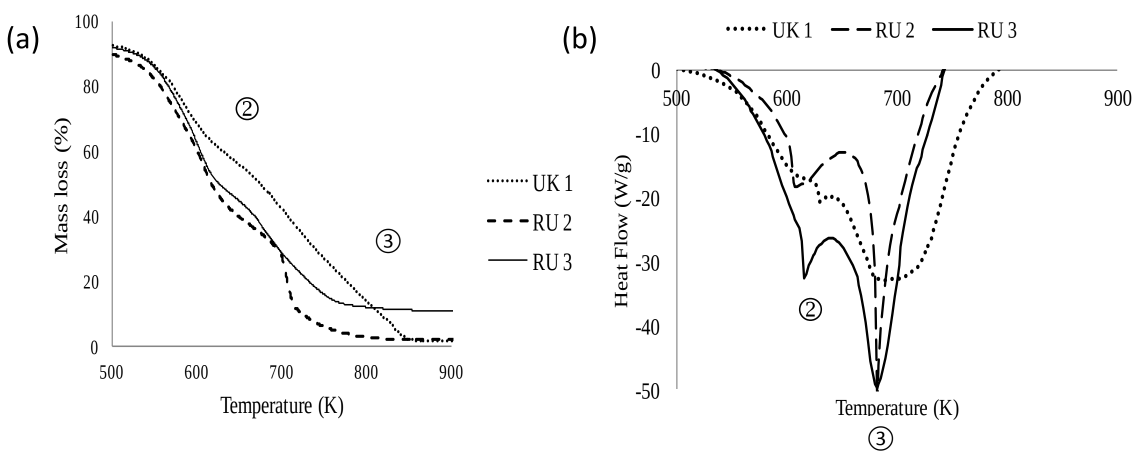


Fig.3: TGA (a) and DSC (b) curves of oven-dried peat samples obtained with a linear heating rate of 20 K.min^{-1} under air atmosphere.

Figure 3 displays two significant weight losses. On this figure, number ② and ⊛ refers to thermal events previously described on Fig.1.

Kinetics

We propose here a way to elucidate the kinetic of thermal degradation of peats. Dealing with kinetics is important in the context of using peat as a renewable energy source. Indeed, the knowledge of combustion velocity (i.e. kinetics) is an essential data for economic strategies linked to energy production.

1rst step-Isoconversional method

In solid-state reactions, isoconversional methods are widely used in order to detect the variations of *E* versus the conversion degree (α).

As mentioned in a previous work (Cancellieri et al. 2012), the Kissinger-Akahira-Sunose (KAS) method was applied on the whole degradation phase, and *E(α)* values were calculated for $\alpha \in [0.15\ 0.95]$ with a 0.05 step. The evolution of E according to the conversion degree was reported in the table 2. A Good correlation coefficient (r^2) was found for each E(α) calculated, although a less satisfactory coefficient was obtained for RU3 sample.

Table 2: Values of E(α) determined by KAS method (Cancellieri et al. 2012).

Conversion degree (α)	E UK1 (kJ. mol^{-1})	r^2	E RU2 (kJ. mol^{-1})	r^2	E RU3 (kJ. mol^{-1})	r^2
0.15	215.12	0.938	165.79	0.951	159.54	0.911
0.2	242.39	0.977	193.75	0.883	175.86	0.940
0.25	256.54	0.993	204.17	0.951	170.17	0.882
0.3	258.01	0.994	202.50	0.946	165.43	0.876
0.35	261.13	0.999	189.92	0.991	171.73	0.935
0.4	257.83	0.999	168.88	0.972	173.48	0.969
0.45	249.38	0.999	176.54	0.987	167.45	0.894
0.5	251.71	0.999	183.13	0.994	148.55	0.892
0.55	260.06	0.996	170.16	0.994	129.70	0.892
0.6	259.77	0.999	155.07	0.981	110.87	0.894
0.65	264.02	0.999	137.60	0.987	118.68	0.900
0.7	256.64	0.999	122.03	0.999	133.26	0.926
0.75	212.43	0.999	107.39	0.999	146.22	0.947
0.85	174.41	0.999	94.75	0.989	136.04	0.962
0.9	156.87	0.994	85.44	0.942	117.88	0.972
0.95	155.77	0.999	78.32	0.945	88.31	0.977

Vyazovkin (Vyazovkin & Lesnikovich, 1990) found that the evolution of the effective activation energy can be used to evaluate the kinetic mechanism. The KAS method highlights three main areas in table 2:

- $0.1 < \alpha < 0.3$: raising values of activation energy which is characteristic of competing reactions that occur during the ignition phase (Vyazovkin & Sbirrazzuoli, 1996).

- $0.3 < \alpha < 0.7$: the dependence of the effective activation energy reveals significant fluctuations attribute to parallel reactions (Vyazovkin & Linert, 1995).
- $0.7 < \alpha < 0.9$: the concave plots observed are typical of diffusion regime.

In spite of the two main reactions (i.e oxidative pyrolysis and combustion) occurring during the degradation of peats, three kinetic events appear by isoconversional method. Other researchers have indicated the presence of an intermediate solid before the oxidative pyrolysis of biomasses (Koufopanos et al., 1989), (Branca & Di Blasi, 2003) which enhances the 3-steps mechanism model.

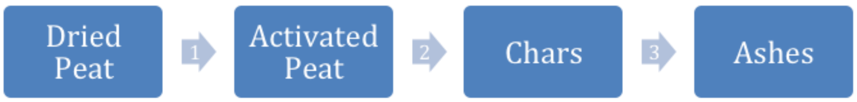


Fig.4. Model of thermal degradation proposed

2nd step-Model fitting method

Model fitting kinetics is based on the fitting of Eq. 2 to the experimental values of *dα/dt*. We used Fork® (CISP Ltd.) software which is provided for model fitting in isothermal or non-isothermal conditions.

The three reactions can be implemented in the three following differential equations (Eqs. 4-6), considering a n-th order model. The n-th order model was selected as in several studies on thermal degradation kinetics of various biomasses and their components (Conesa & Domene, 2011), (Hashimoto et al., 2011), (Senneca, 2007).

$$\frac{d\alpha_1}{dt} = \frac{1}{\beta} k_{01}\, e^{-\frac{E_{a1}}{RT}} (1-\alpha_1)^{n_1} \qquad \frac{d\alpha_1}{dt} = A_1 e^{-\frac{E_1}{RT}} (1-\alpha_1) \qquad (4)$$

$$\frac{d\alpha_2}{dt} = \frac{1}{\beta} k_{02}\, e^{-\frac{E_{a2}}{RT}} (\alpha_1-\alpha_2)^{n_2} \qquad \frac{d\alpha_2}{dt} = A_2 e^{-\frac{E_2}{RT}} (\alpha_1-\alpha_2) \qquad (5)$$

$$\frac{d\alpha_2}{dt} = \frac{1}{\beta} k_{02}\, e^{-\frac{E_{a2}}{RT}} (\alpha_1-\alpha_2)^{n_2} \qquad \frac{d\alpha_3}{dt} = A_3 e^{-\frac{E_3}{RT}} (\alpha_2-\alpha_3) \qquad (6)$$

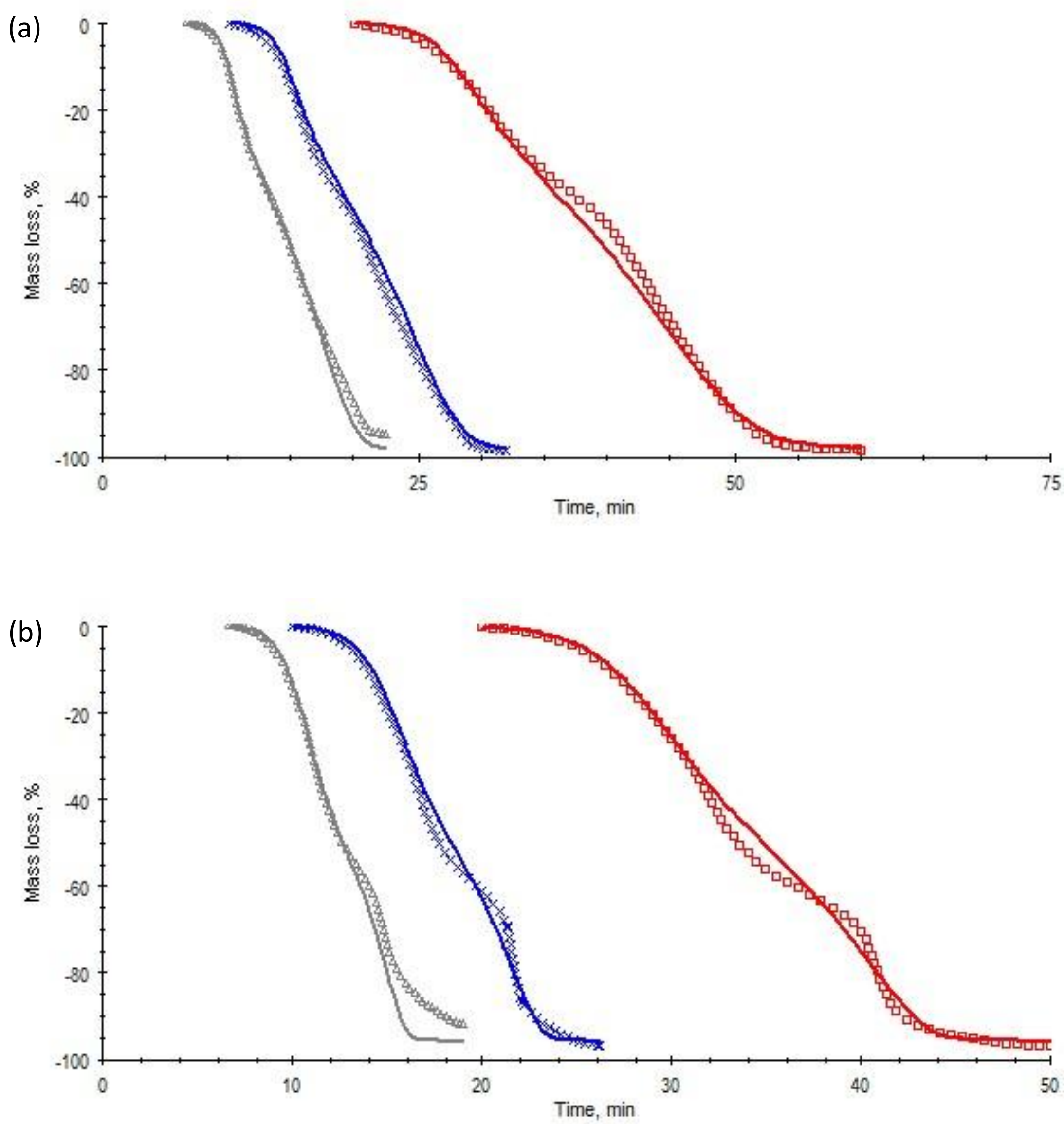
Boundaries values of E (in grey in Table 2) and boundaries mass losses values are taken as initial entries for the model fitting method in Fork® software for a conversion degree varying from 0.1 to 0.9. Table 3 hereafter, summarize the results obtained with the model fitting method. We present the best set of parameters calculated on the basis of the 3 heating rates (i.e.10, 20, and 30 $K.min^{-1}$).

Table 3: Kinetic parameters.

Parameters		UK 1	RU 2	RU 3
Peat → Peat*	$A_1 (s^{-1})$	20.73	14.36	7.81
	E_1 (kJ.mol^{-1})	127.20	118.23	79.33
	n_1	1.69	1.81	1.01
Peat* → Char	$A_2 (s^{-1})$	34.01	20.74	17.44
	E_2 (kJ.mol^{-1})	229.87	147.62	107.71
	n_2	2.57	2.44	1.016

Char → Ashes	A_3(s^{-1})	2.32	6.59	10.12
	E_3 (kJ.mol^{-1})	150.76	70.01	87.23
	n_3	0.68	0.53	1.26

Once the kinetic parameters are determined, the ultimate stage is dedicated to the validation of the proposed mechanism. Figure 5 displays experimental and simulated curves for the three peat species at 10, 20 and 30 K.min^{-1}.



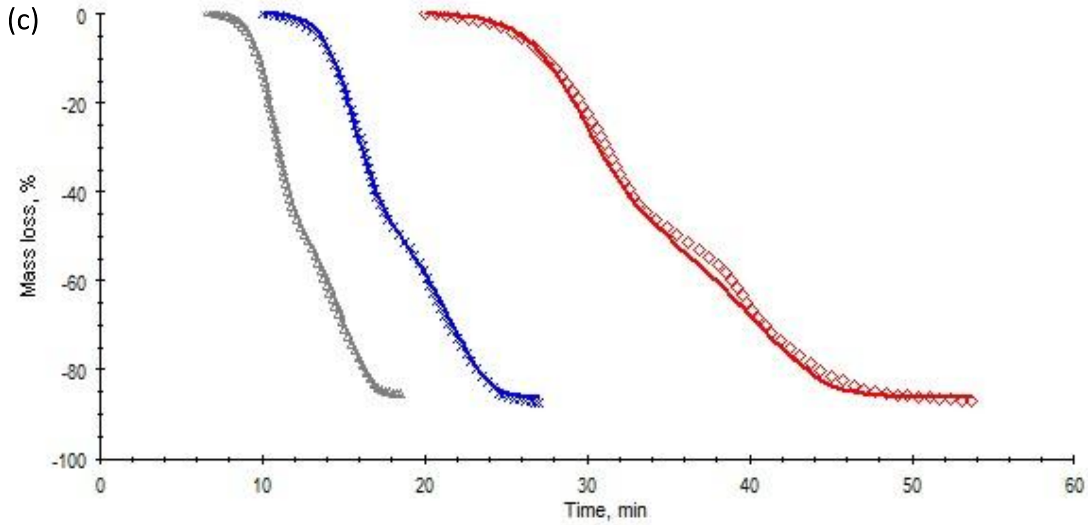


Fig.5: Comparison between experimental (symbol) and simulated (line) curves at 10 (red) ,20 (blue) and 30(grey) K/min under air atmosphere for
a) UK1 b) RU 2 c) RU 3.

The results obtained have confirmed the choice of the model and the kinetic parameter calculated.

Conclusion

The management of production and the safe storage of peat as bio-ressource require a good understanding of its thermal degradation. In this study the applicability of the thermal analysis techniques for the characterization of peats has been verified. We showed that thermogravimetric and calorimetric investigations are useful tools in order to get information on the energetic properties of peats. The choice of a kinetic study using two successive methods (isoconversional method and model fitting method) allows obtaining unambiguous data. Therefore, in a first time, a three-step mechanism was proposed on the basis of isoconversional results. In a second time, the use of three kinetic equations for modelling experimental data of the degradation allows obtaining a stable set of kinetic parameters and adequately describes the pyrolysis and the combustion for several heating rates. Finally, a satisfying agreement between the calculated curves and the experimental curves was put in evidence.

Acknowledgement

This work was supported by the CNRS PICS grant no. 5625, the RFBR grant no. 12-01-00142-a and The Ministry of education and science of Russia, project 14.B37.21.0634. The ultimate analysis was carried out at the SCA (Service Central d'Analyse) USR 59 CNRS

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Algorithms for calculating the radiant heat flux during forest fires

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Abstract:

Radiative heat transfer is not limited to the neighborhood of heated fluid. The advantage of the model proposed in this paper is the ability to consider a radiating surface of any shape and capacity with the resolution and the numerical mesh. Classical methods for its solution require the use of an iterative process that affects the computation time. Diffusion and diffusion-wave approximation of the differential model of radiation are proposed in this paper. The basic idea of approximation amounts to replacing an elliptic equation of radiation to hyperbolic or parabolic one. The proposed model causes delay in the distribution of radiant energy. The proposed approaches have been incorporated into the software system, which simulates the spread of forest fire. It has been shown that these approaches cause minor error.

Additional Keywords: Fire control, numerical simulation, radiant heat transfer, forest fire

Introduction

Radiant heat transfer is one of the most important factors of energy transfer outward from the combustion zone. Radiant heat transfer component has the greatest influence on speed of forest fire propagation. It can either speed up or slow down the speed due to energy distribution.. Unlike other heat transfer processes such as convection and diffusion, radiative heat transfer is non-local, which means it is not limited to the neighborhood of heated fluid. Radiant energy travels at the speed of light, so given the scale of the problem of forest fires, heat transfer can be considered instantaneous.

Analysis of existing models of radiant heat transfer

One of the simplest methods is using a prior model for the shape of the flame, with parameters that depend on the actual dynamics of a fire. For example, the cylindrical shape of the flame considered (Kleymenov 2010). This approach provides high-speed computing, but ignores the actual shape of the flame.

Another approach for modeling the radiation is based on introducing various simplifications to the law radiation propagation (Piljugin 1989; Perminov 2010). For example the intensity of radiation transfer represented in the form of first two terms of the corresponding series of spherical functions (Piljugin 1989) and the dependence of the integrated emissivity of layer (Perminov 2010). On the other hand, the radiation model can also be simplified by representing radiation as diffusion process (Rusin 2007), which rate is proportional to the cube of temperature. This approach is referred to as locally-diffusion model of radiation in this paper.

The authors propose the diffusion approximation is obtained by fictitious diffusion $v\frac{\partial U_R}{\partial t}$ term (Maslennikov 2012):

Differential model and its approximations

$$v\frac{\partial U_R}{\partial t} = \frac{\partial}{\partial x}\left(\frac{c}{3k_\Sigma}\frac{\partial U_R}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{c}{3k_\Sigma}\frac{\partial U_R}{\partial y}\right) - k_s\left(cU_R - 4\sigma T^4\right), \quad (4)$$

where v - value is inversely proportional to the rate of diffusion.

The advantage of this model is the ability to consider a radiating surface of any shape and capacity with the resolution and the numerical mesh. The disadvantages of this model include the neglect of the spectral characteristics of the radiation. Differential equation model has an elliptical type. Classical methods for its solution require the use of an iterative process that affects the computation time. Diffusion and diffusion-wave approximation of the differential model have been developed to avoid iteration process.. The basic idea of approximation amounts to replacing the elliptic hyperbolic or parabolic. Justification is based on the fact that in the developed approximations, the energy distribution over the space of a priori given source converges to that obtained by a conventional differential model. The main negative effect introduced by the proposed approximations - is delay in the distribution of radiant energy. This effect may be reduced to an arbitrarily small value by decreasing the time steps. Diffusion approximation is realized easier than improved diffusion-wave, but is less effective, especially if the energy absorption medium when the laser beam at a distance equal to the step in space does not exceed 10%.

The proposed approaches have been incorporated into the software system, which simulates the spread of forest fire. It has been shown that these approaches pose little error. Table 1 shows the fraction of radiant energy delayed more than specified time (Maslennikov 2012)

Table 1.

The delay in propagation of radiant energy, depending on the time

Time since moment of flash, sec	0,05	0,1	0,15	0,25	0,35
The share of delayed radiation energy	0,165	0,027	0,0045	$1,23 \cdot 10^{-4}$	$3,372 \cdot 10^{-6}$

Acknowledgement

This work was supported by RFBR 13-03-91164-NNSF_A "Experimental study of the kinetics and mechanism of thermal decomposition of combustible forest materials and processes flame spread upon the layer”.

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Forest fires and the environment

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Abstract
The analysis of large forest and peat fires, the peculiarities of their development and the impact on the environment is conducted. The main characteristics of forest fires are considered. The thermal characteristics and evaluation of the heat generation of large forest fires are given. The influence of forest and peat fires on air pollution by combustion products is considered. The qualitative and quantitative composition of the combustion products for different types of fires is estimated.

Additional Keywords: forest fires, combustion products, air pollution

Introduction

The forests of the Russian Federation are almost a quarter of the planet's forest cover. The problem of fighting wildfires was always very acute in the Russian Federation. Every year 15 to 30 thousands of fires are registered in the country covering an area of several hundred to several million hectares (Grishin 1997).

Dimensions of the damage, the growth trend, and the frequency of extreme cases caused by large fires (2-3 times per decade) enable us to consider natural fires as emergencies. Especially great danger is represented by large forest fires that arise during arid weather. The total area of such fires may reach hundreds of thousands of hectares. At the same time there is a direct threat of fire destruction of settlements and economic facilities located in forest areas.

Large forest fires add significant disturbances to atmospheric conditions as well as the environment (forest vegetation). Such fires are accompanied by the development of strong convective plume and diffusion of both gaseous products, and various aerosol admixtures in the atmosphere. Not only forests are destroyed by such fires. The large forming areas of smoke spreading and gas pollution damage human health and the environment. Pollution of the atmosphere by large amount of combustion products at large fires can cause significant ecological and climatic implications.

Large Forest Fires in Russia

Large forest fires in Russia are: for Siberia – the fire area of more than 200 hectares, for the European part – more than 25 hectares. The main cause of forest fires is careless or wrongful actions of population. For example, more than 75% of forest fires in Russia are man-caused (Valendik 1990).

The mass forest fires occur mainly in areas adjacent to settlements and transport tracks, firstly on territory of the most fire hazardous forest land (pine saplings, pine forests, peats, etc.). Fire hazardous areas within a radius of 5-10 km from the boundaries of cities and towns occupy substantial forest areas. For example, the most dangerous plots of conifer forests occupy 46% in Moscow region, in the Khabarovsk region - 25% of the forest. Under dry conditions the growth of mass forest fires seats lead to emergency situations with significant material losses.

In recent Russian history, the largest forest fires occurred in 1972 and 2010. The analysis of these fires has shown that there are three main groups of conditions that lead to emergency situations. An abnormally long presence of the anticyclone in the fire zone and, consequently, the lack of rainfall create the first set of conditions. The second set of conditions stem from the abnormally high temperature in zones of fire occurrence. And finally, the appearance within the anticyclone of storm-force winds with the force up to 30 m s^{-1}.can create emergency situations.

More than 700 large forest and peat fires in seven regions with the total area of 550 hectare arose in August and September of 1972 in the European part of Russia. Total fire covered 17 provinces and autonomous republics, there were more than 40 thousand of forest fires, and fire destroyed more than 1,400 hectares of forest. The peat and forest fires have developed in the area of 300 hectares only in Gorky region. As a result of fires in Moscow region 19 villages in the suburbs were destroyed. 104 people perished. 360 thousand of people and 2.5 thousand units of fire-fighting equipment were engaged to extinguish forest and peat fires in the summer of 1972.

The average height of smoke from forest fires in 1972 was 2-3 km, and sometimes reached 5 km. Clouds of smoke plume with width of 150-400 km stretches for 560 km. Smoke density was such that from the height of 500 m the Earth surface was not always visible (Grigoriev *et al.* 1978).

In late July - early August 2010, because of the extreme heat and lack of rain in the European part of the Russian Federation, a complex fire situation occurred. The number and size of wildfires has increased at an alarming rate. For example, in the Central and Volga federal districts during this period up to 300 fires have occurred, and on some days up to 400, despite the fact that under normal conditions they encountered in ten or more times smaller. 9 villages burned down, about two thousand houses were destroyed by fire, 53 people perished on 29 and 30 July.

By the beginning of August 2010 the total number of fires that occurred in Russia since the beginning of the fire season has exceeded 25,000. The total area affected by fires was more than 860 thousand hectares.

Weather conditions in the summer of 2010 were in many ways more complex than in the 1972. Firstly, the number of regions of the country caught in range of the anticyclone was significantly higher – 23 regions in comparison with 17 regions in 1972. Secondly, the period from late June until mid-August of 2010 was the hottest in the history of meteorological observations. The air in some areas warmed up to 40-43°C. The maximum temperature - 45.4°C – was recorded on 12 July. During the summer of 2010 there were set 22 daily temperature records, two records of month, and absolute record, as well as a monthly record of maximum temperature. Thirdly, the features of the anomaly in 2010 was a severe drought in central Russia - there was not rainfall virtually and the summer was the driest in history in some areas. Fourthly, as in 1972 at the beginning of August in the center of the anticyclone the conditions for the formation of air masses in the form of a strong wind have formed.

In comparison with 1972 year the higher arrangement of the control system aimed at fighting with wildland fires was noted, as well as high quality and efficiency of operation. Operational headquarter, which included representatives of the various departments was established on the basis of the National Center for Crisis Management of Russian Ministry of Emergency Situations.

Clear management structure has enabled to support interagency cooperation, efficiency redeployment of forces and means of regional groups at the federal and regional levels.

The Main Characteristics of Forest Fires

There are three main types of forest fires in Russia depending on the burning materials: surface, crown, and ground (peat, underground) (Kurbatsky 1970).

The share of surface fires is an average of 97-98% of the total number of forest fires and of 87-90% of the forest area affected by fire. Crown fires form 1.5-2.0% of the total number of forest fires, and of 10-12% of the forest area affected by fires. Ground (underground) fires usually occur after prolonged drought. In Russia they account for about 1.7-2% of the total number of fires, and about 0.3% of the area that was destroyed by fire.

There are distinguished running and stable surface fires. Fires with rapidly advancing edge (speed more than 0.5 m min^{-1}) when only ground cover, litter, undergrowth and pine underbrush burn out concern running fires. The fires with an average speed of advance edge of less than 0.5 m min^{-1} concerned stable fires. With stable long burning fires litter, fallen trees and rotten stumps with the release of a strong smoke. The main feature of running fires is flaming combustion, and the main feature of stable fires is flameless combustion. The classification of wildland fires according to their intensity is presented in Table 1 (Konev 1977)

Table 1 - Types of wildland fires

Fire parameters	Weak	Medium	Strong
Surface fire			
The rate of fire spread, m min^{-1}	Up to 1	1-3	Over 3
Flame height, m	Up to 0.5	0.5-1.5	Over 1.5
Crown fires			
The rate of fire spread, m min^{-1}	Up to 3	3-100	Over 100
Underground (peat) fire			
The depth of burn-out, m	Up to 0.25	0.25-.30	Over 0.50

There are usually distinguished running and stable crown fires. At stable fire crowns of trees burn down with moving of the edge of surface fire. The spread of combustion may be ahead of the edge of the surface fire at running crown fires. This is due to the wind transfer of burning sparks and firebrands, as well as the formation of new seat of fire in front of fire front.

Crown fires are accompanied by the release of large amounts of heat. One meter of the edge releases more than 220 kW of heat energy. The heated air and combustion products cause ascending fluxes and form so-called plume with a diameter of several hundred meters. The forward motion of the plume coincides with the direction of advance of the front of a fire. The flame in the middle of the plume can rise to a height of 120 m.

Soil (peat) fires are flameless combustion of organic part of the peat, which is formed from the remains of swamp plants in conditions of high humidity and lack of oxygen. The thickness of the layer of litter can be up to 50 cm, and the thickness of the layer of peat up to 7 m. Sometimes seat of fire hide underground. Fires then called underground peat.

Classification of fires, which highlights conflagration fire, mass fire, firestorm and fireswhirl is more correct from a physical point of view (Carrier *et al.*1984; Pittock *et al.* 1985). Conflagration fires are characterized by propagating flame front. The main mechanism of forwarding is turbulent heat-mass exchange of the front with combustible material due to the forced convection in the wind. Mass fire incorporates multitude of interacting with each other seats burning simultaneously. All available combustible material burns at the fire area. The speeds of propagation of the fire are usually small.

Firestorm - is a more dangerous form of mass fire. It arises when there is space for large loads of combustible material (usually in urban areas). Is characterized by strong plume and the hurricane (20-40 m s^{-1}) horizontal velocities of air pulled into the seat. Is realized at low wind speeds and favorable atmospheric conditions for development of firestorm - lack of strong inversion layers, weakly unstable stratification of the atmosphere.

Swirling fire storm (the fire vortex) - the most destructive type of mass fires. Associated with occurrence of a powerful rotation (around the vertical axis of the convective columns) of the combustion products. It has the highest rate of energy release, extremely strong local speed of gas transfer in the seat, the great height of the flame torch, as well as powerful convective column.

Mass fires generally occupy only a few percent of the total number of wildfires, but they bring the greatest damage. Mass forest fires in Russia form 1-2% of all fires, but they account for 70% of the area destroyed by fire and 90% of area damaged by fire (Gostintsev Yu *et al.* 1994).

The main parameters characterizing the combustion during forest fire are: fire load (weight of combustible material per unit area (kg m^{-2}) or volume (kg m^{-3}); rate of load burning (kg m^{-2} s^{-1}); linear velocity of the flame front spreading (m s^{-1}); flame (fire) temperature; intensity of the descending heat flux (W m^{-2}); speed of ascending flux in the plume (m s^{-1});compound and concentration of combustion products.

The quantity of combustible materials in low-productive forests 1 kg m^{-3}, the most productive forests 25-30 kg m^{-3}. Approximately 15-20% of the material is related to easily ignite, completely burned part - moss, tree waste, litter. In the pinery needles reserves are 0.6 kg m^{-3}, in cedar forests – the tree waste is 0.2-1.1 kg m^{-3} in deciduous forest - 0.3 kg m^{-3}. The average value of the combustible load in the woods with large forest fires is 5-10 kg m^{-3}.

The average temperature of forest combustible materials burning is 500-900°C. The combustion temperature (smoldering) of peat is 500°C (at humidity 10-30%), 300°C (at 65% humidity)

Flame height is determined by the type and intensity of the fire, the wind speed, edge width and has the following average values for the surface fire - 0.05-3 m, for crown fires – 3-15 m (above the stand). The depth of peat burning depends on the capacity of the peat layer, its moisture and can be 0.25-3 m.

The fire classification according to their survival rate is important in terms of predicting the fire growth, as well as ways of fire-fighting and fire-fighting resources. The ability of the fire for self-sustaining mode of existence and development depends on several factors: load density (kg m^{-2}), its spatial structure, and the type of combustible materials; pre-combustion weather and current weather conditions; topography of the terrain.

Thermal Characteristics of Forest Fires

Large forest fires are a powerful factor of thermal disturbances in the atmosphere (Gostintsev Yu *et al.* 1991). The energy-release of mass fire is assessed as follows:

$W = S\ m_s\ H_q\ t_g^{-1}$, MW

Where S (m^2) – total fire area burnt down during the time t_g (s); m_s (kg m^{-2}) – fire load; H_q (MJ kg^{-1}) - combustion heat of 1 kg of fuel. The average power of heat release per unit of the edge of conflagration fire front:

$J = H_q\ m_s\ U$, MW m^{-1}

Where U (m s^{-1}) - the speed of propagation of the front. The average value of heat release per area unit of the mass fire:

$q = m_s\ H_q\ t_g^{-1}$, MW m^{-2}.

For large forest fires average combustible load m_s = 5-10 kg m^{-2}, the heat of combustion of forest fuel H_q = 20 MJ kg^{-1}. According to estimation of the total power of heat-release from fires in 1972 and 2010 these fires are close to the value of 2 10^{12} MJ, which is comparable to the explosion of a nuclear weapon capacity of 100 MT.

On the base of the analysis of the forest and test fires observed in-situ conditions, it was found that during conflagration fire spreading the heat-release per unit of length of front edge make J = 10-80 MW m^{-1}, where the last figure is rarely implemented in extreme situations. The width of the conflagration front is up to 100 m. The average power of heat-release during mass areal fires is q = 10^4 W m^{-2}, and during firestorms is q = 2,5 10^5 W m^{-2}. Thus, the average values of large fires are the following: $q_m = 10^4$ W m^{-2}, J = 5 10^6 W m^{-1}.

For a linear fire of conflagration type with a capacity of heat-release on the edge of J = 5 10^6 W m^{-1} and the width of the front l = 80 m the vertical Z_m and horizontal D_m size of the perturbation, as well as the maximum values that are realized in the convection column of vertical V_m and horizontal U_m velocities are as follows: Z_m = 1,6 km; D_m = 0,5 km; U_m = 10 m s^{-1}; V_m = 1,5 m s^{-1}. Horizontal speed U_m is added with the speed of the wind on the windward and subtracted – on the lee side of the front.

The full-scale experimental forest fires conducted in All-Russian Research Institute for Fire Protection (VNIIPO) have shown that due to the heat emission the heat is dissipated in the atmosphere, and the air temperature in the area of the fire can be increased from 5 to 30 degrees.

Thus, there are created conditions for the fire contributed to an increase in the lifetime of the anticyclone over the arid territory and thus forest-and-peat fires start, how to support themselves.

The Combustion Products of Forest Fires

Up to 400,000 forest fires appear annually on the Earth during fire-hazardous period. These fires emit into the atmosphere millions of tons of combustion products and significant amount of pollutants. Global warming and the greenhouse effect are significant problems, which influence the development of a sustainable civilization in future years. The main role in formation of the greenhouse effect takes carbon dioxide.

The main source of the increase in the concentration of carbon dioxide is the burning of fossil fuels, as well as large urban and forest fires. The compound of the combustion products depends on the type of combustible material, as well as the development of fire conditions development (temperature and ventilation.)

Available data on the quantity and composition of the combustion products are obtained generally in the laboratory conditions and do not reflect the conditions of fire. Thus, the increase in temperature and transition to flaming combustion mode (open-fire conditions) lead to reduction of content of hydrocarbons, aldehydes, alcohols, smoke aerosols in combustion products. Thermal conversion at 400-500°C in a lack of oxygen (conditions of fires in rubble) is characterized by increase in the amount of suboxidized forms of carbon compounds, as well as solid and liquid aerosol particles. Thereby, the complex of certain experimental and theoretical studies, with the objective to assess the quantitative and qualitative compound of the combustion products in the atmosphere from large fires was conducted.

The output of the combustion products into the atmosphere during forest fires substantially modifies its gas composition, which cannot but affect the health of human. Thus, during the fires in 1972, the concentration of carbon monoxide in the cities of Moscow region exceed the maximum allowable area of 5-10 and was in Mytischi - 170 mg m^{-3}, Shatura - 60 mg m^{-3}, Noginsk - 50 mg m^{-3}.

Using data on fires in 1972 and 2010, there can be estimated the general removal of CO and CO_2, smoke aerosol into atmosphere. These estimates vary between 1.5-2.0 10^7 tons for each component. The yield of smoke aerosol at burning of combustible material is measured from 2 to 5% by weight. The most frequent lifting heights of smoke from large wildfires are 2-3 km. At the vortex of mass fires that occur locally (burning time is 1.5-2 hours) convective jet reaches the height of 5-6 km.

It should be noted that if the CO_2 prevents the outflow of heat, i.e. contributes to increasing of atmospheric temperature, so the smoke aerosol escapes solar radiation and thus contributes to cooling of the atmosphere.

This effect was confirmed by observing mass forest fires in Russia in 1915. The maturation of loaves delayed for 2-3 weeks due to a lack of solar radiation at the surface of the earth in that year., formed a The smoke cloud that formed during large fire in the south-west of Canada in 1950 began to move eastward, causing lowering of daytime temperatures on few degrees.

The number of combustion products at forest fires is determined not only by the rate of combustion and the fire area, but also by emission coefficients K_a, which depend on the type of vegetation and burning conditions (Grishin *et al.* 1997).

The averaged values of the emission coefficients are summarized in the Table 2.

Table 2 - The average values of emission coefficients K_a of combustion products

Pollutant	K_a (kg kg^{-1})
Carbon monoxide	0.135
Carbon dioxide	0.094
Nitric oxide	0.000405
Soot (elemental carbon) from combustion	0.0014
Smoke (combustion mode)	0.014
Smoke (decay mode)	0.055
Soot from smoldering	0.011
Methane	0.075
Other hydrocarbons	0.011
Ozone	0.001

The quantity of emissions of combustion products into the atmosphere depends on the stock and the type of forest fuel as well as on its moisture content, weather conditions, terrain and other conditions. The values of emission coefficient for different types of fires are presented in Table 3.

Table 3 - The values of emission coefficient K_a (kg kg^{-1}) for different types of forest fires

Pollutant	Surface fire	Fire on the peat	Crown fire
Carbon monoxide CO	0.135	0.135	0.135
Carbon dioxide CO_2	0.094	0.094	0.094
Nitrogen oxides NO_x	0.000405	0.000405	0.000405
Soot C	0.0062	0.011	0.0014
Smoke (ultrafine particles of SiO_2)	0.0345	0.055	0.014
Methane CH_4	0.075	0.075	0.075
Unsaturated hydrocarbons	0.011	0.011	0.011
Ozone	0.001	0.001	0.001

Conclusion

Forest fires cause not only huge economic losses, but they are also an important factor in local, regional and even global ecodynamics. Large forest fires are accompanied by intense thermal disturbances in the atmosphere and formation of vast areas of smoke and gas pollution by combustion products, which significantly affect the health of people

Pollution of the atmosphere by large quantities of combustion products during large fires can cause significant ecological and climatic effects. Among the global environmental effects is the trend of climate change and the warming on the Earth (the greenhouse effect) associated with an increase of carbon dioxide concentrations in the atmosphere. However, while considering the problem of climate change and the influence of fires it’s necessary to consider combined effects of greenhouse gases and smoke aerosol.

If carbon dioxide makes the greatest contribution to the greenhouse effect and promote the growth of temperature of the atmosphere, so smoke aerosol shields solar radiation, and thus may cause the temperature reduction. The emissions of aerosols in the atmosphere related to forest fire can have a significant impact on the microphysical and optical properties of cloud cover (and therefore on the climate). The emissions of various small gas and aerosol components to the atmosphere during the forest-and-peat fires may have a significant impact on the atmospheric chemistry and other processes.

Assessment of the impact of forest-and-peat fires on the environment is also associated with the development of the following areas of research: analysis of the character of forest fires from a regional perspective; pyrological study of the properties of combustible materials in order to find ways and means of combustion control and fire extinguishing; development of remote sensing methods for fire detection and reconnaissance; development of issues of tactics and organization of large fire extinguishing; comprehensive studies of the fire effects in terms of ecology, as well as the development of methods for better registration of the damage from fire.

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Dominant preheating transfer mechanism in wildfire propagation: Radiation or convection?

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Abstract:
Several studies in the literature explore the connection between rate of spread (ROS) and wind speed in wildland fires. This relationship is often expressed as a power function but the value of the exponent is very different according to different authors. The main goal of this work is to propose a simplified physical propagation model for surface fires that gives the relative contributions of the two transfer modes to the fuel preheating. The dominant heat transfer mode, radiation or convection, involve different curve shapes of the ROS as function of the wind speed which match all the empirical power functions found in the literature. The model exhibits two wind speed thresholds that are defined as transitions between radiation and convection. The predicted ROS is compared with 226 laboratory experimental fires in the literature, with differing fuel bed arrangements (continuous or discontinuous fuel), a wide range of fuel bed properties (such as surface-area-to-volume ratio, moisture content, loading, depth, etc.) and varying slope conditions. Statistical tools are used to check the agreement between predicted and observed ROS.

Additional Keywords: Surface fire; physical model

Introduction

Wind is commonly accepted as one of the major factors determining wildfire propagation. Several studies have described the relationship between the rate of spread and wind speed, where a power function of the wind speed is commonly fitted to the ROS data. The exponent derived from these studies, however, is inconsistent. For example, Thomas and Pickard (1961), Wolff *et al*. (1991) and Catchpole *et al*. (1998), observed an exponent lower than 1 whereas Rothermel and Anderson (1966), Rothermel (1972), and Nelson and Adkins (1986) suggested an exponent greater than 1. The three ROS curve shapes (slow, fast or linear increasing observed by Rothermel and Anderson, 1966) depend on the value of this exponent.

At the University of Corsica, for the last eight years, we have been developing a simplified physical propagation model for surface fires, which only took into account radiation as the heat transfer mechanism (Balbi *et al*, 2007, 2009, 2010). The two main equations of this model give the ROS R and the flame tilt angle γ:

$$R = R_b + R_f \tag{1}$$

$$\tan \gamma = \tan \alpha + U/u_0 \tag{2}$$

where R_b and R_f are the contributions of the flame base radiation and the flame radiation respectively. α is the terrain slope angle, U the wind speed and u_0 is the upward gas velocity. Note that eq. (1) was obtained when integrating the preheating energy balance where the heat content of the fuel is the sum of the radiant heat released by the burning fuel, and of the radiant heat released by the flame and the (negative) heat of latent evaporation.
The numerical data provided by this model were consistent across both a laboratory scale and a field scale. But a good correlation of these results was only obtained when using a continuous fuel bed. The model didn't reproduce correctly the slow increasing of the ROS usually obtained with discontinuous fuel beds (e.g. when the fuel bed is composed of upright sticks that are perfectly aligned). The main purpose of this extended abstract is to present an improved model that takes radiation and convection into account. Using some approximations, his model tries to find numerical solutions of equations governing fluid dynamics, heat transfer, and combustion, and as such can be classified as a simplified 3D physical model.

The radiative-convective model

Convection is the result of hot gases that come into contact with the unburnt fuel bed, which may come from three zones:

- The higher part of the flame - the high mid-height flame. In this area, the flame is unsteady and discontinuous and external air movement can pass through these discontinuities. As the temperature of this zone is low and the contact between this flow and the vegetal stratum is not constant (there might be some turbulent contacts at times) the energy contribution is limited and therefore neglected.
- The lower part of the flame - the first mid-height flame. The quasi-laminar flame in this zone acts as a barrier to the fresh wind stream; its contribution to the convection is negligible.
- The burning fuel bed. This zone is crossed by the air stream and subjected to progressive drag forces. As the upward velocity of the pyrolysis gases is slow, gases may be formed in the actively burning fuel bed and be blown forward through the fuel to rise in front of the fire. The combustion of these gases creates another flame located in front of the main flame. As the temperature of these gases is very high and they are in close contact with the vegetal stratum, it is assumed that the convective energy that plays a part in the fire spread comes from this area (see fig. 1). This flaming zone, in the presence of wind was characterized by Rothermel and Anderson (1966).

The energy balance in a preheated fuel cell is changed with the addition of the convective term (R_c) and eq. (1) becomes

$$R = R_b + R_c + R_f \tag{3}$$

Where the contribution of convection to the ROS R_c depends on the wind speed U, the ROS R and a drag forces coefficient K:

$$R_c = b\,(U/(1+KRU))^2 \quad (4)$$

The coefficient b depends on the slope angle and vegetal stratum characteristics.

Numerical validation

The radiative-convective model is confronted to several sets of experiments at the laboratory scale (226 fires). These experiments are split according to the arrangement of the vegetal stratum:

- Experiments carried out on a homogeneous and continuous fuel bed (Boboulos and Purvis 2009, Burrows 1999, Catchpole *et al* 1993, Mendes-Lopes *et al* 2003, Mendes-Lopes and Ventura 2006, Nelson and Adkins 1986, Rothermel and Anderson 1966).
- Experiments carried out on a discontinuous fuel bed, where the fuel bed is composed of upright sticks that are perfectly aligned (Fons 1946, Steward and Tennankore 1979, Weise and Biging 1996, Wolff *et al* 1991).

We use three statistical tools, normalized mean square error (NMSE), fractional bias (FB) and Pearson's correlation coefficient (r) to check the agreement between predicted and observed ROS. We can see on fig.1a the very good agreement between predicted and observed ROS with a small error and a quasi-zero bias, when confronted to experiments carried out on a continuous fuel bed. The results are better than the ones obtained when using the former radiative only model (NMSE=11.74% and FB=-0.32).

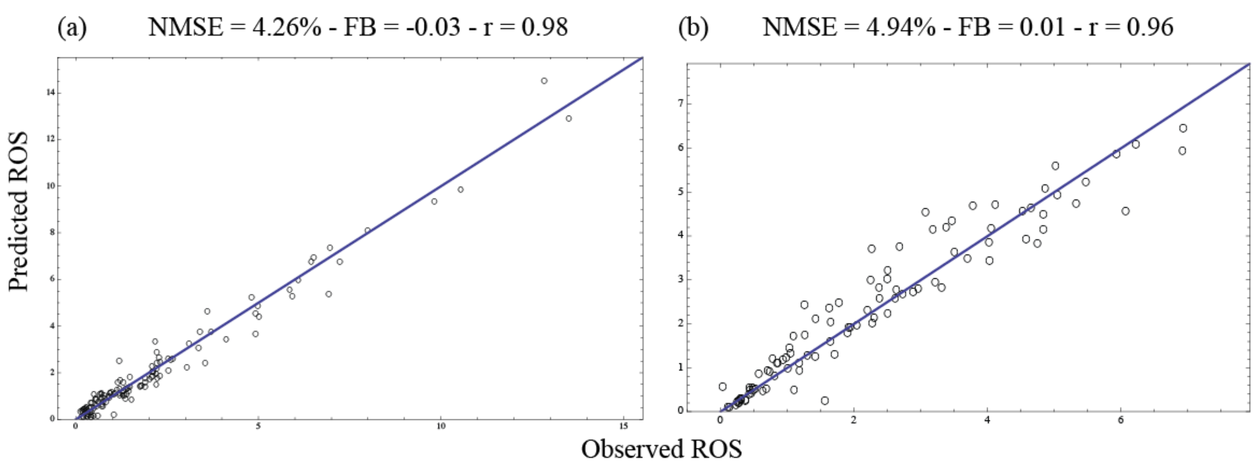

Figure 1 – Predicted ROS given by the radiative-convective model versus observed ROS for the sets of fires spreading in continuous fuel bed (a) and discontinuous fuel bed (b)

When the fuel bed is discontinuous (fig.1b), the agreement is strong too. The improvement clearly makes sense because the agreement between observed and predicted ROS obtained with the radiative only model was very poor (NMSE=648,76% and FB=-1.34).

Conclusion

In conclusion, we can say that we have a simplified physical propagation model which generates numerical values quickly and is able to reproduce all the types of ROS with only two fitted parameters at the laboratory scale (and even no fitted parameter for large fires in an homogeneous continuous fuel bed).

The agreement between predicted and observed ROS is very important.

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Modeling of the fabrics ignition

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Abstract:
Automated experiment technique is developed for fabric's temperature measurement. A new ignition mathematical model of heterogeneous ignition for translucent, capillary-porous, flat materials is proposed under static and dynamic conditions of heating by thermal radiation. A new ignition criterion is justified. Adequacy of the model and the ignition criterion to experimental data is established. Applicability of the models is shown to determine the ignition characteristics of the composite fabrics from cotton, wool, and polyester fibers.

Additional Keywords: Wildfires, thermal theory, critical conditions, model of ignition, dynamic heating, prediction

Introduction

Thermal radiation is the greatest hazard to objects of different physicochemical and biological natures in industrial accidents, abnormal natural phenomena, wildfires, local military conflicts and acts of terrorism. Combustion and the new fires formation can occur under thermal radiation exposure to flammable materials. The main danger for a human is the ignition of an outer layer of clothing fabric. Clothing ignition in crowded places at wildfires is the most dangerous scenario for afety.

Presently, domestic and foreign methods of human thermal injury evaluation during emergencies are focused on the calculation of the thermal radiation damage effect only for exposed skin. Quantitative evaluation of the protection provided by clothing and effects on skin injuries is limited by combustible materials fire hazard experimental assessment (Samotaev 1989). The theoretical basis of predicting fabric ignition under heat radiation exposure is the theory of thermal ignition of condensed systems. Theory has been created by the following domestic and foreign scientists: Semenov N.N., Hicks B.L., Seeger R., Zeldovich Y.B., Frank-Kamenetsky D.A., Merzhanov A.G., Vilyunov V.N. and Averson A.E. In this thermal theory the simplest models of homogeneous ignition of solid propellants are considered without taking into account the physicochemical processes and non-chemical sources at different heating mechanisms.

Research into the heterogeneous porous systems ignition with gaseous and condensed reaction products has not yet been developed. The results of such studies are needed to predict the dangerous zones of mass destruction. Focused study of retardant selection, and the creation of noncombustible fabrics is needed as well. This lack of research has caused the need for new approaches in predicting the ignition characteristics of the combustible materials. Thus, the development of theory and experimental methods of hazards prediction is important socio-economic problem.

The simplest ignition model

For mathematical description of the ignition phenomena in general the system of equations is considered including the equation of thermal conduction and diffusion with chemical sources, volumetric non-chemical sources, hydrodynamic equations, kinetic equation or a system of them. Solution of the equations in a complete mathematical formulation obviously has insurmountable mathematical difficulties. Therefore, the thermal ignition theory accepts a number of the following simplifications.

Heat transfer through the substance is due to the thermal conductivity. During substance heating, the phase transformation (evaporation, pyrolysis, ablation, etc.) and diffusive transport of the reaction products are not taking in account. The system provides only one heat source – a one-step irreversible chemical reaction. Under these assumptions the system of equations, describing the process of thermal explosion, has the form:

thermal conductivity equation in the substance:

$$c\rho \frac{\partial T}{\partial \tau} = \lambda \nabla^2 T + Qk(T, \eta) + f(x, \tau), \qquad (1)$$

equation of a chemical reaction kinetics:

$$\frac{\partial \eta}{\partial \tau} = k(T, \eta) = k_0 \cdot (1-\eta)^n exp\left(-\frac{E}{RT}\right), \qquad (2)$$

where T- temperature, Q- heat of reaction per unit of volume; k_0- pre-exponential factor, η - the degree of conversion, n - the order of reaction; c, ρ- heat capacity and density, respectively; λ-thermal conductivity coefficient, $f(x, \tau)$- intensity of volumetric non-chemical sources.

Described physicochemical model of process represents only the most basic, schematic positions of thermal explosion theory. In reality, additional factors can impose and complicate the nature of this process. For these cases the thermal explosion theory requires further development.

Nonlinear thermal conductivity equation (1) with a chemical heat source does not have analytical solution. The heat balance equation in the area of chemical reaction can be provided as critical condition. The first time such thermal model was proposed by N. Semenov in1928., According to that research, the quantity of heat emitted by chemical reaction, exceeds the heat removal at the ignition point.

All methods of the critical conditions determination are approximate. Mathematical expressions of the critical conditions are based on the fact that the heating step, in which the chemical reaction either does not occur or is not important, is the main part of the ignition delay time. Therefore, in the heating-up phase the nonstationary thermal conduction equation is solved for the chemically inert body and the condition of ignition is additionally recorded.

According to the approximate method of Averson, Barzykin and Merzhanov (1968), ignition occurs when the rate of heat loading from an external heat source and heat removal from chemical reactions are comparable:

$$q(\tau_{ign}) = Qk_0 \int_0^{\infty} exp\left(-\frac{E}{RT}(x, \tau_{ign})\right), \qquad (3)$$

where $q(\tau_{ign})$- value of the heat flux at the moment of ignition.
The calculations results of the ignition characteristics on the thermal model (1-3) are shown on fig. 1. Results of experimental data and model calculations of the basic ignition characteristics (ignition time and the surface temperature) in the thermal theory (Merzhanov and Averson, 1971) are presented on semi-logarithmic coordinates $lg\tau_{ign}$ $-1/T$.
As seen from the graph on fig. 1, linear dependence is obtained for a constant heat flux and constant surface temperature.

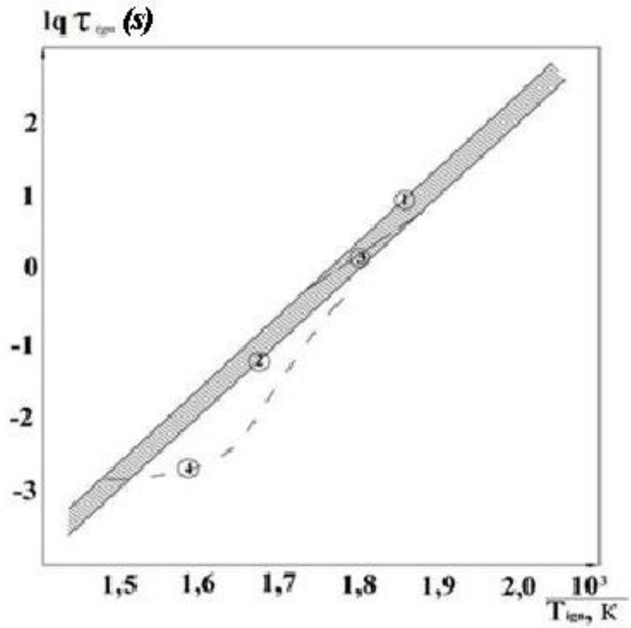


Fig.1. Dependence of the ignition characteristics of nitrocellulose at various heating mechanisms:
1- constant heat flux, 2- constant surface temperature, 3- convective regime, 4- volumetric heating by radiation.

However, in the ignition thermal theory such linear dependence are not established for volumetric radiation heating and dynamic heating conditions, that are most important for fire safety.

Modeling of the fabrics ignition process

In the field of fire safety, thermal radiation is the main factor affecting not only natural wildfires, but also industry fires in petrochemical plants, aerospace technology, nuclear engineering etc. Therefore, the exploration of the new approaches and criteria of ignition, that are adequate for the real ignition characteristics, is an important applied problem in the prediction of ignition as energetic substances and materials, as combustible polymeric materials. In contrast to the basic model of thermal ignition theory, modeling of the fuel polymeric materials ignition with the physicochemical transformations initiates insurmountable mathematical difficulties. The difficulties are not so much in the physical and mathematical formulation as in the identification of numerous variable coefficients and kinetic parameters. These unknown variables parameters are included in the right part of Fourier equation, in which a great many of volumetric chemical and non-chemical sources become available.

Mathematical model.

Ignition of fabrics is a complex nonstationary physochemical process (Baratov et al, 2006). The most important and the least understood processes of intensive thermal decomposition are volumetric evaporation, pyrolysis and the decomposition products ignition in the gaseous and condensed phases.

The physical model of fabrics ignition is presented on (fig. 2). During heating by radiant flux the three stages of material thermal decomposition are observed: evaporation, dry residue pyrolysis, oxidation reaction of pyrolysis coke residue by atmospheric oxygen. According to thermographical data, noticeable evaporation from plant materials begins at 50-60 °C and terminates at temperatures around 110-150 °C (Konev, 1972). For woven fabric the sorption moisture removing occurs at temperatures ranging from 30 to 160 (260) °C (Baratov *et al*, 2006).

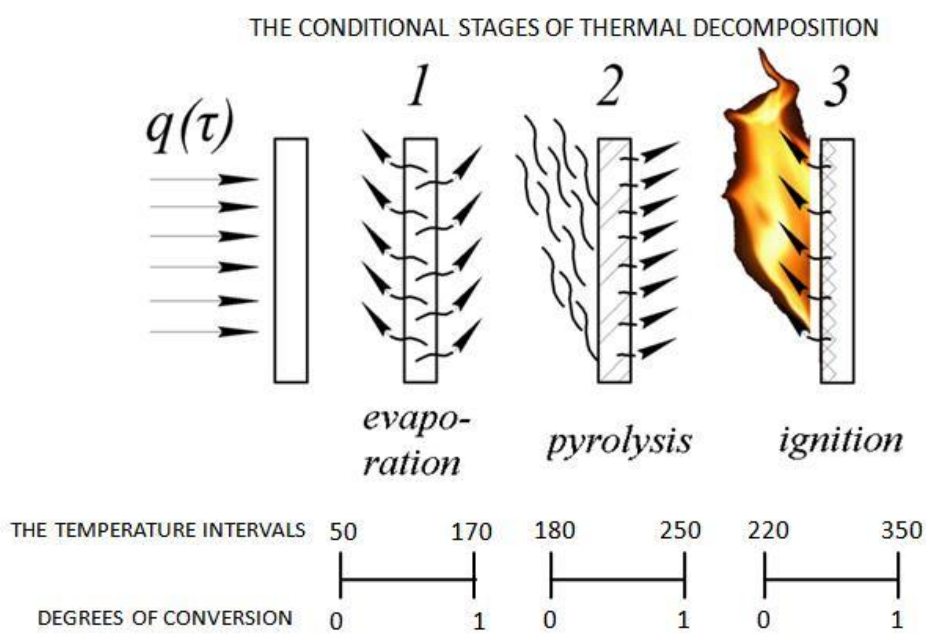


Fig. 2. The physical model of the ignition.

Fuel and oxidant initially are separated in fabrics volume and they are connected only at the rapid heating process, so the application of solid-state model is not possible for fabrics.

In the literature data on the adequate models and criteria of combustible materials ignition are not presented for the wide range of heating intensities and the boundary conditions of heat transfer with the environment. Specific to each stage kinetics and thermal characteristics are proposed for the mathematical formulation of heterogeneous systems ignition with the physical and chemical transformations. For translucent bodies (as fabrics) the volumetric heating of the material due to radiation is necessary to take into account. Then, the equation of the energy conservation law can be expressed as:

$$c\rho\frac{\partial T(x,\tau)}{\partial\tau}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T(x,\tau)}{\partial x}\right)-Q_1-Q_2+Q_3+Q_4 \tag{4}$$

$$Q_1=Q_{ev}\rho_{ev}\frac{\partial\eta_{ev}}{\partial\tau},\frac{\partial\eta_{ev}}{\partial\tau}=k_{ev}(1-\eta_{ev})exp\left(\frac{-L_{ev}}{RT_{ev}}\right) \tag{5}$$

$$Q_2=Q_{pyr}\rho_{pyr}\frac{\partial\eta_{pyr}}{\partial\tau},\frac{\partial\eta_{pyr}}{\partial\tau}=k_{pyr}(1-\eta_{pyr})exp\left(\frac{-E_{pyr}}{RT_{pyr}}\right) \tag{6}$$

$$Q_3=Q_{ch}\rho_{ch}\frac{\partial\eta_{ch}}{\partial\tau},\frac{\partial\eta_{ch}}{\partial\tau}=k_{ch}(1-\eta_{ch})exp\left(\frac{-E_{ch}}{RT_{ch}}\right) \tag{7}$$

$$Q_4=\varepsilon\mu q_o e^{-\mu x} \tag{8}$$

$$\lambda=\lambda_0(1-\omega_{ev}\eta_{ev}-\omega_{pyr}\eta_{pyr}-\omega_{ch}\eta_{ch}) \tag{9}$$

$$\rho=\rho_0(1-\omega_{ev}\eta_{ev}-\omega_{pyr}\eta_{pyr}-\omega_{ch}\eta_{ch}) \tag{10}$$

Initial conditions:

$$T(x,0)=T_0. \tag{11}$$

Boundary conditions:

$$-\lambda(T)\frac{\partial T(0,\tau)}{\partial \mathrm{x}}-h[T(0,\tau)-T_0]-\varepsilon\sigma[T(0,\tau)^4-T_0^4]=0, \tag{12}$$

where ω_{ev},ω_{pyr}, ω_{ch}- mass fraction of moisture, mass fraction of material sample, subjected to pyrolysis, mass fraction of carbon residue; Q_i- thermal effect, *J / kg*; η_{ev}, η_{pyr}, η_{ch} –conversion degree of the stage of evaporation, pyrolysis, chemical reactions, respectively; k_{ev}, k_{pyr}, k_{ch}- the rate of reaction at the stages of evaporation, pyrolysis, chemical reaction, respectively; L_{ev} - effective heat of vaporization, *J / mol*; T_0, T_{ev}, T_{pyr}, T_{ch} – initial temperature, temperature of evaporation, pyrolysis, chemical reactions, respectively; E_{ev}, E_{pyr}, E_{ch} - kinetics parameter at the stage of evaporation, pyrolysis, a chemical reaction, respectively; ε - emissivity coefficient, *h*-convection heat transfer coefficient, σ- thermal radiation coefficient. Indices correspond to: 1 - evaporation stage, 2 - a pyrolysis stage, 3 – stage of chemical reaction in the coke residue with heat emission, 4 - source of absorbed radiant energy.
In the proposed model the following are presented:
six physicochemical volumetric sources;

endothermic - evaporation and pyrolysis;
exothermic - oxidation in the gas phase of gaseous pyrolysis products with each other, atmospheric oxygen and carbon residue; oxidation of carbon residue by atmospheric oxygen after pyrolysis in the solid-phase;
one non-chemical source- volume absorption of heat radiation.

In sum, about 30 variable coefficients and kinetic parameters are presented in the all expressions for the sources. Standard methods are used for determination of some of them and literature data-for others. When polymer materials are high-intensive heated, the vast majority of the coefficients are changed as a result of their dependence of temperature. The data for these dependencies are practically absent. Therefore, the integral values of characteristics are accepted for the models. But information according to the integral values is also extremely limited. Only the method of identification of the variables in the computational experiment is available for determination of the integral values of the coefficients and kinetic parameters. Thus, the problem reduces to the problem of controlling and, more specifically, to the inverse problem of heat conduction controlling with sources. Formulation of these problems relates to the incorrect problems of mathematical physics. Therefore, the functional quality of control, optimization criteria, control functions, control parameters, their constraints, *etc* have to be justified even for the approximate solutions of controlling problems. Data on the identification algorithms are not presented for such multi-criteria multi-parameter control problems.

This paper proposes a simplified identification algorithm, based on a new expression for the ignition criterion.

Ignition criterion

Many studies noted that a qualitative transition from a relatively slow rate of thermal decomposition to the heat explosion takes place at sudden increases in the growth rate of the surface temperature due to the chemical reaction, regardless of heating mechanism and rate of heating from external sources. However a quantitative estimation of the critical values of the temperature rate increasing at the ignition is not presented in the literature.

Three aspects were taken into account at the justification of the ignition criteria.

1. Ignition characteristics during nonstationary heating are determined by the surface temperature. The chemical reactions rate is maximized just on the surface or in the infinitely thin surface layer. Hence, the ignition criterion has to be written for the surface in the form of differential Fourier equations with sources. And all other distributed sources of chemical and non-chemical nature will affect to the spatial division of temperature, including its surface value.
2. In the method of differential thermal analysis (DTA) the evaluation of thermal effects is carried out on the differential recording of inert standard and thermally decomposing material temperature. The similarity of thermal, optical and geometrical properties of the standard and the sample are tried to keep in this experiment, and the difference of their temperatures is fixed. The dynamics of this changing difference depends on the thermal effects of thermal decomposition - evaporation, pyrolysis, thermal oxidation reaction.
3. Ignition characteristics in most experimental studies of condensed systems ignition are determined by measuring the surface temperature and the appearance of a flame in the gas phase. But in some studies (for example, see Rozenband et al, 1968) the temperature change is measured for the inert sample and the sample with the physical and chemical transformations. The moment of ignition of the fuel sample is determined by the indications of the surface

temperature, measured by thermocoupling. For the theoretical and applied aspects, it is important the fact that the surface temperature of flammable and inert samples, measured in the experiment, completely coincide until the moment, close to a thermal explosion. Consequently, the growth of rates ratio is equal to 1 at a slight increase in temperature of the chemical reaction and at reaction's absent. Experimental data obtained during dynamic convective heating from the ignition source are in form of linearly increasing function.

After analyzing all known methods and models the new idea and a new approach are proposed to combine their positive aspects. The concept of the approach is the mathematical modeling of heating in inert and reacting samples.

Two heat conduction equations are integrated simultaneously for two samples with identical properties to realize the full identity of the standard and the sample in the computing experiment. One equation is for inert body without physicochemical transformations, another one is for equations with physical transformation (evaporation, pyrolysis, dispersion etc.) and chemical thermal-oxidative reactions in the solid and gas phases. In this case, not only sample temperature and their difference in the DTA are calculated, but also the rate of the samples temperature changing. The ratio of these rates can be called the criterion of ignition.

Theoretically, the endothermic (vaporization and pyrolysis) and exothermic effects (chemical reaction) are influenced on the value of this ratio. In the computing experiment (CE) the thermal effects of each step of the thermal decomposition appear in the respective temperature ranges. Therefore, four periods of this criterion change are observed. In the first stage, at temperatures below the physicochemical transformations, value of criterion is equal to one. In the second stage, at relatively low temperatures in comparison to the ignition temperature, criterion became less than one and decreases due to endothermic phase transformation. In the third period, oxidative exothermic reaction influence begins with a surface temperature rise and the criterion value starts to increase to one. When the value is equal to one, endo-and exothermic effects became equal. In the fourth period, a sharp temperature increase appears due to the exponential dependence of the rate of chemical reaction. At the end of that period the thermal explosion phenomenon occurs. Duration of the fourth period is about 1% of the ignition time.

Considering, that the rate of temperature change is proportional to the heating rate, the ratio of these rates was invariant to the heating rate from the heat source, to the heating mechanism and to the kinds of fuels. The criterion was called "invariant". Thus, a new criterion of ignition is defined as the ratio of the growth rate of the temperature of the sample subsurface volume, wherein all steps of physicochemical transformations progresses, to the growth of temperature rate on the surface of chemically inert body:

$$IC = \frac{T'_{chem}(\tau)}{T'_{inert}(\tau)} = \varphi(\tau) \approx \frac{\Delta T_{chem}(\tau)}{\Delta T_{inert}(\tau)}; \qquad (13)$$

where $\frac{T'_{chem}(\tau)}{T'_{inert}(\tau)}$ – the difference analogue of the rates ratio.

A comparison of the proposed criterion performed with well-known criteria of thermal ignition theory for surface heating mechanisms (heating by heated block and surface heat flux). Our criterion coincides with the criterion of critical conditions, suggested by Zeldovich (1963) and Averson, Barzykin, Merzhanov (1968), the difference is not more than 2%. However, for the volume heating mechanism the difference in the radiation ignition characteristics of the compared criteria was significant. Then, this criterion was used to determine the ignition characteristics of combustible materials under static and dynamic regimes of heating, and its adequacy to the real data was also established.

Identification of parameters of model.

Algorithm of model's identification for fabrics is based on the minimization of the functional at any single point, in which reliable experimental data of ignition characteristics are known. In this study, heat flux irradiation density of 50 kW/m^2 was chosen. This radiation density is recorded at the wildfires and combustion of hydrocarbon fuels. The literature contains data for only one of the fabric ignition characteristics - ignition time. Data on the of ignition temperature are practically absent. To measure the temperature a special technique is used, which is described below.

The Experimental Technique

Standard and comparative research methods can be distinguished from the variety of the test methods. In the most standard methods one of the characteristics of ignition is experimentally determined: concentration of the oxidant (oxygen index) or ignition time. Measurements of other features, namely the surface temperature at the ignition time, are not provided in the standard methods. Determination of ignition mechanism and the kinetic parameters of thermal decomposition process can't be analyzed without the knowing both of these ignition characteristics. Research methods are oriented to justify the adequacy of solid-phase ignition models. In addition, parameters can be modeled not only for wildfires and indoor fires, but also for industrial accidents.

Domestic GOST 30402-96 method was established to determine the flammability of constructional materials. This method is identical to the international ISO 5657.

The essence of the method is to determine material flammability parameters at exposure of radiant heat flow and flame from ignition source on the sample surface. Flammable material parameters are: critical surface heat flux density, when stable flame combustion occurs, ignition time from the start of radiation until the flame formation over the sample. Radiation panel in the shape of a truncated cone provides the given by standard levels of heat flux density from 10 to 50 kW/m^2. In real wildfires and man-made fires major damage factor is the thermal radiation heat flux up to 600 kW/m^2, which is an order of magnitude higher, than the energy characteristics of the standard methods. Therefore experts are developing the test benches for modeling the parameters of real fires. The radiation sources in these devices are ball and tube xenon lamps.

Due to the high plasma temperatures the xenon lamps produced high-intensity heat fluxes.

Fig. 3 shows the construction of the facility, radiant energy flow source is a xenon lamp DKsR-10000 (Kuznetsov and Filkov, 2011).

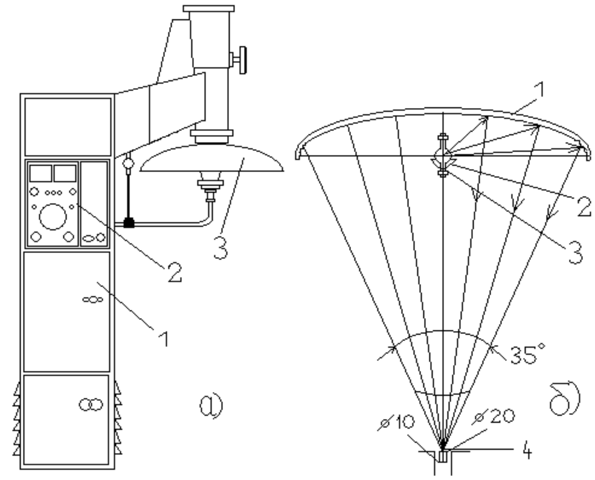


Fig. 3.Optical oven URANIUM - 1 with 10 *kW* xenon lamp:
a- design realization, b - optical emitter, 1 – reflector, 2 – counter- reflector, 3 - lamp, 4 - working spot

The maximum flux density of radiant energy in the spot with diameter 10^{-2} *m* is 4000 kW/m^2. The diameter of the focused flow was about $2 \cdot 10^{-2}$ *m.* Exposure of the sample is performed by mechanical shutter. The central shutter has two blinds. Shutter time is $4{\cdot}10^{-2}$ *s*. Facilities of Uranium-1 are available in Tomsk State University, Institute of Heat and Mass Transfer (Minsk), Siberian Branch of Russian Academy of Sciences.The using of facilities with tubular xenon gas discharge lamps in the nominal mode of power supply (Gainutdinov *et al*, 1972) allows to investigate the flammability of plastic materials up to a maximum heat flux of 0,2 MW/m^2. Patented power supply method for discharge lamps in the mode of multiple overloads increases the heat flux up to 2 MW/m^2 on the 30 cm^2 area (Enalejev *et al*, 1972). The experimental facility scheme is shown on fig. 4.

Facility is designed to study the ignition process of polymeric materials and heat and mass transfer in the package of clothing. The temperature of the sample middle is measured by the belt-microthermocouples, mounted between the meshing of the fiber material. The pressure in the gap is measured by micromanometer, weight loss is measured by torsion balance.

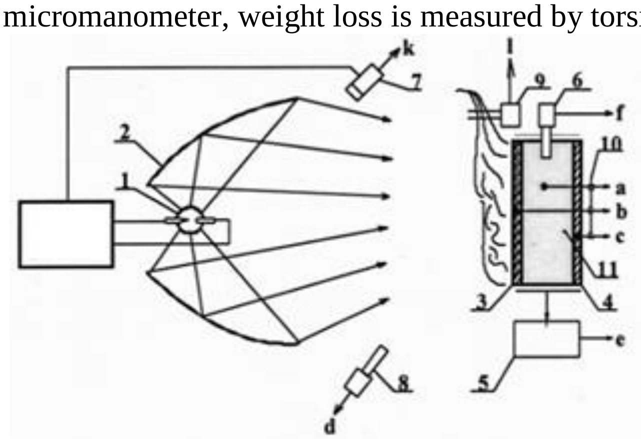


Fig. 4. Experiment's techniques: 1 – xenon radiant source, 300 *kW*, 2 – concentrator, 3 - test sample, 4 - calorimeter, 5 - electronic scales, 6 - pressure sensor, 7 - photoelectric sensor, 8 – thermal imager, 9 - fire detector, 10 – microthermocouple, 11 - air gap

Thus, the analysis of the technical characteristics of the standard methods and experimental benches allows the reasonable selection of the adequate experimental method, depending on the purpose, using of combustible materials and recipes of flame retardants.

Algorithm of identification

A specific feature of the process of ignition and flame propagation of artificial and natural fuels is an exothermic reaction between the fuel and oxidizer – atmospheric oxygen. Fire risk of this reaction is caused by the high rate of conversion of fuel to the enthalpy of high-temperature products. Kinetics of the reaction and heat removal rate at sufficient fuel concentration depends exponentially of the temperature, according to Arrhenius law. This positive feedback leads to a sharp heat release when a critical surface temperature in the relatively narrow range. This fact is confirmed quantitatively by a sharp change in the value of invariant criterion.

In the identification the initial values of the kinetic and thermal parameters in the all stages of physical and chemical transformations are taken according to DTA. In addition, for the evaporation stage the kinetic experiments data of Isakov (1984)are used, for the pyrolysis stage - Kislitsyn (1990), Aseeva *et al* (2010), for evaporation and pyrolysis stages - Grishin *et al* (1990), for textile materials - Baratov *et al* (2006). At the determining of absorption coefficient by the Buger law we compared the data on fabric ignition by thermal radiation with the experimental data of Grishin *et al* (2002) on the ignition of combustible forest materials pressed samples (Fig. 5 and 6) and the definition of the absorption coefficient. As seen from the graphs on Fig. 5 and 6, the fabric ignition parameters are close to the lichen and moss parameters. In accordance with data of Grishin *et al* (2002) fabric thermal absorption coefficient chosen from the range 2000-3000 *1 / m.*

In this paper, study fabric blend of cotton and polyester fibers chosen as an research object . The results of numerical experiments on the fabrics ignition are in good agreement with the experimental data of the Fire Safety Research Institute (Samotaev, 1989).

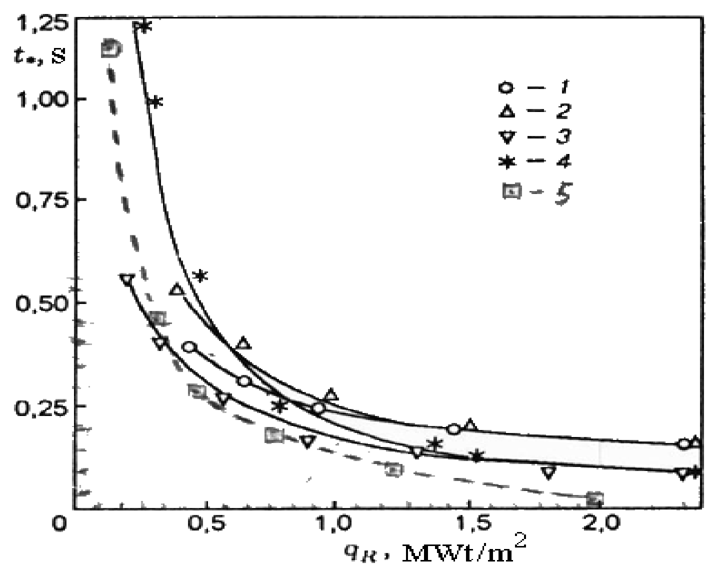


Fig. 5. Effect of the radiant flux density to the ignition time of forest fuels pressed samples: 1 - cedar needles; 2 - leaves of birch; 3 – moss; 4 – lichen; 5 – fabric

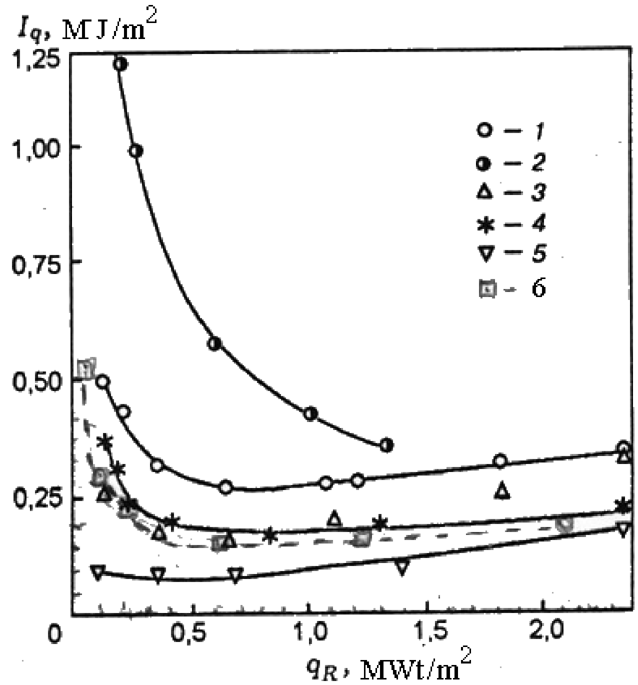


Fig. 6. Effect of the radiant flux density to the ignition energy of litter forest fuel layer:
1 - freshly slipped off pine needles with a moisture capacity of 140%; 2 - cedar needles;
3 – leaves of birch; 4 – lichen; 5 – moss; 6 – fabric

The challenge is solved by source control setting in nonstationary heat conduction problem (Samarsky and Vabitsevich, 2009) .The distributed heat sources can act as a control. To realize this algorithm mathematical model is artificially simplified (4-13) due to the successive elimination from the equations the volumetric source on the chemical reaction, pyrolysis and evaporation.

CE results on the fabrics ignition characteristics with model using (4-12) and the critical values of the ignition criterion (13) are shown on Table 1. Experimental data on the ignition performed by the authors by GOST 30402-96 and shown in Table 1. Experimental key point is highlighted for the density of 50 kW/m^2. In this point the good agreement established for the calculated and experimental results on the ignition time during standard testing and surface and the middle of the sample temperatures in the ignition moment on experimental facility (Enalejev and Kachalkin, 1997). Calculations For other levels of heat flux density were carried out only by the model and compared with experimental data.

Table 1. Comparison of experimental and calculated data on the fabric ignition characteristics. Technique and results of the experiment

Radiative heat flux dencity, kW/m^2	Experiment by GOST 30402-96			Solidphaze thermal model of ignition	
	self-ignition, *s*	piloted ignition, *s*			
		bench-scale	natural		
	time, *s*			τ, *s*	t_s, ^{0}C

fabrics					
20	no ignition	no ignition	81	73	225
30	no ignition	25-30	–	28	240
40	no ignition	14-16	–	15	247
50	no ignition	9-11	10,5	11	250
100			2,9	2,5	268
150			1,5	1,5	274
200			0,92	0,97	283
418,7			–	0,38	297
837			–	0,16	311
2721			–	0,04	333
4186			–	0,025	341

Good agreement between the experimental data and the CE results proves the adequacy of the model to the results of real tests and validity of identification algorithm of integrated values of the coefficients and the kinetic parameters on all stages of thermal decomposition. As noted above, the ignition point depends of the kinetic parameters of the chemical reaction of carbon residue oxidation. Identification algorithm of these parameters is based on the numerical methods of iterations and coordinate-wise descent and includes two cycles - external and internal. In the outer loop the pre-exponential factor and activation energy are given in the known from the literature values range. CE is conducted by numerical model in a wide range of surface heat flux (from 20 to 4000 kW/m^2). Ignition characteristics are defined and their relationship is built in semi-logarithmic coordinates $\ln\tau \sim 1/T$. The linear dependence indicates the legality of the Arrhenius law, as known from the literature data. For example, Shlyonsky et al (1996) presents the experimental data for the two groups of heat-resistant polymers: completely decomposed (or with a little residue) and tended to form nonvolatile carbonized products. For both groups of polymers the dependence of the thermolysis rate of the inverse temperature is linear in a certain temperature range.

CE identifying results of the kinetic parameters for fabric samples oxidative reaction presented on Fig. 7. Processing data of the characteristic ignition by least squares method allow to calculate the value of pre-exponential factor $k = 1{\cdot}10^{15}$, an effective activation energy $E = 173$ *kJ / mol*. This value is in the range of variation of the activation energy, defined for wooden material (Aseeva et al, 2012) and fabrics (Baratov *et al*, 2006).

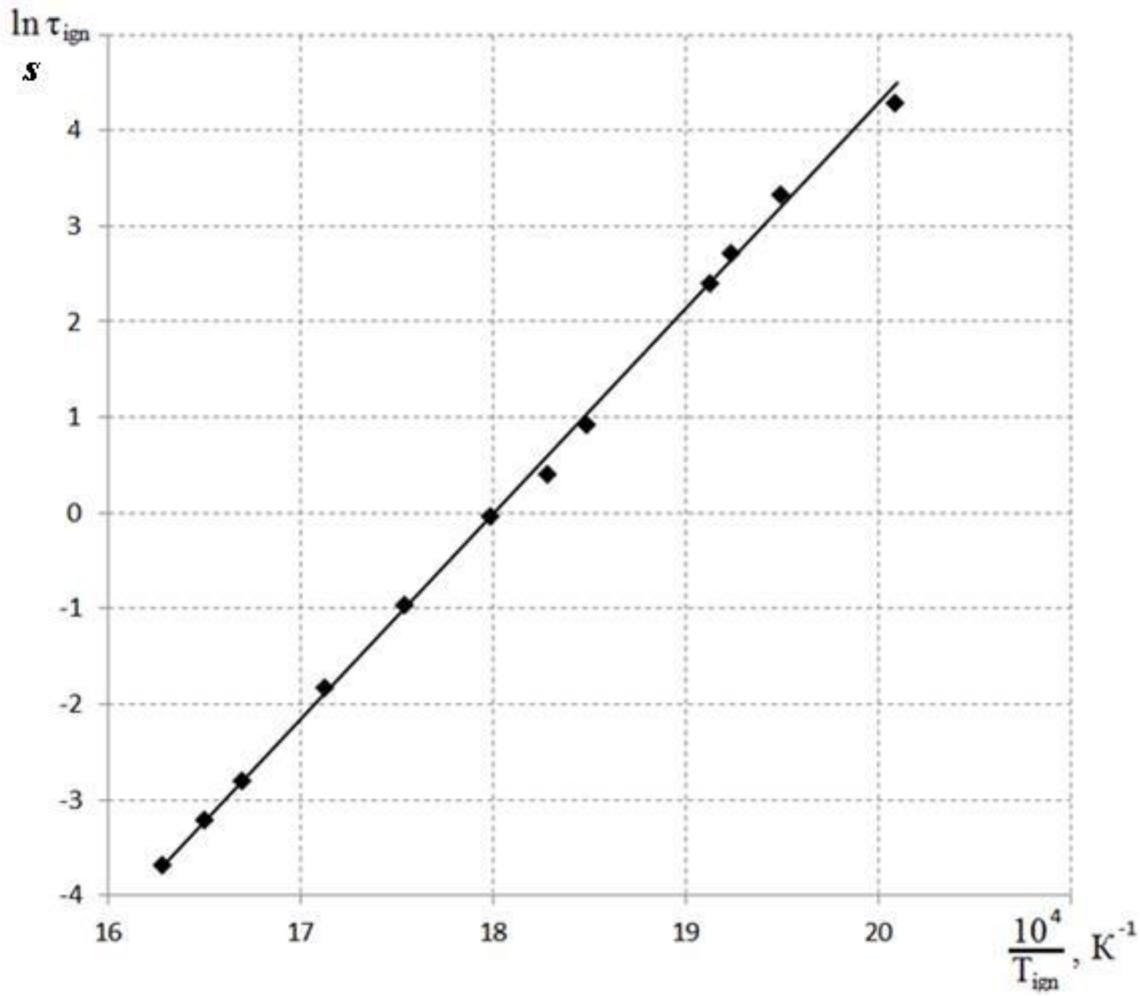


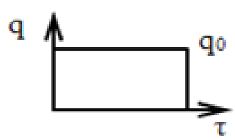
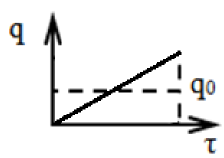
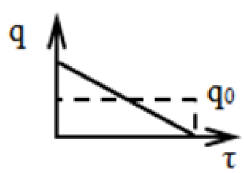
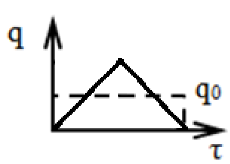
Fig. 7. Results of CE kinetic parameters identification of the fabrics thermooxidative reaction

Good agreement between the calculated and experimental results provides model's use to evaluate the exposure of initial conditions (temperature, humidity), thermal-physics and thermal fabrics properties on the ignition characteristics. We note, that the results obtained by heating under static conditions. In real wildfires and accidents at petrochemical plants (Lees, 2004) the density of the thermal flux is an explicit function of the time. This heating regime in the thermal ignition theory called "dynamic". In this connection the prediction of fabric ignition characteristics under dynamic conditions has important applications in the heating range of the heat flux density of wildland fires.

Dynamic heating

The main objective of model calculations is to evaluate the effect of heating dynamics on the ignition characteristics. To perform this task the elementary linear functions are selected - increasing, decreasing and piecewise linear. Each of these functions simulates real-life scenarios of wildfires with a relative approach, with an object distancing from the fire source, or combined scenario. The heating dynamics compared to the static regime when the heat flux q_0. Value of q_0 was taken as 20, 30, 40, 50, 100 kW/m^2. The selected range corresponds to the density of heat flow in the wildfires. As seen from the results of CE, shown on Table 2, the ignition characteristics depending on the heating regime. At the dynamic heating the ignition time is usually less than at static, and for some regimes it is no ignition.

Tab. 2. The influence of the heating dynamics on the ignition characteristics

№	Dynamics of heating	Heat flux density, *kWt/m²*	Ignition time, *s*	The surface temperature, *°C*
1		20	73	225
		30	28	240
		40	15	247
		50	11	250
		100	2,5	267
2		20	68	242
		30	24	252
		40	12	257
		50	9	261
		100	2,2	280
3		20	no ignition	–
		30	no ignition.	–
		40	no ignition	–
		50	4,4	213
		100	1,5	219
4		20	no ignition	–
		30	16,4	249
		40	8,3	257
		50	5,9	262
		100	1,5	281

At first we note that when the heating of the heat flux density increases at the static regime- the surface temperature increases in the ignition point, and the ignition time - decreases. This tendency is typical to all kinds of natural and synthetic fuels, as well as homogeneous and heterogeneous ignition mechanisms. In theory, this phenomenon is explained by the exponential dependence of the reaction rate on temperature. The growth of temperature rate and rate of the chemical reaction increases as the heat flux density, that leads to the ignition time delay decreasing. However, when the heat flux density decreases, the critical ignition conditions may occur, under which the heat amount, supplied from the external heat source, is not enough for the self-accelerating reaction. In the thermal theory of homogeneous ignition of fuels (Merzhanov and Averson , 1971) three types of conditions are considered:

• the source is valid during indefinitely long time, the heat reserve is unlimited, but heat losses from the system are presented.

• external heat source operates within a limited period of time (pulsed heat input) ;

• the source is valid during indefinitely long time, but heat reserve is limited (ignition by incandescent finite size body) ;

The analysis of these conditions applied to heterogeneous ignition of fabrics with physical and chemical transformations can explain the results of CE of fabrics ignition under dynamic conditions of heating .

Ignition at heat losses.

In thermal theory the heat losses by convection and radiation are considered. Obviously, for fabrics the endothermic effects of thermal decomposition can be classified additionally as the heat losses, when the value of the invariant criterion is less than one. This study has established experimentally, that when the heat flux density is less than 15 kW/m^2, fabrics ignition does not occur at any heating mode. This value for the wood material is 13 kW/m^2 (Abduragimov et *al.* 1986). Minimum heat flux and surface temperature, at which wood ignition doesn't occurs (Babrauskas, 2001), are respectively 12,5 kW/m^2 and 200-210 ^{0} C.

Ignition by heat pulse.

For an approximate calculation of the critical operating time of the external source is Zeldovich critical condition (Zeldovich, 1939). According to this hypothesis, for ignition of the substance it is necessary to make a sufficiently deep heated layer into this substance. If heating is stopped when this layer is not yet formed, ignition will not occur. Thermal theory predicts, that when heat flux is rapidly rising in time, the difference between the time of heat flow stop and ignition time is insignificant (table 2, line 2).

Ignition by incandescent finite size body.

If the supply of heat to the heating plate is sufficiently large, the temperature and declining heat flux are decreased slowly on the surface. Heat emission due to the reaction in heated layer increases rapidly and leads to ignition. A similar mechanism is obviously realized also at the thermal radiation (line 3, table. 2, heat flux density is 50-100 kW/m^2) .

If the less thickness of the plate surface temperature drops rapidly, and the heated layer of sufficient thickness has no time to form. Heat release rate curve passes through a maximum and does not exceed the speed of heat output in the reaction zone. In this case no ignition occurs (line 3, table 2, heat flux density is 20-40 kW/m^2) . When the surface temperature begins to decrease, the ignition criterion is negative.

In a piecewise linear function in the form of an isosceles triangle (line 4, table 2) sufficient to ignition heated layer begins to form from 30 kW/m^2. Adequate model and ignition criterion can be applied to determine the ignition characteristics of combustible materials at static and dynamic heating. The practical significance of the results is the ability to predict the impacts of hazards of natural man-made fires in emergencies.

Conclusions.

- The physical and mathematical model of the interaction of volumetric thermal radiation source with composite materials is represented, taking into account the thermal effects of phase transitions and chemical reactions.
- First invariant criterion for predicting of the heterogeneous ignition characteristics for planar capillary-porous materials with phase transitions at volumetric heating by radiation is proposed. In the numerical experiment adequacy of the ignition characteristics to the experimental data is established with the use of an invariant criterion and the limited application of the critical conditions of thermal ignition theory.
- Research results can be applied for solving of actual problems for Civil Defense and Emergency Situations at natural and technological disasters.

Acknowledgements.
The author is very grateful for the great assistance of Alexander Filkov in the preparation of materials for publication.I also express my gratitude to Gulnar Enalejeva for the great help in editing and obtaining scientific information on the subject of the publication.

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Modeling fuel moisture across the landscape for fire management

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Abstract:
Prediction of fuel moisture across the landscape is a useful tool for planning prescribed burns and predicting the behaviour of wildfires. In the paper we describe a system for predicting the moisture content and flammability of dead fine fuels in forests. Outputs from the fuel moisture model can be used as inputs to fire behaviour models (e.g. Gould et al. 2008), which may be used to identify conditions suitable for conducting prescribed burns or to model the spread of wildfires (e.g. Finney 1998, Tolhurst et al. 2008).

The system is based on an existing fuel moisture model (Matthews 2006) adapted to work with 6 km weather forecast grids (Engel and Ebert 2012). The moisture model represents fluxes of energy and water in a litter bed composed of three materials: litter, air, and free liquid water on the surfaces of the litter. The litter bed is bounded above by the atmosphere and below by the soil. The heat and water budget of each of the three materials is calculated at five equally spaced nodes within the litter layer using equations for six quantities: litter temperature, the temperature of free liquid water on the litter surfaces, air temperature, litter moisture content, amount of liquid water on litter surfaces, and specific humidity.

Predictions of fuel moisture content and fuel availability are calculated hourly for forested areas for 4 to 7 days in advance. Forecasts are output as 3 dimensional grids (latitude, longitude, time), which may be visualised as maps or time series. A single set of predictions are made for each grid cell, based on the assumption of a forest on flat ground with the mean fuel load within a grid cell. Above canopy radiation is estimated from solar position (Meeus 1991) and forecast cloudiness (Iziomon and Mayer 2002). Weather forecasts are adjusted to account for modification of wind and radiation by the forest canopy (Silbertstein et al. 2001, Matthews et al. 2007). Fuel loads are derived from vegetation maps.

Model output was tested against historical data sets (Matthews et al. 2007) and measurements made in the Blue Mountains region of NSW, Australia. The model was able to replicate these observations with some limitations and was able to represent differences in fuel wetting and drying as determined by fuel load and forest structure. Field observations have shown that sheltered, down slope locations may be much wetter than flat areas, which needs to be taken into account when interpreting predictions (Sullivan and Matthews 2012).

Being able to make fuel moisture predictions that take into account small scale variations in weather and responds to changing vegetation will enable managers to improve the efficiency of planning of burning operations. Future work to improve the fuel moisture prediction system could include further testing against field measurements, refinement of forest structure parameters, inclusion of sub-grid scale variability, particularly slope and aspect effects, and inclusion of forecast uncertainty.

Additional Keywords: fuel moisture, model, forecast, forest, prescribed burning

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Proceedings of 4th Fire Behavior and Fuels Conference, July 1 – 4, 2013, St. Petersburg, Russia
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Fuels, fire, and climate change

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Abstract:
Climate change is expected to have an effect on fuels as well as on fire weather. In this paper we use a suite of models to examine the links between climate, fuels, and fire behaviour. Predictions from downscaled climate models (Page and Jones 2001, McGregor and Dix 2008) were used to drive models of fuel amount, the moisture content of fuels (Matthews 2006) and two models of forest fire behaviour (McArthur 1967, Gould et al. 2008) at locations in fire prone areas in south-eastern Australia. Two approaches to fuel modeling were used. In the first, empirical models were used to predict litter fall and decay on sites of varying rainfall and temperature (Matthews et al. 2012). In the second a process-based forest growth model (Battaglia et al. 2004) was used to predict litter accumulation in plantation forests.

We found that a warming and drying climate produced lower fine fuel amounts in native forests, and greater availability of this fuel to burn due to lower moisture content. Changing fuel load had only a small effect on fuel moisture. A warmer, drier climate increased rate of spread, an important measure of fire behaviour. Reduced fuel loads ameliorated climate induced changes in fire behaviour for the McArthur (1967) fire behaviour model. Sensitivity analysis of the other fire model (Gould et al. 2008) showed that changes in fuel amount induced changes in fire behaviour of a similar magnitude to that caused directly by sensitivity to climate.

In contrast to the empirical model for native forest, and in spite of generally lower rainfall, the plantation model showed an increase in litter fuel load over most of south-eastern Australia. This difference was most likely a result of the carbon dioxide fertilsation effect although changes in water use efficiency, photosynthesis, and litter decomposition rates may also have had some effect (Battaglia et al. 2009). The combination of increased litter load and increased fire weather lead to higher than expected fire risk overall in comparison to the empirically based modeling study.

It is also possible that fuel layers that cannot be considered in existing models, such as shrub fuels, may also respond to changing climate and may result in similar magnitude changes in fire behaviour given the sensitivity of fire behaviour models to the shrub layer. Differences in fuel dynamics observed between the two modeling approaches indicate need for further study of litter dynamics including some attempt to include effects of increased carbon dioxide in empirical studies.

Our results indicate that effects of climate change on fire risk via modification of fuels can be of similar magnitude to direct fire weather effects. There is still much to be learned about interactions of climate and fuel structure and it is probably too soon to make decisions on the basis of these predictions. Since changes in fuel are likely to be gradual, managers should monitor fuel structure on their estates and develop adaptation strategies to deal with uncertain

change.

Additional Keywords: Fire behavior, eucalyptus, model, climate change, litter.

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Fuel combustion modeling in wildland fires

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Abstract:
The main goal of this study is to determine the applicability of a multiphase formulation (Larini et al. 1998) using the LES methodology for the prediction of a small-scale burning of porous forest fuel samples in a Computational Fluid Dynamic (CFD) based physical fire model, called ForestFireFOAM (FFF). The latter is under development using FireFOAM, a Large Eddy Simulation (LES) solver for fire applications based on the C++ object-oriented toolbox of OpenFOAM.

The solid fuel constituting a forest fuel layer and its interactions with the gas phase are represented by adopting a multiphase formulation. This approach consists of solving conservation equations (mass, momentum, and energy) averaged in a control volume at an adequate scale that contains a gas phase flowing through N solid phases and considering the strong coupling between phases. The latter consists of particles of the same geometrical and thermo-physical properties, providing the same behavior. Physico-chemical processes such as pyrolysis, chemical reactions, char oxidation occurring in the solid and gas phases have to be taken into account as well as other phenomena including combustion, radiative, and convective heat transfer. The flame shape is controlled by the aerodynamic structure of the complex environment. Hence, a turbulent model and a radiative transfer model have to be considered. The required formulation is made of a set of coupled nonlinear equations that must be solved numerically. Numerical simulations are computed to mimic pine needle litter combustion performed in the FM-Global Fire Protection Apparatus (FPA) in order to test the model and submodels used. The FPA operates on a similar concept to a cone calorimeter. The fuel sample is subjected to an external radiative heat flux, and a pilot ignition source is provided. The mass loss rate of the sample is measured and the exhaust gases are analyzed for composition, temperature, optical obscuration and pressure drop. More details are provided in (Schemel et al. 2008). Its basic layout is presented in Fig. 1.

In order to simulate the FPA properly, the problem was simplified to two dimensions only and one solid phase representative of the pine needles (Morvan et al. 2009). The pine litter is defined as a rectangular zone (in red in Fig.1) with the same dimensions as the sample holder. The flow is represented by a pressure differential set at top of the FPA. The mesh is made of 0.8 mm by 0.8 mm cells in the vicinity of the litter and near the lamps with a total of $2.5x10^5$ cells. Lamps were modeled by fixing walls on the side with a same position and orientation as the real lamps, maintaining the same view factor (in yellow in Fig.1).

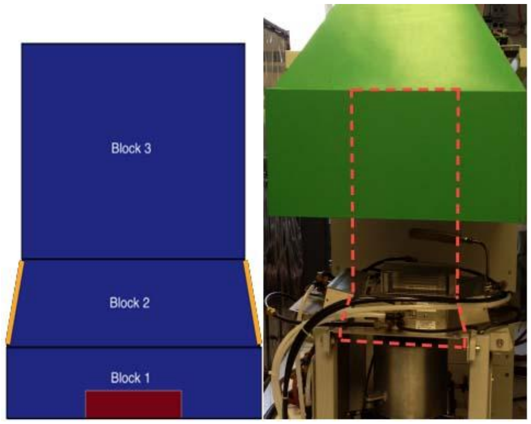
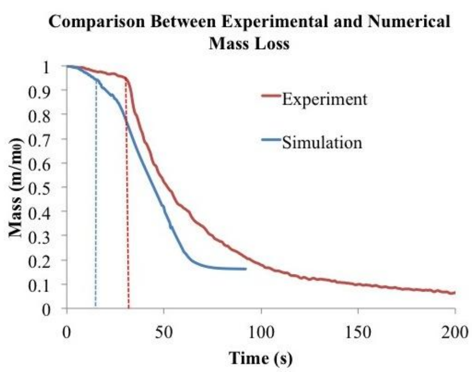


Figure 1- FPA layout and its representation in FFF

These walls have high temperatures providing a 25kW/m^2 flux on the surface of sample. Preliminary results compared with experimental data from (Schemel et al. 2008) are shown in Fig. 2. The evolution of mass loss shows that the fuel evaporates quicker than in the experiment. Therefore, the mass loss drops faster and ignition occurs earlier when the slope is steeper. At the same time, the heat is released earlier. Because of mass conservation, extinction occurs faster than expected. The double peak can be due to the absence of side walls in the simulations that induce a lateral flame spread in the sample whereas this phenomenon was prevented by the presence of the walls in the experiments.



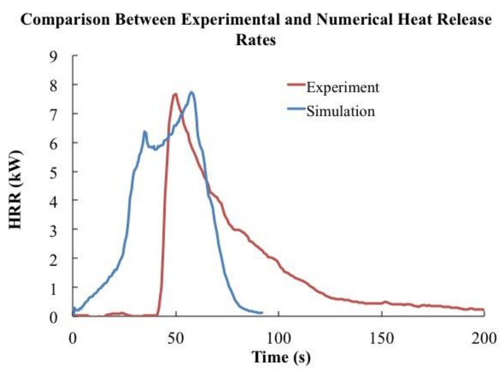


Figure 2- Comparison between Experimental and Numerical a) Mass loss; b) HRR

Despite all the described issues, the relevance of the model to conduct such simulations is established. To avoid unrealistic burning behavior, such as the double peak found in the heat release rate, modifications have to be made to the geometry and the grid size, as well as to the current sub-models and assumptions.

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Effect of fuel moisture content upon the propagation of surface fires

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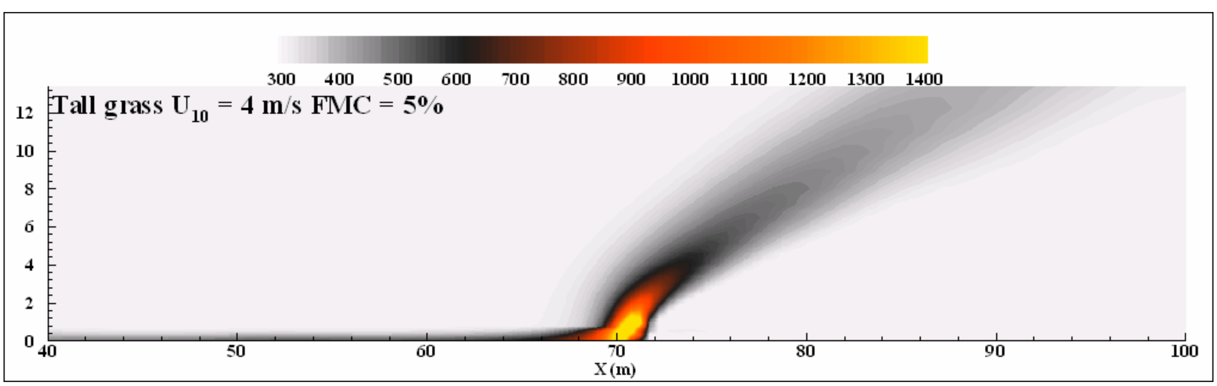
Abstract:
The objective of this study was to clarify the effect of fuel moisture content (FMC) upon the behaviour of surface fire propagating through homogeneous vegetation stratum. This problem was approached using numerical simulations performed in 2D at relatively large scale (the dimensions of the computational domain are: 170 m long and 35 m high). The mathematical formulation was based on a CFD multiphase approach, in which the vegetation was assimilated as a sparse porous media immersed in a gas phase (the atmosphere) (Grishin 1997, Morvan et al 2009).

The numerical results have been analysed in terms of fire residence time, fire front depth, fuel lean / fuel rich conditions, mass loss rate and rate of spread (ROS). Two windy conditions (calm and weak) were studied to evaluate the decay of the rate of spread (ROS) resulting from an increase of the fuel moisture content. The numerical results have highlighted that for calm wind conditions (U_{10} = 1 m/s), the FMC affected the propagation of the fire in reducing the rate of pyrolysis (fuel limited regime), until reaching the extinction observed for FMC around 20%. Whereas for stronger wind conditions (U_{10} = 4 m/s), a propagation can be observed for values of the FMC much larger than this critical value and in this case, the presence of a large amount of water vapour ahead of the fire front contributed to reduce the supply in oxygen of the combustion zone (oxygen limited regime) (see Figure 1). The existence of these two regimes of propagation can be also highlighted in Figure 2 representing the evolution of the fire residence time versus the FMC for two values of 10m open wind velocity. The effect of wind velocity upon marginal burning conditions was also analysed. The numerical results were also compared with empirical data of the literature (Morvan 2013).



Effectiveness of recent prescribed burning on reducing fire severity of the Black Saturday fires in Victoria

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Abstract:

Fire behaviour in Victorian forests on Black Saturday on 7th February 2009 was characterised by fast moving crown fires in eucalypt forest, accompanied by frequent medium-long range fire brand spotting, and deep and intense pyro-convective smoke plumes. Factors contributing to this were desiccated forest fuels, steep dissected terrain and extreme fire weather on the day (temperatures>41°C, relative humidity <10% and wind speeds averaging 45–55 km h^{-1}).

This paper presents an analysis of the effectiveness of fuel management by prescribed burning treatments in limiting the effects of extreme fire behaviour in dry and damp eucalypt forests on Black Saturday. A case study method was used to examine the effectiveness of recent prescribed burns and wildfires during the course of the five most significant fires that occurred in dissected mountainous or hilly, forested terrain. Factors such as relative size, geographical position, observed reduction in fire severity inside and outside the prescribed burning blocks, and the age of fuel treatment, were considered in the evaluation of the treatment's effectiveness in reducing fire severity and in turn fire growth. Fire spread and behaviour data were taken from reconstruction studies of the fires at the time each fire interacted with the each fuel management treatment (Gellie *et al.*, 2014). Analysis was completed in Quantum GIS software using post-fire Landsat TM imagery and digital aerial photography, and terrain, vegetation, and fire history GIS data. Fuel moisture, fire weather and fire danger information at the time of the fires impacted the fuel management treatment were also considered in the analysis. Within and closely adjoining the fire extent burnt on Black Saturday, 56 prescribed burns and 8 wildfires were evaluated at the local scale.

The results from these case studies show that under the severe (Forest Fire Danger Index (FFDI) ~60) to catastrophic or code red (FFDI>100) fire weather conditions on the day relatively small (30–300 ha) and disjunct prescribed burning blocks more than 2-y-old had minimal impact on reducing spread, spotting, and intensity, and in particular the final size of the fires studied. Heat-wave desiccated forest fuel types and the extreme fire weather contributed significantly to the spread, spotting, fire intensity and convection column development that enabled the fires to either overrun or bypass most if not all recent fuel treatments (<4 y).

After the fire weather had moderated to high (FFDI~20) to very high (FFDI~40) FFDIs, only prescribed burns, less than 3 years of age and with a size more than 600−1000 ha, located on flat or undulating terrain, had moderate to strong effect on reducing fire severity of these extreme fires. The study also shows that a 5% target of treatable public land done 4 y before the fire would have treated a relatively low proportion of the total area burnt in the Kilmore East fire because of the natural and man-made vegetation mosaics, wet forest not treatable under prescribed burning conditions, and the significant area of private land in the fire area.

Additional Keywords: Prescribed burning, fire severity, effectiveness of prescribed burning, severe-extreme fire weather, fuel treatments, Black Saturday fires

Introduction

Prescribed burning, also known as controlled 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'. The effectiveness of prescribed burning in slowing the spread and reducing the fire intensity of wildland fire in southeast Australia and has been a contentious issue for fire managers, fire agencies, and for the public at large. Few studies exist that document accurately the interaction between prescribed burning treatments and wildfires (Fernandes and Botelho, 2003). Some Victorian studies have been based on observations of the effectiveness of prescribed burning under less than severe to extreme fire weather conditions (Billing, 1981; Rawson *et al.*, 1985). Only three studies could be found that reviewed prescribed burning effectiveness under severe-extreme conditions: the 1961 Western Australia Dwellingup fire (McArthur, 1962), the 1983 Lorne fire (Billing, 1983) and in the 1988 Bemm River in East Gippsland (Buckley, 1992).

The purpose of this paper is to present findings on the effectiveness of fuel management of forested public land on fire severity and hence fire behavior, which had been previously treated by prescribed burning or burnt by wildfires and which some of the more significant Black Saturday fires on 7th February 2009 had burnt through under severe to extreme fire behavior conditions. The fires studied included the Kilmore East, Murrindindi, Beechworth–Library Road, Bunyip Ridge Track and Dargo–White Timber Spur fires where there were some recent prescribed burning treatments or areas burnt by wildfires prior to the Black Saturday fires. The Churchill–Jeeralang fire in Gippsland burnt through pine and eucalypt plantation, as well as dry, damp and wet eucalypt forest that had little treatment beforehand and so was excluded from this study.

These fires burnt under extreme fire weather conditions on that day; typically, the temperatures ranged from 41–47.5°C, the relative humidity was very low at 8–15%, and the recorded wind speeds ranged from 45–60 km h^{-1}. An additional factor was the 5–6 successive heat-wave days in the two weeks prior to Black Saturday when the temperatures exceeded 35°C, which desiccated the forest and grassland fuels in Central and Southern Victoria. Because of the state of fuel dryness on the day (2–3% fine fuel moisture content) and the turbulent dry atmosphere, fires spread at 9–15 km h^{-1} at Byram fireline intensities (BHFIs) of 35–95,000 kW m^{-1}, as intermittent or running crown fires through dry, damp, and wet sclerophyll forest. Dense ember showers preceded the fire fronts; firebrands detached from the convection column ignited spot fires ahead of the main fire fronts at typical ranges of 5-15 km and some occasional spot fires were found at distances of 25–35 km (Cruz *et al.*, 2012; Gellie *et al.*, 2014). The fires burning in eucalypt forests on hilly or mountainous terrain developed strong convection columns rising to 6,000–9,000 m and in some instances up to 13,500 m. The fires had all the hallmarks of extreme fire behavior as defined by Werth *et al.* (2011):

> Extreme' implies a level of fire behaviour characteristics that ordinarily preclude methods of direct control action. One or more of the following is usually involved: high rate of spread, prolific crowning and/or spotting, presence of fire whirls, and a strong convection column. Predictability is difficult because such fires often exercise some degree of influence on their environment and behave erratically, and sometimes dangerously.

Fire authorities around the world and here in Australia have accepted that fuel management by prescribed burning is a major strategy in reducing the impact and spread of subsequent wildfires. Since the 1960s Jarrah dry sclerophyll forests in south-west Western Australia have been burnt using low intensity prescribed burns at intervals between 5 and 7 years based on an target of 5% of the forest estate being burnt annually. This ongoing fuel management strategy is based on McArthur's pioneering work into the control burning of eucalypt forests and in response to the Dwellingup fire (McArthur, 1962).
Following the drastic effects on lives, property, and the fire severity impacts of the Black Saturday bushfires, the Victorian Bushfires Royal Commission (VBRC) employed a panel of fuel management experts in 2010 to determine whether such a broad scale fuel management strategy could be applied to mitigate these extreme wildfire impacts on public land in Victoria using the same annual target of 5%

(Victorian Bushfires Royal Commission, 2010). Recommendation 56 of the VBRC was that: 'The State commit to implementing a long-term program of prescribed burning based on an annual rolling target of 5 percent minimum of public land" even though there was no detailed supporting evidence from published studies supporting the notion that recent large scale fuel treatments ameliorate the fire behavior of large scale extreme wildfires in dry and damp eucalypt forests. Since the VBRC published its findings in 2010, the State of Victoria has embarked an ambitious campaign by 2015–2016 to treat 5% of public land (7,916,000 ha) throughout Victoria on an annual basis, amounting to ~395,000 ha per annum. This target includes grassland, heathland and scrub fuel types as well as forest.

This study attempts to address the lack of published data on the impact of prescribed burning of reducing fire intensity at the severe to catastrophic end of the fire behavior scale affecting the spread and behavior of extreme fires at the scale of the fuel treatment (100–1,000 ha), the intermediate scale (1,000–10,000 ha) and at the scale of the fire (10,000–100,000 ha). The approach adopted in this study is to examine the effects of prescribed burning within the extent of the larger wildfires on Black Saturday using fire severity assessment within and adjoining each affected fuel treatment, post-fire Landsat TM images, and reconstructed fire behaviour at the time the particular fire run of a fire impacted on each fuel treatment. Using the Kilmore East fire as a case study example, this study also reviews the hypothetical size and configuration of fuel treatments that could be applied to forests on public land within the three-year period prior to this fire and their likely combined effect at the landscape scale on potential extreme fire behavior.

The results of this study will provide knowledge to fire managers and the public as to the likely effect of prescribed burning based on fuel treatment block factors, such as fuel treatment age, size, terrain location, and treatment effectiveness standard, could have on reducing the spread and behavior, including firebrand spotting of future extreme fires under different sets of fire weather, fire behavior and terrain circumstances. The study also proffers a set of limitations of effectiveness of fuel management on public land in mitigating extreme wildfire behavior because of factors such as the proportion of prescribed area burnt to the area of the wildfire, and the local seasonal climate and landscape contexts. Treatability, based on fuel type and their treatability by prescribed burning, as importantly seasonal climate, plays a major role in determining which parts of the landscape can be burnt safely and effectively, in effect determining the treatability of eucalypt forests by prescribed burning. In addition, landscape context is a significant additional factor in determining the effectiveness of prescribed burning on public land. Landscape context is a complex factor, based on attributes such as the configuration and mix of private and public land, and the mosaic of natural and modified vegetation, including dry, damp, and wet sclerophyll forest, plantation forests, grassland and cleared land.

Method

Selection of fires for case studies

The fires selected for this prescribed burning effectiveness study were identified using two main criteria: first, having a high proportion of eucalypt forest within their extent, and second having either some or many prescribed burning treatments or areas burnt by wildfires in the ten years prior to Black Saturday (**Table 1**).

Table 1 Black Saturday fires included in study

Name of fire	Date of ignition	Time of ignition or breakout (hours)	Area burnt on Black Saturday (ha)	Native eucalypt forest (ha)	Pine or eucalypt plantation (ha)	Grassland or non-forest (ha)	Non-vegetation (ha)
Kilmore East	07/02/2009	1145	103,100	79,800	3,090	19,000	1,110
Murrindindi	07/02/2009	1445	65,500	57,320	2,820	5,000	360
Beechworth–Library Road	07/02/2009	1800	23,900	17,520	1,570	7,400	-
Bunyip Ridge Track	04/02/2009	1200	21,170	14,870	-	6,130	-
Dargo–White Timber Spur	04/02/2009	1300	12,370	11,970	-	400	-
Bendigo–Bracewell Street	07/02/2009	1620	1445	335	156	165	14

This table shows the date and time of ignition of these fires together, their size, and the fuel type they burnt. The Kilmore East and Murrindindi fires burnt the largest area on Black Saturday because of the relatively high proportion of forest situated in hilly or mountainous terrain fully exposed to the extreme fire weather on the day. The other fires were either located in a mosaic of forest and grassland, such as the Bunyip Ridge Track, Beechworth–Library Road and Bendigo–Bracewell Street fires or burnt through 6-y-old and 3-y-old forest in the case of the Dargo–White Timber Spur fire. Both the Bunyip Ridge Track and Dargo–White Timber Spur fires started on the days prior to Black Saturday but did not commence major runs until 1200 and 1300

The geographic location of these six fires in southern and central Victoria is presented in Figure 1. The areas shaded in red indicate where these fires burnt on Black Saturday. The areas shaded purple show the areas burnt after Black Saturday.

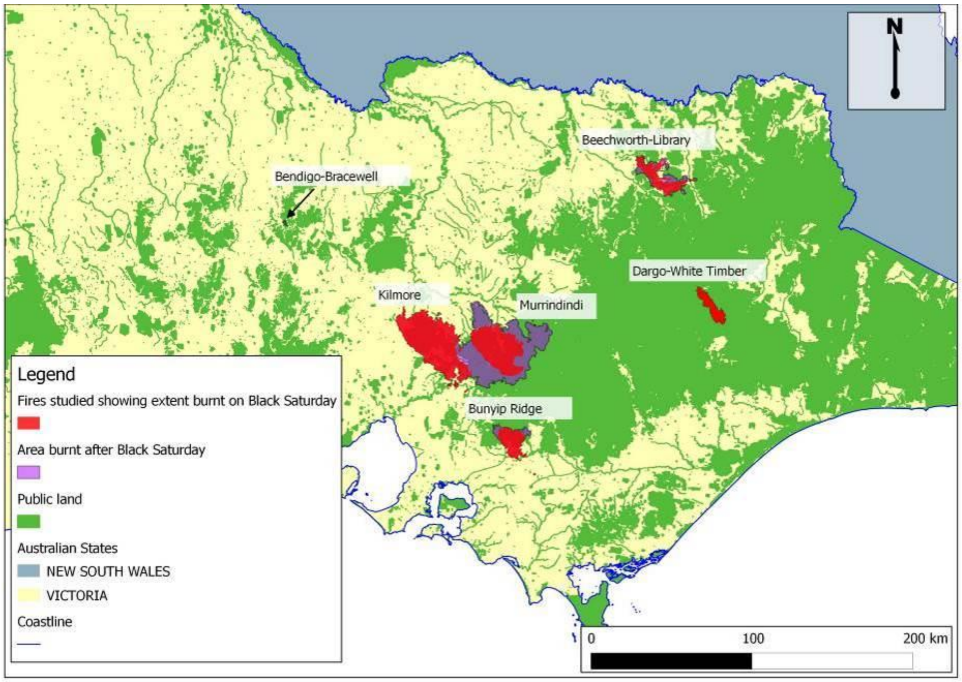


Figure 1 Location of fires in this study

Fuel management treatments within the extent of the six fires in Figure 1 were identified by overlaying the fire boundaries of the fires on the late evening of Black Saturday, or early on 8th February in the case of some fuel treatments in the Beechworth Library Rd fire, with recent fire history data extracted from Department of Primary Industries and Environment fire history database for the ten years prior to Black Saturday (Figure 2). 64 prescribed burns and wildfires were selected for evaluation of effectiveness in reducing fire severity.

Fire behavior and fire weather data

Fire weather, spread and behavior at the times each of these six fires impacted on recent fuel treatments were extracted from a contemporaneous study of the spread and dynamics of the Black Saturday fires (Gellie *et al.*, 2014). Included in the fire weather data were critical measures of fire weather, dead fine fuel moisture content (DFMC), wind speed, Forest Fire Danger Index (FFDI)(McArthur, 1967) and wind direction. The fire weather and fire danger data were estimated from the nearest most representative weather station. These are graphically depicted in Figure 3 for the fires selected in Figure 3 (a) to (h).

There is considerable variation in the diurnal trends of fire weather between each of the fires in terms of the duration of severe to extreme fire weather and the maximum levels of fire weather severity. With the exception of the fire weather severity experienced on the Kilmore East and Murrindindi fires (FFDI> 100 from 1300 to 1600 hours), the other fires, such as Bunyip Ridge Track, were exposed to FFDIs from 70 to 100 from 1200 to 1800 hours. FFDIs for the Dargo – White Timber Spur fire ranged from 50 to 110 at the lower-middle elevations of the fire. The Beechworth–Library Road fire generally had FFDIs ranging from 30 to 50 in the very high to severe fire danger range. However, FFDIs could have been much higher than that recorded during and after the passage of an undular bore, also termed a gravity wave, between 1130 and 0130 hours in the early morning of 8 February. Strong middle level winds came down to the surface and based on local ground observations gusts were 80–100 km h^{-1}.

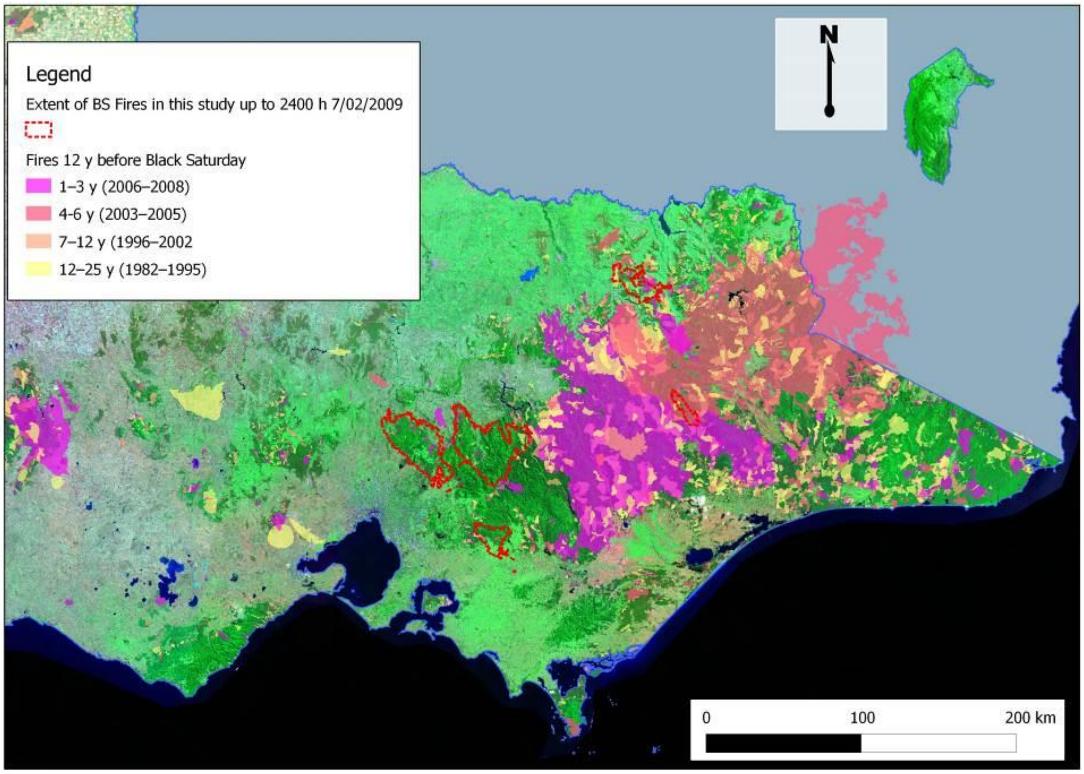
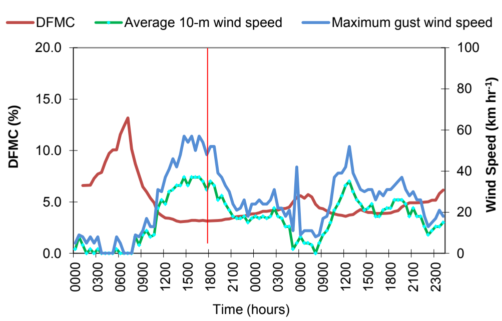
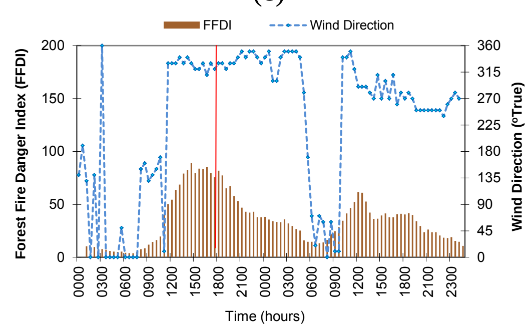


Figure 2 Black Saturday Fires in relation to recent fire history (<12 y before Black Saturday)

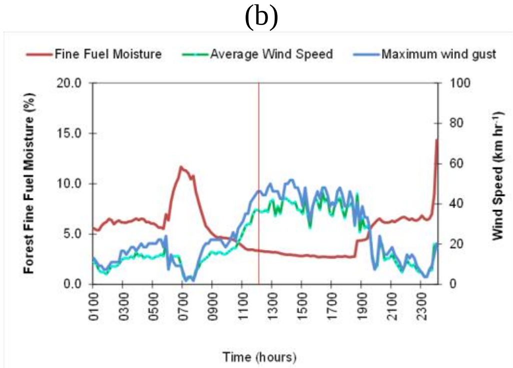
(a)



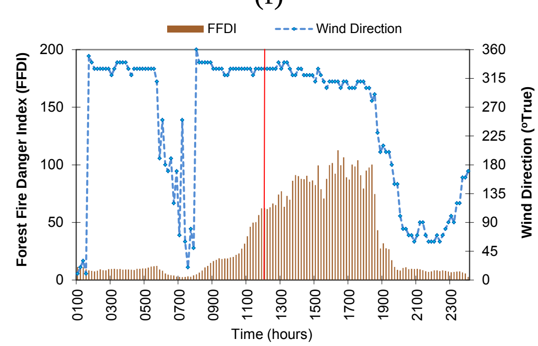
(e)



(b)



(f)



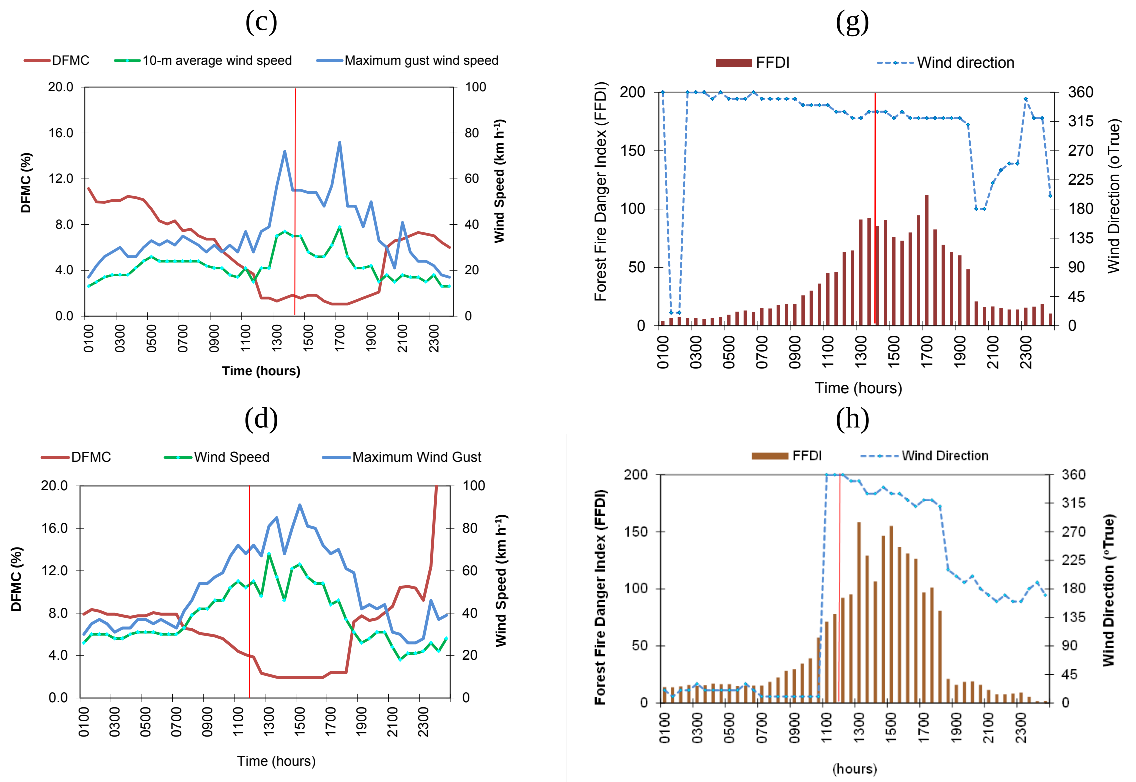


Figure 3 Trends in fire weather: DFMC, average wind and wind gust speed for (a) Beechworth–Library Road, (b) Bunyip Ridge Track, (c) Dargo–White Timber Spur and (d) Kilmore East and Murrindindi, and FFDI and wind direction for the same fires in (e), (f), (g), and (h)
Note: The vertical red line indicates time of ignition or in the case of the Bunyip Ridge Track and Dargo–White Timber Spur fires breakout from containment lines.

A critical factor in the effectiveness of fuel management treatments affecting fire behavior is the dead fine fuel moisture content. Macarthur recognized that very low DFMCs (<6%) create the conditions for unpredictable fire behavior under high wind speeds and give rise to crowning and spot fires, and development of strong convection columns (Luke and McArthur, 1978). The estimation of DFMC here is based on Simard's (1968) equilibrium moisture content equations as used in the United States Fire Danger Rating System:

If RH<10%,
$DFMC=0.0323+0.281\times RH-0.00058\times RH\times T$ Equation 1
Else if 10<RH<50%,
$DFMC=2.2276+0.1601\times RH-0.001478\times RH$ Equation 2
Else if RH>=50%
$DFMC=21.0606+0.005565\times RH^2-0.00035\times RH\times T-0.483199\times RH$ Equation 3

where RH is relative humidity and T is temperature (°C).

These equations cover the full range of temperature and relative humidity encountered in the fire weather data recorded on Black Saturday. There has been no adjustment of the DFMC values to take account of incoming solar radiation or wind speed on fuel temperature using an equation such as Byram and Jemison's (1943) equation to account for the effect of solar radiation and wind speed on fuel temperature and hence fuel humidity. Thus, the DFMCs found in open grassland or woodland surface fuels may be slightly overestimated (0.5–1%) and those in dense shaded damp and wet eucalypt forests may be slightly underestimated by 1–2%. The minimum values of DFMC on Black Saturday approached 2% moisture content. Cruz *et al.* (2012) obtained a similar value of 2% for the minimum DFMC for the Kilmore East fire using the Matthews fuel moisture model (Matthews *et al.*, 2010).

Assessing individual fuel treatment blocks at the local and intermediate geographic scales

Factors considered in this assessment of wildfire effectiveness of individual fuel management treatments included:

- Fuel Treatment factors:
    - age of fuel treatment before the fire (y)
    - size of fuel treatments (ha)
    - coverage and fire intensity of fuel management treatment (%)
    - type of terrain (undulating, moderate; or steep slopes; in either valley, ridge, or plateau locations)
- Fire Factors:
    - likely fuel levels inside and outside the fuel treatment areas at the time of Black Saturday fires
    - fire weather (temperature, relative humidity, dead fine fuel moisture content (DFMC), wind speed, and fire weather index (FFDI) from the nearest most representative weather station;
    - fire behaviour characteristics (rate of spread (ROS), Byrams fireline intensity (BHFI), and fire brand spotting distances
    - Energy release (GW) and complexity of fire behaviour (e.g. multiple fire fronts, mass fire behaviour associated with short-medium range spotting)

This approach to assess the effectiveness of individual prescribed burn blocks involved a remote GIS analysis using an assessment of fire severity burns classes inside and outside each fuel treatment block, considering the fuel treatment and fire factors listed above. Fire severity was classified into seven fire severity burn classes using the schema devised by Cruz *et al*.(2010) but slightly modified for this study. This attempts to link fire severity to the predominant fire type or types within and outside the fuel treatments for the purposes of this study (**Table 2**).

Table 2 Fire severity classes, their descriptions and relationship to fire type

Fire severity class	Description	Fire type
1	75 to 100% crown consumption	Active crown fire
2	25 to 75% crown consumption	Intermittent crown fire
3	<25% crown consumption or >60% crown scorch	High intensity surface fire
4	30 to 60% crown scorch; nil crown consumption	Moderate intensity surface fire
5	0 to 30% crown scorch	Low intensity surface fire
6	Unburnt	No fire
7	Burnt grass	Surface fire

Note: Fire severity classes 7 and 6 defined by Cruz *et al*.(2010) are recoded to 6 and 7 in this study.

Fire severity class 7–burnt grass was not used for comparative purposes in this study. Class 6 cannot be readily distinguished from category 5 from the remotely sensed data available for these fires — only ground observations can readily distinguish between the two fire severity classes. There were field observations done in 2009 and 2010 in some of the treated blocks in the Beechworth-Library Road, Kilmore East and Murrindindi fires but these did not involve systematic ground sampling of burn fire severity patterns.

In terms of evaluating prescribed burning's effectiveness on wildfire behavior, the fire severity inside and outside the block were cross-tabulated to produce a simple comparative table for the purposes of this study (**Table 3**). The blanks left in Table 3 are other possible combinations where the fire severity class outside the prescribed burning block is higher (i.e. a lower fire severity) than inside the block – the effectiveness is set to a negligible fire severity class. This can occur under some landscape conditions such as flanking fire burning outside the block can turn into a head fire because of a wind change. The fuel treatment effectiveness ratings are ranked from low-moderate to very high, depending on the comparative difference in fire severity inside and outside each treated area. A rating of very high effectiveness is given when the fire severity class inside the fuel treatment area is equal to 5 (equivalent 30 to 60% crown scorch; nil crown consumption or a moderate intensity fire) and the fire severity class outside the fuel treatment is equal to 1 (75 to 100% crown defoliation/consumption – active crown fire). Conversely a low-moderate rating is given when there is no difference between fire severity inside and adjoining a fuel treatment block (in both cases fire severity class 1). The other combinations of burn class severity inside and outside the block were accordingly rated as per the table. In many instances both inside and outside each block there were two or more burn severity classes. In these instances the fire severity class was rated according to the fire severity class with the greatest proportional area. Blocks treated by prescribed burning less than 10 ha were eliminated from the analysis as preliminary inspection of fire severity inside and outside showed that there was little or no difference in fire severity.
Each fuel treatment block was evaluated using post-fire Landsat imagery dated 17 February 2009 supplemented with post-fire digital aerial photography in Quantum GIS, and vegetation, fire history, and digital terrain data. Data on fuel treatment and fire behavior factors were catalogued at the same time in order to determine the background contextual factors in each case.

Table 3 Fire severity matrix – fuel treatment effectiveness on wildfire behaviour

		Fire severity classes outside fuel treatment					
		1	**2**	**3**	**4**	**5**	**6**
Fire classes inside fuel treatment	**1**	None					
	2	Low-Moderate	None				
	3	Moderate	Low-Moderate	None			
	4	Moderate-High	Moderate	Low-Moderate	None		
	5	High	Moderate-High	Moderate	Low-Moderate	None	
	6	Very High	High	Moderate-High	Moderate	Low-Moderate	None

Once every fuel treatment block was rated using **Table 3**, the comparative data on treated blocks were reorganized into different classes of effectiveness based on prescribed burning block, topography, and fire behavior factors. Fire weather data was cross-tabulated with each burning block based on the time at which the wildfire went through the block. The times were extracted from the reconstructed fire isochrones for each fire (Gellie *et al.*, 2014) by overlaying the fire isochrones on each of the prescribed burning blocks and determining the approximate start and finish times of interaction between the block and the wild fire. The prescribed burning blocks were grouped into three fire behavior categories using the relationship between the start and finish time interaction and the general fire behavior conditions during those times (**Table 4**).

Table 4 Time periods classified into fire behaviour classes

Time period	Fires	Fire behaviour	DFMC	FFDI range	Fire Danger Classes
12:30–18:00 16:00–19:15	Kilmore East & Bunyip Ridge Track Murrindindi	Running crown fire; dry pyroconvection, and medium-long range firebrand spotting	2–3%	80–140	Extreme – catastrophic (code red)
18:00–20:30 19:15–21:30	Kilmore East & Bunyip Ridge Track Murrindindi	Intermittent crown fire, moist pyroconvection, short-medium range firebrand spotting	3–4%	40–80	Severe–extreme
21:30–22:30 and 11:00–21:00 (08/02/2009)	Kilmore East, Murrindindi, Beechworth-Library Road	Sub-canopy to intermittent crown fire; intermittent pyroconvection,	4–6%	20–40	High–very high

Another factor considered in the effectiveness of prescribed burning was whether the size and shape of the prescribed burning blocks were large enough to prevent the wildfire spreading through the block and to stop firebrands from reaching the other side of the block, in effect creating fire-free islands on the leeward side of the treated blocks.

In the case of the Bunyip Ridge Track fire and the Kilmore East fire there were some large areas of recently burnt areas in the path of the fire, greater than 1,000 ha. Instead of the method described above, the effectiveness of prescribed burning was assessed in terms of the effect on the wildfire's fire severity patterns, the distance travelled, and the shape of the fire.

Assessment of fuel treatments on wildfire behavior at the landscape scale

Although all fires were evaluated at the landscape scale, this paper presents only the Dargo–White Timber Spur and Beechworth–Library Road fires as case study examples of the effectiveness of actual prescribed burn blocks as an illustration of the complexity of the effectiveness of recent prescribed burns and wildfires on the shape and extent of these fires.

Assessment of the impact of the 5% target of treatable public land on potential fire behaviour

First this analysis involved breaking up the forest area within the extent of the Kilmore East fire burnt on Black Saturday into public and private ownership based on DSE's Ecological Vegetation Class (EVC) and public land GIS data layers. Then the pattern of treated fuel blocks carried out before Black Saturday was added to the vegetation map. The EVC vegetation types within the extent of the fire were then classified into fuel types based on the EVC descriptions and expert assignment of each vegetation class to a fuel type. These fuel types along with others, such as plantation forest, grassland, water storage bodies, and urban areas were then combined into one fuel type map. These fuel types were then further classified into treatability classes by prescribed burning (**Table 5)** based on expert assignment of the fuel types from seasonal climate, soil, and topographic factors as well as practicability considerations.

Table 5 Treatability classes for prescribed burning in relationship to forest types

Treatability class	Description	Fuel type

1	Treatable	Dry eucalypt forest
2	Somewhat treatable	Damp eucalypt forest
3	Practicably not treatable	Wet sclerophyll forest, eucalypt and pine plantation, & urban areas
4	Not treatable	Water bodies, urban areas, road surfaces

A map of treatability classes for prescribed burning was then created for the Kilmore East and for the other fires in this study. These treatability classes were then analysed in terms of what treatable and somewhat treatable classes in
were burnt by prescribed burns before Black Saturday and then by a theoretical best case scenario using this and the 5% target of treatable forest on public land. In each case the total area and proportion of the landscape treated or could have been treated on public land in the 3–6 year period prior to Black Saturday was then determined.

Results and Discussion

Effectiveness of Individual Blocks

The results for the effectiveness of individual blocks for each of the fires are presented in **Table 6**. The results are arranged in order of the time since the prescribed burning block was last treated, effectiveness of the block on fire behavior, and slope steepness combined with position in terrain. Based on the time period groups presented in **Table 4**, the effectiveness of prescribed burn blocks were then summarized into **Tables 7, 8**, and **9**.

Table 6 Results – evaluation of effectiveness of prescribed burns on fire severity

Fire	Year block treated	Fire Class	Block or Fire No	Date Burnt	Area (ha)	Years before Black Saturday	Fire Severity Class (inside)	Fire Severity Class (outside)	Effectiveness	Fire sector	Time Start of Impact	Time End of Impact	TERRAIN
Beechworth–Library Road	2008	B	T090	9/04/2008	1683	1	6	5	Low-Moderate	Head flank	14:30	17:30	Steep; dissected ridges
Murrindindi	2008	B	TFA0901	13/04/2008	178	1	3	2	Low-Moderate	Flank	15:30	17:30	Steep; ridge slope
Beechworth–Library Road	2008	B	W111	10/04/2008	2209	1	5	3	Moderate	Head flank	16:30	17:30	Steep; dissected ridge
Kilmore East	2008	B	KFA0501	16/04/2008	76	1	2	1	Low-Moderate	Head	17:40	17:50	Steep; ridge slope
Kilmore East	2008	B	288	23/04/2008	147	1	2	1	Low-Moderate	Head	18:00	18:15	Steep; valley slopes
Kilmore East	2008	B	KFA0801	24/04/2008	154	1	3	3	None	Head	18:05	18:20	Undulating; plateau ridge
Murrindindi	2008	B	MFA0805	18/04/2008	641	1	3	1	Moderate	Head flank	18:15	18:45	Steep; dissected ridges
Kilmore East	2008	B	O8O61	25/09/2007	23	1	1	1	None	Head	18:15	18:30	Undulating; Plateau ridge
Kilmore East	2008	B	P05	27/02/2008	41	1	5	2	Moderate-High	Head	19:20	19:45	Steep; ridge slope
Kilmore East	2008	B	TFA0802	17/04/2008	277	1	6	3	Moderate-High	Head flank	19:20	21:00	Steep; ridge slopes
Kilmore East	2008	B	BFD0503	10/04/2008	30	1	2	1	Low-Moderate	Head	19:40	19:50	Steep; ridge slopes
Kilmore East	2008	B	TFA1004	17/04/2008	326	1	6	3	Moderate-High	Head	20:00	20:30	Steep; ridge slopes
Kilmore East	2008	B	KFA0604	16/04/2008	118	1	4	2	Moderate	Head	20:15	20:30	Undulating; plateau slopes
Kilmore East	2008	B	BFD0601	15/04/2008	342	1	4	1	Moderate-High	Head	20:30	21:30	Undulating; plateau ridges
Beechworth–Library Road	2008	B	S105	25/04/2008	282	1	4	3	Low-Moderate	Head flank	22:00	23:50	Steep; dissected ridges
Murrindindi	2007	W	110	3/03/2007	159	2	5	3	Moderate	Flank	16:30	17:00	Moderate; dissected ridges
Kilmore East	2007	B	KFS0701	25/04/2007	86	2	2	2	None	Head	17:30	17:45	Moderate; ridge slopes
Kilmore East	2007	B	BFD051	9/04/2004	238	2	3	2	Low-Moderate	Head	20:00	21:00	Undulating; plateau slopes
Beechworth–Library Road	2006	B	W12	12/04/2006	298	3	4	2	Moderate	Head flank	13:30	17:00	Steep; dissected ridges
Kilmore East	2006	B	KFA6303	27/04/2006	82	3	1	1	None	Head	16:20	16:30	Steep; ridge slope
Kilmore East	2006	B	BFD0801	18/10/2005	25	3	1	1	None	Head	18:15	18:30	Undulating; Plateau ridge
Kilmore East	2006	B	TFA0601	12/04/2006	121	3	3	2	Low-Moderate	Head	19:45	-2015	Steep; ridge slope

Table 6 continued

Fire	Year block treated	Fire Class	Block or Fire No	Date Burnt	Area (ha)	Years before Black Saturday	Fire severity Class (inside)	Fire severity Class (outside)	Effectiveness	Fire sector	Time Start of Impact	Time End of Impact	TERRAIN
Kilmore East	2006	W	W2006320	22/01/2006	1651	3	6	5	Low-Moderate	Flank	20:00	21:00	Steep; dissected ridges
Kilmore East	2006	B		17/10/2005	34	3	4	3	Low-Moderate	Head flank	20:00	20:30	Steep; ridge slope
Kilmore East	2006	W	W2006320	22/01/2006	92	3	5	5	None	Flank	20:00	23:00	Undulating; Plateau ridges
Bendigo-Bracewell Street	2006	B	BGO043	23/11/2005	8	3	4	2	Moderate	Head	18:00	18:20	Flat to undulating
Beechworth–Library Road	2005	B	S080	12/04/2005	574	4	5	5	None	Flank	14:30	17:30	Steep; dissected ridges
Kilmore East	2005	B	BFD0502	10/03/2005	279	4	3	2	Low-Moderate	Head	16:30	17:00	Moderate; valley slopes
Bunyip Ridge Track	2005	W	N05	May 2005	42	4	3	3	None	Flank then head	17:00	18:00	Moderate; ridge slope
Kilmore East	2005	B	BFD0504	20/10/2004	78	4	2	1	Low-Moderate	Head	18:15	18:30	Moderate: valley slopes
Kilmore East	2005	B	KFA0404	20/04/2005	131	4	3	3	None	Head	18:15	18:30	Steep; ridge slope
Kilmore East	2005	B	BFD0702	26/04/2005	35	4	1	1	None	Head	18:15	18:30	Undulating; Plateau ridge
Kilmore East	2005	B	BRM0501	3/05/2005	33	4	3	1	Moderate	Head	18:15	18:30	Undulating; plateau ridge
Murrindindi	2005	B	MFS0403	23/03/2005	22	4	3	1	Moderate	Head	18:15	18:45	Undulating; ridge slope
Kilmore East	2005	B	P67	19/10/2004	42	4	2	2	None	Head	18:20	18:40	Steep; ridge slope
Bunyip Ridge Track	2005	B	N07	May 2005	684	4	3	1	Moderate	Head	18:30	19:30	Moderate; dissected ridges
Kilmore East	2005	B	TFA0603	19/03/2005	306	4	5	3	Moderate	Head	18:45	19:15	Undulating; plateau ridge
Murrindindi	2005	B	MFA0502	13/03/2005	61	4	2	3	None	Head	19:00	19:15	Undulating; valley slope
Kilmore East	2005	B	KFA0507	3/03/2005	128	4	3	2	Low-Moderate	Head	19:30	20:00	Undulating; plateau slopes
Kilmore East	2005	B	P68	20/10/2004	46	4	4	3	Low-Moderate	Head flank	20:00	20:30	Steep; ridge slope
Beechworth–Library Road	2005	B	S076	5/04/2005	120	4	5	3	Moderate	Flank	20:00	21:00	Undulating; plateau
Kilmore East	2005	B	TFA0402	9/03/2005	112	4	3	2	Low-Moderate	Head	20:15	20:30	Steep; ridge slope
Beechworth–Library Road	2005	B	S076	5/04/2005	51	4	3	3	None	Head flank	21:30	22:30	Steep; ridge slope

Table 6 continued

Fire	Year block treated	Fire Class	Block or Fire No	Date Burnt	Area (ha)	Years before Black Saturday	Fire severity Class (inside)	Fire severity Class (outside)	Effectiveness	Fire sector	Time Start of Impact	Time End of Impact	TERRAIN
Bunyip Ridge Track	2004	W		15/04/2004	714	5	2	2	None	Head	12:45	13:15	Flat-moderate; valley floor
Bunyip Ridge Track	2004	B	G11	Apr 2004	103	5	2	2	None	Head	12:45	13:00	Undulating; valley floor
Murrindindi	2004	B	MFS0401	25/11/2004	21	5	3	1	Moderate	Head	18:15	18:45	Undulating; ridge slope
Murrindindi	2004	B	MFA0401	8/04/2004	18	5	3	2	Low-Moderate	Head	19:00	19:15	Moderate; slope ridge
Kilmore East	2004	B	KFA0505	9/04/2004	246	5	2	1	Low-Moderate	Head	19:45	20:00	Steep; ridge slopes
Kilmore East	2004	B	BFD0401	10/11/2003	37	5	2	1	Low-Moderate	Head	20:00	20:20	Steep; ridge slope
Kilmore East	2004	W	21	14/04/2004	294	5	4	4	None	Head	21:00	22:30	Moderate; ridge slope
Murrindindi	2004	B	AFA0407	9/04/2004	35	5	3	3	None	Head flank	21:00	22:00	Moderate; ridge slope
Kilmore East	2003	B	BFD0301	7/05/2003	58	6	1	1	None	Head	15:00	15:10	Moderate; ridge slopes
Kilmore East	2003	B	KFA0504	31/03/2003	130	6	1	1	None	Head	16:20	16:30	Moderate; ridge slope
Kilmore East	2003	B	BFD0403	13/05/2003	53	6	1	1	None	Head	18:15	18:30	Moderate; valley slopes
Murrindindi	2003	B	MFA0310	16/04/2003	20	6	3	2	Low-Moderate	Head	18:15	18:45	Undulating; ridge slope
Beechworth-Library Road	2003	W	056	21/01/2003	2209	6	3	3	None	Head	18:45	19:45	Undulating; plateau slopes
Bunyip Ridge Track	2003	W		18/03/2003	179	6	4	2	Moderate	Flank-Head	21:30	22:30	Moderate; dissected ridges
Beechworth–Library Road	2007	B	S109	24/04/2007	775	1	5	3	Moderate	Flank	11:00	19:00	Steep; ridge slope
Kilmore East	2006	B		18/10/2005	29	1	5	4	Low-Moderate	Flank	14:00	19:00	Moderate; slope ridge
Beechworth–Library Road	2007	B	P109	16/04/2007	1674	1	5	3	Moderate	Head	18:30	20:30	Steep; dissected ridges
Beechworth–Library Road	2007	B	W136	18/04/2007	2691	1	5	3	Moderate	Head	14:00	18:00	Steep; dissected ridges
Kilmore East	2005	B	P66	25/10/2004	34	2	4	4	None	Flank	11:00	14:00	Moderate; ridge slope
Beechworth–Library Road	2005	B	S051	12/04/2005	303	2	3	3	None	Head	14:00	19:00	Steep; dissected ridges
Kilmore East	2004	B	P60	10/11/2003	21	2	4	4	None	Flank	13:00	17:00	Steep; ridge slope

Note: the blocks shaded gray interacted with the Kilmore East and Beechworth–Library Road fires on 8 February 2009, the day after Black Saturday, on 8 February 2009.

Under severe–catastrophic conditions from 12:45–18:00 for Kilmore East and Bunyip Ridge Track, and from 16:00–19:15 for Murrindindi, there were 8 prescribed burning blocks that had a negligible or slight effect on fire severity in steep terrain, mainly in the 1–2-y and 3–4-y fuel age classes. Only 2 burning blocks had a moderating effect on fire severity in steep terrain, one of which had a flanking fire spread through it. Of the 21 prescribed burning blocks in undulating terrain or ridges with moderate steepness, 8 prescribed burning blocks had a modifying effect on fire severity, the remaining 13 having a negligible or a slight effect (**Table 7**). In most instances the wildfires spread through the prescribed burning blocks with a running crown fire in the older 3–4-y and 5–6-y fuel age classes and as an intense sub-canopy fire in the 1–2-y fuel age class. During this extreme phase of fire behavior none of the prescribed blocks stopped the fires from spotting beyond the burning blocks. In the case of the Kilmore East and Murrindindi fires, intense pyroconvection overtopping the fires suggested that mass fire behavior (i.e. large numbers of coalescing fire fronts and spot fires) occurred at times during this period (Gellie *et al.*, 2014). This effect most likely reduced the effectiveness of either the small (<100 ha) or the medium size (100–400 ha) burn blocks in retarding the spread of these fires.

Table 7 Effectiveness of Prescribed Burns to reduce fire severity in head fires under severe–catastrophic fire behavior conditions (DFMC<3%, FFDI>=60, intense pyroconvection, dense short-range firebrand spotting)

		Terrain		
		Flat-undulating valleys or plateau	Moderate steep sided ridges	Steep sided ridges
Age of Prescribed burning block (Y)	1–2			Negligible (1) Slight (3) **Moderate (1)**
	3–4	None (3) Slight (1) **Moderate (4)**	Negligible (1) Slight (1) **Moderate (2)** **Moderate (1) - flank**	None (1) Slight (2) **Moderate (1) - flank**
	5–6	None (3) Slight (2) **Moderate (1)**	Negligible (2)	Negligible (1)

Note: Number of prescribed blocks evaluated in total in 28. The blank cells in the table indicate there were no instances of combinations of fuel age treatment and terrain type in the fuel treatment blocks impacted by the fires.

As the fire behavior conditions moderated to very high-severe conditions during the period from 18:00–20:30 for the Kilmore East and Bunyip Ridge Track fires and 19:15–21:30 for the Murrindindi fire the prescribed burning blocks showed an overall slight effect in reducing fire severity (**Table 8**). In effect the fire spread through the blocks with an intermittent crown or an intense sub-canopy fire. This was most evident in steeper terrain where past fuel treatments in 7 out of the 9 blocks had a slight effect on fire severity in the case of the 1–2 and the 3–4 fuel age classes. In two instances, the prescribed burning blocks had a moderate effect on fire severity on flanking fires.

In flatter terrain, for the most part the 3–4-y and 5–6-y old prescribed burning blocks had a moderate effect on fire severity (3 out of the 6) and the remaining 3 had a negligible or a slight effect. Again, the size of these blocks, mostly small but some 200–400 ha in size, had little effect in reducing the overall spread of the fires owing to the short-range spotting (estimated to have been from 500–2,000 m) easily leap-frogged over the blocks (Gellie *et al.*, 2014). This agrees with Luke and McArthur's determined that fire behavior is dominated by short-range ember and more frequent medium-long range spotting at DFMCs less than 4% (Luke and McArthur, 1978). It is also likely that the chances of firebrands igniting spot fires increases significantly below a DFMC value of 4%, which is another finding from the Black Saturday fire reconstruction report (Gellie *et al.*, 2014).

Table 8 Effectiveness of Prescribed Burns to reduce fire severity in head fires under very high-severe fire behavior conditions (3<=DFMC<=4%) 30<FFDI>60), intense pyroconvection, moderate short-range firebrand spotting)

		Terrain		
		Flat-undulating valleys or plateau	Moderate steep sided ridges	Steep sided ridges
Age of Prescribed burning block (Y)	1–2	Negligible (1)		Slight (4)
	3–4	Slight (2) **Moderate (2) - flank**		Slight (3)
	5–6	**Moderate (1) - flank**		**Moderate-High (2) - flank**

Note: Number of prescribed blocks evaluated in total in Table 8 is 15. The blank cells in the table indicate there were no instances of combinations of fuel age treatment and terrain type in the fuel treatment blocks impacted by the fires.

As the fire behaviour conditions further moderated from "very high" to "high" fire behaviour conditions, most of the prescribed burning blocks showed some slight to moderate effect on fire severity. In the steeper terrain there were 7 out of 10 burning blocks that had a slight effect on fire severity on the head fires spreading through them (**Table 9**). In two instances the prescribed burning blocks had a moderate effect on the wildfires' flanking fires. The prescribed burning blocks in flatter terrain had a much greater effect on fire severity with 3 out of the 6 showing a moderate effect on fire severity and the remaining 3 blocks having a slight effect. Since firebrand spotting had decreased in range to 100 to 300 m, many of the larger blocks were having an influence on the overall shape and spread of the fire narrowing the width of the fire fronts and in some instances breaking up major runs across steeper terrain, particularly reducing the lateral spread of the flanking fires (Gellie *et al.*, 2014).

Table 9 Effectiveness of Prescribed Burns to reduce fire severity in head fires under very high behavior conditions (4<=DFMC<=6%; 15<FFDI>30), limited pyroconvection, moderate short-range firebrand spotting)

		Terrain		
		Flat-undulating valleys or plateau	Moderate steep sided ridges	Steep sided ridges
Age of Prescribed burning block (Y)	1–2	**Moderate-High (1)**	None (1) Slight (1) **Moderate (1)**	None (1) Slight effect (1) **Moderate (3)**
	3–4		None (2) **Moderate (1)**	None (2) Slight (1) **Moderate (1) - flank**
	5–6		None (2)	

Note: Number of prescribed blocks evaluated in total in Table 9 is 18. The blank cells in the table indicate there were no instances of combinations of fuel age treatment and terrain type in the fuel treatment blocks impacted by the fires.

A factor in the effectiveness of all the treatments examined in this study is the rapid accumulation of fuel post-treatment in wet, damp, and dry eucalypt forests and healthy woodlands (Figure 4). The threshold level of 1.2 kg m^{-2} for surface and near-surface fuels (the recommended level for safe and effective fire suppression (McArthur, 1962)) can be exceeded in 2, 5, and 10 y after a fire in each of the three principal fuel types respectively.

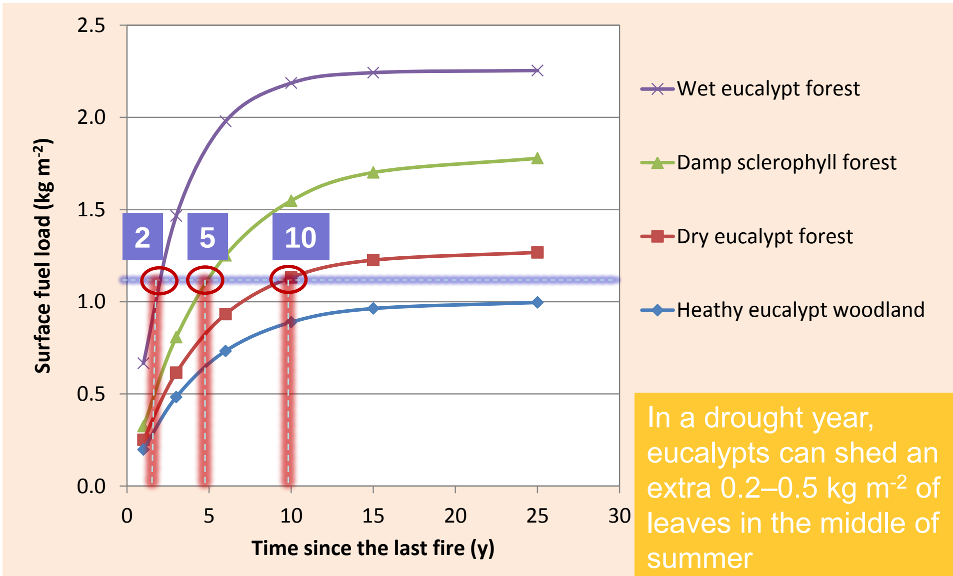


Figure 4 Fuel accumulation in dry, damp, and wet forests following a fire, assuming 100% removal of surface and near-surface fuels
Note: Equilibrium fuel levels in wet, damp, and dry eucalypt forest are taken from studies done by Ashton (2000), Attiwill (1979), and Tolhurst and Kelly (2003) respectively. Fuel data for heathy eucalypt woodland were taken from Lee and Correll (1978).

Simmons and Adams (1986) found that in drought years surface fuel accumulation can be even more rapid, due in part to leaf fall from canopy scorch in recently burnt dry sclerophyll forest, and accelerated leaf fall due to moisture stress. Heat-waves are also known to desiccate the live near-surface fuels to a fully cured state. Additional leaf-fall from the eucalypt canopy of 0.2–0.5 kg m^{-2} can also occur during summer drought stress and heat-waves, resulting in the threshold value of 1.2 kg m^{-1} being exceeded in 2–4 years instead of 5–10 years in damp and dry sclerophyll forest fuel types (Pook, 1986; Gellie *et al.*, 2010). These three factors combined can reduce the effectiveness of prescribed burns to reduce rate of spread, fire intensity, and fire severity (fire damage) during summer periods of drought and heat-waves.

Effectiveness of prescribed burning at the landscape scale

The first example reviewing the effectiveness of prescribed burning at the landscape scale is the Dargo–White Timber Spur fire (Figure 5). In this fire, the fire spread through predominantly 6-y-old fuels burnt in the 2003 Alpine fires from its origin in the north-west corner from 14:30 until ~20:30 when it encountered 3-y-old fuels burnt in the 2006 Great Dividing Range fire which had resulted from 50 fires ignited by lightning most of which merged into one fire. It spread a distance of 25 km in ~6 hours at a rate of spread of ~4 km h^{-1}. In comparison the Murrindindi and Kilmore East fires had effective rates of spread of 7.3–7.8 km h^{-1}. During the course of its spread it spotted 1–2 km ahead with occasional spot fires reaching 5–7 km ahead of the main fire front as the fire approached the top of a ridge or a plateau in its path.

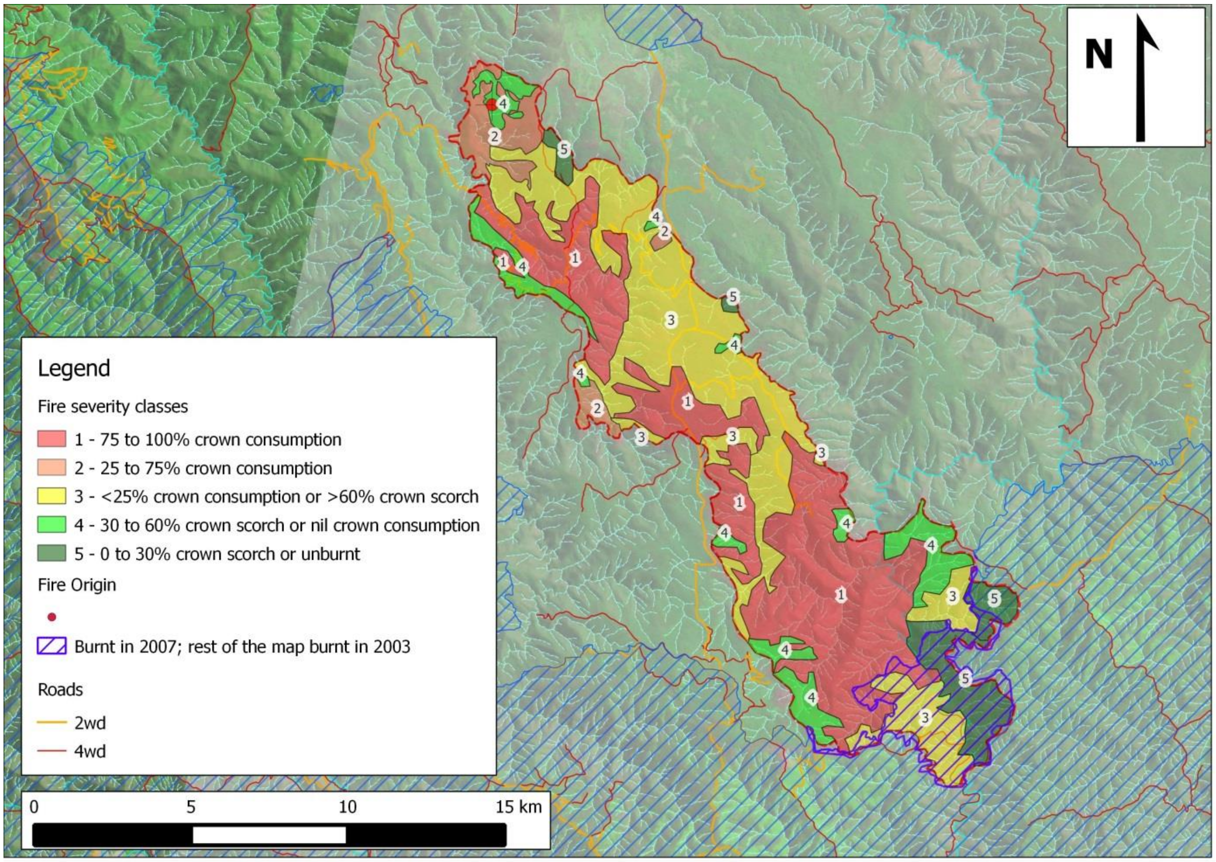


Figure 5 Fire severity classes in the Dargo–White Timber Spur fire in the plateau and dissected ridge landscape systems of the Dargo Ranges in central eastern Victoria

The fire severity map shows that in the 6-year-old fuels burnt in the 2003 wildfire, the fire spread less intensely through the plateau areas (areas shaded yellow on the map), typically with a resulting fire severity class 3 (predominantly scorched areas). This contrasts with the areas on the steeper ridges and deep gully systems that had fire severity class 1, which equate to continuous crown fires predominantly burning through these areas. When the fire reached the 3-y-old fuels burnt in the 2006/2007 wildfire, it decreased in fire severity from class 1 to class 3 (the purple hatched area). This occurred in the early evening sometime after 20:00 when the DFMC was increasing from a minimum of 3–4% to 6–7% within an hour of the passage of a weak trough. The fire severity class changed to classes 4 and 5 as the fire burnt into the late evening under milder less windy conditions.

The major effect of recent fuel treatments (<6y) was in restricting the lateral spread of the flanks. The expected LB ratio for this fire could be expected to be ~4:1 at wind speeds averaging 35 km h^{-1} during the 6 h period. Instead the LB ratio was ~7:1, very close to that estimated for the Kilmore East and Murrindindi fires, which spread 1.5 times the distance of the Dargo–White Timber Spur fire.

The second example shows how recent prescribed burning blocks affected the shape of the Beechworth–Library Road fire by restricting the lateral spread of the fire along the length of its runs before and after the south-west wind change (Figure 6). It should be noted that suppression in the grasslands in the area to the south of the Mudgegonga Township stopped the fire spreading north-east towards Glen Creek. There were 12 prescribed burns carried out in the 6 years prior to the fire and of these 11 had been carried out in the 4 years prior to Black Saturday. In the first part of the fire's run in the north-west corner of the map, the fire's spotting limited the effectiveness of prescribed burning even when there were considerable areas burnt on the forested plateau. Fire weather was in the very high-severe range (FFDI 40–60) during this period from 18:00 to 21:00. For the remainder of the fire's southeast run it traversed a mosaic of grassland and forest. During the late evening on Black Saturday, the fire transitioned into a pyro-convective fire (Gellie *et al.*, 2014), even though the prevailing surface fire weather was in the high-very range (FFDI 20–40). Later, the next day, the fire broke out on six different fronts along its north-east flank. Some of these breakouts burnt through slightly older prescribed burns (4–6 y) in dry sclerophyll forests or in areas left unburnt within recently treated fuels (1–2 y). Overall at the landscape scale, prescribed burning under very high to severe conditions had a moderate effect on fire severity in moderate-steep terrain conditions (Table 9), and in places slowed the spread of flanking fires. Interestingly mature pine plantations on southern aspects on the higher plateau south of Stanley had the greatest effect in reducing flank fire spread under very high-severe fire weather conditions.

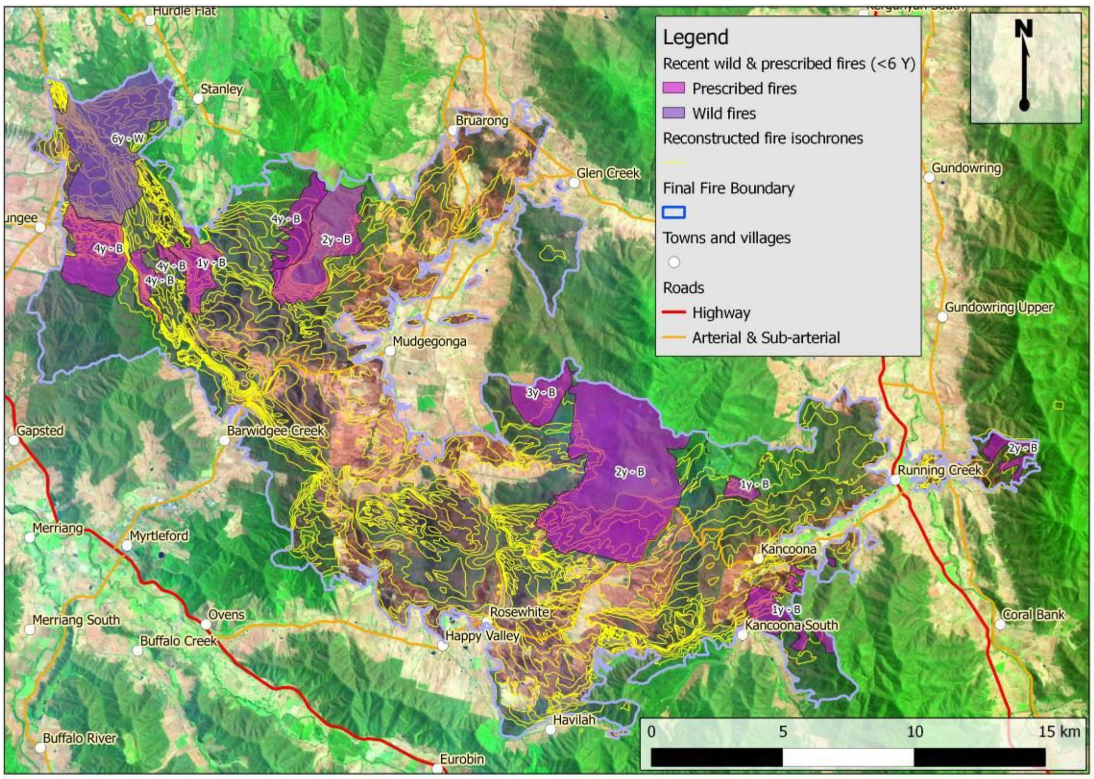


Figure 6 Fire pattern of the Beechworth–Library Road fire influenced by recent prescribed burns in the forested areas

Assessment of the 5% prescribed burning target of treatable public land

Landscape context plays a major role in determining whether a target area for public land being burnt per annum will have an effect at the landscape scale in limiting the impact of a wildfire. The fires selected in this paper have considerable variation in the proportion of public land and hence forested land in their extent (Table 1).

The example selected in this paper is that of the Kilmore fire since it is located on the wildfire urban interface (WUI), it has a relatively high proportion of forest and a mix of land tenure, and it has had a recent burn history of both wild and prescribed fires within its extent. The vegetation based on the Ecological Vegetation Classes (EVCs) has been classified into the treatability classes according to the classification in **Table 5** (Figure 7). Pine plantations, grasslands, and urban areas have been excluded from this analysis since they are largely not treatable by prescribed burning. These fuel types have been placed in the category of not being readily treated by prescribed burning. Fuel management is still possible by other means such as silvicultural treatment in pine plantations; grazing and slashing on grasslands, and intensive fuel management in built-up areas. This leaves the native forests, woodlands and heathlands as potential candidates for fuel management by prescribed burning. The assumption here is that wet sclerophyll forests are too difficult to treat and are generally not treatable under prescribed burning conditions as surface fuels are not available to burn. There may be also ecological reasons for not burning some of the smaller swamps and heaths, or shrublands such as habitat protection for small mammals or invertebrates, or leaving riparian strips because of weed invasion after burning.

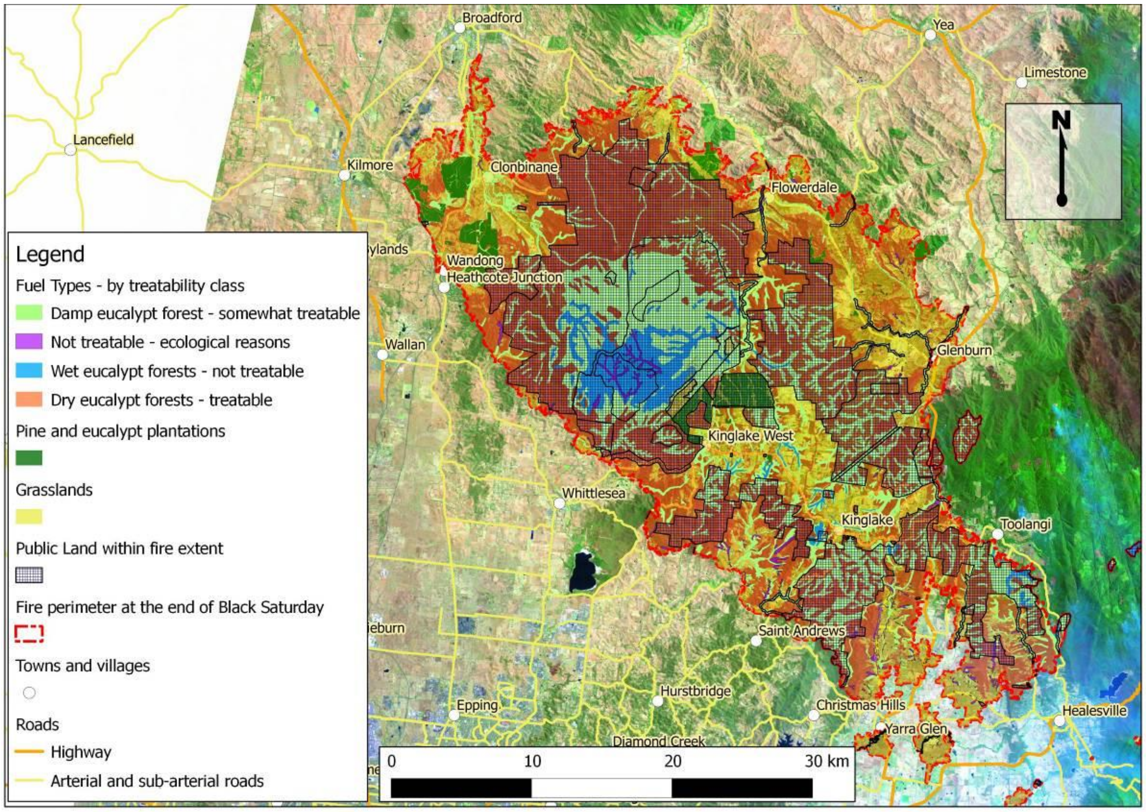


Figure 7 Extent of treatability classes within the Kilmore East fire in public and private tenure

Statistics for the areas of the four different treatability classes is presented in **Table 10**. Native vegetation comprises 78% of the total area of the area burnt on Black Saturday in the Kilmore East fire. Of that 74,180 ha or 72% is potentially treatable on all public and private tenure, leaving 28% of the area as not being feasibly practicable for fuel management by prescribed burning in other fuel types. Forests on private land are excluded from the 5% target of potentially treatable area for prescribed burning, this leaves 45,550 ha or 61% of the potentially treatable area in treatability classes 1 and 2.

Under the extreme fire weather on Black Saturday and the desiccated fuels in the dry, damp, and wet eucalypt forests, only the fuel ages less than 4 years of age in dry and damp sclerophyll forests had a slight or moderate impact depending on where the prescribed burning blocks were located. The fuel treatments had more effect on flatter or moderately steep terrain (Table 7 and Table 8). The predominant geographic aspect of the fuel treatment made little difference to the fire severity in most cases. If these results are accepted from this study, then applying a 5% treatable target to public land in the area burnt in the Kilmore East fire would achieve just over 9,000 ha of prescribed burnt areas in the 4 years prior to 2009 (back to 2005).

Table 10 Statistics of Treatable and Non-Treatable vegetation for prescribed burning on public and private tenures in the area burnt on Black Saturday in the Kilmore East fire

	Treatability Class for Prescribed Burning	Public tenure (ha)	%	Private tenure (ha)	%	Total in fire extent	5% target applied over 3 years
Native Vegetation	1 Dry eucalypt forest - treatable	27,900	57%	21,440	43%	**49,340**	5,580
	2 Damp eucalypt forest - somewhat treatable	17,650	71%	7,190	29%	**24,840**	3,530
	3 Non-treatable fuel types	460	34%	880	66%	1,340	
	4 Wet eucalypt forests - not treatable	3,950	91%	390	9%	4,340	
						79,860	9,110
Non-native Vegetation & modified areas	3 Grasslands - not readily treatable	-		19,000		19,000	
	3 Eucalypt and pine plantations	-		3,100		3,100	
	3 Urban Areas	-		1,040		1,040	
		0		23,140		23,140	
	Total area of Kilmore East fire					103,000	
	Treatable	45,550	61%	28,630	39%	74,180	7**2%**
	Non-treatable	4,410	15%	24,410	85%	28,820	**28%**
		49,960		**53,040**		**103,000**	-

Note: the rows shaded grey in the above table indicate fuel types not readily treatable by prescribed burning

Based on a GIS analysis of the area burnt by prescribed burning in and around the Kilmore East fire, 5,600 ha was burnt in the 4 y prior to the fire. This includes prescribed blocks on the northern side of the Toolangi State Forest and excludes 1,740 ha burnt in the 2006 wildfire to the north of Kinglake. If this area burnt by this wildfire is included 7,380 ha was burnt by prescribed burning and wildfire, just 1,730 ha below the 5% target of 9,110 ha. If that is the case, then a further 1,730 ha or more would need to be found somewhere else in the area burnt by the Kilmore East fire to meet a 5% target. Typically, fuel treatment coverage within individual burn blocks typically averages 50–75% because of the varying topography, fuel type, and moisture differences within a prescribed fuel treatment. Since prescribed burning is carried out in autumn and spring the lower sun angles limit solar exposure to the deeper gullies and lower sheltered slopes and limits what can be burnt at that time of the year in dissected hilly or mountainous terrain. In addition, seasonal dryness affects the treatment coverage of prescribed burns across their whole area. Even with this additional treated area, the mosaic of different burn severities, including a significant proportion unburnt areas with the lower southern and eastern slopes and gullies further reduce the effectiveness.

Another 5,600 ha of potentially treatable areas was identified within the area burnt by the Kilmore East fire that largely had flatter or undulating terrain or were in strategic locations close to settlements (Figure 8). Most of these blocks are two-three times larger than most of the previous prescribed burns carried out prior to 2009, which corresponds with the current emphasis to treat larger prescribed burn blocks. Two blocks, closer to Kinglake West, were selected as potential candidate areas for prescribed burning even though they were on steeper terrain, not being ideal areas to limit or slow the spread of the extreme Kilmore East fire. A decision would need to be made as to which of these six strategic blocks was either going to protect the damp and wet eucalypt sclerophyll forest assets on the Kinglake Plateau (P2, and P3) or the life and property closer to densely settled areas (P1, P4, P5, and P6). With the former choice there would have been a slight-moderate effectiveness of the prescribed burns being on flat to moderate slopes and at higher elevations. With the latter choice this study suggests there would have been a negligible to slight effect because the prescribed burning treatments would have been located within steeper more dissected terrain.

Even with the additional prescribed burns, the limited effectiveness under extreme-code red fire weather conditions on Black Saturday and the large gaps in the coverage of the fuel treatments in the extent of the Kilmore East fire would have made negligible difference to the impact and extent of the fire at the landscape scale, particularly given the dominant spotting mechanism propagating the spread of the fire at distances ranging from 300 m up to 15 km, with occasional spot fires occurring 20–35 km ahead of the main fire.

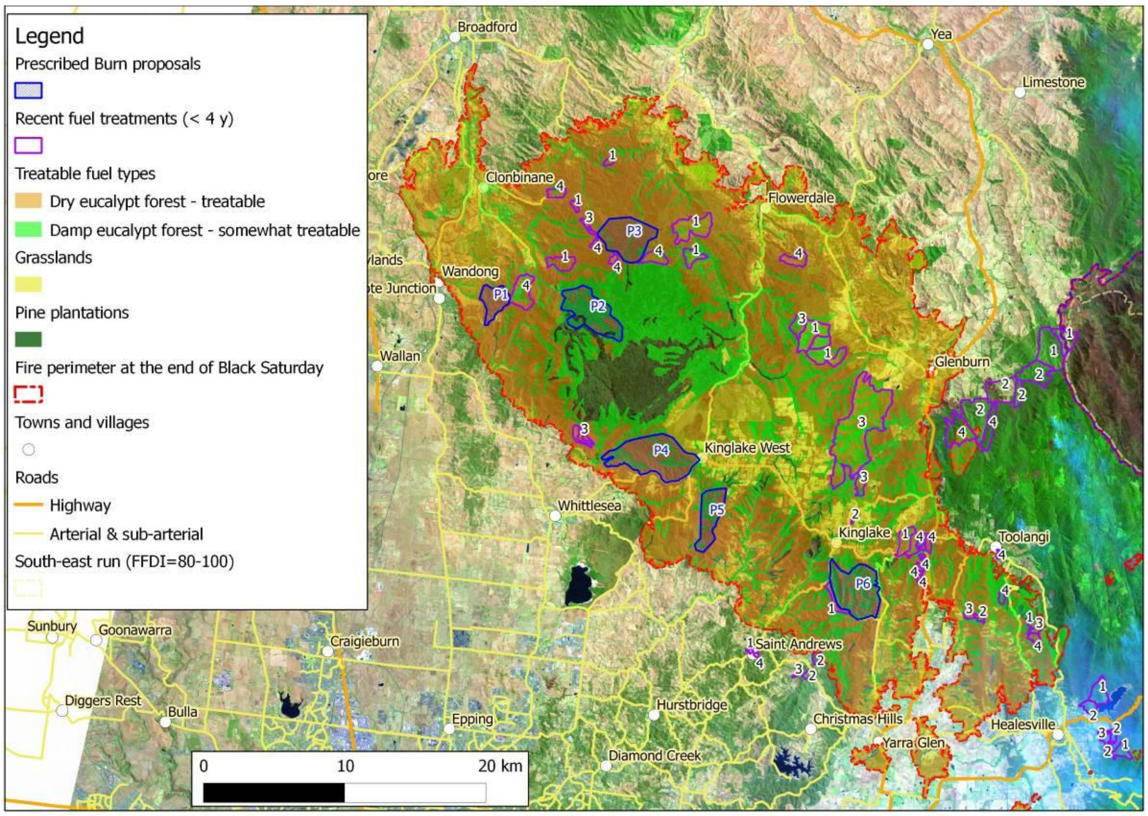


Figure 8 Recent fuel management treatments and possible additional prescribed areas to meet target of 5% of treatable public land.

Conclusions

Three principal factors – the fire weather severity, the terrain, and finally the age and efficacy of the fuel treatments – determine the effectiveness of prescribed burning in dry and damp eucalypt forest under very high-code red fire weather conditions.

Of these three factors, fire weather severity has the largest effect on the effectiveness of prescribed burning. Even most recent (< 4 y) burns had little effect on reducing fire severity on moderate to steep terrain while the fire weather was in the severe-extreme range of FFDI (75<FFDI<140). This conclusion is in agreement with the conclusion reached by Fernandes *et al.* (2003) that prescribed burn effectiveness was limited to 2–4 year post-treatment but did not state under what fuel, terrain, drought, and fire weather conditions these were effective. McCaw *et al.* (1992) reported crown fires in 3-y-old fuels in Jarrah–Karri dry eucalypt forest in Western Australia, even under severe FFDIs (60–65) approximately two-thirds to one half of FFDI's recorded on Black Saturday. They concluded that firebrand spotting was diminished in the lighter and younger dry sclerophyll forest fuels later aided suppression in the evening as the fire weather conditions moderated. The results here also supports the view expressed by Schmoldt *et al.* (1999) that prescribed burning will be less effective in regions where droughts in combination with strong winds are a frequent occurrence, which is the case in Victoria where such conditions have been experienced every 1–3 years since 1995. Recent prescribed burning treatments had slight-moderate effectiveness in reducing fire severity in forests on flat to moderate terrain in the FFDI range from severe to extreme. Effectiveness of prescribed burning treatments improved once fire weather conditions had moderated to high-very FFDIs.

At the landscape scale recent prescribed burning treatments more than 5 y-old had limited if no effect on fire severity in dissected country under severe to extreme FFDIs and DFMCs between 3 and 4%. However, once the fire weather had moderated further to high–very high FFDIs and DFMCs greater than 4%, there were noticeable reductions in fire severity from prescribed burning treatments, particularly along most flanks of the Black Saturday fires. Under these conditions the head and lateral spread of the fires were reduced significantly, particularly as the winds moderated below 20–25 km h^{-1}.

Although only examined in three examples in this paper, landscape mosaics of dry, damp, and wet eucalypt forest and non-forest, and the location and extent of prescribed burning within those mosaics, also determine the effectiveness of prescribed burning in mitigating wildfire extent and behavior at the landscape scale. Using the Kilmore East fire as a case study example, a 5% target of treatable public land would have had negligible difference in limiting the overall impact and growth of the fire at the landscape scale, because insufficient area would have been treated in a 3-y burning window prior to the fire, leaving over 90% of the fire area being left untreated. A considerable proportion of this untreated area was made up of damp and wet sclerophyll forest on public land, untreatable pine and eucalypt plantations, and untreated dry forest on public and private land (35 and 28% respectively of the total extent of the Kilmore East fire on Black Saturday). Fire managers, fire agencies, and the public at large need to recognize that broad-scale prescribed burning is not the sole panacea to reduce the extent and severity of extreme-catastrophic wildfires. It should be considered as part of a suite of fire prevention measures, such as minimizing potential fire ignitions, restricting developments near to or in forest along with fuel management on the WUI, to limit the potential impact of severe-extreme wildfires.

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A methodology for the assessment of infrastructure vulnerability to forest fires in wildland-urban interfaces

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Abstract:
The aim of this study is to develop a model for the evaluation of the vulnerability of infrastructures to forest fires in Wildland-Urban Interfaces (WUI). The model, developed using GIS, permits the exposition of the different grades of infrastructure vulnerability through the use of dedicated maps, and the analysis of factors which are most significant in determining a specific level of vulnerability. The factors introduced in the model are: types of vegetation, historical number of fire incidents, slope, and operational difficulties relative to fire suppression.
A Multi-Criteria Analysis technique (Analytic Hierarchy Process - AHP) was used to compare the data, and fuzzy logic functions were adopted in an attempt to reduce errors. The AHP was based on interviews with experts (operative room managers, firebosses, researchers).
The final product was a pixel map classifying five levels of risk which may prove useful to decision makers in planning prevention action and in establishing priorities.

Additional Keywords: Forest fires, wildland urban interface, multi-criteria decision analysis, analytic hierarchy process

Introduction

Fire is a natural part of the evolution of many forest ecosystems but it has always been regarded with some ambivalence. On one hand, fire was used as a way to make land available for farming; while on the other, it was perceived as a threat to be fought with all possible means. This is particularly true in European Mediterranean countries where at the end of the last century a policy of ‘zero tolerance’ was applied, especially in areas where forests fires represented a threat to people and settlements in a WUI context.

In Italy the wildfire events involved public awareness only after a series of tragic fires in 2007, though WUI fires was already subject of research investigation. Unfortunately, at the present time it is not easy to identify the number of WUI fires in Italy because of the lack of a national historical database including this kind of information.

The study of WUI involves multiple disciplines and consequently requires the cooperation of various actors (forest fires specialists, fire brigade, volunteers, etc). The present study only evaluates variables connected to the forest sector, but the model could easily be adjusted to accept data from different fields (i.e. the evaluation of building characteristics and materials). The objective was to develop a model for the classification of the risk level of infrastructures located in a WUI in the context of widespread forest fire, and to identify how and where to operate in order to reduce susceptibility. The model takes into account the following variables: morphology, vegetation, difficulty of suppression, spatial distribution of the infrastructures and the historical wildfire events recorded in the national database. The methods chosen for the development of the model is Multi-Criteria Decision Analysis (MCDA) in conjunction with some fuzzy logic functions; all results were processed using a GIS. The final results are two types of maps: one demonstrating risk classification of buildings, and another which presents elements necessary for the reduction of risk itself. Finally, some proposals for future development of the model are given.

Materials and methods

On the basis of the variables established by Lein and Stump (2008) and taking into account the availability of data in the area of investigation (a representative group of municipalities in the Tuscany Region), the following data have been processed:

- Slope
- Historical fire incidence (A.I.B. Anti Incendi Boschivi - the historical wildfires events national database)
- Fuels

Other variables considered in the Operational Firefighting Difficulties Index ODIF (Marchi et al. 2006) have been included in the analysis, seeing as ODIF model is an integral part of work.

Description of Variables

Slope

Slope is an important element in forest fire spread. In infrastructures risk study statistical analysis show that if the slope is over 20%, infrastructures have very few possibilities to avoid damages. (Bovio et al., 2001b). In the model, the values of the variables were normalized and spatialized using the following linear function (Bernetti and Romano 2007):

$$\{y = ax + B\} \qquad \begin{pmatrix} y = 0{,}3; x \le 20 \\ y = 1; x \ge 40 \\ y = 0{,}035x - 0{,}4; 20 \triangleleft x \triangleleft 40 \end{pmatrix}$$

The coefficient *a* assumes the maximum value 1 in the case of slope over 40%, while the value is always 0,3 in the case of slope under 20%.

Historical fire occurrence (A.I.B.):

The study of this variable is essential to determining the susceptibility of a territory to wildfires. Marchi e Zanzi Sulli (2005) underline that the analysis of historical fire incidents allows to investigate different aspects of wildfires and supplying useful tool to modify operating aspects both for suppression activities and forest policy in a specific area".

Bovio et al (2001b) explain that it is possible to identify WUI areas, which are potentially threatened by forest fire through the simultaneous analysis of historical fire incidents and urban and forested areas.

For the evaluation of this variable statistics relative to suppression interventions (recorded from 2000 to 2008 by fire fighting regional forest service personnel) were analysed. The municipality with the largest number of events was classified as having the highest risk score and the municipality with the smallest number of events as having the lowest score; remaining municipalities were assigned a proportional value.

Vegetation

In accordance with similar opinions expressed by other researchers, "due to the complex nature of fuel characteristics a fuel map is considered one of the most difficult thematic layers to build up especially for large areas" (Lasaponara e Lanorte, 2006, p.164). The elaboration of this variable was also very difficult because an official fuel types map does not exist in Tuscany. This is a very limiting factor because many models use this parameter to estimate fire behavior and its main components: spread rate, linear intensity, flame height, and firefront energy released (Allgöwer et al. 2004; Maxwell and Ward 1981; Carlini e Capitoni 2001; Scott e Burgan 2005). Because of the lack of fuel maps, we decided to create a classification of fuels based on existing and available vegetation layers. For this, two databases were analyzed and overlapped: the Regional Forest Inventory and Corine Land Cover 2000. In addition, photointerpretation, supported by field campaigns, have been used where spatial resolution of maps was unsuitable. Four main fuel types have been defined to identify main land cover type: herbaceous (i), shrubs (ii), trees (iii), bare or urban areas (iv) (Camia et al., 2003); then fuel pixels including settlements were classified in function of infrastructures position (uphill or downhill) with respect to the forest. The result is a value assigned for each vegetation urbanized pixel, classified following previous criteria.

Firefighting difficulty (ODIF index)

The analyses of fire-fighting conditions allow fire reserchers to identify constraints and difficulties in defending a specific area from wildfire. Firefighting difficulty is described using the ODIF (Operational Difficulty Index in Firefighting) model, elaborated by University of Florence, which adopts a hierarchical structure to analyze the following sub-indices:

- VAT (Vehicle Access Time);
- HAT (Helicopter Access Time);
- FOD (Firefighter Operational Difficulty);
- VST (Vehicle Supply Time);
- HST (Helicopter Supply Time)

In this way a value is obtained both for ground means difficulties (GODI - Ground Operations Difficulty Index) and aerial means (HODI - Helicopter Operations Difficulty Index); for each of these sectors a maximum value, in a specific area, is obtained respectively by VAT, VST and FOD for GODI index and HAT and HST for HODI index.

The interpolation of obtained max values determines the operational difficulties index (ODIF) following equation:

$$ODIF = GODI*0,7 + HODI*0,3$$

The weights (multiplicative factors) have been determined by statistical analysis on the number of terrestrial and aerial interventions, and token place in the defined area. The percentage of aerial operations is in a ratio of 30% of total. (Marchi et al., 2006).

Multi-criteria Decision Analysis (MCDA)

In environmental risk indices, developing indicators and variables (apparently incompatible and having different measurement units) have to be considered and jointly analyzed.
To overcome this problem multicriteria analysis techniques were applied (Bernetti e Romano, 2007).
MCDA application requires identification of the following elements:

- the goal or objective: purpose for which the analysis is undertaken;
- the decision-makers: responsible for making an assessment of the variables;
- the evaluation criteria: allow decision makers to make judgments, often by weighing the alternatives;
- the variables that must be assessed;
- the scores: express the value of the variable in terms of the declared objective.

Considering the complexity of the variables and their interrelations in a natural context, the difficulty of simultaneous consideration in a model becomes evident. To minimize the possibility of errors, fuzzy logic functions for the quantification of the results have been employed.

The values of each territorial variable considered (slope, vegetation, A.I.B. and ODIF) have been distributed between 0 and 1 applying the concept of "level of belonging" to determine, through the use of fuzzy logic, a continuous distribution of values in this interval (Borselli, 2002). After this value redistribution and adaptation, the Analytic Hierarchy Process (AHP), developed by Saaty as an operative methodology of MCDA, was chosen for the determination of the infrastructure risk index (Lapucci et al., 2005).

Analytic Hierarchy Process (AHP)

AHP is a mathematical method for relating subjective preferences of an individual or a group of individuals within a decision-making process.

When a number of variables has to be compared, the difficulty could consist in assigning the level of importance (weight) that each variable must assume in the model. A group of actors, involved for different aspects in forest fire phenomena, was interviewed to identify these values. The AHP allowed the opinions of these decision-makers to be compared, and consequently provided for a more objective quantification of the territorial factors analyzed.
Expert Choice© software was employed for this study. This sw tool allows to determine a variables weight value, through successive comparison of pairs of these variable, generating a hierarchical tree.

Results

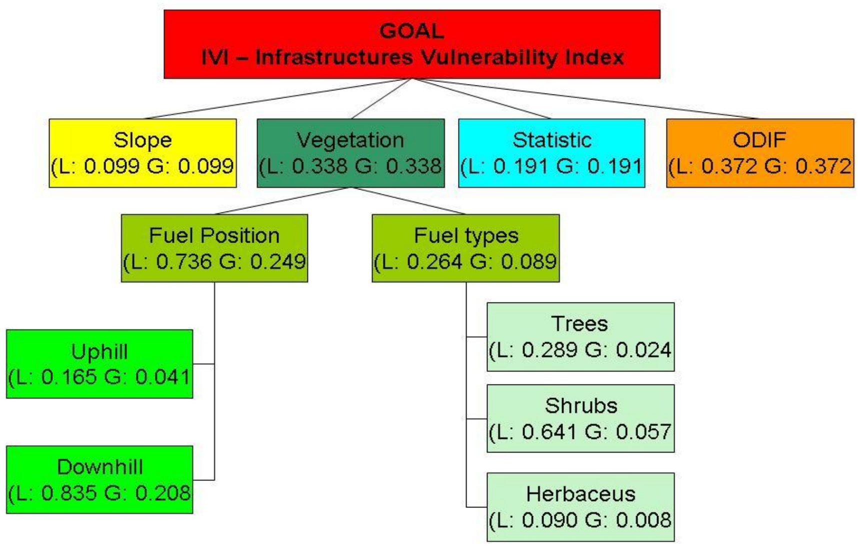
The settlements investigated in this analysis have been chosen as structures located in rural areas (i.e. farms and/or tourist destinations with guest accommodations) and occupied during the entire year and representing a typical WUI environment in Italy.

Interview Results

The experts and stakeholders interviewed for the present study know deeply the area of investigation and are the actors playing an operational role in wildfire prevention and fighting in those areas.

In addition to operative figures, people from the academic community, active in forest fires research, were involved and interviewed; in total sixteen interviews were conducted, it could be considered a representative set of opinions to carry out a methodological analysis. Moreover the software calculated the 'inconsistency' of responses that expresses possible errors, which have occurred in giving opinions. According to Saaty an inconsistency value below 0.1 is acceptable; the inconsistency value in this study assumed the value of 0.006.

The following table shows the different weights obtained from the analyzed variables. The L (Local) value indicates the weight the variable assumes in a specific hierarchical level of judgement; while the G (Global) value indicates the weight the variable assumes with respect to the declared objective.



Infrastructure Evaluation

In the model we have evaluated only those infrastructures included in zones with presence of forests or shrubs, detected by a buffer of a 250m radius from the central axis of the main building. Each area, which comprises a surface of 19.6 hectares, has been divided into pixels of 10m.

For each considered buffer the three different vegetation types, trees, shrubs and herbaceous have been defined. A fourth component, urbanized areas or other facilities and infrastructure, was created but not evaluated in the model. Than the topographical position (uphill or downhill from the settlement) of the vegetation polygons was determined.

The identification of polygons has been used not only in the calculation of risk, but also for the identification of prevention activities as will be discussed. Tacking in account the answers of interviews, the weight of vegetation variable is decided and values were assigned to the vegetation in the GIS. Once the layers for all the variables were established, the Infrastructures Vulnerability Index (IVI) was determined using a Weighted Linear Combination (WLC) according to following formula:

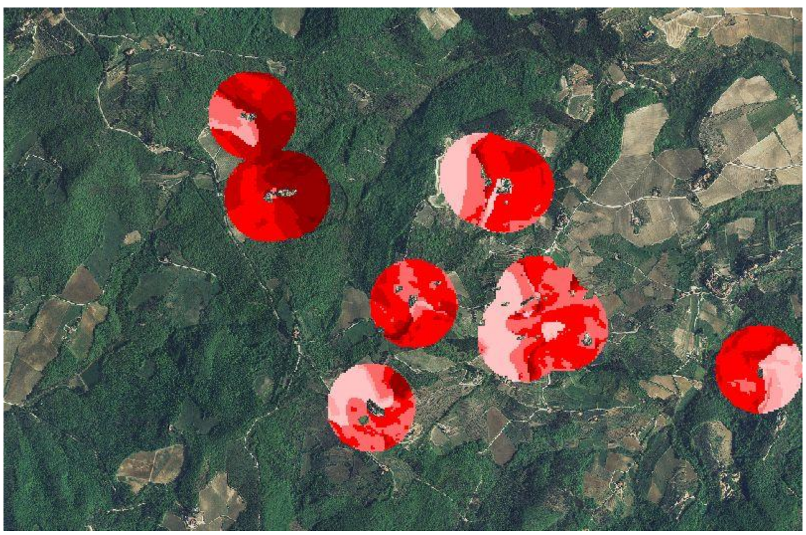
$$\mathbf{IVI = [(IDS*W_{IDS})+(IDF* W_{IDF}) +(IDV* W_{IDV}) + (ODIF* W_{ODIF})]}$$

where:
IDS is the normalized value for the slope
IDF is the normalized value for the historical fire incidents
IDV is the normalized value for the vegetation
ODIF is the normalized value for the fire fighting difficulties
W_x are the weights calculated through the AHP interviews

For each variable, a layer of “fuzzy” values was normalized and multiplied by the weight coefficient of the variable resulting from the interviews.

IVI = [(IDS*0,099)+(IDF*0,191) +(IDV*0,338) + (ODIF*0,372)]

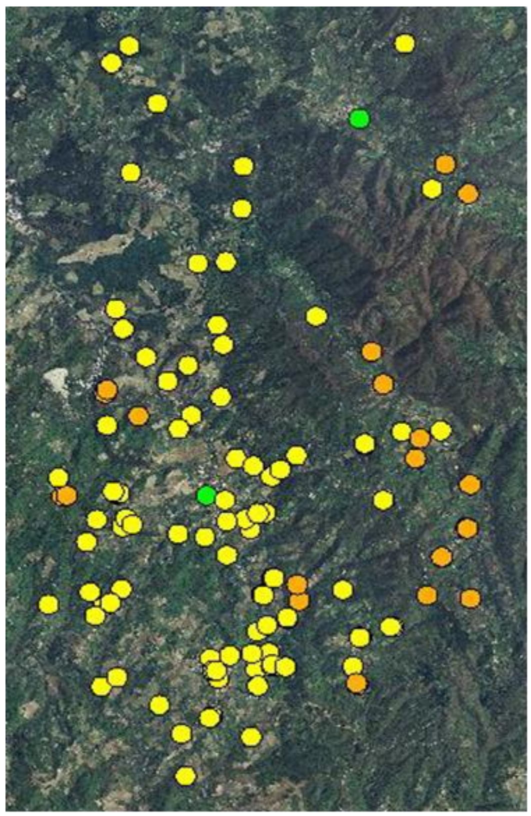
For each infrastructure examined, the pixels inside the buffer were defined.



Average pixel values were calculated and then data was grouped into five proportionally-divided risk classes.

IVI Infrastructure Vulnerability Index		
Value		Classification
0,00 – 0,20	Very low	0
0,21 – 0,40	Low	1
0,41 – 0,60	Medium	2
0,61 – 0,80	High	3
0,81 – 1,00	Extreme	4

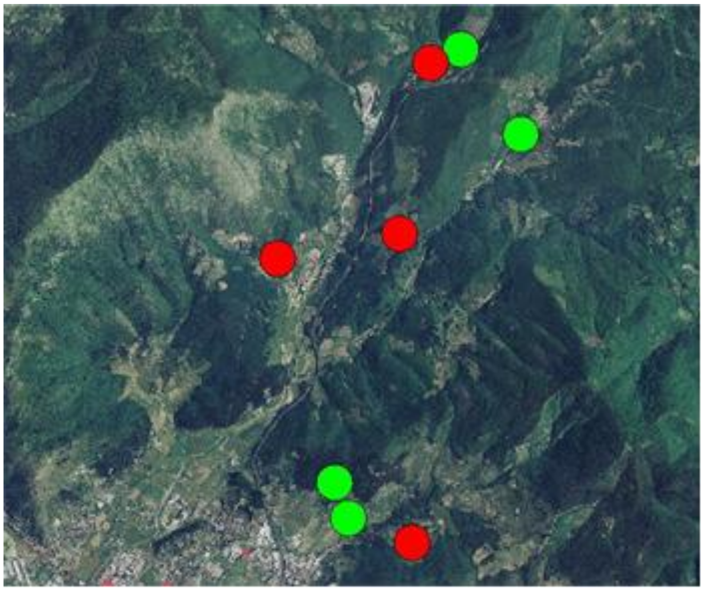
• Class 0: Very low risk – wildfire prevention activity is not necessary;
• Class 1: Low risk – during the fire season some basic wildfire prevention activity is necessary;
• Class 2: Medium risk – the structures could be damaged in case of wildfire, it is necessary to analyze the sources of risk and remove them where possible;
•Class 3: High Risk – the structures will be damaged in case of wildfire, it is necessary to analyze risk variables and to activate some specific measures for fires prevention and suppression;
•Class 4: Extreme risk – the structure will be destroyed in case of fire, it is necessary to create a defensive space around it and some specific prevention measures should be taken.



After this classification it was necessary to understand which factor had the greatest impact on the assignment of a specific building to a specific risk category. The analysis was carried out in order to suggest appropriate interventions for fire prevention and was conducted only on the structures in the medium and high risk classes.

Slope and statistical variables were immediately eliminated from the analysis for two reasons: first, because in the opinion of the experts the weight is limited (slope 0.099 - 0.191 statistical), and secondly, because the slope may not be changed or modified and the statistic is related to a set of components, including socio-economic ones, which require time to be verified and eventually modified.

Therefore vegetation and operational difficulties were given precedence. The average of the pixels for each of the two factors within the buffer were calculated in order to determine which predominates, as shown in the figure below (green for vegetation, red for operational difficulties).



To take a deeper look, the acquisition of more detailed and specific data on the area will will allow the definition of a type of procedure concerning possible operative steps in terms of territory management and fight actions, but it is beyond the objectives of the present study. This was particularly true for the vegetation layer for which no information about structure, density, vertical distribution and horizontal load etc. was available.

For the operational difficulties it would be necessary to see which of the subindexes (GODI ground operation – HODI helicopter operation) have a greater impact and eventually carry out a simulation with the allocation of new resources to see how the index would evolve.

Conclusions

The aim of this study was to create a model able to provide maps for the evaluation of forest fire risk to infrastructures located in a WUI area. After the selection of the model data a method to compare these variables quantified by different units of measurement is applied. The weight assigned to model variables, determined through interviews with forest fire prevention and suppression stakeholders represent an unbiased methodology expression of the different stakeholders typologies.

The result is a five-level risk classification, which is also easy to use during the suppression activities. The model testing based on tourism-related facilities as a WUI structure type was because of this kind of infrastructure are one of the most dangerous situations to manage in case of fire. In fact rural tourist accommodations are typically situated in remote areas, far from the places where firefighting means are located and the most important variable for risk determination was identified for each type of infrastructure.

The model structure allows insertion of new variables, as buildings construction material or number of fire extinguisher tool inside structures. It should be underlined that the introduction of new variables necessarily requires new expert interviews to recalculate variable weight.

The evaluation of forest fire statistics data is useful to provide trigger points location and maps of the burned areas, information necessary to complete the structure vulnerability overview. The analysis of vegetation have to be enhanced in terms of structural types and fuel distribution to evaluate and model fire intensity and consequent real threat to structures.

Once the territorial and anthropic variables have been defined, analyzed, classified and weighted (above-mentioned items have been perfected), the model could be used as a decision support system tool for planning and operative phases. In fact, during planning, the model simulates the risk variability derived from those variables that change slowly as vegetation distribution or roads network. Instead, during operational phases, the model might associate standard operating procedures for threat verification and/or emergency services action.

In conclusion, considering that WUI analyses and classifications represent debatable aspects in fire prevention and fire fighting, in particular because the typologies and space distribution and pattern of the structures are very different in different areas and countries, the described approach permits an objective and impartial evaluation based on peculiarities and specificities present in different contests.

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Spatial variation of driving factors of fire density at the local scale in SE France

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Abstract:
SE France is the area most affected by wildfires and there is a variation of the fire occurrence and of the fire size within this region. So for better fire prevention on a local scale, it is necessary to better understand this variation of wildfires in space.

Using the forest fires database of the French Forest Office, the fire density (1960-2011) was investigated at local scale in the département Bouches du Rhône. The municipalities of the study area were divided into 5 clusters according to descriptive variables (climate, land cover, WUI) using hierarchical cluster analysis. Statistical analyses showed that the mean fire density differed significantly according to the territory. Co-inertia and spatial analyses analyses were performed on each of the 5 clusters taking into account climate conditions, topography, land cover, WUI, network and population/housing densities as explanatory variables and 3 classes of fire density as dependent variables.

According to both types of analyses, high fire density was mainly linked to high proportions of WUI except in cluster 4, of wildland vegetation in clusters 1 and 5 and of agricultural area only in cluster 4. Cool and wet climate conditions and steep slope were linked to high fire density in clusters 1 and 2 (for the slope only) and high population/housing density was an important driving factor in clusters 3 and 4. Network density (especially minor roads) was linked to high fire density only in cluster 3. Low fire density was mainly linked to high proportion of agricultural area except in clusters 3 and 4 in which relief climate conditions and high elevation as well as steep slope (only in cluster 4) were the main factors that mitigated fire density.
This work showed that, at the local scale, the fire density driving factors varied within the study area. Their identification could improve fire prevention as they can better be targeted. This method can be extended to other regions regardless of the ecosystems

Additional Keywords: Wildfire; fire density; Southern France; spatial analysis; fire driving factors

Wildland urban interface growth during the last 50 years in North Sardinia, Italy: Implications for fire risk

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Abstract:
Mediterranean Basin countries are historically subjected to forest fires, which often threaten wildland-urban interface (WUI) areas. Throughout most of Mediterranean coastal areas, potential fire risk for villages, tourist resorts, other human activities and people is really high, particularly in summer when human presence increases, extreme weather conditions can occur, and vegetation is highly flammable. Therefore, developing planning policies is essential for implementing strategies to prevent and reduce wildfire risk in WUI areas. Recently, several authors stressed the importance of estimating trend in expansion of WUI areas. Tracking past and recent expansion trends allows us to minimize their impact, to determine likely extent, location and pattern of WUI in the future, and to provide information for long-term land use planning and natural resource management. In this study, we focus on analysing and evaluating the temporal evolution (1954-2008) of WUI areas in three coastal areas located in North Sardinia, Italy, characterized by large tourism development during the last fifty years. Several simulation by FlamMap simulator were also performed at different temporal steps in order to evaluate the potential of this approach in planning urban development and in land use decision making.

Keywords: WUI, Mediterranean coastal areas, WUI expansion trends, fire prevention planning

Introduction

Sardinia is a 24.000 km^2 island in the middle of the Mediterranean, with a coastline length of about 1.900 km, and a population above 1.600.000. Coastal municipalities represent the 19% of the total municipalities, but 50% of the population live in coastal areas. In addition, during the summer and fire season more than 2.000.000 tourists stay in the coastal areas of Sardinia. Since Sardinia is in general the Italian region with the largest number of fire and the largest burnt surface area per year, significant regional resources are used to prevent wildfire, to protect forests and structures and safeguard the people, in particular people who live in the WUI. The cost of the regional fire season in 2013 is estimated to be € 50 million, about $ 65 million.

These are the main motivations that justify the study briefly presented in this paper. The general objective was the analysis of the WUI dynamics in three typical tourism locations in North Sardinia over a relatively long-term period, 1954-2008, with the subsequent purpose of evaluating the potential danger in WUI areas using a fire simulator approach.

Materials and Methods

The study sites are located in three coastal areas of North Sardinia that are typical tourism destination, with a lot of resort, hotels, camping areas, and private homes available for holiday accommodation, and a sharp increase of the population during the summer season.

The analysis of the temporal evolution of the WUI areas was performed using a set of aerial photographs from the period 1954-2008, which were geo-referenced using a set of ground control points, photointerpreted and digitalized in a vector. Six temporal steps (1954, 1968, 1977, 1987, 1998, and 2008) were used to obtain the spatial themes needed to perform the analysis. Classification of the housing configuration types (isolated, scattered, dense clustered, and very dense clustered houses) and characterization and mapping of WUIs were conducted following the approach proposed by Lampin-Maillet et al. (2009, 2010) and using the WUImap TOOLBOX (Lampin-Maillet and Bouillon, 2010).

In order to determine the burn probability and give information useful for reducing fire risk, we simulated fire spread and behaviour using FlamMap following random ignitions across the study areas, four wind scenarios, and two fuel moisture content scenarios, and using land cover information of 1954, 1977, and 2000.

Results

The housing configuration dynamic at all sites during the period 1954-2008 shows an impressive housing growth, in particular during 70' and 90' and along the coastal areas. The most relevant housing configuration is in general "very dense housing", with the total WUI area more than double-tripled compared to 30 years ago.

The burn probability from FlamMap simulation shows in general a clear spatial trend. However, in 2000, when housing and WUI areas reached the maximum expansion, the areas with high burn probability sharply decreased, due to the changes in land cover and landscape that occurred during the study period.

Acknowledgements

This work was partially funded by the EU FP7 project FUME - Forest fire under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the World (grant agreement n°243888).

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Cloud Computing in Geospatial Analysis of Wildfire Danger and Fire Growth

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Abstract: Today's wildfire fighting needs require information systems that are able to conduct fire danger and fire behavior predictions in a timely manner. Based on knowledge gained from participation in the EU-funded research project VENUS-C, the current article presents the conceptual approach and design of AEGIS; which is an under development, state-of-the-art IT system that integrates fire danger rating and fire growth modeling. The utilization of a cloud computing platform ensures scalability and promptness of the calculations. The efficiency of the proposed platform will be based on the Cloud's flexibility to scale up or down the number of computing nodes needed for the requested processing. In this context, end users will be charged only for their consumed processing time and only during the actual wildfire confrontation period. Reliable and fine-resolution maps regarding the forecasted fire danger for the next five days will be provided including ignition risk, values at risk/ vulnerability and burn probabilities. Fire behavior modeling is to be conducted in the Cloud by utilizing the Minimum Travel Time (MTT) algorithm of the fire behavior mapping and analysis program FlamMap.

Additional Keywords: Web GIS, parallel computing; wildfire prevention; fire behavior.

Introduction

Significant alterations in fire regimes have been occurred in the recent decades (Liou *et al*. 2010), primarily due to socioeconomic changes and climatic anomalies, increasing dramatically the catastrophic impacts of wildfires (Kontoes *et al*. 2012). Almost every summer massive wildfires break out in several areas, leaving behind severe destruction of forested and agricultural land, infrastructure and private property, and losses of human lives (Koubarakis *et al*. 2013). During the summer of 2010, widespread wildfires in western Russia burned thousands of hectares of rangelands and forested areas, and the fire-caused death toll exceeded 50 human loses (Stocks *et al*. 2010). In the Mediterranean basin, the number of ignitions and the area affected by wildfires has increased exponentially over the last 20 years (Pausas *et al*. 2008). In 2007, the fires that ravaged southern Europe were among the worst on history record with over 3000 km^2 of forests burned (Kalabokidis *et al*. 2013).

Being able to predict where and when a fire is most likely to strike is vital during wildfire seasons across the globe. Difficulties in confronting such natural phenomena include not only an assessment of their biophysical causes, territorial distribution and damage inflicted in time, but also their dependence on human socioeconomic activities and lack of the necessary technological infrastructure to mitigate their catastrophic effects (i.e. loss of human lives, resource and property damages) (Kalabokidis *et al*. 2013). As hazards and vulnerabilities are spatially and temporally distributed, risk is inherently a dynamic phenomenon; and risk assessment should address both the degree of risk and its spatiotemporal distribution (Chen *et al*. 2003). Therefore, fire risk management and fire behavior modeling require large volumes of data that change continuously over time and space, creating both the need and the opportunity to automate the tasks (Yuan 1997). These large volumes of data required for spatiotemporal calculations often rely on huge computer resources (i.e. processing power and storage). However, local civil protection agencies often do not own the required computer resources to conduct these heavy spatiotemporal calculations due to limited financial means. Furthermore, they may not have the expertise to utilize state-of-the-art fire management tools. Within this context, the operational necessity for a state-of-the-art, low cost and easy to use platform for forest fire management emerges.

The main objective of the present paper has been the conceptual approach and design of AEGIS; i.e. a currently under development Web GIS application that will integrate fire danger rating and fire behavior modeling. The proposed system may be a cost effective, easy to use forest fire management system, independent of commercial software for the end users. Based on an innovative computational model, the proposed approach will provide reliable, fine-resolution maps regarding the forecasted fire danger for the next five days including ignition risk, values at risk/ vulnerability and burn probabilities for several areas around the country of Greece. Computations in AEGIS will rely on cloud computing; this ensures scalability and efficiency of the calculations. Fire ignition danger computation in AEGIS will depend on the usage of several parameters in a quantitative calculation algorithm providing high geographical detail and the ability to refresh and recalculate the map with newly acquired data during the day. In addition, outcomes from existing international research such as the Minimum Travel Time (MTT) algorithm will be integrated into AEGIS to conduct fire behavior modeling for estimating fire size, spread direction, fire intensity and calculation of burn probabilities (Finney 2002, 2006). Through the Web GIS interface, AEGIS will deliver fire behavior estimations, fire danger maps, current and forecasted weather data and fire management data in a timely manner and without devastating delays.

Study areas

AEGIS is currently under development and will be applied in seven different study areas with high-hazard, high-value and high-use forest and other multi-purpose lands. Each area covers a mix of different conditions either in socioeconomic situations (i.e. rural/ urban and interface areas, changes in population size/ density, etc.) or in environmental factors (i.e. climate, vegetation, topography, geographical distribution, etc.). By applying results and outcomes of this research, knowledge is gained and tools are developed that may allow us to apply the system to the rest of Greece or elsewhere with minimal efforts and resources in the future. The study areas are (Figure 1):

1. The island of Rhodes located in the southeastern Aegean Sea of Greece covers an area of 1400 km^2 (with 117000 permanent residents; i.e. 83 persons per km^2). There is an extreme human pressure on the island's ecosystems due to the increased tourism and the resulting urban expansion into the wildland-urban interface to cover housing and recreational needs.

2. The island of Lesvos (with 90000 permanent residents; i.e. 55 persons per km^2) located in the northeastern Aegean Sea of Greece covers an area of 1636 km^2. Lesvos encompasses high fire-prone and fire risk ecosystems of Greece. Pine forests and olive groves dominate almost on half of the island's area, making it one of the most tree-covered

islands of Greece.

3. Chalkidiki, which is a three-pronged peninsula located centrally in the region of Macedonia, covers an area of 2886 km^2 (with 80000 permanent residents; 28 persons per km^2). The whole region is heavily wooded with pines and olive trees, and while there are vineyards and fertile farmlands inland, there are no regular rivers flowing all year long.

4. West Attica, located in central Greece, close to the metropolitan area of Athens covers an area of 1060 km^2 (with 151038 permanent residents; 143 persons per km^2). The area is affected by large wildfires and is under continuous pressure and threat. In 28/6/2007, the worst fire event of the past two centuries devastated over 3633 hectares, 2180 of which were forested areas with true-fir trees.

5. The area of Chania (with 156371 permanent residents; i.e. 66 persons per km^2) is located in the western part of Crete Island, with a total area of 2375 km^2 of which 1476 km^2 are mountainous areas. The ever-increasing tourist pressure of the area has increased its vulnerability and fire events do have devastating results on nature, society and the economy.

6. Messenia, located at the southwest edge of Peloponnesus with a total area of 2991 km^2 (176876 permanent residents; i.e. 59 persons per km^2). During the summer of 2007, devastating forest fires affected a big portion of Peloponnesus including Messenia.

7. The area of Kastoria, located at the northwest part of Macedonia, with a total area of 1720 km^2 (53483 permanent residents; i.e. 31 persons per km^2). Climate change has lead to increased fire activity, even in high mountainous areas such as Grammos, where fire has always been a low frequency natural disaster but with high intensity; within this scope, our proposed management tools may also facilitate the ecological research of these very important fire regimes in the area.

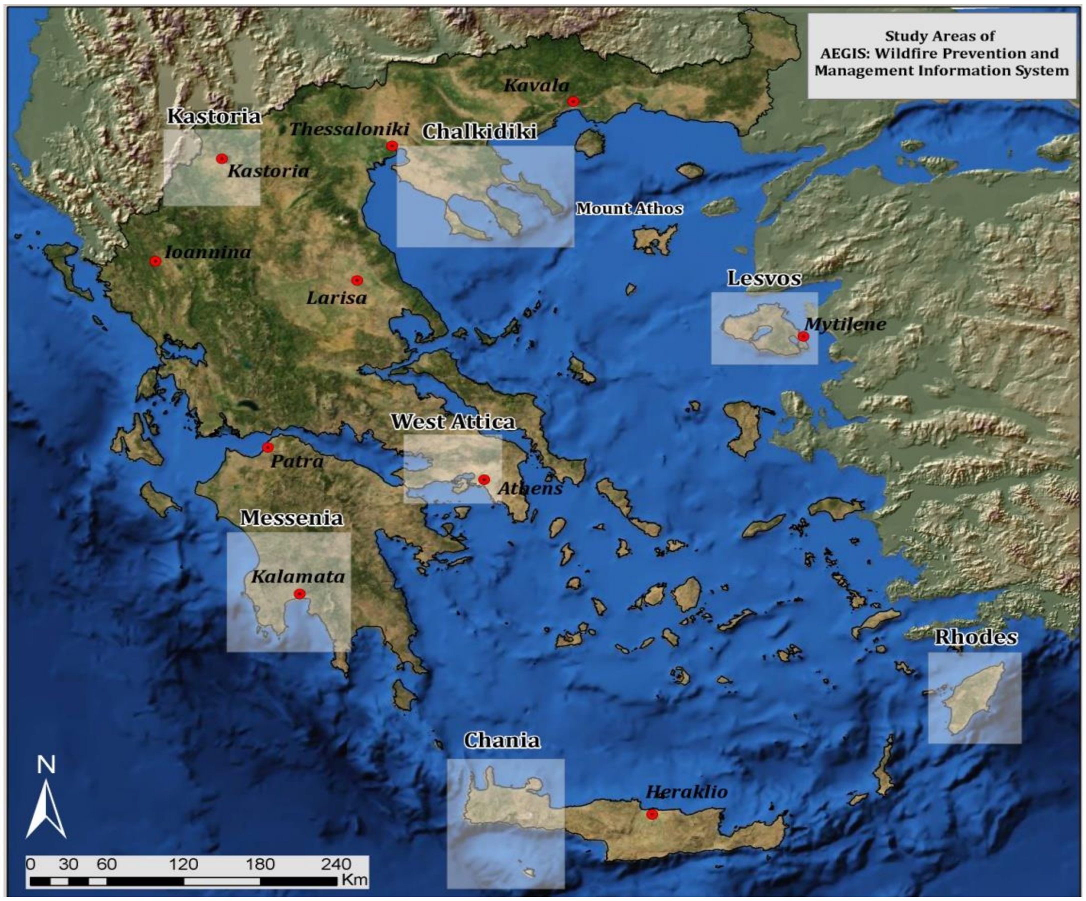

Figure 1: The seven study areas of AEGIS in Greece

Conceptual design of AEGIS

For fire danger calculation and fire behavior modeling, the principles of cloud computing will be followed. Cloud computing enables the users to harness abstracted and virtualized resources, and permit computations over huge amount of information without having their own processing power (Bhat *et al*. 2011). The National Institute of Standards and Technology (NIST) (Mell and Grance 2009) defines cloud computing as "...a model for enabling convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." The Cloud offers flexible configurations that allow increasing or decreasing the occupied hardware resources dynamically, depending on the real-time demands of hosted applications.

Cloud computing will perfectly fit into the needs of the AEGIS application because of the large amount of data and the complexity of the processing. Taking advantage of the Cloud's ability to increase/decrease the number of available virtual machines (VMs) on demand, end users will be charged only for their consumed processing time and only during the actual wildfire confrontation period.

AEGIS will utilize the public cloud of Windows Azure, based on knowledge gained from participation in the EU-funded research project VENUS-C (Virtual multidisciplinary environments using Cloud infrastructures[1]). VENUS-C developed and deployed a cloud computing service for research and industry communities in Europe by offering an industrial-quality service-oriented platform based on virtualization technologies. The programming model of Generic Worker (Simmhan *et al*. 2010) will be utilized for executing tasks in the Cloud's VMs machines and storing the output results in Cloud's storage containers. End users will consume the cloud resources through the web interface of the application (Figure 2).

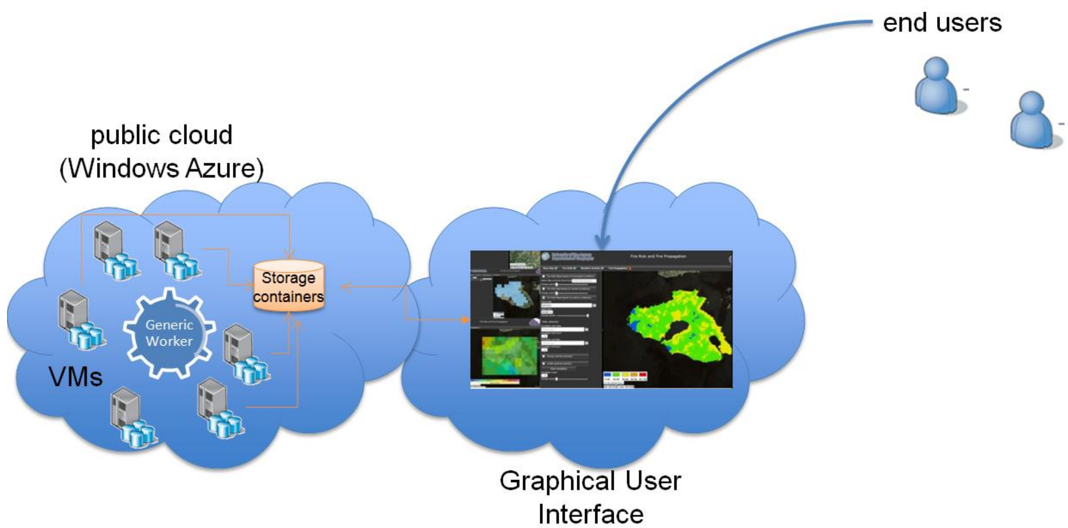

Figure 2: Conceptual approach of task execution in the Cloud

Fire danger maps based on five-day forecasted weather data will be calculated for every study area in a time interval of one hour, once per day. The danger map portrays the geographical probability of a new fire ignition and its expected impacts. Artificial Neural Networks are used for the mathematical modeling of these complex phenomena (Vasilakos *et al*. 2007, 2009). The number of available virtual machines will be increased when new forecast weather data are available (i.e. every morning at a predefined time). After scaling up, every virtual machine will download external data (i.e. real time weather for a specific hour of the next five days data), internal data (i.e. static data stored in the Cloud such as topography, vegetation, fuel types and socioeconomic inputs) and generate the corresponding fire danger map. Furthermore, weather prediction maps of wind fields, air and soil moisture and temperatures, cloud cover, etc. will also be calculated and visualized. The weather prediction maps will be prepared with the operational use of the NonHydrostatic SKIRON/Eta Modeling System (SKIRON) from the Atmospheric Modeling and Weather Forecasting Group (AM&WFG) of the Department of Physics, University of Athens. SKIRON is a state-of-the-art integrated limited area modeling system developed from AM&WFG (Janjic 1994, Kallos *et al*. 1997).

Execution will run in the Cloud by assigning a task to a specific virtual machine (Figure 3). Following job execution, the deployment will be automatically scaled down. After the map creation, users will view the map of interest by selecting the corresponding date and time through the graphical interface of AEGIS.

[1] www.venus-c.eu

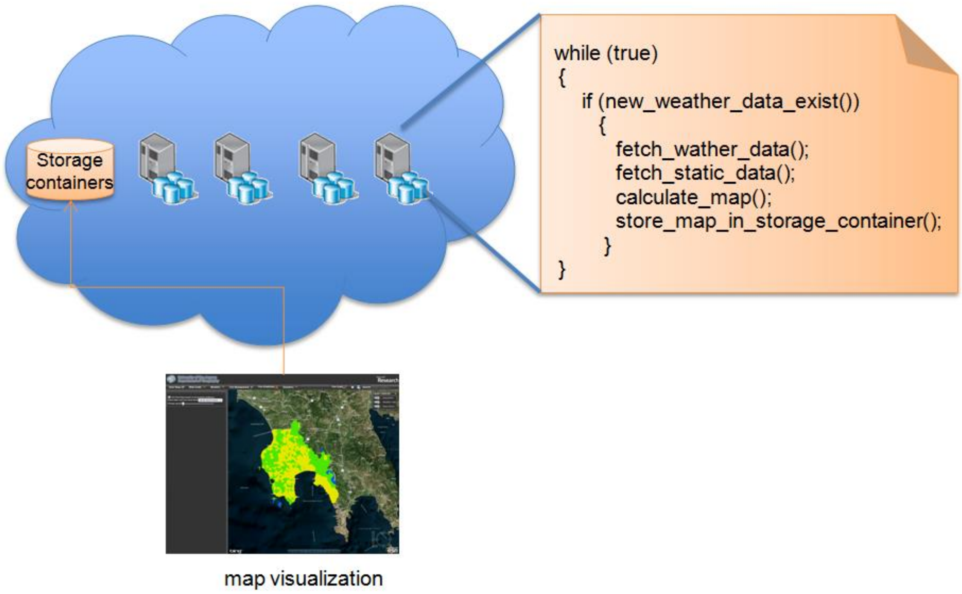

Figure 3: Fire danger computation in the Cloud

Fire behavior modeling in AEGIS is to be conducted by utilizing the MTT algorithm. MTT computes potential fire behavior characteristics (spread rate, fireline intensity, time of arrival, flow paths, etc.) for a single fire, and burn probabilities/ flame length for the entire landscape from several fires based on weather and fuel moisture scenarios. The fire perimeters created by MTT are similar to wave-front expansion (Richards 1990, Finney 2002), but they are mathematically and computationally more efficient. Holding all environmental conditions constant, the MTT algorithm searches for the fastest path of fire spread along straight-line transects connected by nodes (cell corners) (Finney 2006) and it exposes the effects of topography and arrangement of fuels on fire growth (Ager *et al*. 2007).

MTT has the advantage of producing burn probabilities of the entire study area by simulating thousand of potential fires that could burn throughout the area. It permits Monte Carlo simulations of many fires (i.e. more than 100000 fires), to evaluate burn probability and fire intensity for very large (e.g. more than two million ha) landscapes (Ager and Finney 2009). Burn probability is an estimate of the likelihood of a pixel burning given a single random ignition under burn conditions in the simulation. Burn probability modeling represents a major advancement in wildfire behavior modeling compared to previous methods, such as those where fire likelihood was quantified with relatively few predetermined ignition locations (i.e. fewer than 10). As a result, the product of this process is the burn probabilities map that reveals which areas are more susceptible to encounter a fire event and which are more fireproof.

Initial MTT simulations have been executed in a 4-core PC with eight threads and six GB RAM (i7 CPU 2.67 GHz). These tests revealed that the execution time for a simulation based on an Ignition Probability Grid (100000 ignition points) took approximately 48 hours to be completed, while for randomly located ignitions the execution took about 24 hours to be finished. The time needed to run an execution reveals the need for a parallel processing approach to minimize the processing time and to make the results available on a timely manner.

To calculate the burn probabilities for the entire landscape, partitioning of the fire simulations will be applied by running in parallel several MTT simulations in the Cloud. By applying MTT simulations in the Cloud, the execution time is expected to reduce significantly.

Each simulation will be running in a different virtual machine with a fraction of the total targeted number of fires and thus create an intermediate burn probabilities map. For example, if the targeted total number of simulations is 1000 and the available VMs are 10, then every VM will have its own dataset and will execute 100 fire simulations. When all simulations are finished, the final burn probability map will be composed by merging all intermediate results into one of the available VMs (Figure 4).

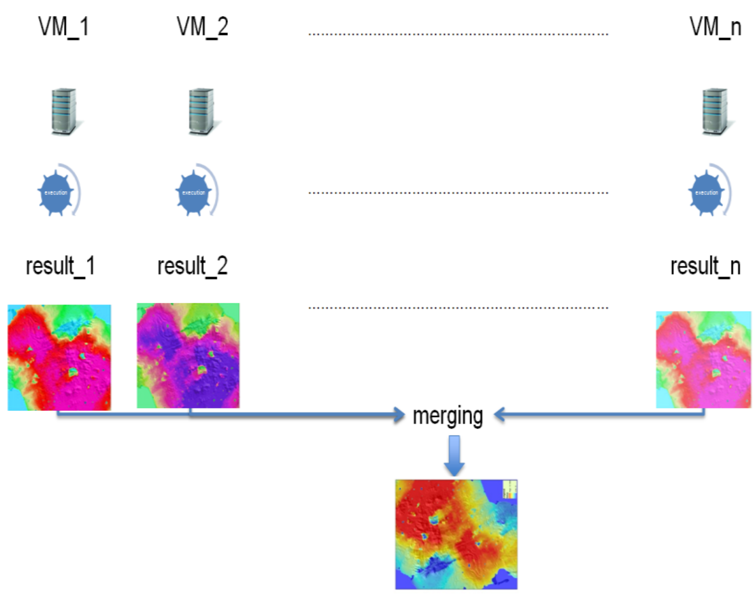

Figure 4: MTT decomposition in the Cloud

The value of each cell in the final map will be evaluated by aggregating all values of the intermediate burn probabilities. Let us assume N virtual machines in the Cloud will be utilized. Then, each intermediate map is created by giving a fraction "**f**" of the total fire ignition points where "f" times "N**"** equals the total number of fire ignition points. Suppose the top-left cell of the first intermediate map has been burned **t1** times. In a similar way, suppose the same cell of the second map has been burned **t2** times, etc. Then, each intermediate burn probability of this pixel would be (Figure 5):

$$bp_1 = t1/f \quad (1)$$
$$bp_2 = t2/f \quad (2)$$
$$\ldots$$
$$bp_N = tN/f \quad (3)$$

And the burn probability of the final (i.e. merged map) would be:

$$bp = (t1+t2+\ldots+tN) / (f+f+..f) = \sum_{i=1}^{N} ti \; / (N*f) \quad (4)$$

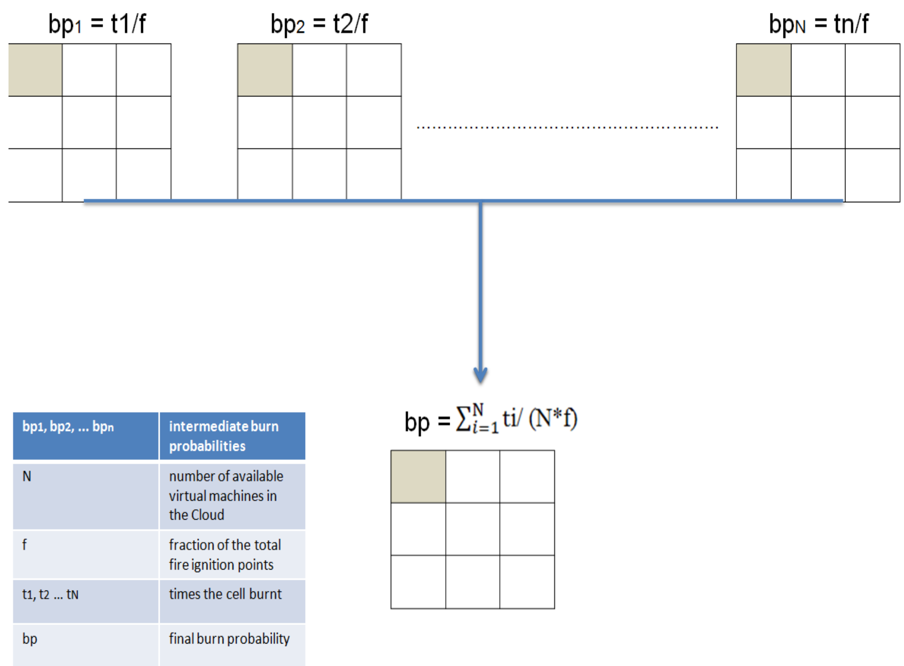

Figure 5: Calculating the burn probabilities of the intermediate and final maps

Services and data provided by AEGIS will be accessible through a web-based front end, eliminating the need to install special desktop software. This will cut down on client deployment time and costs to zero, and will enable any authorized user to immediately access the platform from anywhere in the world. Users will have the ability, without the requirement of knowing the handling of complicated GIS applications, to utilize the capabilities of the system. The fire danger and behavior prediction data, along with a plethora of other information spanning from roads, location of water tanks, the positioning of aircrafts and vehicles, images from detection cameras, vegetation types, terrain and weather data will be visualized over web satellite images from Microsoft Bing Maps[2], enabling firefighters in control centers or *in-situ* to manage more effectively forest fires and deal with any other emergency situations that may arise.

Bing Maps will be the predefined background mapping scheme, providing high resolution satellite images and detailed thematic maps with annotations and road network information. Aerial orthophotos, topographic/ thematic maps, satellite images and land use / land cover types from other sources/ independent providers can also be selected and displayed at will. Apart from background layer selection, users will have access on fire information that may aid in forest fire suppression efforts. This information includes the road network, water tanks, pumping stations, fire hydrants, fire watch outlooks, monuments, weather stations, helipads, gas stations, landfills, evacuation sites and fire fighting vehicles patrol sites.

Several tools and services such as fleet tracking, live camera image streams, geo-processing tools and GeoRSS feeds is planned to be integrated. Coordinates of fire service vehicles and patrol light-aircrafts can be located online and in real-time with Global Positioning System (GPS) tracking devices. Firefighting officers can locate and track online the real positions of vehicles and airplanes during a fire event to manage and coordinate them.

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[2] http://www.bing.com/maps

Besides the real-time positioning of the firefighting forces, users will be able to ask for the closest fire suppression facilities such as water tanks from any spot on the case study area. "Closest route" queries regarding the location of closest water tanks, fire hydrants and pumping stations will also be supported, as well as the analysis of the shortest distance among locations on the map and finding the drive time distances from a site.

Discussion and Conclusion

This article describes the conceptual approach and design of AEGIS, a state-of-the-art cloud-based Web GIS system that will integrate fire danger rating and fire growth modeling schemes. By using and testing the innovative proposed fire behavior algorithms, maps will be produced on demand and real-time to graphically represent the spread and intensity of a forest fire at different times and places, including burn probabilities and fire effects.

The AEGIS application will offer services beyond simple coordination of emergency activities. Remote automatic weather stations and a weather forecasting system based on the SKIRON weather model will provide crucial data needed for fire prevention and early warning. "Shortest routes" queries will provide in real-time the sites of the closest water tanks, pumping stations and fire hydrants. Fire management professionals will be able to locate, in real-time, the coordinates of a fire patrol aircraft and a fire vehicle. Web cameras will augment enhance the capabilities of AEGIS by transmitting images of high-risk areas into the system, while live feeds will further enhance the communication between end users.

Geographical representation of fire danger potential and identification of high-risk areas is to be provided daily, based on cloud computing techniques. With the AEGIS innovative and advanced programming tools, firefighting personnel, emergency crews and other authorities will be able to design an operational plan to encompass the forest fire, pinpointing the best ways to put it out with new levels of precision. Regarding the forecasted fire danger, maps of ignition risk, values at risk/vulnerability and burn probabilities will be provided. Fire behavior modeling will be conducted by utilizing the MTT algorithm of the FlamMap, which is a fire behavior mapping and analysis program that computes potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.) over an entire landscape for constant weather and fuel moisture conditions.

One of the compelling advantages of AEGIS lies in leveraging GIS capabilities without the need for extensive training on commercial or complicated GIS applications. The Cloud will provide the necessary processing power and storage that is required. Thus, end users will not need to possess any huge processing power or storage capabilities locally. From the end-user point of view, all that is needed to access the tool will be a standard computer or laptop, an Internet connection and a web browser. All of the application's data will be stored in the Cloud, while the visualization of the outputs is to be achieved through a Silverlight-based graphical interface. The instant and prompt availability of processing power along with the cost effectiveness, reliability and scalability of the Cloud will be key benefits of the application. The sharing of resources among fire agencies will lead to reduced costs, higher efficiency and effectiveness in fire confrontation.

By applying the results and outcomes of this research, knowledge gained and tools developed may allow application of the system into more geographical areas of Greece or countries and in larger spatial contexts with minimal effort and resources in the future; of course, under the assumption that the necessary input databases and services for these regions will be provided.

Acknowledgments

The research project "AEGIS: Wildfire Prevention and Management Information System" {Code Number 1862}, is implemented within the framework of the Action ARISTEIA of the Operational Program "Education and Lifelong Learning" (Action's Beneficiary: General Secretariat for Research and Technology), and is co-financed by the European Social Fund (ESF) and the Greek State. Final results and outcomes of the project are expected by September 2015.

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Fire Behavior Simulation in Mediterranean Forests Using the Minimum Travel Time Algorithm

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Abstract
Recent large wildfires in Greece exemplify the need for pre-fire burn probability assessment and possible landscape fire flow estimation to enhance fire planning and resource allocation. The Minimum Travel Time (MTT) algorithm, incorporated as FlamMap's version five module, provide valuable fire behavior functions, while enabling multi-core utilization for the calculations. The primary goal of this study was the MTT implementation for two study areas in Mediterranean forest types of Greece, *i.e.* Lesvos Island (in North Aegean Sea) and Messenia (in Southwestern Peloponnesus) by calculating burn probabilities, fire size and flame length probability from thousands of simulated fire events (located either randomly or based on historical ignitions). A second goal aimed on estimating fire hazard and vulnerability for several values-at-risk of the study areas. To achieve these goals the necessary geospatial datasets were created by field inventories, remote sensing techniques, geo-statistics and Geographic Information Systems (GIS). Weather and fuel moisture inputs were retrieved from nearby weather stations. Maps showing the most fire-prone and high-risk parts of each area were created, along with fire hazard scatter plots for values-at-risk. Interpretation of the results may suggest possible fire fighting strategies, places that need vegetation management, areas that require more patrols and surveillance and areas with increased fire intensity.

Additional Keywords: Wildfire; burn probabilities; FlamMap; MTT; ArcFuels; values-at-risk.

Introduction
The ever-increasing occurrence of large-scale wildfire events in Greece is a concern for the firefighting agencies, public safety and government authorities. The size of Greece and the configuration of its terrain and municipalities create "islands", either natural in the sea or "ecosystem enclaves" surrounded by urban development. The density of human activities near wildland areas means that even small wildfires can have high consequences. The recent example of Chios Island fire that burned over 15,000 ha (almost 1/6 of the islands size) devastated part of the island's economy and most of the forest ecosystems in 2012. It also proved that the situation is getting worse in several parts of Greece in terms of vegetation condition, preparedness of local or national firefighting agencies and resources availability. The new challenges and realities coming from the country's economic situation emphasize the need for pre-fire burn probability assessment and possible landscape fire flow estimation to enhance fire planning and resource allocation. This study reports on an implementation of the Minimum Travel Time algorithm (MTT) (Finney 2002) to explore its potential to estimate and calculate fire hazard for several values-at-risk for two study areas of Greece, Lesvos Island and Messenia. These areas face the

risk of future large-scale fires due to their fire history, human practices, and physiographic characteristics. The results of this research are essential for early warning/protection and need to emphasize not only to where a fire can initiate and spread, but also to those particular values and assets that must be protected to avoid a new catastrophe. Results can also be used for vegetation management planning and fuel treatment practices to reduce the risk of a wildfire to attain characteristics of megafires.

The bulk of the analysis was conducted with the command-line version of MTT called "Randig" (Finney 2006*a*). MTT computes fire growth between the cell corners at an arbitrary resolution and fire growth is computed under the same assumptions as the basic fire behavior, holding all environmental conditions constant in time (Finney 2006*b*; Stratton 2009). The new version of FlamMap 5.0[1] also enables end-users to create all the necessary results and files from multiple ignition simulations (burn probabilities, fire perimeters, flame length probabilities, fire size list) ready to be used for a quantitative wildland fire risk assessment. Furthermore, MTT results can be used both for fuel management planning and for single event fire propagation (spread and intensity); a convenient way to conduct this kind of analysis is by using ArcFuels, developed to streamline fire behavior modeling and spatial analyses for fuel treatment planning through macros that are executed via custom toolbars in ArcMap (Vaillant 2013). ArcFuels is used to rapidly design and test fuel treatments at the stand and landscape scale via linkages to models such as FVS-FFE (Forest Vegetation Simulator with the Fire and Fuels Extension; Reinhardt and Crookston 2003), SVS (Stand Visualization System; McGaughey 1997), FARSITE (Fire Area Simulator; Finney 2004), FlamMap (Finney 2006*a*), Nexus (Scott 1999), and FVS (Forest Vegetation Simulator; Crookston and Dixon 2005) within a spatial interface.

Currently, there are several studies that used FlamMap, MTT and ArcFuels for quantitative wildland fire risk assessment. Ager *et al.* (2007) modeled wildfire risk to northern spotted owl habitat by calculating spatially explicit probabilities of habitat loss for fuel treatment scenarios on a 70,245 ha study area in Central Oregon, USA. Simulations revealed that a relatively minor percentage of the forested landscape (20%) resulted in a 44% decrease in the probability of spotted owl habitat loss averaged over all habitat stands. Ager *et al.* (2010) conducted a comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. The burn probabilities were used to calculate wildfire risk profiles for each of the 170 residential structures within the urban interface, and to estimate the expected (probabilistic) wildfire mortality of large trees. Salis *et al.* (2013) used simulation modeling to analyze spatial variation in wildfire exposure relative to key social and economic features on the island of Sardinia, Italy. Historical fire data and wildfire simulations were used to estimate burn probabilities, flame length and fire size. These risk factors were examined to understand how they varied among and within highly valued features located on the island. Ager *et al.* (2012) used simulation modeling to analyze wildfire exposure to social and ecological values on a 0.6 million ha national forest in central Oregon, USA. They simulated 50,000 wildfires that replicated recent fire events in the area and generated detailed maps of burn probability (BP) and fire intensity distributions. Results were used to create scatter plots showing patch-scale variation within selected land designations (human values, wildlife habitat and ecological values) for burn probability versus fire size and versus conditional flame length.

[1] http://www.firemodels.org/downloads/flammap/5.0/ReleaseNotes_FMP5.pdf

In our study, simulations of 100,000 fire events were conducted for two study areas of Greece, *i.e.* Lesvos Island (in North Aegean Sea) and Messenia (in Southwestern Peloponnesus), both with randomly located ignitions and based on a historical ignition probability grid. Results are interpreted to understand the fire hazard produced by the different ignition patterns. FARSITE simulations from recent fire events were simulated to assess the modeling accuracy and to understand which parameters should be changed to better capture the actual fire patterns of each area. The next step of the analysis involves the usage of ArcFuels to assess the fire hazard and risk for several values-at-risk of the two areas. This will be achieved by constructing fire hazard scatter plots and identifying which values face the greater fire risk. Finally, several maps were created to describe and portray the results of each area.

Materials and methods

Study areas

This study is focused on two areas of Greece that have unique features and characteristics and different fire history. Lesvos is an Aegean Sea island, located on the east part of Greece, close to coast of Asia Minor, Turkey (Figure 1). It covers an area of about 1,650 km^2, with about 121 km^2 located on areas of over than 500 m elevation, 312 km^2 between 300 and 500 m, 713 km^2 between 100 and 300 m and 469 km^2 located across the coastal areas, below 100 m a.s.l. Land degradation and desertification problems occur on an extensive part of the island (1/4 of its total size) due to overgrazing, frequent fire events and lack of precipitation. These lands are semi-arid, while the rest of the island is dry to sub-humid with 450 mm to 700 mm average precipitation (Kosmas *et al.* 2000). During the summer, the island is affected by the yearly influence of Etesian winds having high speeds (usually 5-7 Beaufort or BF) from NE to NW directions. In the island, several world heritage sites and monuments exists, such as a 20 million year-old petrified forest, medieval monasteries, historical settlements and castles, prehistoric sites and ancient Greek and Roman temples. Furthermore, the island is an important bird habitat and immigration route, with rare local species (*Sitta krueperi, Buteo buteo, Circaetus gallicus, Accipiter gentilis*).

Its touristic sector is of medium size in terms of infrastructure and small scale in terms of the overall island's economic activities, with only few developed areas of large tourist concentration. In terms of vegetation, the island is covered by the largest pine (*Pinus spp.*) forest complex of all the Aegean Sea islands relatively to its size (300 km^2, *i.e.* about 20%), while the rest of the island is covered by olive groves (500 km^2), phryganic ecosystems and grasslands (580 km^2), broadleaf forests and oak (80 km^2) and evergreen shrublands (30 km^2). Significant parts of the island face land abandonment with the subsequent reforestation, and due to the fact that forests are mostly unmanaged privately owned, no fuel management exists on these lands and the risk for increased fire intensities and ignitions is of great concern for the local firefighting agency. Finally, small-scale wildland-urban interface areas (WUI) are located on the SE, where 1/3 of the total population resides in a densely vegetated area.

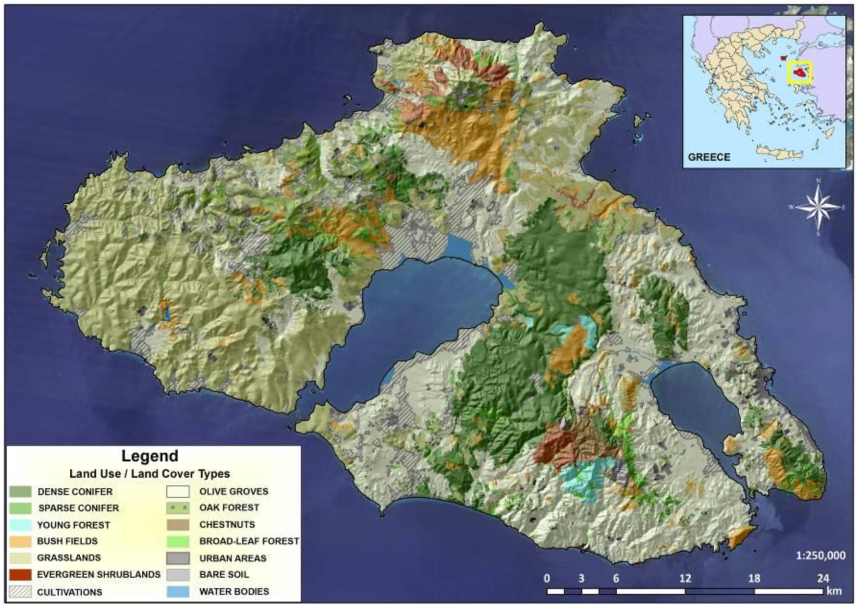


Figure 1: Land use / land cover types of Lesvos Island, Greece

Regarding the island’s fire history, 900 incidents were recorded during the last 40 years resulting in about 10,000 ha of burned land (Figure 2). The vast majority of these events (92%) were of minor importance with size less than 10 ha, while only four events burned more than 500 ha and nine between 100 and 500 ha. The most common cause of ignitions is arson for land clearance and agricultural/livestock production improvement, followed by negligence/accidents and arsons from people with economic or other interests.

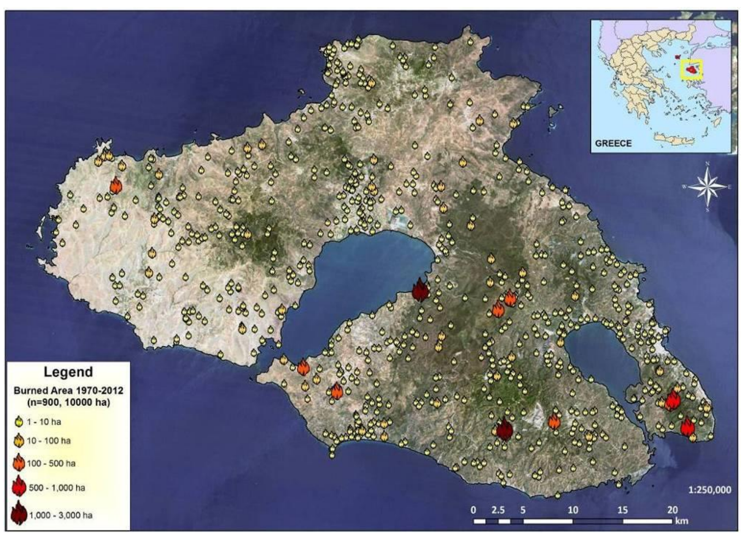


Figure 2: Fire history map of Lesvos Island for the years 1970–2012

Messenia is located on the SW tip of Greece, Peloponnesus, having shores to the Ionian Sea (Figure 3). It covers an area of about 3,000 km^2, with about 45 km^2 located on areas of more than 1,500 m elevation (Mt. Taigetos peak), 254 km^2 between 1,000 and 1,500 m, 660 km^2 between 500 and 1,000 m, 560 km^2 between 300 and 500 m, 860 km^2 between 100 and 300 m and 620 km^2 located across the coastal areas, below 100 m a.s.l. The average annual precipitation of Messenia is higher than Lesvos Island, with a range between 600 to 900 mm. During the winter, the area is affected by the passage of depressions forming over the Mediterranean Sea, while in the summer it is influenced from heat waves coming from N. Africa. The steep and differentiated topography creates several local and diurnal wind regimes and forms local microclimates.

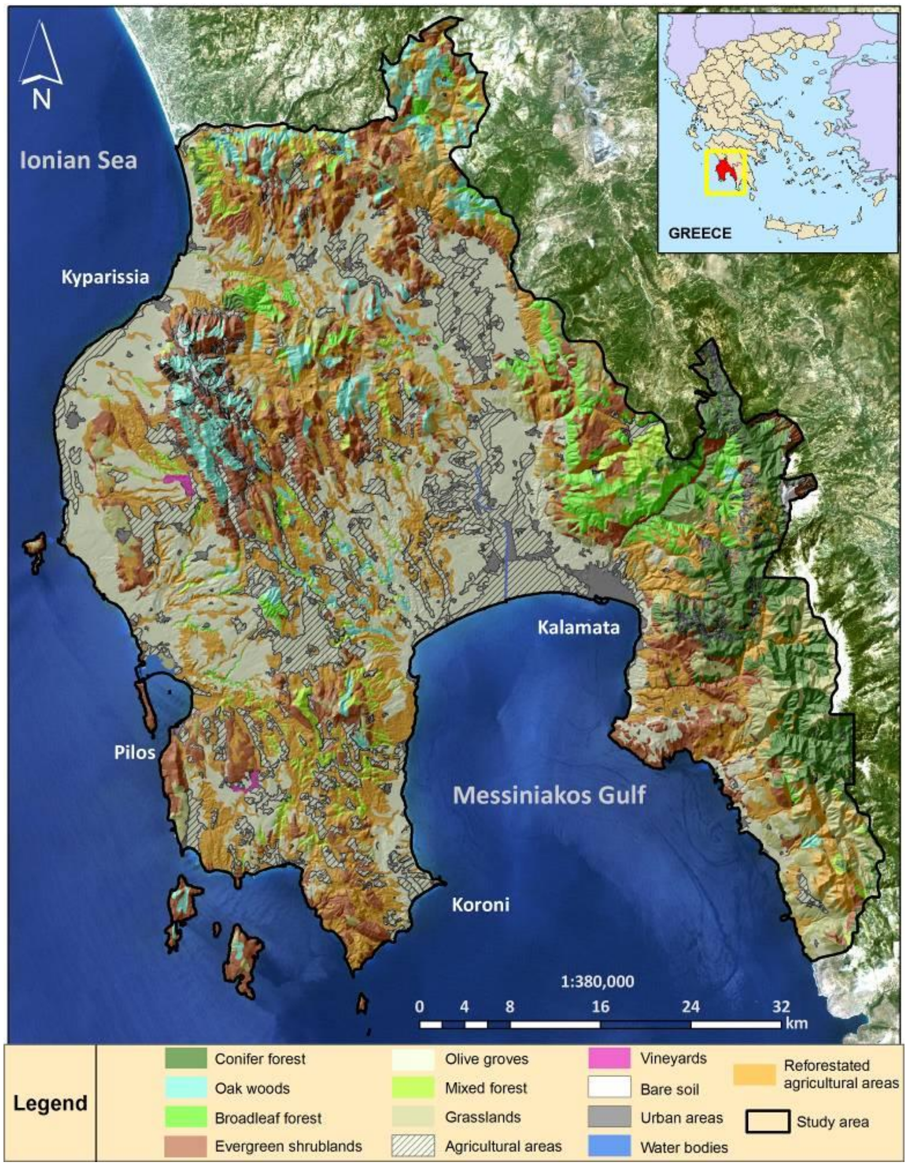


Figure 3: Land use / land cover types of Messenia, Greece

Several archaeological sites of world importance (dated back to 2000 B.C.) exist on forested and densely vegetated areas. Furthermore, extensive WUI areas can be found around the 400 urban areas, villages and settlements and, in conjunction with land abandonment and reforestation, increase the risk for causalities. The tourist infrastructure of the area is widespread across the coasts and one of the largest and most luxurious hotel complexes of Greece is located there. In addition, several people camp (either legally or illegally) close or inside high fire risk areas during the summer fire season.

Vegetation of Messenia consists of 140 km^2 covered by oak forests (*Quercus conferta, Quercus ilex, Quercus coccifera, Quercus pubescens, Quercus ithaburensis Decaisne subsp. Macrolepis*), 85 km^2 with *Pinus nigra* ssp. *pallasiana* and *Pinus halepensis*, 127 km^2 with *Abies cephalonica,* 116 km^2 with broadleaf forests (*Castanea sativa*, *Platanus orientalis*, *Acer pseudoplatanus*, *Sorbus domestica*, *Fraxinus ornus*, *Alnus glutinosa*, *Prunus cerasus*), 1,150 km^2 with evergreen shrublands, 250 km^2 with grasslands and phryganic ecosystems, while the rest of the area is mainly covered by olive cultivations (600 km^2) and agricultural areas (orchards, crops, vineyards, etc.).

Frequent fire events have been recorded during the past 20 years, with more than 600 fire events resulting in over 45,000 ha of burned forests and other lands (Figure 4). A 78% of fires burned an area of less than 10 ha each, a 16% burned from 10 to 100 ha and a 5% burned from 100 to 1,000 ha each. Seven events burned an area exceeding 1,000 ha each, six of which occurred during the catastrophic summer of 2007. There is evidence that several ignitions are caused by lightning's (Mazarakis *et al.* 2008; Defer *et al.* 2005), but the vast majority initiated from agricultural practices, arson and accidents/ negligence, similar to Lesvos Island and typical for Greece.

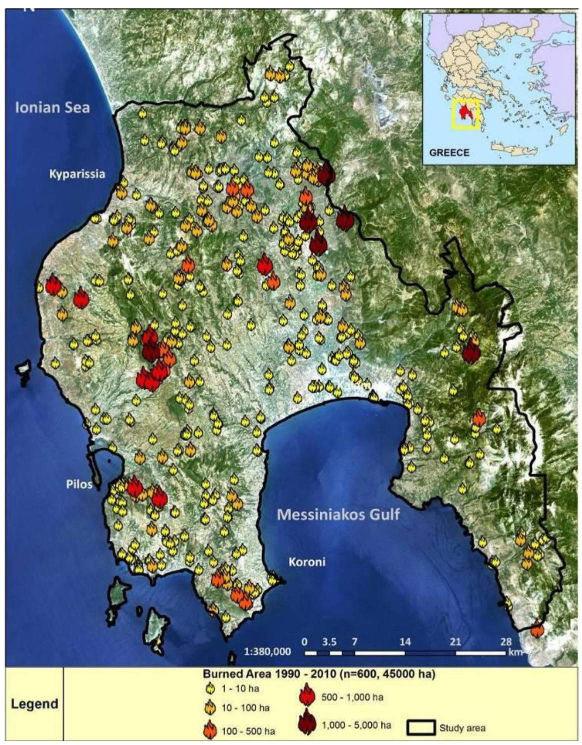


Figure 4: Fire history map of Messenia for the years 1990 – 2010

MTT simulations

For simulations, we used the command line version of MTT called "Randig". This version is more stable and lightweight compared to FlamMap, while it enables the simulation of thousands of fire events. Furthermore, it allows the usage of multiple weather scenarios by selecting a random sequence among the scenarios defined in a specific input file according to their relative probability. MTT produces minimal distortion to fire shapes because there are no limits on angles or distances for searching (unlike Cellular Automata, etc.). It is very reliable for the huge numbers of simulations, very sensitive to complex environmental conditions (space and time) and can represent influences of spotting. The MTT algorithm replicates fire growth by Huygens' Principle where the growth and behavior of the fire edge is a vector or wave front (Richards 1990; Finney 2002).

Randig can take advantage of multi-core processors and simulation time is substantially reduced when more processors participate in the procedure. When running many fires, it is most efficient to use one core/thread per fire. Each fire will run slower but it is the most efficient for the entire run. If running one fire or just a few (fewer fires than processors) then it is more efficient to have two or more cores/threads running each fire. The parallelization is done in two levels and hierarchical – among fires and within fires. By choosing one core/thread per fire, then each fire will have its own thread and run simultaneously on as many processors as available. For example, if you have 16 processors, then 16 fires will be run at once. With 16 processors, choosing two cores/threads per fire will result in eight fires running at once. MTT simulations is parallelized only if you have one fire, though the processing is not perfectly scalable, it shows good scaling from two to four cores/threads per fire if the fire is large. Simulations were conducted with one thread per fire on a 32-core machine (Four Intel Xeon CPU E5-4640 with 32 cores and 64 threads, 128 GB RAM, model PowerEdge R820, DELL Inc.), located at the Oregon State University, College of Agricultural Sciences, Biological and Ecological Engineering, USA.

The necessary inputs for Randig are the landscape file, a fuel moisture file (FMS), a custom fuel model file (if any used), the weather scenario file (contains information about one or more weather scenarios; *i.e.* FMS, wind speed and direction, fire duration, spot probability and probability of selection for each scenario) and the ignition probability grid (if defined). Furthermore, users must provide the number of scenarios involved in each fire, resolution, number of ignitions, number of threads for each fire, output file, units, crown fire calculation method and usage of WindNinja (Forthofer 2007), as arguments in Randig executable file.

Results of Randig are a burn probability grid, fire perimeters shapefile, flame length probabilities (text file and binary grid) and fire list (text file with coordinates and area in ha of each fire). Burn probability is defined as (1):

$$BP = F/n \qquad (1)$$

where, F is the number of times a pixel burns and n is the number of simulated fires.

The BP for a given pixel is an estimate of the likelihood that a pixel will burn given a random ignition within the study area and burn conditions similar to the historic fires (Ager *et al.* 2012). Flame length probabilities are calculated in 20 classes (0.5 m interval) or six classes (2 ft internal). The fireline intensity (FI – kW/m) for a given fuel type and moisture condition can be calculated from the fire spread rate normal to the front (Byram 1959; Catchpole *et al.* 1982), and then it is converted to flame length (FL – m) based on Byram's (1959) equation (2):

$$FL = 0.0775\,(FI)^{0.46} \qquad (2)$$

Conditional flame length is the probability weighted flame length given a fire occurs and acts as a measure of wildfire hazard (Ager *et al.* 2010), while it is calculated by incorporating the flame length distribution generated from multiple fires burning each pixel in equation (3):

$$CFL = \sum_{i=1}^{20} \left(\frac{BP_i}{BP} \right) (Fi) \qquad (3)$$

where, BP is Burn Probability and F_i is the flame length midpoint of the ith category.

Wildfire transmission among land designations was measured by a source–sink ratio (*SSR*) of wildfire calculated as the ratio of fire size (*FS*) generated by an ignition to burn probability (4):

$$SSR = \log\left(\frac{FS}{BP} \right) \qquad (4)$$

The SSR ratio measures a pixel's wildfire contribution to the surrounding landscape (in terms of the fire size it produces) relative to the frequency with which it is burned by fires that originated elsewhere or were ignited on the pixel (expressed by the burn probability). In relative terms, pixels that have a high burn probability but do not generate large fires from an ignition are wildfire sinks, and those that generate large fires when an ignition occurs and have low burn probability are wildfire sources (Ager 2012). By using the Randig output text file with information about fire size of the simulated fires, we analyzed their spatial variation by calculating a density surface with the Inverse Distance Weighting (IDW) method (smoothed with 12 neighbors).

Ignition probability grid

The current Randig version cannot use an ignition point file. The only way to influence the position of the ignition is by providing an ignition density grid made either with Kernel Density Smoothing (KDS) or IDW. There is some subjectivity as to how smooth it should be. Typically, it is made quite smooth over broad areas rather than highly detailed. The KDS is very useful for using the information and can produce a variety of density surfaces from the data.

Ignition probability grids for the two study areas were created with historic ignitions points, based on the actual fire size they produced (Koutsias *et al.* 2004). In particular, fire sizes where categorized in a scale from 1 to 11, where 1 was assigned to fire sizes less than 1 ha, 2 from 1 to <10 ha, 3 from 10 to <100 ha, 5 from 100 to <500 ha, 7 from 500 to <1,000 ha, 9 from 1,000 to <2,000 ha and 11 for fire sizes greater than 2,000 ha. These values served as weighting parameter in the KDS method. A bandwidth (search radius) of 4 km for Lesvos Island (Figure 5) and 7 km for Messenia (Figure 6) was assigned; and these values were selected to ensure that only minor parts of each study area will fail to receive a density value and to avoid over-smoothing.

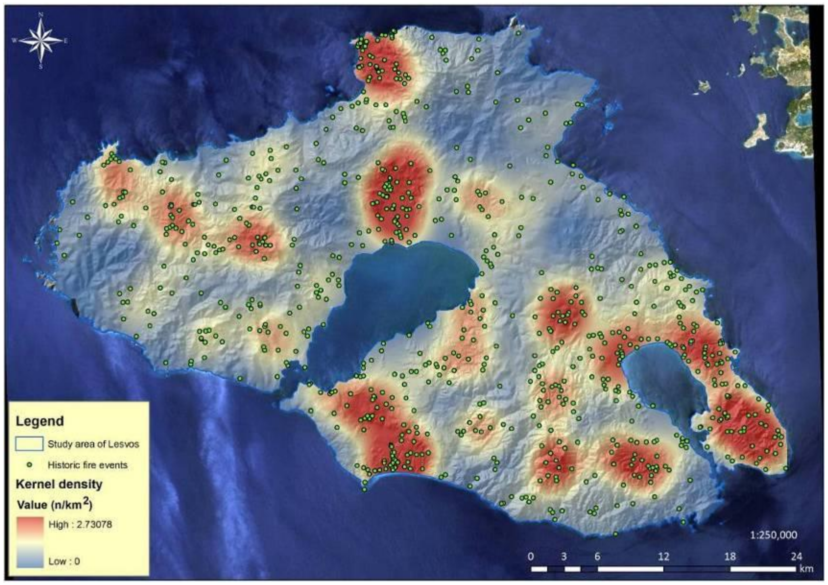


Figure 5: Ignition density map of Lesvos Island

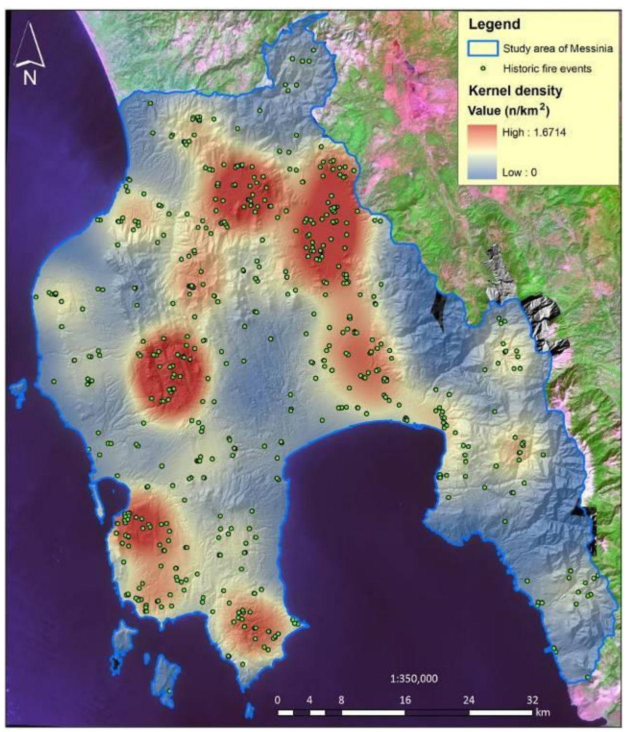
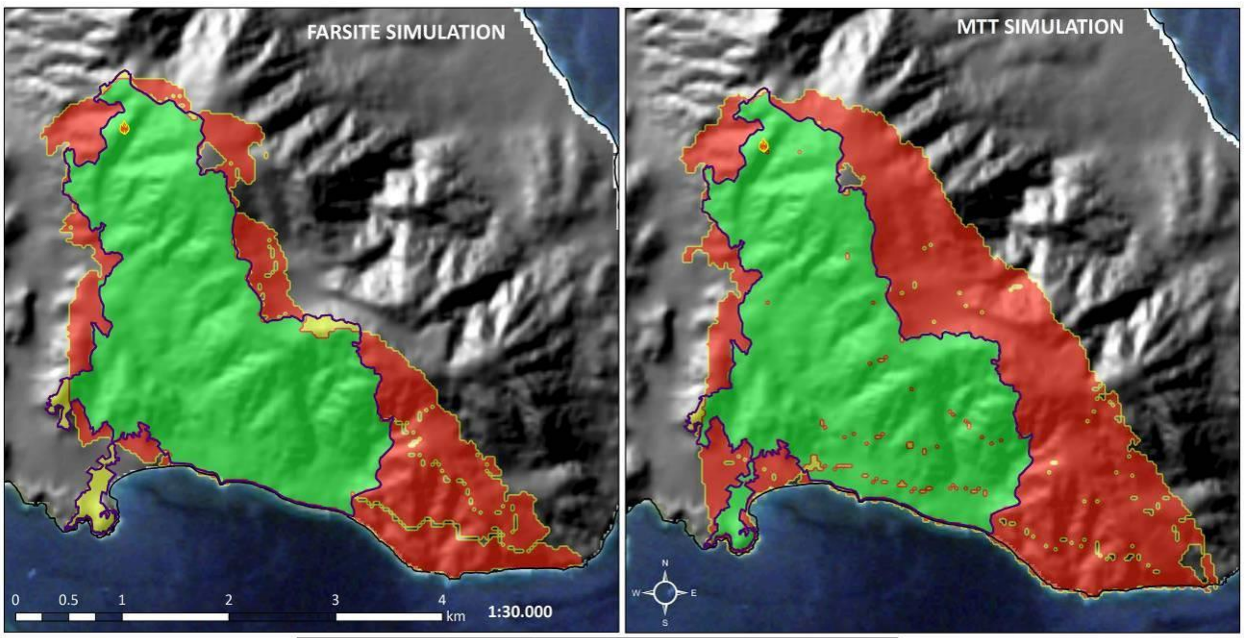
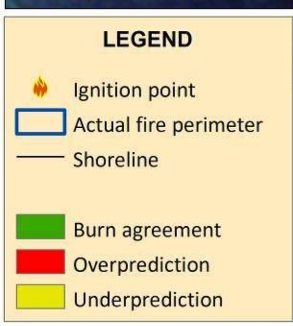


Figure 6: Ignition density map of Messenia

Data critique and model calibration

To test the modeling accuracy, two recent fire events, one on each study area were simulated, both on FARSITE and FlamMap. Prediction and modeling accuracy was assessed by calculating statistics and measures of similarity such as Sørensen coefficient (SC) (Greig-Smith 1983), Cohen's kappa coefficient (kappa) (Cohen 1960), Jacard's similarity coefficient (JC) (Jaccard 1901) and Coefficient of Areal Association (CAA), which includes the similarity of both burned and unburned regions, and ranges from 0.0 to 1.0 in the same way as Jacard's coefficient. For FARSITE simulations, hourly wind speed and direction data were retrieved from nearby Remote Automated Weather Stations (RAWS), while for FlamMap wind direction and speed were kept constant for the entire simulation. No suppression activities were modeled, even though they were intense and with large firefighting forces.





	SC	KAPPA	JC	CAA
MTT	0.67	0.49	0.50	0.74
FARSITE	0.77	0.65	0.62	0.85

Area	Lesvos - E. Greece
Start Date	*19/7/2006*
Start Time	*23:00*
End Date	*20/7/2006*
Total Control	*20:00*
Avg. Wind Speed (bf)	*5-6*
Dominant Dir (°)	*N and NW*
Burned Area (ha)	700

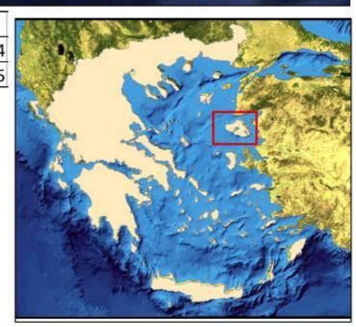
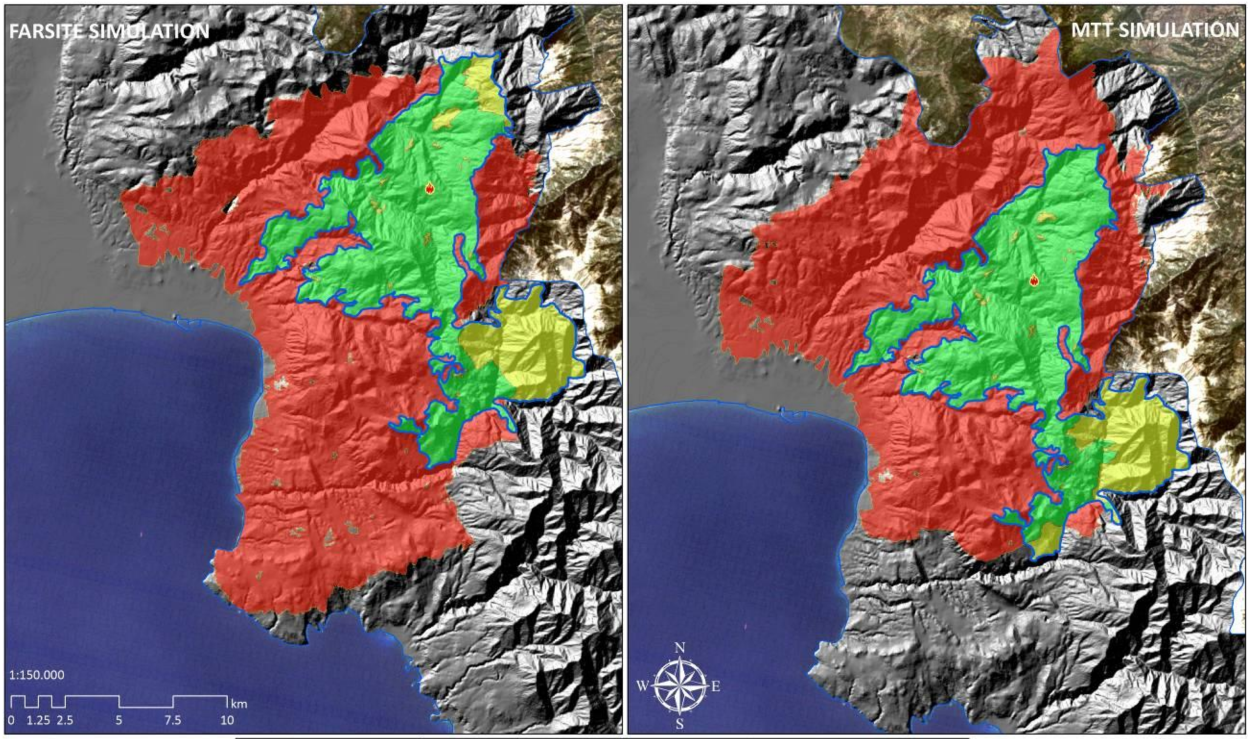


Figure 7: Lesvos fire simulation results and statistics

In Lesvos Island, the fire started on 19/7/2006 and its duration was about 20 hours, burning under average wind speed on 5-6 BF from N and NW directions, resulting in 700 ha of burned forests (Figure 7). Results revealed that FARSITE simulation statistics were slightly better compared to the FlamMap ones for all indices, but their difference was small (about 0.1). Serious over-prediction was noted on the E (flanks) and S (head) parts of the fire.



	SC	KAPPA	JC	CAA
MTT	0.43	0.28	0.27	0.71
FARSITE	0.41	0.26	0.26	0.70

Start Date	23/8/2007
Start Time	14:00
End Date	26/8/2007
Total Control	14:00

Avg. Wind Speed (bf)	6-7
Dominant Dir (°)	N and NNE
Burned Area (ha)	10500

Figure 8: Messenia fire simulation results and statistics

The fire of Messenia was a large-scale fire event occurred during the 2007 extreme fire season. During this summer, several simultaneous fires occurred throughout the region, several of them spread inside Messenia from nearby regions. The simulated fire lasted for three days and resulted in 10,500 ha of burned area, spreading from NE to SW, with an enclave on the SE, probably ignited from spotting (Figure 8). Both simulations seriously over-predicted fire spread on the fire front (SW and S) and on the flanks (N and NW), while under-prediction was noticed on the enclave. Accuracy of simulations was moderate for all statistical measures of similarity.

Vegetation and fuel data

For Lesvos Island, the geospatial datasets regarding canopy characteristics (Cover, Canopy Base Height - CBH, Canopy Bulk Density - CBD and Tree Height) were created by field inventories, remote sensing techniques, geo-statistics and Geographic Information Systems (GIS) (Palaiologou *et al.* 2013). A combination of custom and standard fuel models was used. Four standard fuel models (Scott and Burgan 2005) were assigned; *i.e.* GR1 on agricultural areas, GS1 on oak dominated lands, GS2 on olive groves and TL2 on broadleaf forests. Eight custom fuel models were used, four of them from the research of Dimitrakopoulos and Panov (2002) defining eight new Mediterranean fuel models that can be applied on Greece, and the rest four were created from field sampling conducted inside Lesvos pine forests (see Palaiologou *et al.* 2013 for sampling methods). The characteristics of the eight custom fuel models used are presented on Table 1.

Table 1: Parameters of the custom fuel models used in Lesvos simulations

FUEL MODEL	Fuel Model Code	1 - h Fuel Load (tons/acre)	10 - h Fuel Load (tons/acre)	100 - h Fuel Load (tons/acre)	Live Herbaceous (tons/acre)	Live Woody (tons/acre)	Fuel Depth (ft)	Dead Fuel Moisture of Extinction	1-h SA/V (1/ft)	SA/V Lh (1/ft)	SA/V Lw (1/ft)
XO01	205	1.76	0.19	0	0.3	0	0.98	14	2000	1800	1500
AS01	206	1.41	0.41	0.12	0.36	0	1.31	14	2000	1800	1800
SC01	208	2.99	2.75	1.45	0	3.11	3.67	14	750	1800	1600
SC02	209	5.86	5.38	3.43	0	4.28	7.15	14	750	1800	1600
FM01	210	3.53	1.27	1.47	0.03	5.08	1.97	15	750	1800	1600
FM02	211	3.43	1.45	0.73	0.04	1.32	0.82	25	1500	1800	750
FM03	212	3.05	1.09	0.98	0.04	0.88	0.52	35	1800	1800	1600
FM04	213	1.12	1.00	0.49	0.06	0.79	0.49	20	2000	1800	1600

In Table 1, fuel models 205-209 (Dimitrakopoulos and Panov 2002) are referred to Mediterranean grasslands (205), phrygana (S*arcopoterium spinosum*) (206), Evergeen-sclerophyllous shrublands (maquis) with a height up to 1.5 m (208) and from 1.5 to 3 m (209). Fuel models 210-213 are generally referred to Mediterranean pine forests (Palaiologou *et al.* 2013):

- with maquis dominating understory (>20% cover) and an average height of over 1.5 m (*Pistacia lentiscus, Quercus coccifera, Arbutus unedo, Phillyrea media*), mixed with litter from *Pinus brutia* (210);
- with a mixture of brush and short phrygana dominating understory (>20% cover) and an average height lower than 1.5 m (*Erica malipuliflora, Sarcopterium spinosum, Cistus creticus, Cistus savofolius, Genista acanthoclada, Juniperus oxycedrus*), mixed with litter from *Pinus brutia* (211);
- with litter and other downed dead fuels dominating understory (>70% cover), mixed with short brush (<30% cover) (212); and
- grazed, burned, or managed (timber or resin collection) with enclaves of regeneration where the general fire carrier is low loading of canopy litter mixed with annuals, short brush, seedlings and saplings (213).

For Messenia, one fuel model was assigned to every vegetation type, regardless of the appearance area (elevation, slope, aspect, distance from sea and human influences). The selected fuel model types came from the same references as we did for Lesvos Island, but there were notable differences between the two areas for the same vegetation types (Table 2). For example, oak dominated lands in Lesvos are sparse with phrygana on the understory with little litter, while in Messenia they are dense and the primary fire carry agent is low load of grass and shrub with litter. Another example is the olive trees, which in Messenia are cultivated mostly in flat areas, with low tree height and cleaned understory, while in Lesvos most are located in terraced elevated sites with grass and shrub understory.

Table 2: Vegetation types, fuel models and fuel moistures used for Messenia simulations

Vegetation type	Fuel model	1-h fuel moisture	10-h fuel moisture	100-h fuel moisture	Live herbaceous	Live woody
Oak forest	TU1	4	5	6	40	70
Sparse oak forest	SH4	4	5	6	40	70
Mixed oak with Quercus ilex	TL6	4	5	6	60	90
Fir forest	TU3	6	7	8	90	120
Pinus nigra	FM03	4	5	6	60	90
Pinus halepensis	FM02	4	5	6	60	90
Broadleaf forest	TL9	4	5	6	60	90
Mixed forest	TU5	4	5	6	60	90
Shrubs	SC02	4	5	6	60	90
Sparse shrubs	SC01	4	5	6	60	90
Mixed forests and shrubs	SH5	4	5	6	60	90
Plane trees and chestnuts	TL2	6	7	8	60	90
Pine reforestation	SH6	3	4	5	40	70
Brush and grass (phrygana)	AS01	5	6	7	60	90
Olive groves and WUI	GR2	3	4	5	40	70
Abandoned and reforestated agricultural areas	GS2	4	5	6	40	70
Agricultural areas	GS1	3	4	5	30	60
Orchards and vineyards	GR1	4	5	6	40	70
Non-burnable areas	NB9	n/a	n/a	n/a	n/a	n/a

Weather inputs

Weather scenarios were created by using data from several RAWS located across the two study areas. In Lesvos Island, a network of four RAWS is recording data from 2003 (Palaiologou *et al.* 2011). In contrast to FARSITE, the MTT algorithm assumes constant weather and is used to model individual burn periods within a wildfire rather than continuous spread of a wildfire over many days and weather scenarios. For each year, the 98th percentile wind speed value was calculated for the high fire risk season (May to September). For the same period, wind rosegrams were created to portray the dominant directions and prevailing wind speeds (Figure 9). It is clear that there are two wind direction trends on the island, one with NE and NNE winds, and another with NW and NNW winds, while frequent winds appear also from N. Based on these facts, five scenarios were created, each with a fire period of 5 hours which is the common average duration, and 0.1 spot probability (Table 3).

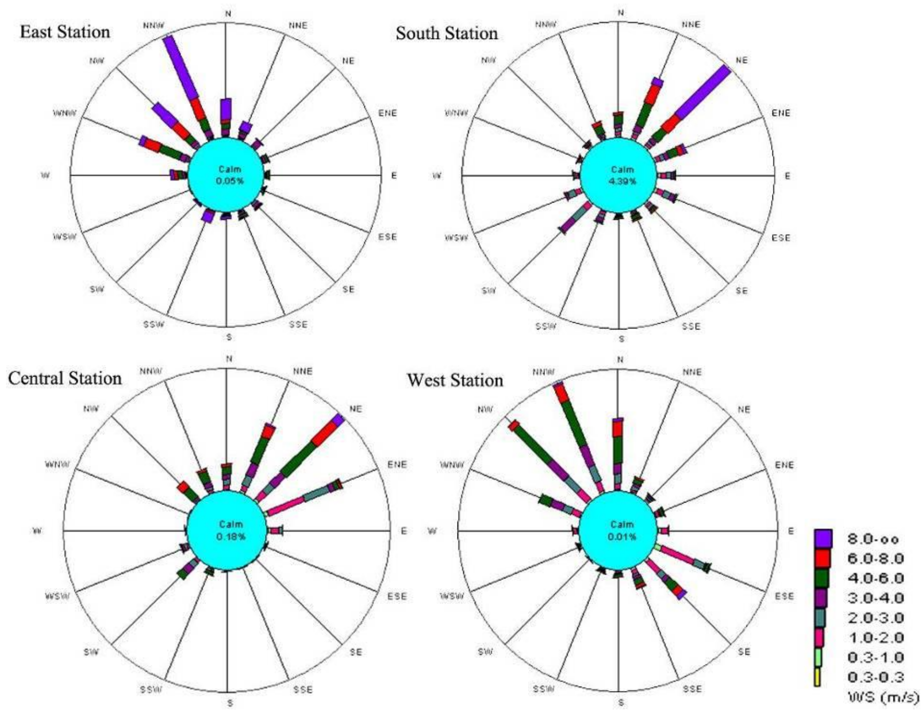


Figure 9: Wind roses of the four RAWS of Lesvos Island

Table 3: Parameters and weather scenarios for Lesvos Island simulations

Scenario number	Wind Speed	Direction	Duration	Spot Probability	Probability
1	27	330	300	0.1	0.20
2	31	45	300	0.1	0.25
3	16	40	300	0.1	0.20
4	14	315	300	0.1	0.15
5	24	10	300	0.1	0.20

Fuel moisture values were also retrieved by calculating average values per month for the 10-year working period of RAWS (sensor CS506 Campbell Scientific). The vast majority of serious fire events appear during July and August, and there are three trends for 1-h, 10-h and 100-h fuel moisture values. The high altitude parts of the island have low dead fuel moisture with 2/3 cured herb and low live woody moisture values (*i.e.* 5%, 6%, 7%, 60%, 90%), the lower elevated dry parts have very low dead fuel moisture with 2/3 cured herb and low live woody moisture values (*i.e.* 4%, 5%, 6%, 60%, 90%) and the very dry west parts with extremely low dead fuel moisture with fully cured herb and very low live woody moisture values (*i.e.* 3%, 4%, 5%, 30%, 60%). Based on these trends, a fuel model specific moisture file was created with adaptations made by considering canopy cover and tree density, altitude, actual rate of spread and understory vegetation (Table 4).

Table 4: Vegetation types, fuel models and fuel moistures used for Lesvos Island simulations

Fuel model	Vegetation type	1-h fuel moisture	10-h fuel moisture	100-h fuel moisture	Live herbaceous	Live woody
101	Agricultural areas	3	4	5	30	60
121	Oak	3	4	5	60	90
122	Olives	4	5	6	60	90
182	Broadleaf trees	6	7	8	60	90
205	Mediterranean grasslands	6	7	8	90	120
206	Phrygana	6	7	8	90	120
208	Shrublands < 1.5 m	5	6	7	60	90
209	Shrublands > 1.5 m	5	6	7	60	90
210	Pines with shrubs > 1.5 m	5	6	7	60	90
211	Pines with shrubs < 1.5 m	5	6	7	60	90
212	Pines with short brush	4	5	6	30	60
213	Pines cleared undestory	4	5	6	30	60

For Messenia, weather inputs were retrieved from four RAWS, of different types and available data range. The oldest station is located on the W very close to the sea (11 m a.s.l.), recording data from more than 50 years. Records revealed that weak winds frequency (<2 BF) is about 30% during the year, while moderate winds (3-5 BF) frequency is about 58%, with 65% during July and August. Strong winds (6-8 BF) have a frequency of 8% during the winter and 3% during the summer. Regarding wind direction, W winds are the strongest compared to other directions and have an appearance frequency of 30% annually, but exceed 50% during the summer months. Northern winds have also high frequency during the summer (about 10%), while E winds appear for less than 10% and NW winds for about 20% frequency. Another station on the SE is recording data for two years on Mt. Taigetos (1,310 m a.s.l.), with frequent winds from NE and ENE and average wind speeds of 6-7 BF during windy days. The third station is located inland on the N part of Messenia (509 m a.s.l.), recording data for two years. Records revealed that wind speeds during the summer are moderate (4-5 BF) mainly from SSW and with lower frequency from NE directions. The fourth station is located on the NE mountainous part of Messenia (723 m a.s.l.), recording data for two years with winds coming mainly from SE with moderate winds (5-6 BF) during windy days. Six scenarios were created by considering the above results (Table 5).

Table 5: Parameters and weather scenarios for Messenia simulations

Scenario number	Wind Speed	Direction	Duration	Spot Probability	Probability
1	15	10	300	0.1	0.13
2	24	300	300	0.1	0.15
3	27	330	300	0.1	0.24
4	22	210	300	0.1	0.12
5	30	55	300	0.1	0.24
6	24	135	300	0.1	0.12

Results

Randig results revealed several places with high burn probability around study areas. For Lesvos, high BP is noticed on the SE, NW, W and S parts of the island, mainly covered by evergreen shrublands and phrygana (Figure 10). The main pine forest complex (central part) has only a few sites with high values, while the pine forest of the SE, which is also a WUI area has very high values. Compared to random ignitions results, the pattern is the same with only more extended areas with high values on the west (Figure 10b). There are also some small parts which had few ignitions due to low or zero kernel values (e.g. small islands and islets), creating data gaps in the results (Figure 10a).

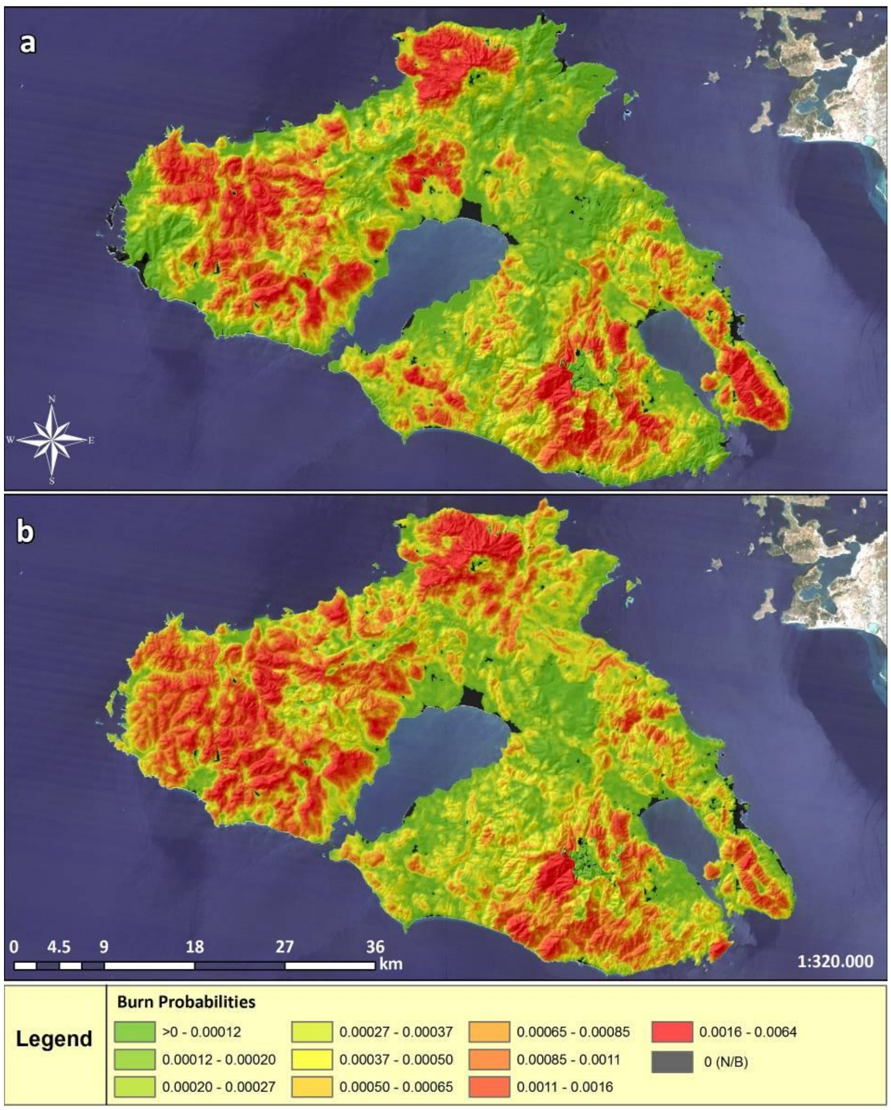


Figure 10: Burn probabilities for historic ignitions (a) and random ignitions (b) in Lesvos Island

The average fire size of historic ignitions is 108 ha, with minimum and maximum size of 1.44 and 917 ha, while percentiles (of 25, 50 and 75) have fire sizes of 45, 82 and 117 ha, respectively; results that are in agreement with the recorded fire sizes. Conditional flame length values are high only in places with evergreen shrublands (>2.5 m), while pine forests have moderate values (1-2 m) and the rest of the island has low values (up to 1.5 m) (Figure 11). Several parts of the island create fires with large size, especially on the west and north. Points with large values in the source sink ratio map had ignitions that generated large fires relative to the probability of being burned by other pixels (burn probability). Conversely, pixels with small values generated small fires relative to the probability of being burned by a fire originating elsewhere (Ager 2012).

Patch variation within land designations is described by scatter plots of average patch values for simulation outputs. Scatter plots helped in locating which of these features are in greater fire risk. For Lesvos, scatter plot in Figure 12 shows which vegetation types have the potential of frequent and large fires. Evergreen shrublands has both high burn probabilities and conditional flame length, followed by sparse *Pinus brutia* forests, while the lowest values are found on agricultural areas and chestnut trees. For the creation of the other scatter plots, buffer zones were defined around each feature. In particular, scatter plot in Figure 13a shows fire risk for monuments and sites of important historic value, calculated within a 300 m buffer zone. All of the sites have a small fire hazard, with CFL less than 1 m and only four sites have burn probabilities greater than 0.001. In Figure 13b, houses outside urban areas have been buffered with a 50 m zone, the majority of which have low CFL (<1 m), but several sites were identified to have high hazard (BP >0.001 and CFL >1.5 m). In Figure 13c, touristic sites such as beaches and hotels have a buffer zone of 300 m around them, and only five sites were identified with high hazard. Finally, the important nesting places of bird populations in the island are showed in Figure 13d scatter plot (*Sitta krueperi* and raptors: *Buteo buteo, Circaetus gallicus and Accipiter gentilis*). Several nests where identified of having high fire hazard, especially for *Sitta krueperi*, while raptors reside in more safe areas.

For Messenia, kernel based BP (Figure 14) have higher values compared to random based BP, especially in the areas of N and central parts. High BP can be noticed on the S and SW edge on chaparral sites, places that have important tourist activities. On central and N, vegetation types are mostly abandoned and reforestated old agricultural areas dominated by a mixture of grass, phrygana, evergreen shrublands and olive and oak trees. Also, high BP values can be seen on the SE part on the leeside of Mt. Taigetos, where dense forests exist (fir and pine trees). The average fire size of historic ignitions is 206 ha, with minimum and maximum size of 1.44 and 1,640 ha, while percentiles (of 25, 50 and 75) have fire sizes of 66, 120 and 300 ha, respectively. Fire sizes are larger compared to Lesvos Island results, similar to the real fire pattern.

There are several extensive areas with CFL values greater than 2 m, but the majority of the study area has values less than 1 m in Messenia (Figure 15). The parts that produce the largest fire events are mostly located centrally and on the SW and N. The source sink ratio reveals that big fires are originated mostly on the SE and in several parts of the west coast where strong western winds prevail. From the scatter plot of vegetation types (Figure 16) it is evident that the higher hazard is produced on shrublands, mixed forest with shrublands and *Pinus halepensis* forests (sparse and dense). High BPs are produced on oak forests and grasslands. Orchards and vineyards have very low hazard and the rest vegetation types have CFL values less than 1.5 m.

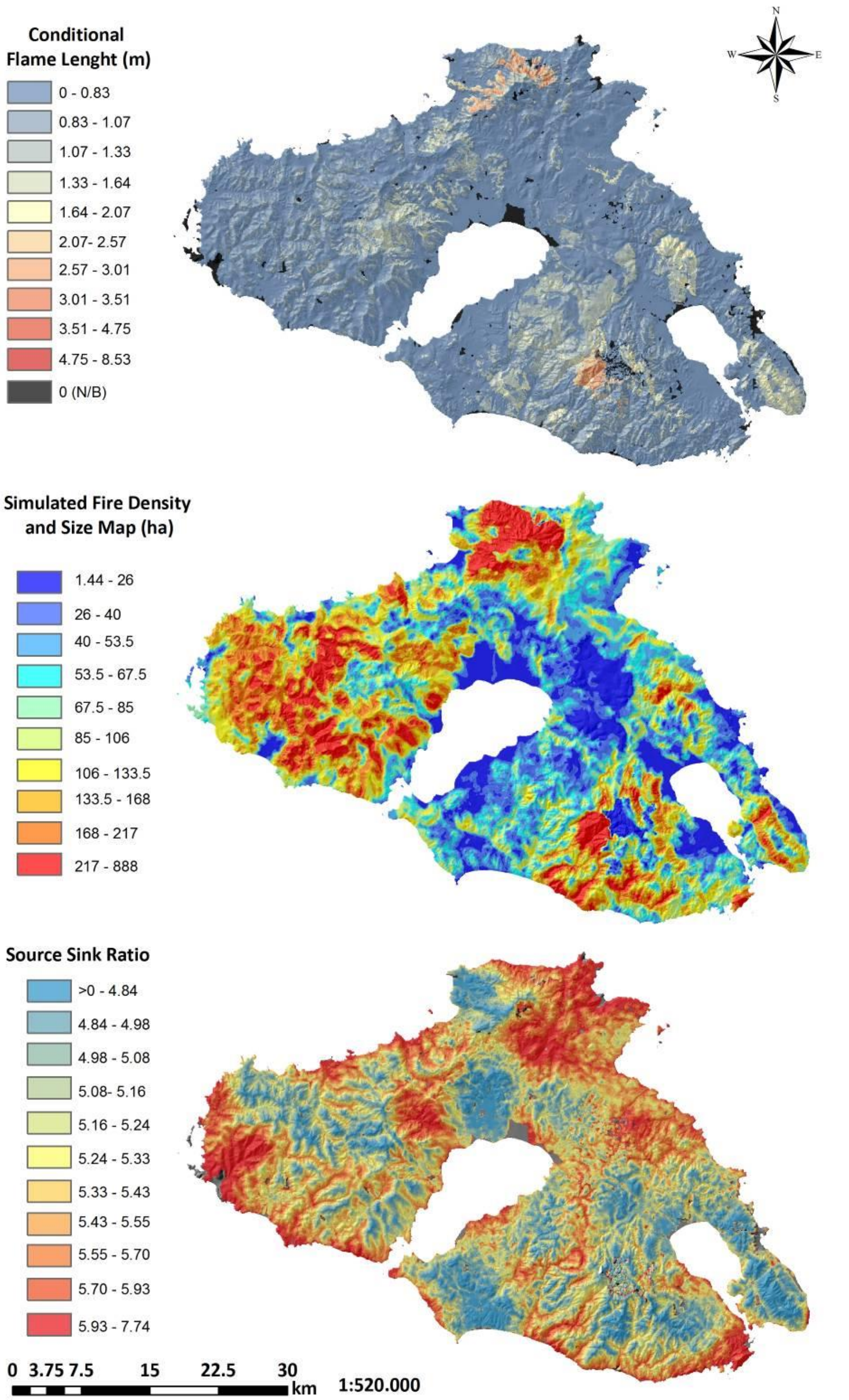


Figure 11: Conditional flame length, fire density and source sink ratio maps of Lesvos Island

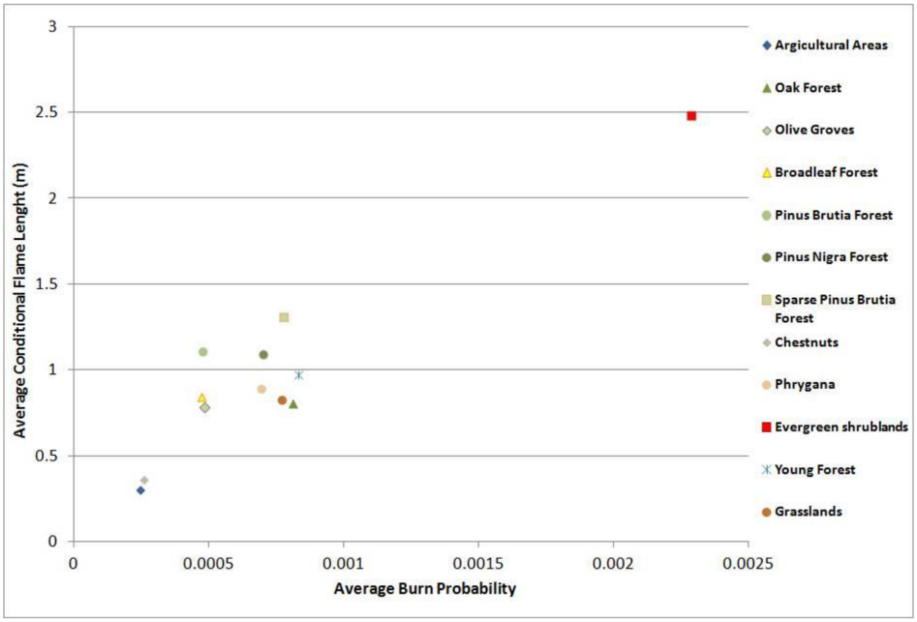


Figure 12: Fire risk for each vegetation type of Lesvos Island

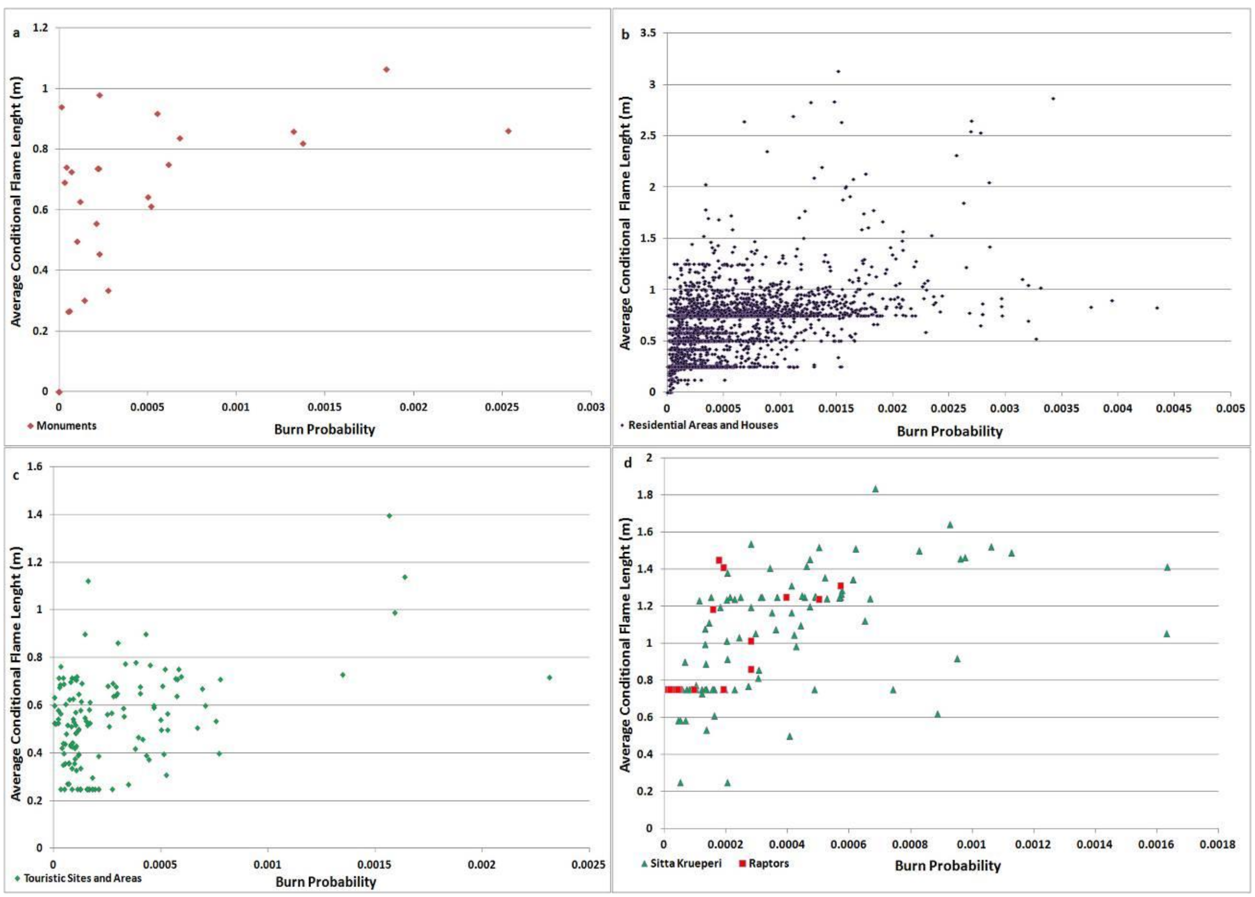


Figure 13: Fire risk for monuments (a), houses in WUI areas (b), touristic sites and places (c) and important bird nesting sites (d) of Lesvos Island

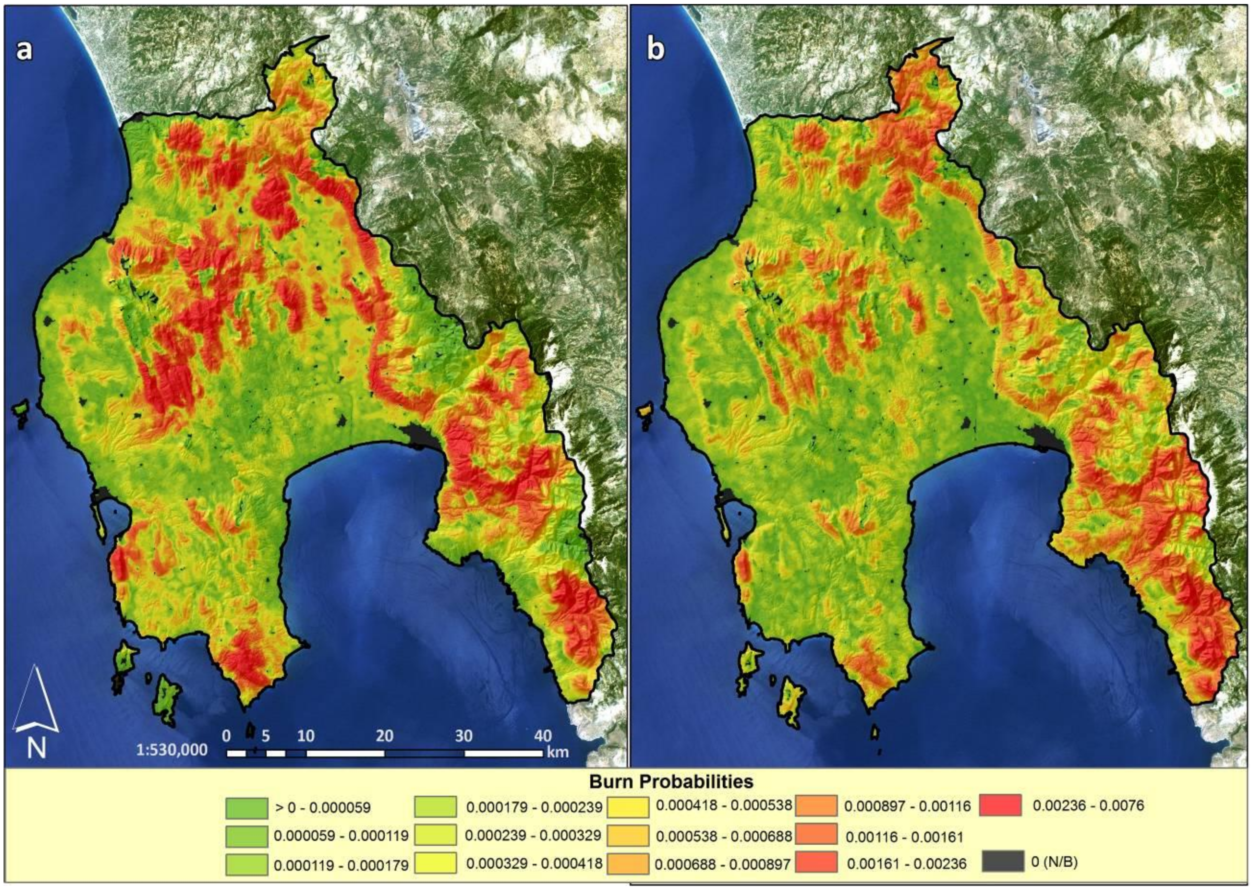


Figure 14: Burn probabilities for historic ignitions (a) and random ignitions (b) in Messenia

Fire hazard in Messenia for monuments was calculated on a buffer zone of 300 m around monasteries and 100 m around archaeological sites (Figure 17a). In contrast to Lesvos monuments, fire hazard is high for several sites, having high BP and CFL values (>0.002 and >2 m, respectively). The majority of WUI areas (Figure 17b) exhibit low fire hazard expect for 30 sites. Regarding touristic places (Figure 17c), only very few sites have high fire hazard. Finally, the vast majority of wildlife habitats (Figure 17d) have moderate to low fire hazard in Messenia.

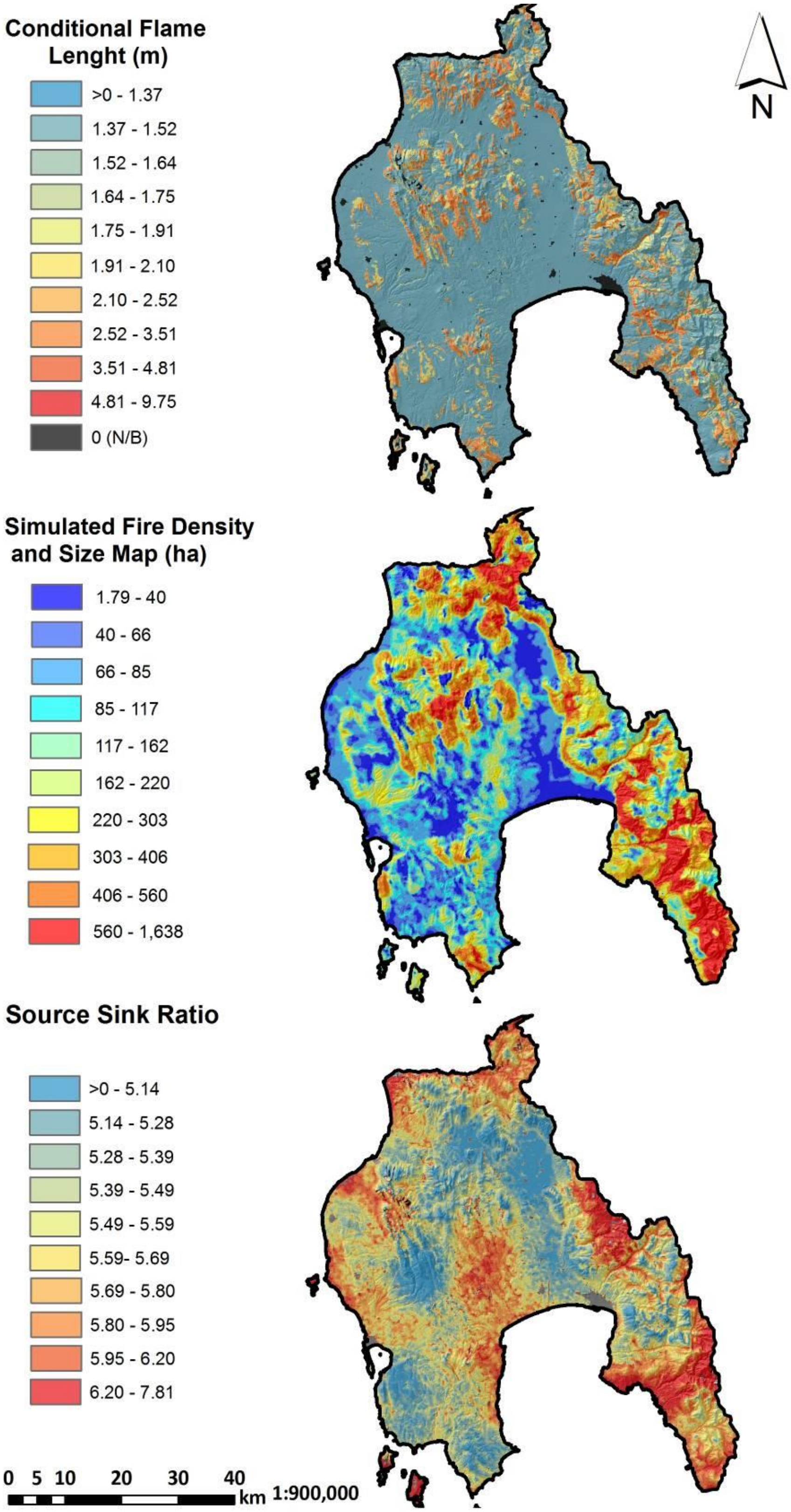


Figure 15: Conditional flame length, fire density and source sink ratio maps of Messenia

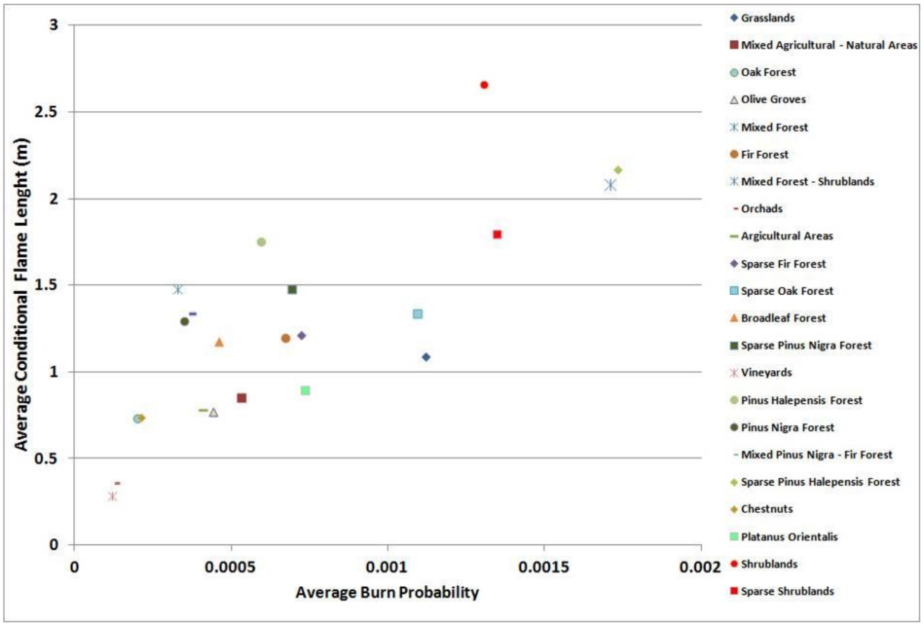


Figure 16: Fire risk for each vegetation type of Messenia

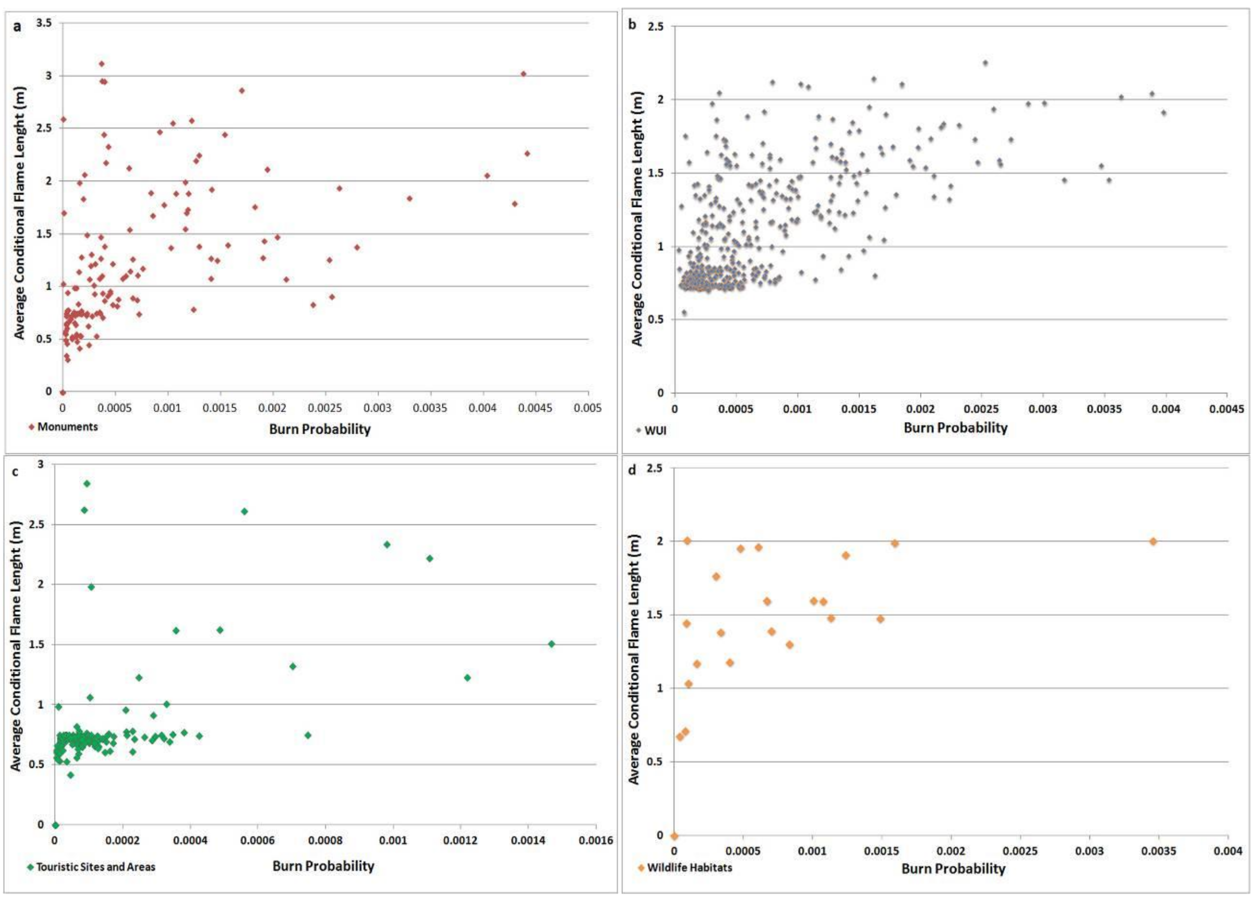


Figure 17: Fire risk for monuments (a), WUI areas (b), touristic sites and places (c) and wildlife habitats (d) of Messenia

Conclusions

The calculation of fire hazard through thousands of fire simulations with Randig revealed an underlying pattern of the phenomenon for two study areas in Greece. The most hazardous parts of Lesvos Island are located in the west in terms of burn probabilities and fire size, while the most intense fire events can be produced in the N and S. For Messenia, the SE part has the highest BP, followed by the N, central and SW areas, with high fire intensities in several places and substantially increased compared to Lesvos Island. Different ignitions patterns revealed that there are no substantial differences of whether the simulation is conducted with historic or random ignition, except for the exclusion of some areas that had low kernel values and had only few ignitions; while CFL values were identical with minor differences. This suggests that burn probability patterns are largely created by fire growth under combinations of weather and fuel patterns rather than ignition sources.

Regarding simulation of historic fire events, FARSITE achieved better fire prediction results but MTT results were not much different. The simplicity of inputs to MTT compared to FARSITE means that it is efficient for risk analysis involving thousands of simulations. For Messenia, fire prediction accuracy is moderate, but for Lesvos is high. Wind speed and direction inputs played an extremely important role in the prediction accuracy, dependant on weather station type and specifications (e.g. wind measurement height, instrument accuracy, data recording intervals etc.), location / elevation (exposure of installation area, terrain ruggedness, presence of wind obstacles etc.) and proximity to the fire, wind direction input method (e.g. uphill, gridded, user defined) and wind speed data type (e.g. time interval, gusts, averages). Errors may also be introduced from possible insufficient fuel model assignment and coarse-scale canopy characteristics layers, especially for the case study of Messenia. Simulations revealed key factors that should be altered before conducting simulations with Randig. It proved extremely important to have fuel model specific fuel moisture values instead of similar values, based on weather station measurements close to certain vegetation types. Adjustments were also made based on the knowledge gained from observations of the actual fire behavior on each vegetation type. Another adjustment was made on the geographic data used to define the fire environment (landscape file). Messenia is not an island like Lesvos that has boundaries defined by shoreline, but an intact land with adjacent regions that produce fires that can enter inside the study area (a usual and noticed event). As a result, we need to provide data from the adjacent regions to create a broader area that will enable fire to spread back and forth and then clip data to Messenia's borders. Simulations needed a very powerful machine to support them, otherwise the amount of time required to finish the simulations of 100,000 fires exceeded a four-day period on a regular four-core machine.

The use of scatter plots to identify fire hazard revealed several sites and values-at-risk that have the potential to be harmed by a future fire event. Maps or coordinates could be used to warn and inform both the owners (in case of hotels and houses) and the state (for the case of wildlife habitats) to take the necessary measures and precautions for protection. Finally, future research will implement further this method to study areas of Greece and will propose fuel treatment and fire risk reduction measures.

Acknowledgments

This research has been co-financed by the European Social Fund (ESF) and the Greek State within the National Strategic Reference Framework (NSRF) 2007-2013 (Actions' Beneficiary: General Secretariat for Research and Technology). Authors also want to express their gratitude to Dr. Alan Ager for his advice and help, and the Oregon State University, College of Agricultural Sciences, Biological and Ecological Engineering in USA for providing access to the necessary hardware recourses.

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Automatized creation of local fire danger scales

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Abstract:
The notion of fire danger is complex and rather nebulous because its values have no real measurement units. Numerous fire danger rating methods raise a question concerning their actual performance. Final assessments through fire danger classes turn out to be incomparable not only among regions, but even among periods of a fire season in one region.

This paper suggests a method of making comparable local fire danger scales. The method is based on optimal absolute criteria for daily fire danger rating, which is a probable density of active fires (fires / million ha). An example of the suggested local scales of fire danger is made for the Slyudyanka forest office (Irkutsk oblast, Russia) and software for their automatized creation is being developed.

Additional Keywords: fire danger scales, optimal absolute criteria, Slyudyanka forest

Introduction

Fire danger is a general term, which assesses various factors of fire environment: topography, fuel, fire weather. One can distinguish several types of fire danger: typical seasonal, an equivalent of fire hazard; daily fire danger according to weather conditions, fire risk, i.e. the probability of ignition sources, and current fire hazard of given homogenous plots, i.e. whether they are ready to burn or not under current weather conditions if ignition sources appear (Table 1). This paper will focus on daily fire danger according to weather conditions.

Table 1. Types of fire danger

Types	Area	Period	Objective
Typical seasonal fire danger (climate & fuel ≈ fire hazard)	10^2-10^3 ha	10 years	planning of fire prevention
Daily fire danger (according to weather conditions; index)	10^4-10^6 ha	one day	fire detection
Fire risk (probability of ignition sources)	10^4-10^6 ha	10 years	fire detection and planning for fire prevention

Fuel flammability (current fire hazard)	1-10 ha	hours	fire behavior prediction

Fire danger rating was studied in Russia by I.S. Melekhov (1947), V.G. Nesterov (1949), N.P. Kurbatsky (1963), M.A. Sofronov (2005), etc. Of interest are those foreign fire danger rating systems with natural conditions similar to Russia (Finland, Norwegia, Sweden, and Germany) and with high fire occurrence (Portugal, Spain, France, etc.) (Viegas *et al.* 1999; Cheney 1991; Goldammer 1993). The national complex systems of fire danger rating in the US (Deeming *et al.* 1977) and Canada (Alexander *et al.* 1984) deserve special attention.

Almost every country has its own methods of fire danger rating. In 1990-s European countries attempted to integrate in this respect and to choose one most effective method for use. Performance test of various methods proved none of them to have the best overall performance (Viegas *et al.* 1999).

Fire danger implies a probability of fire occurrence which can inflict damages. However, all countries assess fire danger in relative or qualitative values (usually, in classes of fire danger). These values are not linked to any specific quantitative values to describe the fire situation which corresponds to the assessed fire danger. The irony is that with factors of fire danger measured quantitatively, the fire danger itself as a function has no quantitative expression. Thus, selection of an absolute criteria to reflect daily fire danger and to measure the day after realization of fire danger is of high importance for improvent of daily fire danger rating. Forward-looking is to automatize the creation of local fire danger scales with comparable classes of fire danger.

Methods

To unify the assessment of daily fire danger on a regional level we suggest that a simple measurement unit of fire danger should include the following mentioned above measurable notions of weather, fires and area. Then the measurement unit of daily fire danger would be the correspondence of fire danger classes according to weather conditions to the daily number of active fires per million ha.

Based on long-term data obtained from different regions of Russia it was found out that maximum number of registered active fires per million ha was 50. This number was then turned into a 5 class scale where the maximum number of active fires increases 4 times the higher the fire danger class is: 1st fire danger class – up to 0.2; 2nd class – 0.2-0.8; 3rd class – 0.8-3.2; 4th class – 3.2-12.8; and 5th class – over 12.8 *fires / million ha a day*.

If we use this easily measurable scale then we will know what to expect from each fire danger class and will be able to improve fire detection and will be able to compare fire situations between regions and between different periods of a fire season in one region.

The input data which are needed for making improved regional fire danger scales are: daily fire weather indices for 10 years; daily number of active fires for 10 years; region's area in million ha; and dates for periods of a fire season. The simplified algorithm of making such scales is shown in Table 2.

Table 2. Algorithm of making comparable local scales of daily fire danger

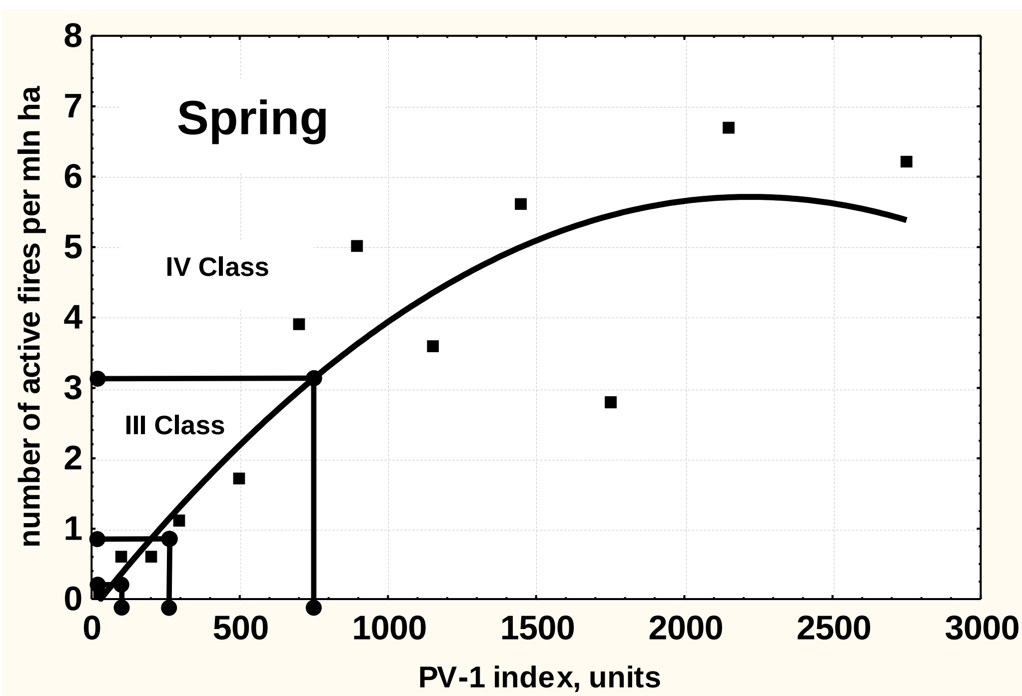
Input data and calculations	Example
1) Area, million ha	• 0,351
2) Period of a fire season	• Spring (April 15 – June 20)

3) Gradation of weather index	• 0-50; 51-100; 101-150; 151-200 …
4) Number of days for each gradation	• 52; 37; 38; 31…
5) Number of active fires (occurred plus lasting)	• 12; 5; 10; 13…
6) Mean number of daily fires: (5) / (4)	• 0.2; 0.1; 0.3; 0.4…
7) Mean density of daily fires per million ha: (6) / (1)	• 0.57; 0.28; 0.85; 1.14…
8) Correlation graph between (3) and (7)	• See Fig. 1

The final correlation graph is made between two rows of values: between gradation of weather index and mean density of daily active fires per million ha (Fig. 1). Using these graphs it is possible to find the correspondence between the comparable fire danger classes and the weather indices for each period of a fire season.

As you can see the tested research area of the Slyudyanka forest office (Irkutsk oblast, Russia) did not experience the 5th fire danger class during the last 10 years. However, this may happen under extreme drought. The 5th fire danger class can be assessed by prolonging the correlation graphs. Then the regional scales would have all 5 fire danger classes including one that only potentially can be observed in this very region.

To help automatize regional assessment of daily fire danger we developed a program for making improved regional fire danger scales and made a beta version of the software.



IV Class

III Class

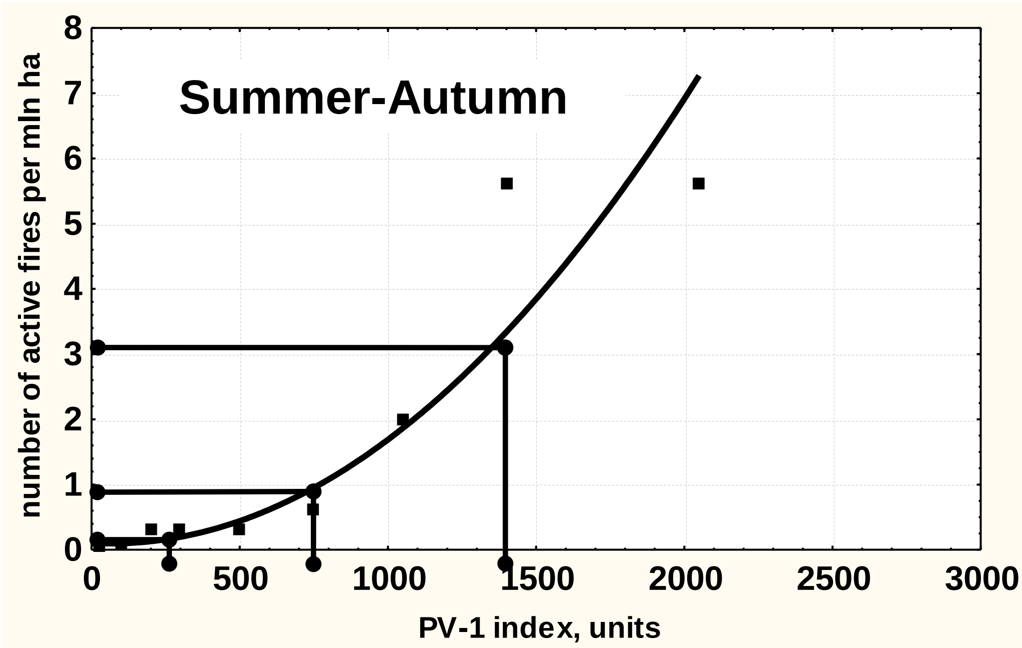


Fig. 1. Correlation between PV-1 fire weather index value and probable number of active fires per million ha in the Sludyanka forest office for making local scales according to an improved technique (Sofronova *et al.* 2006).

Conclusion

Forest and other wildfires are unevenly distributed in time and space. To effectively use the means of fire detection (air patrol) and concentrate them in the regions in danger of fire outbreaks, it is necessary to adequately assess and predict fire danger and monitor it over large areas.

Fire danger is determined not only by the level of drought but also depends upon the number of ignition sources, vegetation composition, phonological condition, etc. Therefore under similar drought there may be different levels of fire danger both in different regions and in one and the same region but in different periods of a fire season. For more accurate regulation of forest fire protection services and maneuvering of forest protection forces it is necessary to have local scales of daily fire danger rating with comparable fire danger classes.

As a result of the studies, we developed a technique and a beta version of software for making improved regional fire danger scales with comparable fire danger classes. Introduction of this elaboration into forest fire protection would considerably improve its effectiveness in fire detection and in planning of fire prevention.

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Extinguishing of flames by fine-dispersed powders

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Abstract:

Extinguishing of the premixed propane-air flame by means of inorganic salts and their mixtures is discussed and values of their flame-extinguishing ability are quantified. It is illustrated that flame extinguishing starts in the high-temperature zone of the flame and mainly occurs in the gas phase, the particles sized less than 20-30 μm being subject to decomposition when they pass the high-temperature zone. The effect of flame on the shape of the inhibitor powder particles has been established.

Additional Keywords: Fire extinguishing powders, inhibition, inorganic salts.

Introduction

Extinguishing powders are an effective means of fire extinguishing therefore powder fire extinguishers are often used to suppress ignition. Certain researchers (Rosser *et al.* 1963; Dewitte *et al*. 1964; Baratov *et al.* 1976; Bulewicz and Kucnerowicz-Polak 1987) have studied flame inhibition by the powder compounds. However obtained results do not reflect the true picture of the flame extinguishing as the latter is achieved not only by inhibition. Actual flame extinguishing by means of the powders is described in the papers presented by Birchall (1970) and Apanovich *et al*. (1990).

Despite quite numerous publications, the powder extinguishing mechanism is still insufficiently studied. This paper describes the effect of the powder inhibitors on the preliminarily mixed propane-air flame.

Experimental

Study of the premixed propane-air flame extinguishing by the powders has been carried out using a special purpose unit (Antsupov 2010). A burner is made of a molybdenum glass tube and has the following size: length - 400 mm, external diameter - 10 mm, and nozzle diameter - 8 mm. The burner is installed vertically with its nozzle directed downward. The top part of the burner contains an ejector through which the powder is fed to the flame zone either in a pulse mode or continuously. To improve fluidity of the powders and mixtures they are supplemented with AM-1-300 aerosyl.

[1] On October 11th, 2013, Evgeniy V. Antsupov passed away. His co-authors and colleagues, as well as the IAWF express condolences over the loss of a great specialist in combustion science. All of the modifications and corrections in this paper were made by his co-author Sergey M. Rodivilov.

The composition of the gas mixture has $\alpha = 0.87$ (an oxidizer excess factor). The volume of the luminescent flame cone is about 0.18 cm^3. Flame-extinguishing ability (FEA) of the powder depends on its concentration in this volume, the fire extinguishing concentration being measured both for individual salts and their mixtures. Obtained FEA values for certain individual salts are given in Table 1.

The nature of the mixture composition non-additivity has been identified based on expression (Antsupov *et al* 2000; Antsupov 2010) below:

$$1/m_0 = a_1/m_1 + a_2/m_2 + \ldots + a_n/m_n,$$

where m_0, m_1, m_n are extinguishing mixture masses of the first and n-th components of the mixture, correspondingly, and a_1, a_n are shares of the first and n-th components of the mixture, correspondingly, as well. Equality of both parts of this expression indicates additive action of the mixture components; prevalence of the left-hand part over the right-hand one indicates a synergistic effect whilst prevalence of the right-hand part over the left-hand one indicates an antagonistic effect.

Table 1. Extinguishing power of individual salts

Substances	FEA, mg cm^{-3}	Substances	FEA, mg cm^{-3}
$CaCO_3$	222	$LiOH \cdot H_2O$	28
$CuCl_2 \cdot 2H_2O$	44	MoO_3	100
$K_2C_2O_4 \cdot H_2O$	11	$Na_2B_4O_7 \cdot 5H_2O$	72
$K_2CO_3 \cdot H_2O$	28	$Na_2Cr_2O_7$	56
$K_2Cr_2O_7$	39	$Na_2Cr_2O_7 \cdot 2H_2O$	22
$KHCO_3$	28	$Na_2SO_4 \cdot 4H_2O$	89
KI	61	NaF	111
Li_2CO_3	133	$NaHCO_3$	56
$Li_2SO_4 \cdot H_2O$	72	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	56

Earlier it was supposed that inhibitors started acting in the preliminary flame zone and it was there that they affected the active centers. Our specialists have studied the process of the air-gas flames extinguishing by the powder inhibitors. Fig. 1 illustrates dynamics of the propane-air flame extinguishing by means of calcium hydrophosphate. It is apparent from Fig. 1 that flame extinguishing starts in the high-temperature zone. The first powder particles reach the top of the luminescent flame cone 0.04 seconds after the powder leaves the nozzle; this is the start of the decomposition process. A shining cloud of the decomposed powder rises up to the burner nozzle 0.20 seconds later. Within the next 0.28 seconds the luminescent cloud resulting from salt decomposition becomes smaller, separates from the burner nozzle, and the flame is extinguished. A similar picture is observed for other powder inhibitors.

Consequently, destruction of the active centers occurs after the start of the powder decomposition in the high-temperature zone. The number of active centers supporting the combustion chain reaction decreases when the formed gas cloud moving upstream towards the burner nozzle increases.. Hence one may assume that flame inhibition begins in the high temperature zone wherefrom the inhibitor starts being decomposed.

Combined compositions affect flame in different ways, i.e. either increasing fire-extinguishing power compared with individual components (synergism), decreasing it (antagonism), or causing additive summation of the extinguishing concentrations. Of highest practical value is the synergism effect. Data in Table 2 describe the flame-extinguishing ability of some combined compositions with the mass percentage of their components given in brackets.

When powders and their mixtures get to the high-temperature zone of the flame, they are exposed to the temperature effect followed by mixture melting, decomposition, and evaporation to the gas phase. They are heated almost up to 1300ºC. Thermal inhibitors that do not enter any reactions are aluminum and silicon oxides. Flame suppression that occurs during this process is due to a decrease in the flame temperature rather than a chemical reaction.

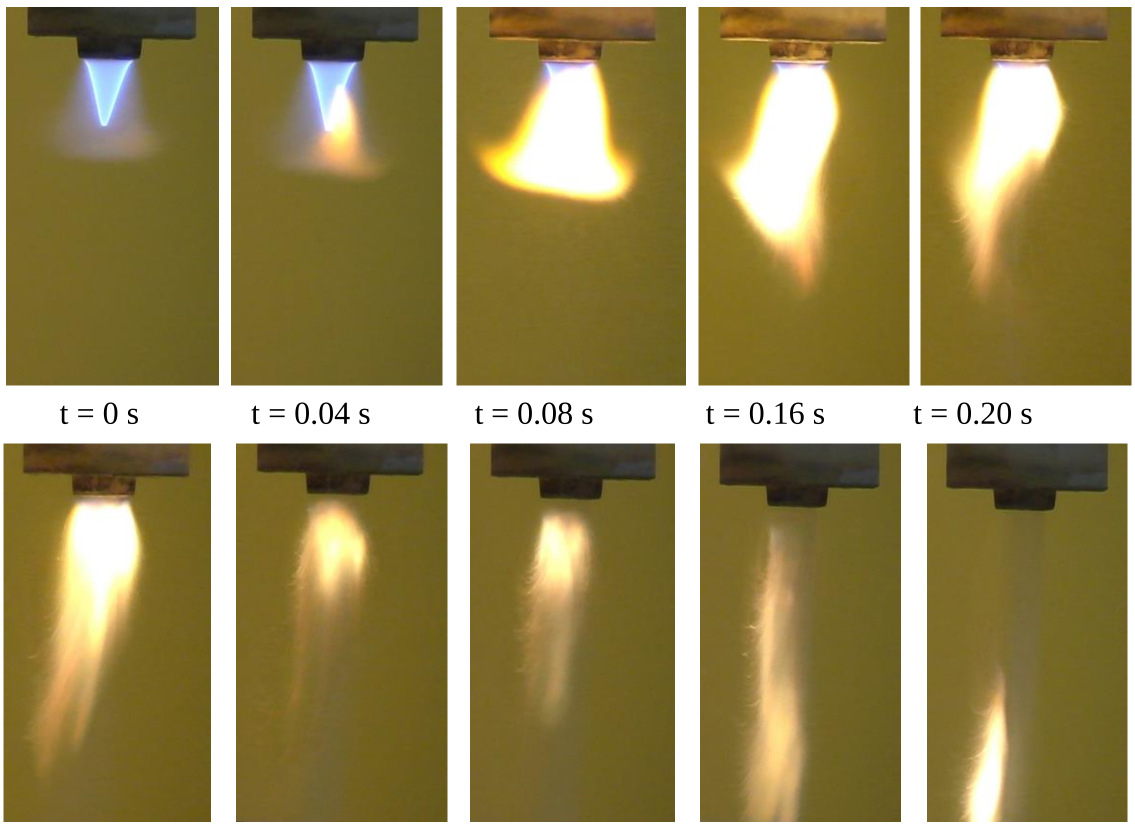


Fig.1. Dynamics of the propane-air flame extinguishing by calcium hydrophosphate.

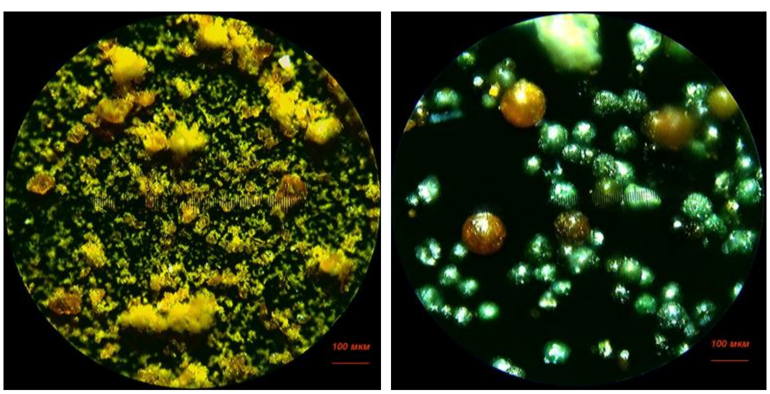
One of the basic mechanisms of the powder inhibitor fire extinguishing is discontinuation of the combustion chain reaction. In this case inhibitors affect the active centers and, by reducing their number, terminate the combustion reaction. There is also a possibility of flame heat loss and a decrease in the combustion temperature; a decrease by 600 K results in flame extinguishing.

Depending on the particle size, temperatures of substance melting and decomposition, the flame affects inhibitors in different ways. Fig. 2-5 illustrate change in the shape of the particles following the flame effect. Fig. 2 illustrates $K_2Cr_2O_7$ crystals before and after the flame effect. The mass loss curve that practically grows at a continuous rate up to 1000ºC testifies to the fact that about 8% of the mass is lost prior to 400ºC possibly due to oxygen release. Then potassium bichromate is subject to melting presumably accompanied by release of K_2O in the gas phase with formation of KOH in the flame. Theoretically, during the salt decomposition reaction O_2 – 16.3%; Cr_2O_3 – 51.6% and K_2O – 32.1% are released.

Table 2. Combined structures

Mixture components	FEA, mg cm^{-3}	Notes
$CaCO_3$(50)+Li_2CO_3 (50)	78	Synergism
$CuCl_2 \cdot H_2O$(50)+$NaHCO_3$(50)	78	Antagonism
$K_2C_2O_4 \cdot H_2O$ (33,3) + $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ (66,6)	22	Additivity
$KHCO_3$(50)+$NaHCO_3$(50)	33	Additivity
KI(50)+NaF(50)	94	Antagonism
$K_2Cr_2O_7$(50)+$Na_2Cr_2O_7 \cdot 2H_2O$(50)	39	Synergism
LiF(50)+NaF (50)	67	Additivity
MoO_3(50)+NaF (50)	89	Additivity
$Na_2B_4O_7 \cdot 5H_2O$(50)+NaF (50)	56	Synergism

Most particles in the initial powder are 6-10 μm yellow crystals, however some crystals are bigger, i.e. up to 60 μm and of irregular shape. After the flame effect most particles sized 50-60 μm acquire the dark green colour and an almost spherical shape, the surface of these particles is uneven and rough. There are also observed: insignificant number of the yellow spheres with 60-80 μm diameter, red particles of the same size, and a small number of the yellowish-green balls sized up to 100 μm.

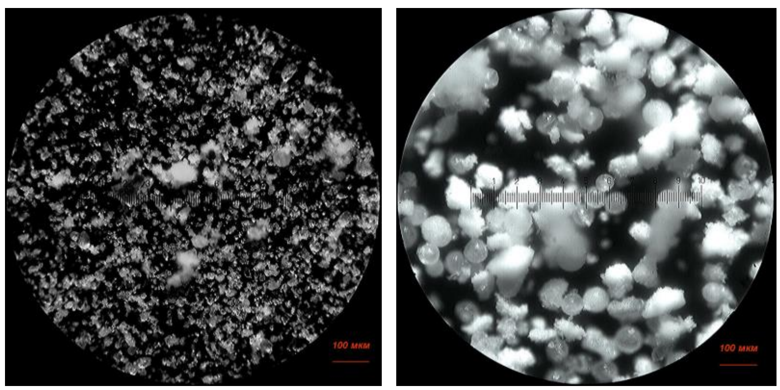


a b

Fig.2. Particles of $K_2Cr_2O_7$ powder: a – prior to flame effect; b – post flame effect.

Fig. 3 illustrates crystals of $K_2CO_3 \cdot H_2O$ powder before and after the flame effect. Based on the derivatogram, the mass loss starts at the temperatures above 200ºC. Prior to 1000ºC the mass loss is about 38%, whilst above 900ºC the curve shape does not change (the plateau phase). Prior to the flame zone the number of the particles sized less than 20 μm is approximately 90%, there are agglomerates sized about 60 μm mainly consisting of the particles of less than 20 μm in diameter. There are few 50-60 μm irregular-shaped crystals. After the flame zone there are observed 40-60 μm transparent spherical particles. Almost the same number of 60-80 μm irregular-shaped crystals is found here while smaller particles are practically absent. The mass loss after the flame zone is about 80%.

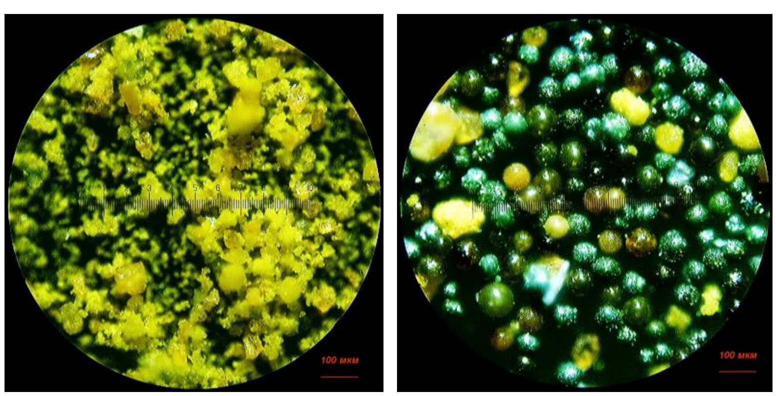
Fig. 4 illustrates a mixture of $K_2Cr_2O_7 + Na_2Cr_2O_7 \cdot 2H_2O$ powder before and after the flame zone. According to the mass loss curve, water (6%) evaporates within the temperature range 80-100ºC. Then, the mass stays almost unchanged until 350ºC. Starting from 350ºC the curve smoothly rises up to 1000ºC, the mass loss being 18% within this interval.



a b

Fig.3. Particles of $K_2CO_3 \cdot H_2O$ powder: a – prior to flame effect; b – post flame effect.

Considering the theoretical equation, the products of the decomposition reaction should be as follows: O_2 - 16%, Cr_2O_3 – 51.6%, H_2O - 6%, K_2O - 16%, and Na_2O – 10.4%. About 93% becomes gaseous in the flame. The initial mixture contains numerous 6-10 μm yellow crystals with inclusion of larger irregular-shaped crystals sized up to 60 μm, and also agglomerates.

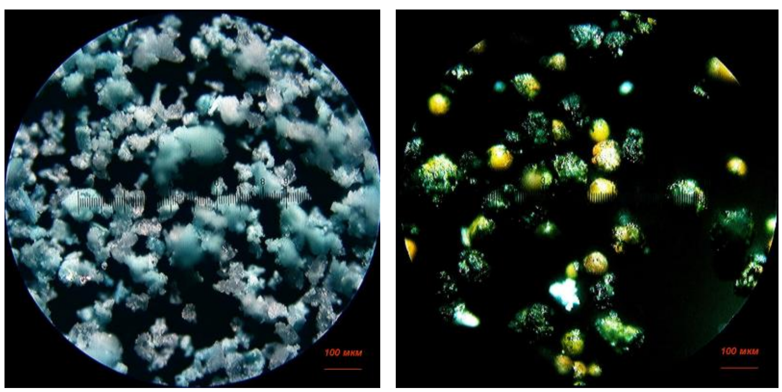


a b

Fig.4. Particles of $K_2Cr_2O_7$ + $NaCr_2O_7 \cdot 2H_2O$ powders mixture:
a – prior to flame effect; b – post flame effect.

After the passage of the flame zone there are mainly observed red, yellow and green spherical particles of approximate diameter 30 µm and a few spherical particles sized approximately 60 µm. The yellow and red particles that presumably have not been exposed to any significant flame affect are related to $Na_2Cr_2O_7$ and $K_2Cr_2O_7$. The derivatogram shows that about 6% water is intensively released in the gas phase at the temperatures above 85ºC, then the mass loss gradually increases up to 8% at 500ºC followed by a slight increase in the mass loss growth: the mass loss at 1000ºC being 18%. The green spherical particles are hollow inside.

Fig. 5 illustrates a mixture of $CuCl_2 \cdot 2H_2O$ + $NaHCO_3$ before and after the passage of the flame zone. Staring from 800ºC the mass loss curve sharply rises, the loss value being 42%. Prior to the flame zone most crystals of both substances have diameter exceeding 40 µm, the number of small particles is insignificant. After the flame zone there are observed smooth yellow and yellow-red balls with diameter range from 50 to 80 µm, and 50 to 80 µm black particles of odd shape and rough surface; smaller particles are practically absent. Yellow, red, and black colours of the particles can be attributed to formation of $CuCl_2$, Cu_2O, and CuO, respectively.



a b

Fig.5. Particles of $CuCl_2 \cdot 2H_2O$ + $NaHCO_3$ powders mixture:
a – prior to flame effect; b – post flame effect.

Discussion

Birchall (1970) studied temperature effect on 70 µm $NaHCO_3$, $KHCO_3$, $K_2C_2O_4 \cdot H_2O$ and $K_4Fe(CN)_6 \cdot 3H_2O$ particles that passed through a quartz pipe heated up to 1000ºC. He found the average size of the potassium oxalate and potassium ferricyanide particles after they passed through the pipe was about 1 µm. In the case of the oxalates the smoke consisted primarily of the alkali carbonate, while with ferrocyanide the smoke contained mainly alkali cyanate and carbonate and traces of cyanide together with iron compounds.

The potassium bicarbonate particles are least subject to any change, whilst the size of the sodium bicarbonate particles slightly decreased. Insignificant change in the shape of the sodium and potassium bicarbonate particles depends on their big sizes and heating temperature that is below that of the flame. As shown above, we have studied the particles that have passed through the flame.

Table 1 illustrates that potassium oxalate has the best fire extinguishing power. Analysis of the thermogram of potassium oxalate decomposition at heating shows that in the temperature range from 80ºC up to 160ºC the salt loses crystallization water, whilst heating up to more than 450ºC resulting in the release of carbon monoxide and the transformation of potassium oxalate to potassium carbonate. Above 750ºC carbon dioxide is released and potassium oxide is formed. The latter is subject to decomposition at 350ºC, therefore potassium atoms can be formed in the flame. The potassium atoms quite effectively remove from the flame active radicals that support the combustion chain reaction. Practically complete decomposition of potassium oxalate occurs within the flame zone, which testifies to the homogeneous mode of the flame extinguishing process.

All substances shown in Figure 2-5 practically have no particles sized less than 30 µm after the flame zone, besides most of them become gaseous in the flame. Similar analysis of the inhibitors described in Table 1 shows that flame extinguishing occurs either due to homogeneous inhibition or due to combined action of the homogeneous and heterogeneous inhibition.

Particles below 20 µm evaporate and decomposition products that can enter reaction with the combustion products occur in the gas phase. The particles that do not have enough energy for evaporation undergo the surface changes, namely they are melted off.

A mixture of $K_2Cr_2O_7 + Na_2Cr_2O_7 \cdot 2H_2O$ powders demonstrates a synergistic effect. The roentgenogram of this mixture (Fig. 6) subject to the flame effect shows lines testifying to significant quantity of Na_2CrO_4 and Cr_2O_3 and presence of a considerable amount of the roentgen-amorphous phase. The green spherical particles are hollow inside.

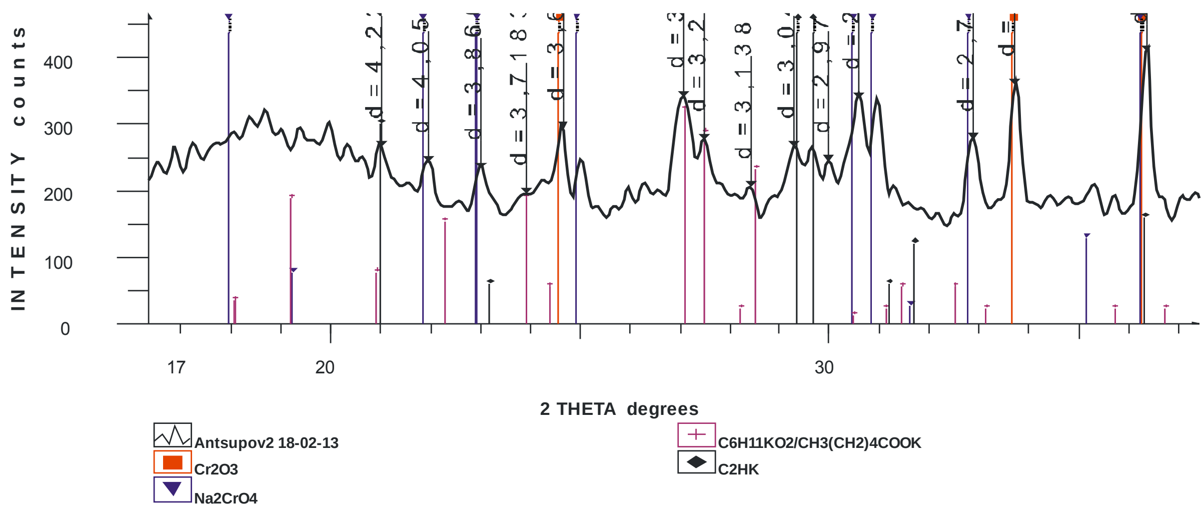


Fig.6. Roentgenogram $K_2Cr_2O_7 + Na_2Cr_2O_7 \cdot 2H_2O$ powders mixture subject to flame effect.

Another mixture $CuCl_2 \cdot 2H_2O + NaHCO_3$ is of the antagonistic nature upon extinguishing of the hydrocarbonic flame. After the mixture has passed a high-temperature zone of the flame (Fig. 6) there is observed an insignificant number of the particles referred to as the sodium salts.

Of high interest is a mixture of calcium and lithium carbonates. Within the flame about 77% of the substance has become gaseous, the extinguishing concentration is 78 mg cm^{-3}, and the extinguishing nature is synergistic. Carbon dioxide with approximate mass 52% is released during the gas phase in the process of heating. Oxides being formed during this process have a high melting temperature (CaO - 2360ºC, Li_2O - 1453ºC).

A mixture of potassium tetraborate with sodium fluoride has a synergetic effect. Potassium tetraborate extinguishes flame mostly due to the considerable amount of the water molecules. Over 80% of the mass is decomposed in the flame. The fusion temperature of sodium fluoride is 996ºC, and boiling temperature 1787ºC, about 20% of extinguishing batch becomes gaseous in the flame. The synergetic effect is possibly caused by reaction of the substances released with the combustion products to the gas phase.

The derivatographic curve of the mixture mass loss reaches plateau above 750ºC. One can suppose that CaO and Li_2O in the flame interact with formed water vapours. According to the powder extinguishing mechanism described in the reference, formed hydroxides ($Ca(OH)_2$ and LiOH) react with OH radical or hydrogen atom, while free metal atoms resulting from the reaction contribute to the destruction of the active centers and terminate the combustion reaction chain. It is noteworthy that lithium hydroxide is a good inhibitor itself (Table 1). It is quite possible that molybdenum oxide has the same mechanism as well.

Dispersive distribution of the particles in the extinguishing substances batch is rather important. This can be illustrated by sodium bromide with particles exceeding 60 μm as it was far less subject to decomposition in the flame than at thermal heating because its particles reached the temperature below 900ºC. A similar result has been observed in ammonium chloride as well.

Conclusions

This example of calcium hydrophosphate shows that the extinguishing effect of the powders on the preliminarily mixed propane-air flame begins from their decomposition in the high-temperature flame zone. The powder particles that have passed to the gas phase have undergone considerable change. The powder crystals, which have a low melting temperature (below 1000ºC) were fused and became spherical, whilst practically all particles sized less than 30 μm became gaseous. Flame suppression basically depends on the homogeneity mechanism.

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Thermodynamic modeling of oxidation of the PB-Bi Alloy

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Abstract:
Pb-Bi alloys are used as a heat carrier for nuclear power units. The study of their oxidation under various conditions has the scientific and practical significance and is important for safety. Experimental studies of the oxidation of alloys at high temperatures and pressures, the evaporation of oxides and metals, and the oxidation in complex media, which contain more than one oxidant, are laborious and complicated, leading to large errors. Studies of this kind can be reasonably performed by methods of thermodynamic simulation, i.e. mathematical modeling of equilibrium states in heterogeneous multicomponent systems. Thermodynamic simulation of oxidation of the perspective alloy Pb-Bi for nuclear power units is studied. The basic physicochemical processes are erected for this alloy at temperatures from 400 to 3000 K.

Additional Keywords: Thermodynamic modeling, oxidation, alloy, Pb-Bi

Introduction

The lead-bismuth alloy is one perspective heat-transfer media for nuclear power units. A disturbance of energy supply for a nuclear power station, with a simultaneous failure of all operating controls, creates the most difficult situation of all design failures of nuclear reactors. The probability of this accident does not exceed $4 \cdot 10^{-12}$ $year^{-1}$ without possible duplicating by the personnel of activity of the refused safety systems. The study of these processes has shown that fuel and steel do not melt in the reacting region at this settlement accident. However, a fuel fusion is possible in more extreme conditions. In working areas of reactors, where melting is taking place, fusion is likely to occur. Fuel fusion in all of the reacting regions is also of interest. Therefore, studying of behavior of the pool heat transfer medium at high temperatures is necessary (Kashcheyev 2007).

The systematic research of the Pb-Bi alloys oxidation is absent from the wide field of temperatures till now. The experimental studying of these processes at high temperatures is both labour-consuming and difficult. It is accompanied by significant errors.

In this case, application of methods of thermodynamic modeling (TM) is expedient. Accuracy of thermodynamic simulation is determined by selection of a mathematical model and precision of the thermodynamical data of all components.

Methods

TM consists in the thermodynamic analysis of the equilibrium state of systems in whole (a complete thermodynamic analysis). Here, thermodynamic systems are conditionally selected material areas where interaction with environment is reduced to the exchange of heat and work. The application of TM allows us to simulate quantitatively and predict compositions and properties of complex heterogeneous, multi-element, multiphase systems in the wide range of temperatures and pressures, taking into account chemical and phase transformations (Vatolin 1994, Moiseev 2002). Calculation methods have been developed on the basis of various principles of thermodynamics (Alemasov 1971):

1. Of all the permissible values of moles of individual substances in the thermodynamic system, only those that minimize the thermodynamic potential of the system, correspond to equilibrium values.
2. Of all the permissible values of the energy added by each independent component (atom), those maximizing the total contribution of energy of individual atoms to the system, correspond to equilibrium values.

The components of the system are all possible and existing substances in different aggregate states, which are formed from the elements included in the system under study. The substances, which are the minimum necessary for forming of this system, are called thermodynamic system components. The number of components equals the number of substances in the system minus the number of independent reactions bonding these substances. At TM compounds with a multiple number of atoms forming them are considered condensed individual substances. Substances with fractional stoichiometric coefficients are assumed to be solutions. Condensed phases include compounds in the solid (crystalline or amorphous) and liquid states. Individual compounds, which have the same chemical formula, but enter into different phases, are assumed to be different composite substances. The components of the gas phase are molecules, radicals, atoms, ions, and electron gas.

Extensive thermodynamic parameters of the system, i.e. those proportional to the amount or mass of substance in the system, are volume V, entropy S, internal energy U, enthalpy H, free energy F (F = U – TS), and Gibbs energy G (G = H – TS). Intensive thermodynamic parameters, i.e. those independent of the quantity or mass of the system, are pressure P, thermodynamic temperature T, concentration, and mole and specific thermodynamic values.

Two independent parameters out of V, S, U, H, P, T, F and G, and the complete original chemical composition of the system should be assigned for explicit representation of any thermodynamic system. Each pair of the independent parameters defines a characteristic function, which is “the function describing the state of the thermodynamic system of the corresponding thermodynamic parameters, whereas this system is characterized by the fact that all its thermodynamic properties can be expressed explicitly by this function and its derivatives with respect to the thermodynamic parameters” (Vatolin 1994).

The criterion of attainment of the equilibrium state by the system is the extremum of its characteristic function. If the parameters P and T are independent, the characteristic function is the Gibbs free energy G, while the minimum of this energy in the system (G_{min}) is the criterion for reaching of the equilibrium state. Taking the parameters U and V, the characteristic function in the isolated system is the entropy S, while the maximum entropy of the system, S_{max}, is the criterion for reaching the equilibrium state.

One of the most efficient computation programs is the TERRA program package, which is the development of the ASTRA.4 soft (Vatolin 1994, Moiseev 2002).

Results and Discussion

Pb-Bi melts are represented by the model of ideal solutions of interaction products (model ISIP, Moiseev 1997). Condensed Bi, Pb, PbBi, Pb_3Bi_4, Pb_3Bi_5, Pb_3Bi_7, and $PbBi_7$ are included into this composition.

The intermetallic compounds in the lead-bismuth melt are described by thermodynamic properties and functions of compounds Pb_xBi_y at the melt temperature. The mixing heats (ΔH_{mix}) between [Pb], [Bi] and groups [Pb_xBi_y] are accepted to be equal to zero, and the entropies of mixing (ΔS_{mix}) are calculated as for ideal solutions.

At TM the concentration of the intermetallic compounds in the melt is defined by the equilibrium state of the system, i.e. the preset parameters (for example, P and T) and the original ratio of Pb, Bi. Besides, TM also reveals equilibrium concentrations of all the gaseous components of the system, resulting from a of complex chemical and phase transformations. The equilibrium concentrations of the condensed and gaseous components represent products of all the possible reactions between [Pb], [Bi] and [Pb_xBi_y] and the gas phase at reaching of the global extremum of the thermodynamic potential by the system (S_{max}) (Il'inykh 2006).

We have considered possibilities of formation of the following compounds: PbO, PbO_2, BiO_2, BiO, Bi_2O_3, Pb_2BiO_4, Bi_4PbO_7, $PbBiO_3$, $Pb_3Bi_2O_6$, $Pb_2Bi_6O_{11}$, $Pb_5Bi_8O_{17}$, $PbBi_{12}O_{19}$, $Bi_{12}PbO_{20}$ in the oxidic phase.

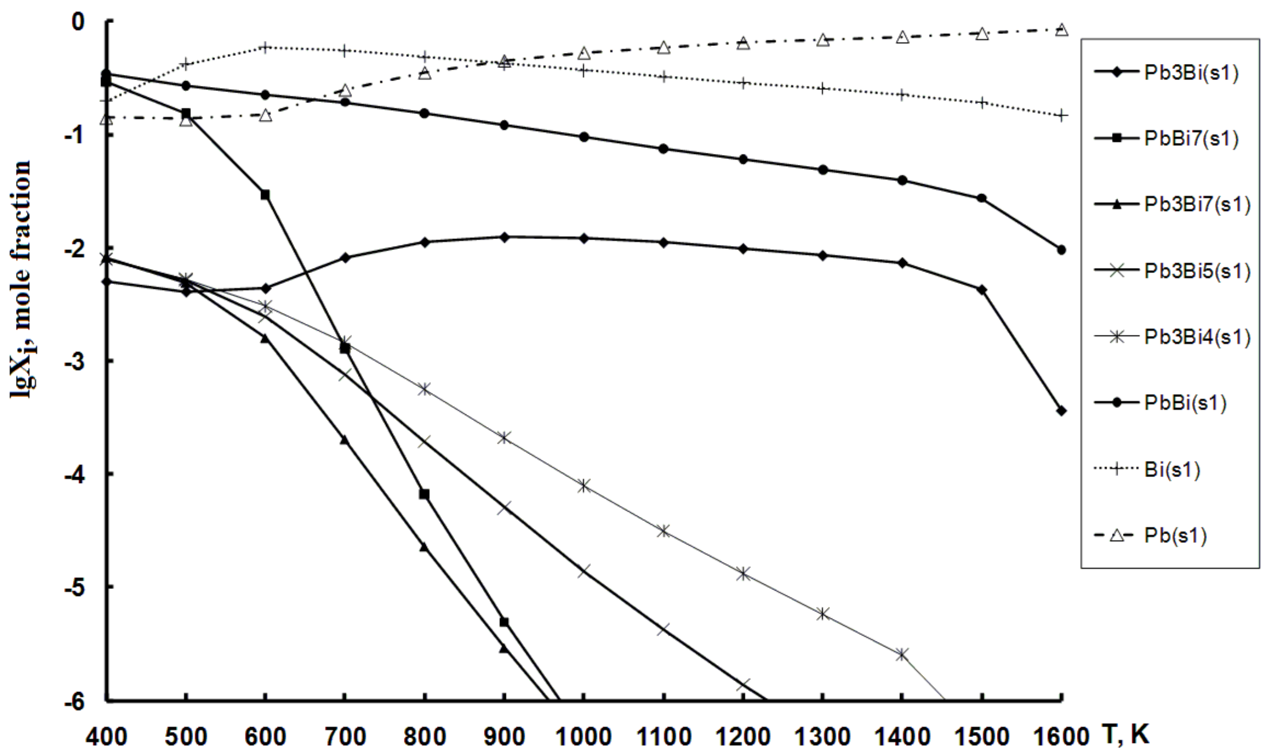
Temperature dependences of the equilibrium compositions of the metal (s1), oxide (s2) and gas phases are shown in Figs 1a-c accordingly. The basic component of the oxide phase at temperature 400 K is lead (about 87%). The bismuth content makes 58% in this phase. 13% Pb and 42% Bi are present at the metal phase.

Growth of a mole fraction of the metallic lead and bismuth occurs during an increase of temperature to 1200 and 700 K respectively. It results from thermal dissociation of an intermetallic and the complex oxide of $Pb_3Bi_2O_6$. Products of these reactions are lead, molecular oxygen and the stable oxide of $PbBi_{12}O_{19}$.

$$7Pb_3Bi_2O_6(s2) + 34BiO(s2) = 4PbBi_{12}O_{19}(s2) + 17Pb(s1) \quad (1)$$

This reaction occurs in the interval temperatures from 600 to 1300 K. Thermal decomposition of intermetallic compounds and synthesis of PbBi and Pb_3Bi take place in the temperature range of 400-900 K. Thermal dissociation of oxide $Pb_3Bi_2O_6$(s2) proceeds after completion of reaction (1) at temperatures to 2100 K.

$$19Pb_3Bi_2O_6(s2) + 34Bi = 6PbBi_{12}O_{19}(s2) + 51Pb \quad (2)$$



lgX$_i$, mole fraction
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-1
-2
-3
-4
-5
-6
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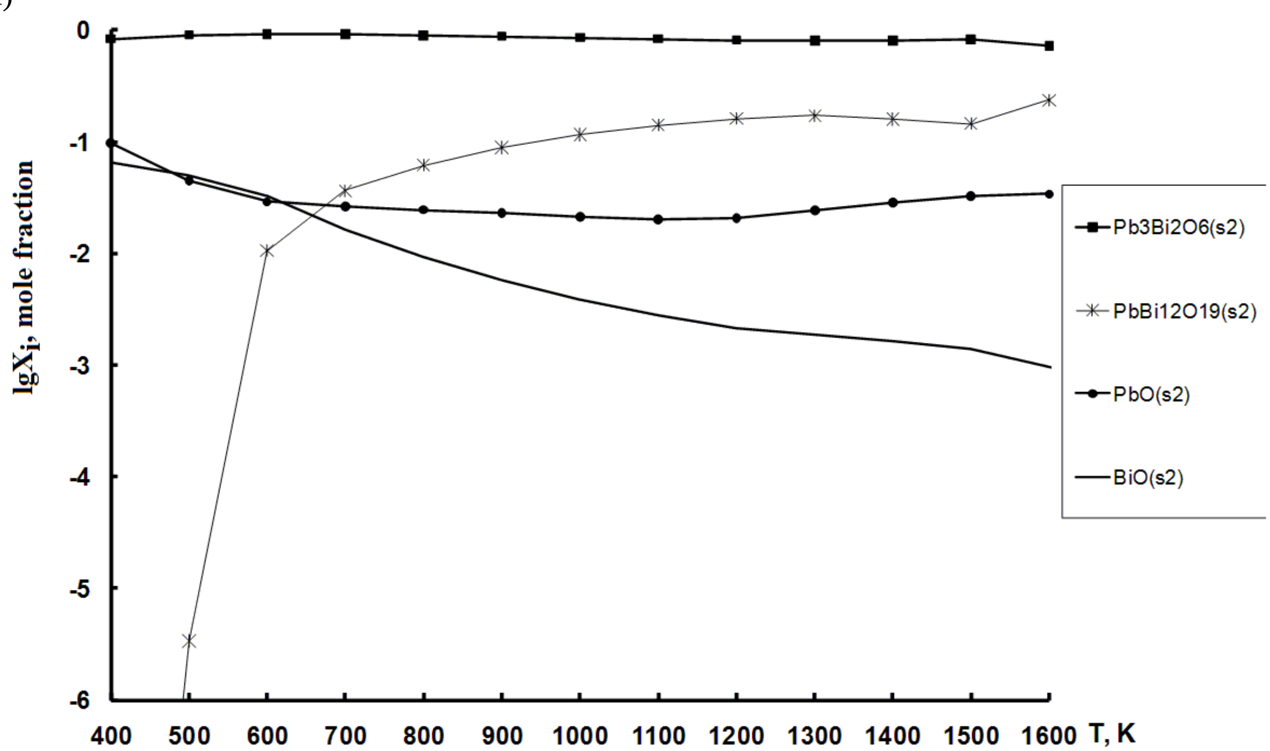
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
T, K
Pb3Bi(s1)
PbBi7(s1)
Pb3Bi7(s1)
Pb3Bi5(s1)
Pb3Bi4(s1)
PbBi(s1)
Bi(s1)
Pb(s1)

a)



lgX$_i$, mole fraction
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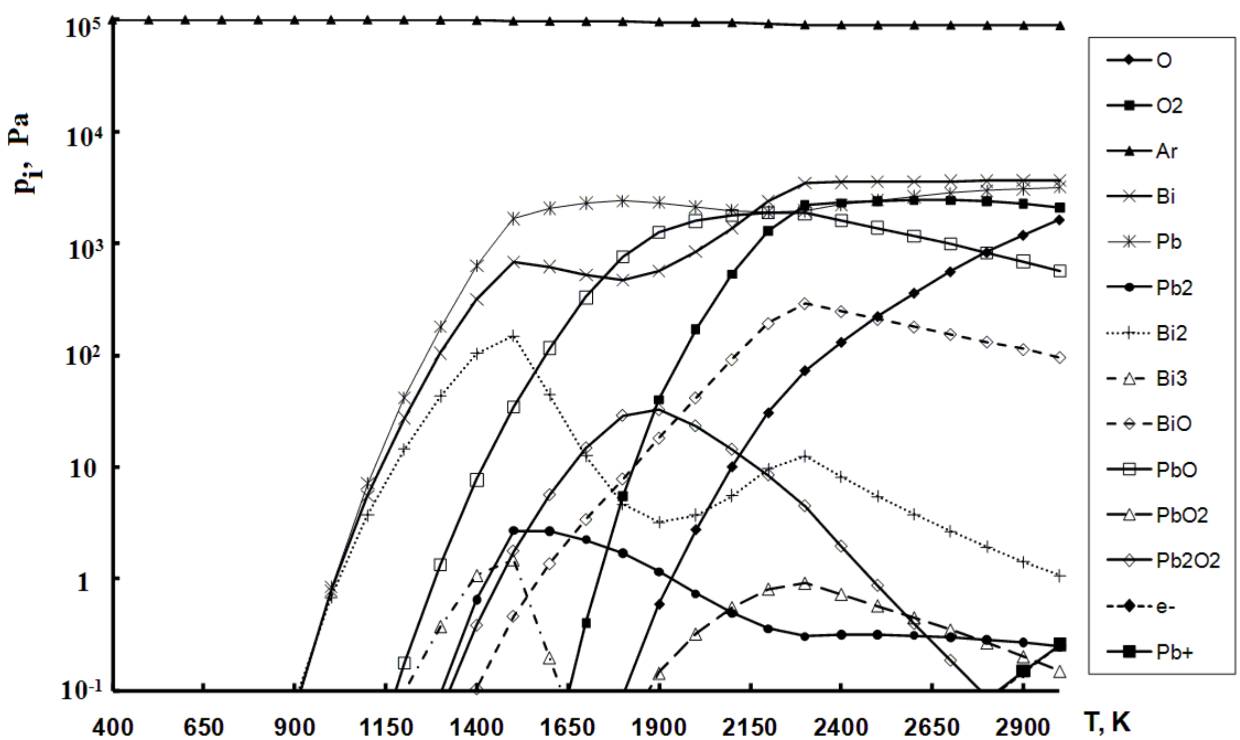
-1
-2
-3
-4
-5
-6
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
T, K
Pb3Bi2O6(s2)
PbBi12O19(s2)
PbO(s2)
BiO(s2)

b)



c)

Fig. 1. Temperature dependences of the equilibrium composition. a) The metallic phase, b) the oxide phase, c) the gas phase.

$PbBi_{12}O_{19}(s2)=12Bi+PbO+9O_2$ (3)

Thermal dissociation of $PbBi_{12}O_{19}$ oxide proceeds by the reaction (3) over the range of temperatures of 1900–2300 K.

The basic components of a gas phase are argon, oxygen, and steams of Pb, Bi, PbO. The partial pressure of the vapor of Pb rises by increase of temperature from 400 to 1800 K. It reach the maximum ($\sim 2.4\cdot 10^3$ Pa) at 1800 K, then the partial pressure of the vapor Pb lowers to $2\cdot 10^3$ Pa in the temperature interval of 2200-2300 K. The maximum partial pressure ($1.9\cdot 10^3$ Pa) of the PbO vapor is fixed at 2200 K. It makes conditional on the chemical oxidation of the Pb vapor.

$2Pb + O_2 = 2PbO$ (4)

The equilibrium partial pressure of the Pb vapor reaches $3.2\cdot 10^3$ Pa in the temperature range of 2500-3000 K, then it falls because of the chemical reaction (5).

$PbO = Pb + O$ (5)

The partial pressure of the vapor of Bi rises by increase of temperature from 500 to 1500 K. It reaches the maximum ($6.8\cdot 10^2$ Pa) then it lowers to $4.7\cdot 10^3$ Pa in the temperature interval of

1500-1800 K. After the partial pressure of the Bi vapor growth again at 1900-3000 K, and it reaches $3.5 \cdot 10^3$ Pa at 2300 K.

The equilibrium partial pressure of the Bi_2 vapor reaches $1.5 \cdot 10^2$ Pa in the temperature range of 400-1500 K then it falls because of presence of the chemical reaction (6) at 1700-3000 K.

$Bi_2 = 2Bi$ (6)

The partial pressure of the vapor of PbO reaches the maximum ($1.9 \cdot 10^3$ Pa) at 2200 K then it falls in the temperature interval of 2200-3000 K. This circumstance is explained by the decomposition reaction (5).

The partial pressure of O_2 does not exceed a trace of quantities over range of temperatures of 500-1700 K. The further growth of temperatures from 1700 to 2700 K leads to its rising. The maximum of the partial pressure (pi) of O_2 is fixed at $6.3 \cdot 10^2$ Pa. Then it lowers because of presence of the reaction of thermal dissociation (7) at 2800-3000 K.

$O_2 = 2O$ (7)

The partial pressure of the vapor of BiO is minor at 500-1500 K. It rises by increase of temperature from 1500 to 2300 K. Its maximum is fixed about $2.9 \cdot 10^3$ Pa. The reaction (8) takes place in these conditions.

$Bi+O=BiO$ (8)

Then partial pressure of the BiO vapor reduces because of presence of the chemical reaction (9) at 2300-3000 K.

$BiO = Bi + O$ (9)

The content of the Pb_2O_2 vapor is small in this system. The maximum of its partial pressure is fixed about 32.5 Pa in the temperature interval of 1800-1900 K. The further growth of temperatures leads to its reduction. This circumstance is explained by the dissociation reaction (10).

$Pb_2O_2=2Pb + O_2$ (10)

The equilibrium partial pressure of the Pb_2 vapor is small in the system. The partial pressure of the Pb_2 vapor increases at 2300-3000 K and reaches to 2.7 Pa. At 1600-3000 K it reduces because of presence of the PbO synthesis (the chemical reaction (11)).

$Pb_2 + O_2 = 2PbO$ (11)

Concentration of vapors Bi_3 is insignificant in this system. The partial pressure of the Bi_3 steam rises by increase of temperature from 1200 to 1500 K and reaches the maximum (1.48 Pa). Then it lowers at higher temperatures because of the chemical reaction (12).

$Bi_3 = 3\ Bi$ (12)

Partial pressures of the Bi_4 and PbO_2 vapors are very minor (<0.1 Pa) in our system. Thus, distribution of elements of Pb and Bi on phases in this system at equilibrium temperature increase can be featured as follows.

At 500-600 K more than 83 % of all lead there are as $Pb_3Bi_2O_6$ in the oxide solution, 6-8 % as intermetallic PbBi in the metal solution, and 4-6 % in the form of metallic Pb. Substitution reaction occurs at magnification of equilibrium temperature to 1300 K. $Pb_3Bi_2O_6$ and metal bismuth react with formation $PbBi_{12}O_{19}$ and metallic lead.

The maximum concentrations of $PbBi_{12}O_{19}$ and a metal lead are observed at 1200 K. 37 % of all Pb are existed in the metal form and 52 % in the form of $Pb_3Bi_2O_6$. Intensive evaporation of a metal solution takes place between 1200 and 1500 K. 40% of all lead transfers in a gas phase. The further accumulation of $PbBi_{12}O_{19}$ in the oxide phase occurs because of prolonged decomposition of $Pb_3Bi_2O_6$.

The process of oxidation by oxygen of the metal lead steams from the oxide solution and begins at 1500-2000 K. Oxidation of bismuth vapor occurs at temperatures above 2000 K. The second maximum of the content of metals (83 % Bi and 7 % Pb) in the oxide phase is attained at 1900 K. Evaporation of the oxide solution at 1900-2300 K quickly leads to growth of the partial pressures of the Pb, Bi, PbO steams again. All lead of system exists as 51 % Pb and 49 % PbO at temperature 2300 K. Bismuth is proportioned as 92 % - steams of Bi, and 8 % - vapor of BiO. Processes of decomposition of the oxide compounds steams, and formation of the metal steams and oxygen in a gas phase develops at growth of temperature to 3000 K. Increase of the partial pressures of O_2 and steams of Pb, Pb_2, Bi, Bi_2, Bi_3, O, PbO, Pb_2O_2, BiO occurs at 400–2700 K.

Conclusion

Computer simulation of processes of oxidation of the lead-bismuth alloy is made in the wide temperature interval by software TERRA. The basic chemical reactions of oxidation, thermal synthesis and decomposition of perspective heat-transfer media for nuclear power units are considered. The received results of calculations are allowed to predict the behavior of the Pb-Bi heat-transfer medium at a severe accident of a nuclear reactor.

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Fuel loads and predicted fire behavior in the Veluwe Region of the Netherlands

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Abstract: The Netherlands is a densely populated country in NW-Europe that experiences several 'major' wildfires every spring and summer. Agencies responsible for wildland firefighting in the Netherlands have little fuel data available to use when making critical decisions on wildland fire management. Dutch and American students assessed the fuel loadings of five typical vegetative communities (Douglas-fir, Scots Pine, Beech, Heather, Grassland) in the Veluwe, the largest nature area in the Netherlands. Using these field data and BehavePlus, we predicted a set of fire behaviors, and created a photo series document that agency personnel, fire fighters, and foresters can use to quickly assess fuel conditions and fire risk within these ecosystems.

Additional Keywords: Wildland fires, Veluwe, fuel loads, northwest Europe, the Netherlands,

Introduction

The Netherlands covers approximately 41,530 km^2 (twice the size of New Jersey) with a dense population of 16.7 million people. With a population pressure of 402 inhabitants per square kilometer, close to 95% of the over 6,000 km^2 of wildland area could be classified as wildland-urban interface. While there is a lack of a wildland fire culture in society or management, the country, like much of northwestern Europe, is experiencing increasing number of and area burned by wildfires each year. Concerned agency staff members are attempting to develop fire behavior prediction models to assist managers in making informed decisions regarding the proper approach to fighting these wildfires. However, accurate on-the-ground data to make these models accurate are currently lacking.

The objectives of this study were to:

- Assess fuel loads and vegetation structure in five typical vegetation types in the Veluwe Region;
- Match these field data to US fuel models or develop new models specific to Netherlands;
- Estimate fire behavior based on these fuel models.

Vegetation Sampling

Vegetation sampling was performed at 38 sites between Arnhem and Apeldoorn following Ottmar and Vihnanek (e.g. 1998, 2000). The sites were scattered within five dominant vegetative communities in the Veluwe region (Scots pine, Douglas-fir, Beech, Heather and Grasslands) across a range of fuel loading conditions. Site parameters measured included GPS location, aspect, slope and canopy cover. Vegetation parameters included density, percent cover, and basal area, as well as downed and woody fuels. Collected data were entered into excel spreadsheets and converted into the appropriate units for use in BehavePlus.

Figure 1. Location of the Netherlands (left) and study area (right).

Fire Behavior and Effects Modeling

The weather conditions used were "bad fire weather" information (29-32°C air temperature, 3-32 km/h wind speeds, 15-20% RH) obtained from the weather conditions during wildland fire events in the Netherlands over the past 10 years. 100 different BehavePlus runs per site were run, each with slightly different fuel and weather conditions. The results were then used to classify fuels and weather conditions into groups within each community.

Results

Douglas fir.

Two groups: 1) very high load, timber-shrub; and 2) moderate load, conifer litter. In thinned/open areas with shrubs or saplings, fires can easily move into canopy of trees. Dense stands are less likely to burn very hot or fast, little chance to climb into canopy. Low rate of spread <0.5 km/h, maximum fireline intensities of 3,000 kW/m, with 20-60% probability of crowning.

Beech.

Four groups: 1) beech; 2) upland beech; 3) beech-mixed hardwood; and 4) closed canopy. Low rate of spread (0.6-0.8 km/h), maximum fireline intensities of 850 kW/m and 10% chance of crowning, with low intensities unless long-term dry periods, then adjacent areas may be exhibiting more hazardous fire behavior.

Heather. Three groups: 1) low fuel loads with grass; 2) moderate fuel loads; and 3) high fuel loads. Rate of spread <3.5 km/h, with 4-7 m flame heights, and maximum fireline intensities of 8,400 kW/m.

Scots Pine.
Three groups: 1) moderate load, timber-shrub; 2) moderate load, timber-shrub with grass; and 3) high loads timber-shrub. Rate of spread < 3 km/h rate of spread, with < 5m flame heights, <75% chance of crowning, and maximum fireline intensities of 3,400 kW/m.

Grassland.
Two groups: 1) moderate grass; and 2) thick grass. Rate of spread 1 km/h, flame heights <5m, and fire intensities maximum fireline intensities of 8,800 kW/m. A bigger problem may be fires moving in from typically adjacent Scots Pine and Heather areas.

In many forested areas in this region, branches, tree tops and post-cutting slash are often left in small piles for a variety of reasons: "diversity", small animal habitat, and tradition. Regardless of the reason, this practice does add to the fire risk by providing pockets of higher fuel loads, and can increase the chance of a surface fire climbing into the canopy of the overstory, increasing both the ecological damage and the difficulty in controlling a wildfire.

Application

The results of this study are being used to develop a photo guide of potential wildland fire behavior that will be made available in the Netherlands. Through active collaboration with fire and forestry agencies in the Netherlands, these data will be used in risk management, training, firefighting and forestry planning. Because climate change is expected to increase fire weather in NW Europe, awareness and management of fuel loads will become increasingly important in the future.

Acknowledgements

Special recognition is due to a number of individuals and agencies. Dr. Coen Ritsema at Wageningen University for access to drying ovens for the samples; Fire department in Apeldoorn for housing the SFA students; Margreet Zoer (VNOG) and Ester Stalenhoef (IFV) provided incredible assistance throughout the project. A special thanks is extended to Alette Smeenk with VNOG who four years ago introduced Dr. Oswald to the growing wildland fire issue in her native Netherlands. Funding for this project was provided by a SFA Faculty Research Grant.

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Proceedings of 4th Fire Behavior and Fuels Conference, July 1-4, 2013, St. Petersburg, Russia
Published by the International Association of Wildland Fire, Missoula, Montana, USA

The influence of wind direction on flow field around a rectangular heat source

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Abstract
Winds near fires are important in wildland fires because they affect fire behavior and firebrand throwing. The influence of cross flow direction on flow field around a rectangular heat source was investigated in a wind tunnel using particle image velocimetry (PIV) and a flow visualisation. The PIV images show that when the cross-flow direction is perpendicular to the long side of the heat source, the strong wind areas near the floor are downwind of the heat source. However, when the cross-flow direction is parallel to the long side of the heat source, the strong wind areas are to each side of and near the heat source. The flow visualisation shows that the difference of the location of the strong wind areas is most likely caused by the difference of the location of the counter-rotating vortex pair (CVP), a dominant flow feature in a plume inclined by the cross flow. The difference of the location of the CVP is caused by the difference of the plume angle. This result suggests the cause of strong winds near fires in cross flow and the cause of past wildland fires in which firebrands were scattered after rapid changes in wind direction and fire spread.

Bulgarian fuel models developed for implementation in FARSITE simulations for test cases in Zlatograd area

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Abstract: As a key component of the cross-border project between Bulgaria and Greece known as OUTLAND, a team from the Bulgarian Academy of Sciences and Rocky Mountain Research Station started a collaborative project to identify and describe various fuel types for a test area in Bulgaria in order to model fire behavior for recent wildfires. Although there have been various efforts to map vegetation in Bulgaria, these datasets have not directly provided the types of data necessary to use the wildfire spread models. This project focuses on using available data sources for Bulgaria including paper maps displaying Bulgarian vegetation in 1991 (Bondev 1991), high resolution orthophotography from 2011, Corine Land Cover spatial data (http://www.eea.europa.eu/data-and-maps), and both paper and spatial vegetation maps from the local municipal forestry department. The objective of this paper is to describe a methodology that can be used in simulating wildfires for the Zlatograd region of Bulgaria. This methodology includes classifying the surface fuels using both custom fuel models and fuel models developed and commonly used in the United States (Anderson 1982; Scott and Burgan 2005), reformatting local weather data, and performing fire behavior simulations using the FARSITE fire area simulator for fifteen fires in the study area.

Additional Keywords: Zlatograd, OUTLAND project, Greece-Bulgaria cross-border program, FARSITE, fire behavior modeling, custom fuel models**.**

Introduction

In 2011, the Institute of Mathematics and Informatics of the Bulgarian Academy of Sciences (BAS), in cooperation with multiple consortium partners, received a grant from the European Union for a project titled “Open protocols and tools for the edUcation and Training of voLuntary organisations in the field of Civil Protection, against nAtural Disasters (forest fires) in Greece and Bulgaria”, known as the OUTLAND project (http://www.outland-project.eu). Consortium partners include: the municipality of Thermi as lead partner, the municipalities of Komotini and

Zlatograd, the management authority of the "Dadia-Lefkimi-Soufli Forest" national park, and the Centre for Research and Technology Hellas, Informatics & Telematics Institute.

The main objective of the OUTLAND project is the establishment of a framework for the vocational training and preparedness of volunteers who operate within the civil protection mechanisms in Greece and Bulgaria and are involved in the prevention of wildfires, as well as protection and rehabilitation of ecosystems affected by fire. The project focuses on the exchange of experiences and best practices, the production of multilingual training materials, and development of a joint understanding in the cross-border territory to improve safety and response efficiency of the volunteers.

OUTLAND’s primary focus is to provide a permanent mechanism for the municipal authorities, where volunteer groups are established in both countries, to communicate and cooperate in cases of common disaster. The research and teaching procedures are based upon technical, economic, and procedural criteria to provide for adequate preparation of volunteer groups in institutional level programs. Educational materials developed as part of OUTLAND include instructions for using computer-based tools such as fire behavior prediction systems. Where necessary input data representing terrain, weather conditions, vegetation, and surface fuels exist or can be developed, these tools could be used to simulate past fire events for calibration purposes and actively burning fires for decision support. As part of our project we sought to create a fuels classification adapted to the Zlatograd test area and subsequently test existing fire behavior modeling tools developed in the United States to analyze the spread of past wildfires, neither of which has ever been done for the Zlatograd area or any Bulgarian municipal territory. If successful, this effort could be used to guide operational implementation of these computer-based decision support tools in the future.

Along with the basic educational materials developed for the volunteer groups, the team at BAS started collecting information for recent wildfires occurring between 2011-2012 within the Zlatograd municipal territory, including the towns of Zlatograd, Madan and Nedelino. The fifteen reported wildfires were fairly small, but caused the deaths of four volunteers in 2012. No statistical records are kept for such casualties and the only sources of information are from people who worked in the field during such incidents. We also considered that scenarios displaying possible movement of the fire front, especially as impacted by the effects of wind and topography, could be used as a training tool in educating local volunteers. BAS partnered with the USDA Forest Service’s Fire Modeling Institute, part of the Rocky Mountain Research Station located at the Missoula Fire Sciences Laboratory in Missoula, Montana, to establish methods for analyzing fire behavior and fire growth using the FARSITE fire area simulator (Finney 2004) and the BehavePlus fire modeling system (Andrews 2007) for fifteen Zlatograd area wildfires.

Methods

Study area

The territorial state-owned forestry department in Zlatograd covers an area of 33,532 ha, of which 31,856 ha are state forests. Most forests are in early to mid-seral successional stages, with only small amounts of mature to old forest. Stand age is highly variable, ranging from 20 to 80 yrs; most stands range between 35 to 50 yrs with the average being 46 yrs. Average stem stock is 140 $m^3 ha^{-1}$. The average forest canopy cover is 81%.

In terms of climate, the region is part of the continental-Mediterranean climatic region, south-Bulgarian climatic sub-region and East Rodopi mountain low climate region. The average annual temperature is 10.8ºC, with a maximum temperature in July of 20.6ºC and minimum temperature in January of -0.8ºC, indicating moderate summers and relatively mild winters. Extreme values of annual average maximum and minimum temperature are respectively 17.1ºC and 4.9ºC, the monthly maximum is in August (28.9ºC) and the average monthly minimum occurs in January (-3.9ºC). Average annual rainfall reaches 1000 mm. Maximum precipitation amounts for the period from April to October range from 10.0 mm for 5 min to 46.3 mm for 60 min and 59.7 mm for more than 60 min. The average annual relative humidity is 75%, which is an indication of good growing conditions; maximum relative humidity values of 85% occur in November. However, approximately 13-15 days per year have relative humidity less than or equal to 30%, during which time wildfires may be of higher concern.

Fire Locations

Data for fifteen wildfires that occurred in 2011 to 2012 within the Zlatograd municipal territory were provided by the Zlatograd forestry department; this data included vegetation type, area burned (in decares where 10 decares = 1 hectare), date, and start and end hours of the fire event (table 1). These wildfires burned in a variety of vegetation types and were more than likely started by humans to clear agricultural debris or prepare fields, based on the proximity to villages. Paper maps from the forestry department identified the ignition location and final fire shape; this data was digitized in a GIS, which allowed each ignition point to be viewed with background orthophotos and the spatial Zlatograd vegetation classification showing pre-fire vegetation (Figure 1).

Fire No.	Vegetation type	Burned area in decares	Date of occurrence	Hour of start	Hour of end
1	Durmast	3.0	25 March 2012	1330	1530
2	Beechwood	5.0	29 March 2012	1400	1800
3	Scotch pine	1.0	16 June 2012	1500	1700
4	Scotch pine	7.0	6Aug. 2012	1640	1950
5	Scotch pine	5.0	6 Aug. 2012	1710	2130
6	European black pine	4.0	27Aug. 2012	1200	1600
7	Scotch pine	3.0	5 Sept. 2012	1400	2030
8	Scotch pine	6.0	6 Sept. 2012	1400	1930
9	Scotch pine	2.0	6 Oct. 2012	1600	2320
10	Scotch pine	1.0	16 March 2011	1310	1400
11	Scotch pine	1.0	5 April 2011	1715	1900
12	Scotch pine	1.0	10 April 2011	1130	1530
13	Grassland	3.0	30 Aug. 2011	1400	1800
14	Scotch pine	4.0	12 Sept. 2011	1230	1900
15	Scotch pine	1.0	15 Sept.	1600	1830

			2011			

Table 1: Fire information provided by the Zlatograd Forestry Department for the period 2011-2012

Figure 1a: Digitalized shapes from paper map

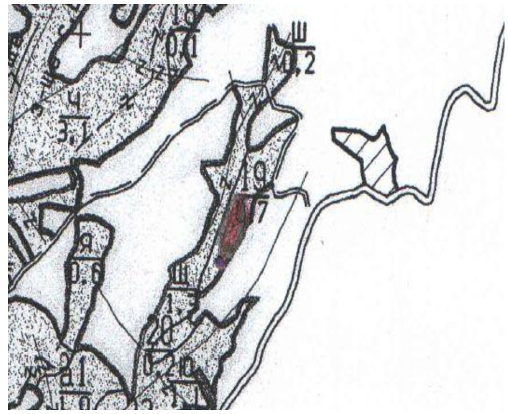

Figure 1b: Paper map sample

Data preparation and analysis

The first step in preparing data to run spatial fire behavior analyses was to determine suitable fuel models for fire locations in our Zlatograd test area. We did this using BehavePlus (Andrews 2007). BehavePlus is a point fire behavior prediction system that can be used to analyze fire growth and behavior for homogeneous vegetation with static weather data. Using a number of standard fuel models developed for the United States (Anderson 1982; Scott and Burgan 2005), we evaluated which fuel models were best able to produce estimates of fire behavior and growth in BehavePlus similar to those observed on each of the fifteen fires.

In addition to fuel model, BehavePlus requires inputs for weather, fuel moisture, slope, and duration of the burning period. We obtained weather data for each fire from TV Met, a private company in Bulgaria, which provided the ability to calculate fine dead fuel moisture values (Rothermel 1983). Due to the paucity of available weather data in Bulgaria, we had to assume that weather recorded for the weather station closest to each particular fire is consistent with weather experienced on the wildfire. We estimated live herbaceous and live woody fuel moisture values based on the expected phenological stage for the time of year that the fire occurred. To estimate slope, we first acquired a 30 m resolution digital elevation model (DEM) from the National Institute of Geophysics, Geodesy, and Geography in Bulgaria, then subsequently calculated the average slope for each fire using standard geospatial processing in ArcGIS (ESRI 2010). Burn period length for each fire was obtained from the Zlatograd forestry department data (Table 1).

Based on initial BehavePlus results using standard fuel models, custom fuel models were developed for some vegetation types not well represented by the US fuel models. Custom fuel models were developed for native durmast oak and grass as well as one of the Scotch pine sites by modifying fuel loading parameters to better match local vegetation and reflect the lack of woody debris in the understory, as it is collected as firewood by the local population. The custom fuel model developed for grass has a much lower rate of spread and flame length than any of the standard grass fuel models.

Following evaluation of fuel models with BehavePlus, we then performed analyses in FARSITE, a spatial fire growth system that integrates fire spread models with a suite of spatial data and tabular weather, wind and fuel moisture data to project fire growth and behavior across a landscape. We defined our test landscapes using a 500 m buffer zone around each of the fifteen Zlatograd fires (figure 2); this footprint comprised the extent of the spatial analysis for each individual wildfire.

Input for FARSITE consists of spatial topographic, vegetation, and fuels parameters compiled into a multi-layered “landscape file” format. Topographic data required to run FARSITE include elevation, slope, and aspect. Using the aforementioned 30 m DEM, we calculated an aspect layer, and then clipped elevation, aspect, and slope rasters to the extent of our fifteen test landscapes. Required vegetation data include fuel model and canopy cover. Fuel models within the 500 m buffered analysis area for each individual fire were assigned based on our BehavePlus analyses; fuel model assignments were tied to the dominant vegetation for each polygon based on the Zlatograd forestry department’s vegetation data. Canopy cover values were visually estimated from orthophoto images and verified with stand data from the Zlatograd forestry department. Additional canopy variables (canopy base height, canopy bulk density, and canopy height) that may be included in the landscape file were omitted, as these variables are most important for calculating crown fire spread or the potential for a surface fire to transition to a crown fire. None of the fifteen fires analyzed experienced crown fire.

Tabular weather and wind files for FARSITE were compiled using the weather and wind data from TV Met, Bulgarian meteorological company that included hourly records. Tabular fuel moisture files were created using the fine dead fuel moisture values calculated for the BehavePlus analyses for 1-hr timelag fuels. The 10-hr fuel moisture value was estimated by adding 1% to the 1-hr fuel moisture and the 100-hr fuel moisture was generally calculated by adding 3% to the 1-hr fuel moisture. The live fuel moisture values previously estimated for BehavePlus analyses were used to populate live herbaceous and live woody moisture values.

All simulations performed in FARSITE used metric data for inputs and outputs. An adjustment value was not used to alter rate of spread for standard fuel models, rather custom fuel models were created. Crown fire, embers from torching trees, and growth from spot fires were not enabled.

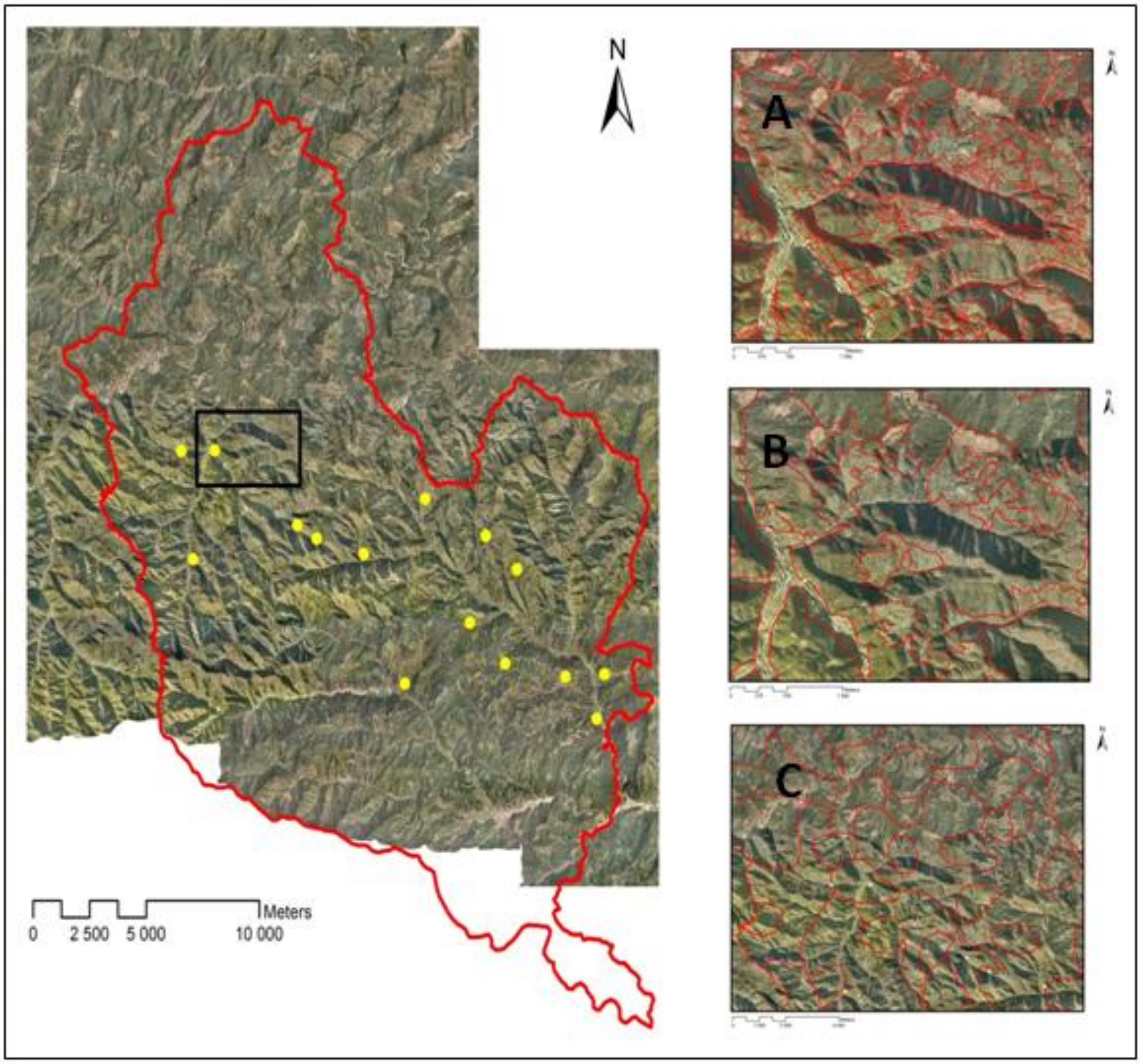

Figure 2: Location of the 15 fires (yellow dots) in the Zlatograd area that occurred in 2011-2012 that were used to develop fire behavior analysis methodology. The outline of the municipality of Zlatograd is shown in red, with the orthophoto imagery used to identify canopy cover underneath. The black box indicates the location of the three inset maps on the right. Inset maps are: A) Zlatograd forestry polygons; B) Corine land cover polygons; and C) Bondev vegetation map polygons.

Results

Although the fifteen case study wildfires were not large, we were able to establish a process to compile the necessary inputs and complete fire behavior analyses using both BehavePlus and FARSITE. As the first attempt to complete these types of analyses for Bulgarian landscapes, we successfully navigated the challenges of assembling input data for a location where data sources are scarce. We also successfully applied both modeling systems outside of the environment in which they were developed. In doing so, we learned important lessons (see below). More importantly, though, we were able to establish a defined methodology for the OUTLAND project for future use of BehavePlus and FARSITE for wildfires in Bulgaria.

As an example of one of our successful FARSITE runs, we present the results from a single wildfire that burned in grassland vegetation, for which we developed custom fuel models. This fire occurred on August 30, 2011, starting at 1400 and ending around 1800, and burned a total area of 0.3 ha. We used the following input parameters to model this small grassland fire in FARSITE:

Fuel moisture values: 6% (1-hr), 7% (10-hr), 9% (100-hr), 45% (live herbaceous), and 75% (live woody);
Daily maximum temperatures: 17-21°C;
Daily minimum relative humidity: 24-50%;
Winds: generally from the west-southwest at 1-2 k h^{-1}

The fire size as calculated using FARSITE was 0.5 ha, which seems reasonable considering the modeled size would not have included the suppression actions that most likely occurred given the close proximity of a village to this fire (figure 3).

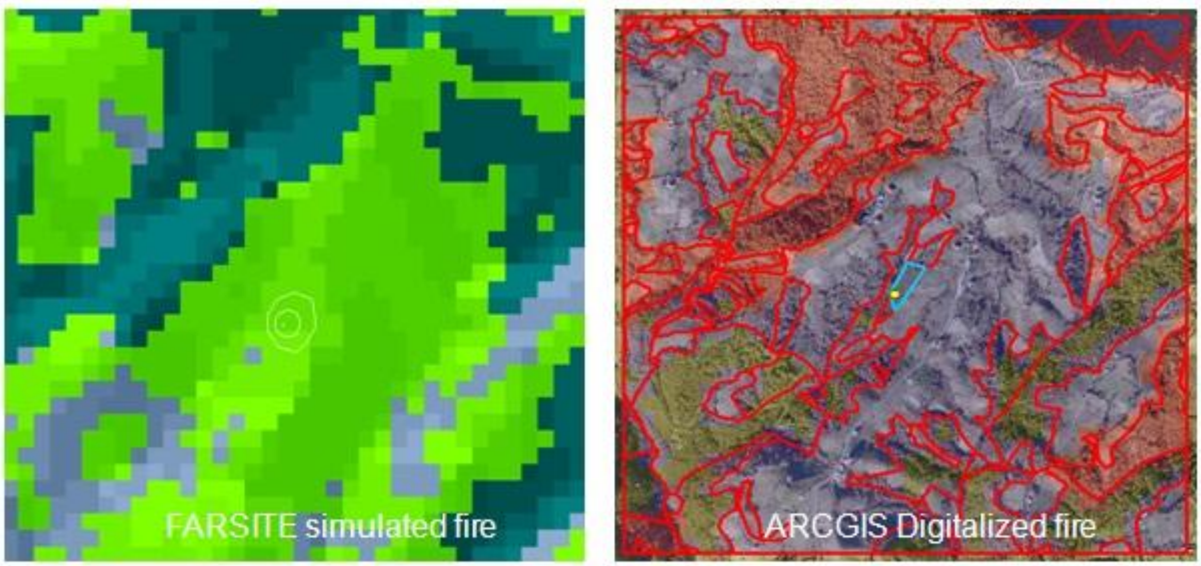

Figure 3: FARSITE run for a grassland fire

An example of another fire we modeled in FARSITE using standard fuel models was a fire that occurred on March 29, 2012 in a beechwood forest. This fire burned for a total of four hours, starting at 1400 and ending around 1800, and burned a total area of 0.5 ha. Wind speeds were variable throughout the burning period as they were quite high during the early afternoon but tapered off throughout the day. In this case we used the following input parameters in FARSITE:

Fuel moisture values: 3% (1-hr), 4% (10-hr), 5% (100-hr), 40% (live herbaceous) and 70% (live woody);
Daily maximum temperatures: 7-10°C;
Daily minimum relative humidity: 36-40%;
Winds: generally from the north-northeast at 10-2 k h^{-1}

The projected fire size from FARSITE was 0.9 ha. Based on the close proximity of a village to the fire location (figure 4) it is quite reasonable to assume that local residents responded to the fire in a volunteer capacity; these suppression actions are not accounted for in the FARSITE analysis. Decreasing winds through the afternoon may have significantly helped suppression activities.

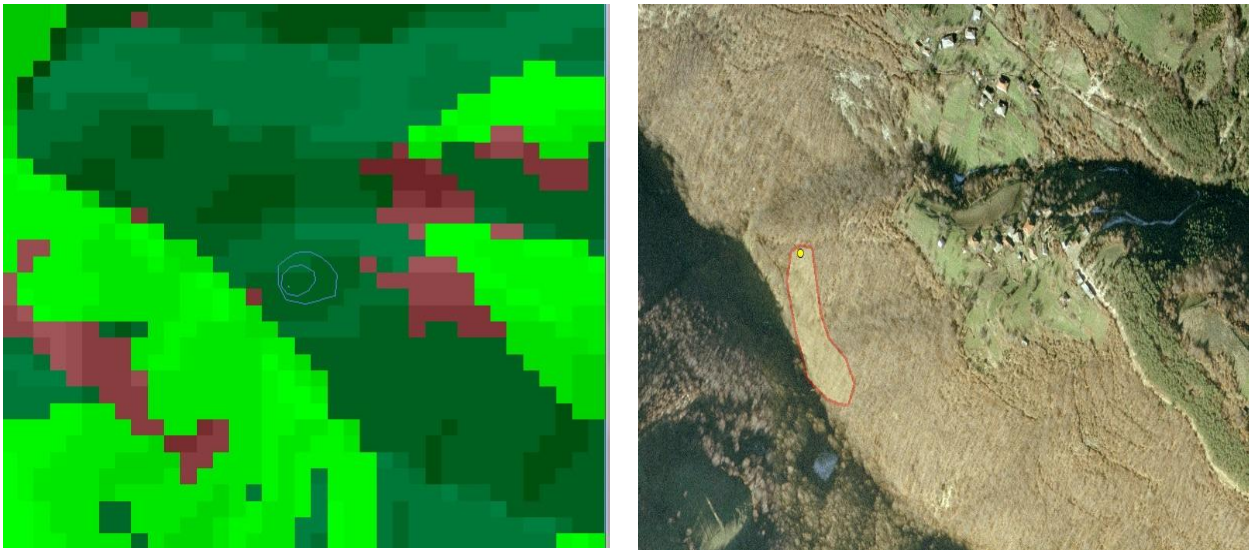

Figure 4: FARSITE run for wildfire that burned in a beechwood forest

Lessons Learned

In the presented work we describe the application of FARSITE and BehavePlus fire behavior systems for a test area in the Zlatograd municipal territory of Bulgaria, something that has never been accomplished in Bulgaria. These simulations will serve as a foundation for future work. Bulgaria is not nearly as data rich as other countries and therefore the process developed reflects the types of data readily available. This methodology was developed to be flexible and make use of potential future sources of data.

Through this process, we were able to identify shortcomings in the fire behavior systems, most notably how they deal with metric data. Applying fuel models developed elsewhere can be difficult, yet we were able to identify standard fuel models from the U.S. that seem compatible with Bulgarian surface fuels and also identify gaps in the standard fuel models indicating the need for custom fuel models for the Zlatograd area. Weather data is expensive in Bulgaria as it must be purchased; having better access to weather station data would more readily allow for future simulations without the monetary burden currently involved. Future simulations would require fewer assumptions if data specific to each fire were available, including the suppression actions and specific fire weather observations.

Conclusions

The work presented here represents the initial step in completing analyses to predict fire behavior and growth of recent wildfires in an area of Bulgaria. Information that would be valuable in refining this work in the future includes observed fire weather, observed flame lengths and rates of spread, direction of growth, suppression actions, and documentation of pre-fire vegetation. The availability of this data would allow comparison of modeled fire behavior with observed fire behavior, and improve the accuracy of computer-based simulations.

Preliminary fire behavior analyses identified which variables may need to be modified, for example which vegetation types may require creating custom fuel models. Through an iterative trial and error process, it became apparent how Bulgarian data can be used to perform simulations in BehavePlus and FARSITE, including the inherent nuances within each of these systems in working with metric data.

Acknowledgements

This work is supported by the National Science Fund of the Bulgarian Ministry of Education, Youth and Science under the call for "Fundamental scientific research support - 2012" – grant number I01/0006 and the EU project "Open protocols and tools for the education and Training of voluntary organisations in the field of Civil Protection, against natural Disasters (forest fires) in Greece and Bulgaria" with acronym (OUTLAND), funded under the Territorial Cooperation Program Greece-Bulgaria 2007-2013. The Fire Modeling Institute at the Rocky Mountain Research Station provided instrumental funding for data analysis and preparation of this manuscript.

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Proceedings of 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

A US national fuels database and map for calculating carbon emissions from wildland and prescribed fire

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Abstract:
Biomass burning has become an important component of Earth-system models as understanding improves about fire as a global ecosystem process. Smoke emissions are a health hazard to nearby communities, can impair air quality and visibility for hundreds of kilometers downwind, and contribute substantially to the global carbon and aerosol budgets. The Fuel Characteristic Classification System (FCCS) is both a conceptual framework and a software tool for quantifying fuels over spatial domains from a few square meters to many square kilometers. The authors and colleagues developed a spatially continuous classification of fuels, based on the FCCS, for the continental United States and Alaska. The FCCS 1-km fuel map is a core spatial data component of WFEIS, the Wildland Fire Emissions Information System, a web-based tool for computing emissions from wildland fires. The FCCS provides a detailed accounting of the carbon content of fuels, and the proportional consumption of biomass in each fuel category depends on both the fuel type and environmental conditions, such as fuel moisture and wind speed. Applications such as WFEIS can take advantage of the geographic variability of fuels captured by FCCS maps to increase the accuracy of estimates of the contribution of wildfires to the carbon budget.

Additional Keywords: Fire emissions, fuels

Introduction

Biomass burning is an increasingly important component of Earth-system models as understanding improves about fire as a global ecosystem process (Bowman *et al.* 2009; Krawchuk *et al.* 2009). Improvements in global fire occurrence databases continue with remote-sensing methods maturing along with more standardized record-keeping and reporting (Giglio *et al.* 2010; Raffuse *et al.* 2012). Carbon released from fires during combustion alters the global carbon balance (van der Werf *et al.* 2010). Smoke emissions are also a health hazard to nearby communities (Wegesser *et al.* 2009), can impair air quality and visibility for hundreds of kilometers downwind, and contribute substantially to the global aerosol budget.

A need for improved tools to map and quantify emissions from wildland and prescribed fire is evident. Integral to mapping fire emissions is information on the biomass that burns during fire, also known as fuel. The Fuel Characteristic Classification System (FCCS; http://www.fs.fed.us/pnw/fera/fccs/) is both a conceptual framework and a software tool for quantifying fuels over spatial domains from a few square meters to many square kilometers. Unlike fire-behavior fuel models, whose purpose is to provide parameters useful for predicting fire behavior and fire spread, the FCCS specifies vegetation composition and fuel loading of live and dead fuels, which are easily connected to remotely sensed vegetation types (McKenzie *et al.* 2007). The FCCS fueldbed descriptors provide details on fuel structure and loading (density) by vertical strata (Figure 1), providing data that have relevance for both emissions and basic fire behavior. In this paper we review a spatially continuous classification of fuels, based on the FCCS, for the continental United States (CONUS) and Alaska developed for emissions modeling. The initial versions of the FCCS maps covered forested and shrublands types in CONUS and Alaska leaving large areas of croplands and managed rangelands unmapped. The newly developed map reviewed in this paper includes fuels in forest, rangeland, and croplands across CONUS to allow for modeling of fire in both naturally occurring fires and prescribed burning.

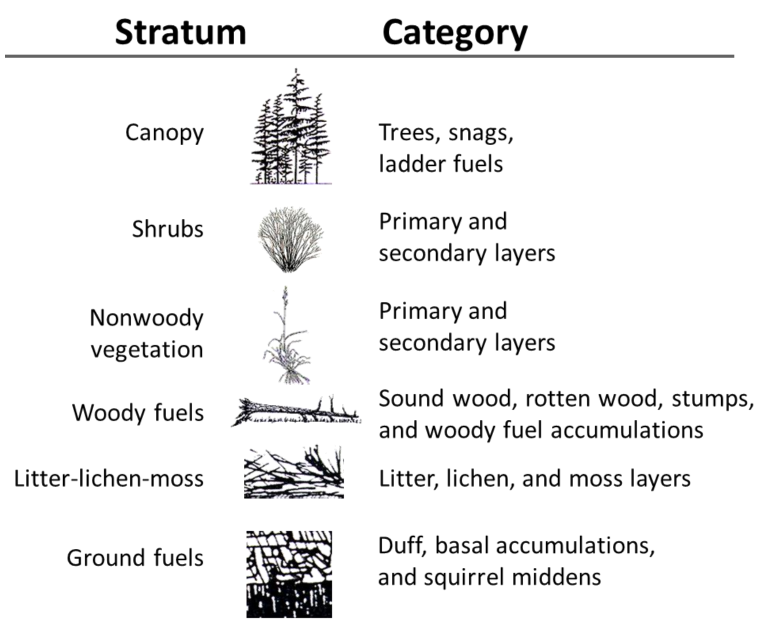


Figure 1: FCCS fuelbed strata used in describing the characteristics of fuels, including fuel structure and loading.

Mapping FCCS forest, rangeland, and cropland fuels

Maps of forest and shrubland fuels across CONUS and Alaska at 30-m resolution were created using a crosswalk to FCCS fuelbeds from the existing vegetation type (EVT) layer of LANDFIRE (www.landfire.gov). Upscaling to a 1-km grid scale was done by aggregating the FCCS fuelbed based on the majority type. Four hierarchical levels were used to decide type majority: fuelbed, species, cover type, and two life-form levels (Table 1). In the upscaling process most fuelbeds were retained with only five fuelbeds across lost due to their rarity.

Assignments for the upscaling were made based on the following decision steps:

- If the majority (>50%) of 30m FCCS fuelbed cells are of a single fuelbed category then the 1km FCCS fuelbed cell will be assigned the majority category.
- If there is no majority fuelbed among the 30m cells in the 1km cell extent, a majority species is sought;
    - if a species holds a majority within the 1km cell extent, the most common fuelbed associated with the species will be used.

- If no majority species exists, the same logic is repeated for the cover type, then life-form1, and finally life-form2 levels.

The final 1-km map (both CONUS and AK) contains 234 FCCS fuelbeds with just five fuelbeds from the original 30-m map lost in the aggregation process due to their rarity. The map of FCCS fuelbed map at the 30-m scale is publicly available from the Landfire webisite (http://www.landfire.gov/NationalProductDescriptions25.php), and the 1-km scale map from the USFS FCCS web site (http://www.fs.fed.us/pnw/fera/fccs/maps.shtml).

The forest and shrubland versions of the FCCS maps were created by the US Forest Service (USFS). They have now been augmented for the CONUS region with data on cropland types for two years, 2009 and 2010. This integrated product is the result of combining the spatially discrete Fuel Characteristic Classification System (FCCS) data of the USFS with the cropland and grassland-specific location information of the US Department of Agriculture's (USDA's) Cropland Data Layer (CDL). Fuel information and loadings on crop types developed by McCarty (2011) were translated into the FCCS format. Based on the CDL type maps, fuelbeds in cropland regions, which were set to zero in the original forest FCCS maps, were mapped. This integrated FCCS fuels map is available at the 30-m scale from the Oak Ridge Distributed Active Archive (ORNL-DAAC; French *et al.* 2013; Figure 2).

Table 1: Excerpted from the full hierarchy table used to downscale the FCCS map from 30-m to 1-km cell size.

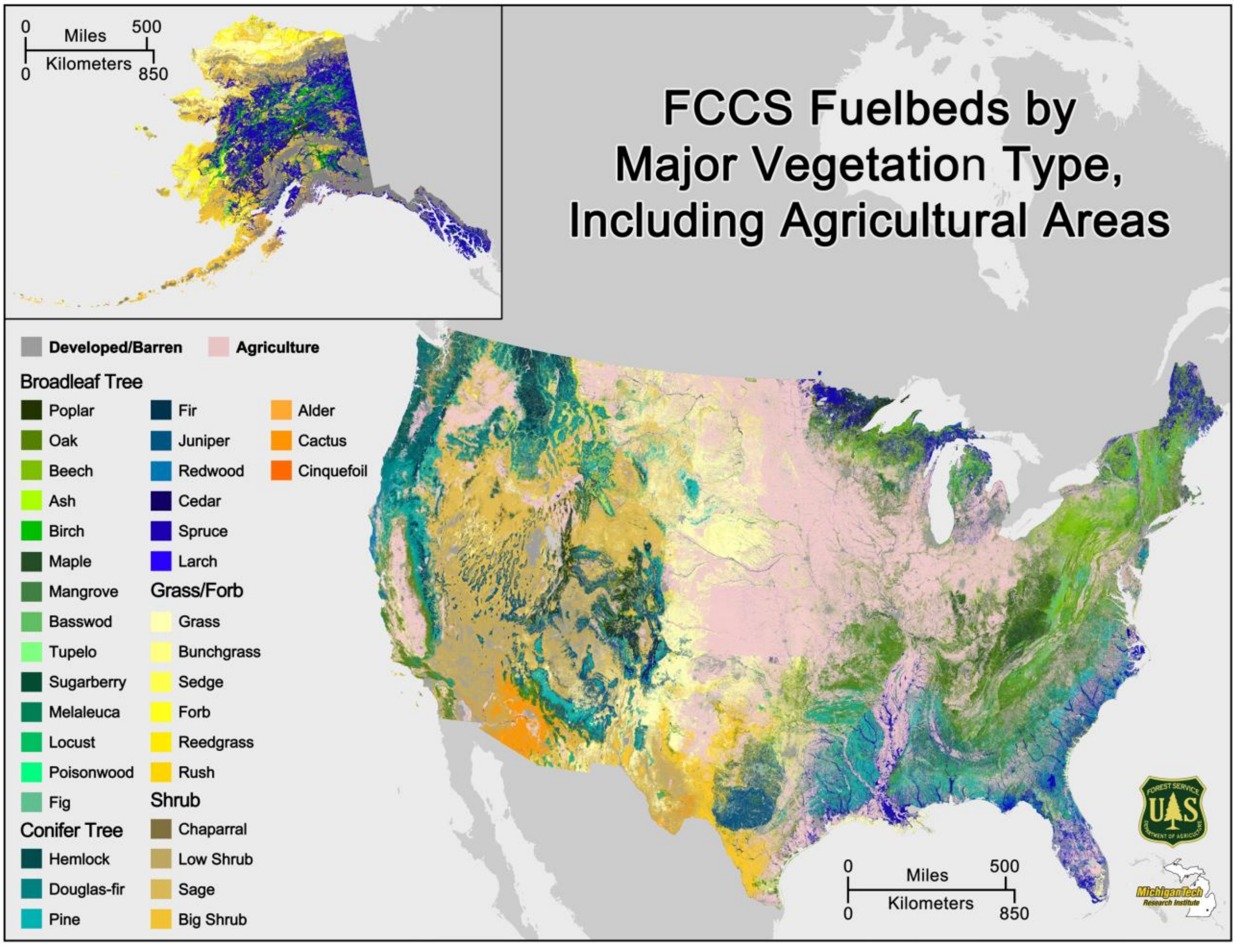
Figure 2. Final map of combined fuelbeds for the US.

Uses of the FCCS map databases

The FCCS map databases are used in diverse modeling efforts from real-time carbon-emission calculations for individual fires to continental-scale simulations of air quality. The FCCS provides a detailed accounting of the fuels available for burning in each stratum. Fire affects each fuel stratum in specific ways that influence the emissions produced. Specifically, fuels in the various strata have specific structures and are composed of many combustible materials.

FCCS hierarchy

fccsID	fuelbed.name	species	covertype	lifeform1	lifeform2
0	Agriculture – Urban – Barren	barren	barren	barren	barren
1	Black cottonwood - Douglas-fir - Quaking aspen	cottonwood	poplar	broadleaf	tree
2	Western hemlock - Western redcedar - Douglas-fir forest	whemlock	hemlock	conifer	tree
4	Douglas-fir / Ceanothus forest	Douglas-fir	Douglas-fir	conifer	tree
5	Douglas-fir - White fir forest	Douglas-fir	Douglas-fir	conifer	tree
6	Oregon white oak - Douglas-fir forest	owhite-oak	oak	broadleaf	tree
7	Douglas-fir - Sugar pine - Tanoak forest	Douglas-fir	Douglas-fir	conifer	tree
8	Western hemlock - Douglas-fir - Western redcedar / Vine maple forest	whemlock	hemlock	conifer	tree
9	Douglas-fir - Western Hemlock - Western redcedar / Vine maple forest	Douglas-fir	Douglas-fir	conifer	tree
10	Western hemlock - Douglas-fir - Sitka spruce forest	whemlock	hemlock	conifer	tree
11	Douglas-fir / Western hemlock - Sitka spruce forest	Douglas-fir	Douglas-fir	conifer	tree
12	Mountain hemlock - Red fir - Lodgepole pine - White pine forest	mhemlock	hemlock	conifer	tree
14	Black oak woodland	black-oak	oak	broadleaf	tree
15	Jeffrey pine - Red fir - White fir / Greenleaf manzanita - Snowbrush forest	Jeffrey-pine	pine	conifer	tree
16	Jeffrey pine - Ponderosa pine - Douglas-fir - Black oak forest	Jeffrey-pine	pine	conifer	tree
17	Red fir forest	red-fir	fir	conifer	tree
18	Douglas-fir / Oceanspray forest	Douglas-fir	Douglas-fir	conifer	tree
19	White fir – Giant sequoia – Sugar pine forest	white-fir	fir	conifer	tree
20	Western juniper / Huckleberry oak forest	wjuniper	juniper	conifer	tree
21	Lodgepole pine early seral forest	lodgepole	pine	conifer	tree
22	Lodgepole pine forest	lodgepole	pine	conifer	tree
24	Pacific ponderosa pine - Douglas-fir forest	ponderosa	pine	conifer	tree
25	Pinyon - Juniper forest	wjuniper	juniper	conifer	tree
27	Ponderosa pine - Two-needle pine - Juniper forest	ponderosa	pine	conifer	tree
900	Water	barren	barren	barren	barren



Also, fire can burn in flaming or smoldering combustion in any of these strata, which produces different emissions composition, and this can vary between strata. Therefore, characterizing fuels and combustion by stratum aids in more accurate accounting of emissions and the proportion of CO_2 versus other gaseous emissions released. Here we review a few of the applications where the spatial fuels maps we have developed have been of value.

Carbon emissions mapping: The FCCS 1-km fuels map is a core spatial data component of WFEIS, the Wildland Fire Emissions Information System (http://wfeis.mtri.org/), a publicly available web-based tool for computing emissions from fire in the CONUS or Alaska at landscape to regional scales (1-km spatial resolution). WFEIS was initially developed with funding from the NASA Carbon Cycle Science Program for the North American Carbon Program (http://www.nacarbon.org/nacp/). A principal use of WFEIS outputs is regional-scale spatially explicit estimates of carbon emissions from fire (French *et al.* 2011). The proportional consumption of biomass in each fuel category is modeled in WFEIS based on the fuel type, fuelbed structure, and the environmental conditions such as fuel moisture and wind speed. Applications such as WFEIS that take advantage of the geographic variability of fuel characteristics captured by the FCCS maps can increase the accuracy of estimates of the contribution of wildfires to the carbon budget. With the FCCS fuel maps as a core spatial data layer, the WFEIS provides access to fire-perimeter maps from one of two sources, MODIS-derived burn area (Giglio *et al.* 2009) and the Monitoring Trends in Burn Severity products from the USGS (http://www.mtbs.gov/), overlays them on the fuel maps, and calculates fuel consumption and emissions with an open-source version of the Consume model, also publicly available (http://code.google.com/p/python-consume/). Besides tabular results, WFEIS produces multiple vector and raster output formats, including ArcGIS shapefiles, KML, GeoTIFF, and netCDF. The system is built entirely from open-source software that follows international standards developed by the Open Geospatial Consortium (http://www.opengeospatial.org/).

Emissions monitoring of greenhouse gases and pollutants: In addition to carbon cycle science, the FCCS maps are a valuable data source for mapping emissions of several important pollutants. The US National Emissions Inventory (NEI; http://www.epa.gov/ttn/chief/), the Regional Haze Rule (http://www.epa.gov/visibility/factsheet.html), and the US-EPA climate-change program (http://epa.gov/climatechange/emissions/usinventoryreport.html) require monitoring of pollutants from a variety of sources, including fires. National fire databases provide fire location information that can be overlain on the FCCS maps to estimate total fuel loadings within a fire perimeter. Consumption estimates and emission factors are then applied to calculate amounts of pollutant species, both aerosols and particulates, lofted into the atmosphere. This methodology was used in calculation of emissions from cropland burning for the 2005 and 2008 NEIs (Pouliot *et al.* 2008; Soja *et al.* 2008). Until the 2005 NEI, burning in agricultural regions was not fully accounted for due to a lack of information on where and how much burning was occurring in US agricultural operations. Using new information on fire occurrence, overlain with fuels information, these emissions are now more reliably included in the NEI. The 2011 NEI will include cropland burned area and emissions from the approach developed by McCarty (2011), which was used to inform the development of the improved FCCS data.

Air-quality simulations: Projections of future air quality rely on meteorologically-based simulations of transport and on inventories of pollutants that can be measured or otherwise estimated consistently over large spatial domains (regions to continents). The FCCS maps have become a key component of integrated modeling frameworks such as BlueSky (http://airfire.org/bluesky), which links independent models of fire information, fuel loading, fire consumption, fire emissions, and smoke dispersion (Larkin *et al.* 2009). BlueSky is used daily by air-quality and fire managers in the Pacific Northwest, USA, for smoke forecasts from ongoing fires, but also is used for future projections at both regional (McKenzie *et al.* 2006) and national (Chen *et al.* 2009) scales.

Watershed-scale fire management: Local applications of fuels databases, such as planning fuel treatments to reduce fire hazard, especially around the wildland-urban interface, would ideally use local fuel inventories. These are time-consuming and expensive to assemble, however, and are lacking in many critical fire-prone areas, such as the chaparral ecosystems of Southern California. The high-resolution (30-m) FCCS map layer provides surrogates for local databases when they are either lacking or of questionable accuracy, out of date, or incomplete. For example, the 30-m resolution FCCS was used to estimate emissions from the 2007 southern California wildfires to inform respiratory health research in San Diego (Koziol et al. 2010).

Updating and refining the map layers

In croplands, the spatial location of crops varies annually, meaning that the fuels burning at a particular place can be different from year to year. In cropland areas, FCCS can be mapped annually from the CDL so accurate loadings are used in assessments. In some forested ecosystems, such as arid mountain forests with frequent wildfires, fire affects up to 10% of the total area in one year. Like many broad-scale geospatial databases, the FCCS maps within these forested landscapes will gradually become obsolete because they reflect a static vegetation layer (based on LANDSAT imagery) that involved substantial computation and cannot feasibly be updated annually. To improve on this, updates of the FCCS can be made using information on disturbance. For example, in the US fire perimeters are mapped annually from Landsat imagery under the Monitoring Trends in Burn Severity (MTBS) project lead by the USGS (http://www.mtbs.gov/). The LANDFIRE project updates vegetation products every five years using this and other disturbance information. From these products and using simple forest succession models the FCCS maps could be updated annually, ensuring that they remain reasonably current. For both agricultural and forested sites, therefore, information is available for creating more temporally dynamic fuels that would improve emissions assessments.

Another fuels mapping improvement under development is a method to refine fuel loadings in the dominant vegetation layer at each location by informing the FCCS map layer with MODIS-derived data. First is the Vegetation Continuous Fields (http://glcf.umiacs.umd.edu/data/vcf/) product, which gives proportional estimates for vegetative cover, and second is a map of estimated total biomass in forested ecosystems developed by the NASA Carbon Monitoring System Phase 1 activity (http://carbon.nasa.gov/cgi-bin/cms/inv_pgp.pl?pgid=582#datasection). These overlays will provide improved canopy fuel loadings for each cell, which can be updated as the MODIS products are refreshed and give more precise estimates of: 1) fuel loadings within a cell; and 2) their variability at spatial scales from watersheds to the continent.

Conclusion

Mapping fuels is important in developing improved assessment of fire emissions across local to global scales. We have developed maps of fuels appropriate for regional to continental-scale fire emissions assessments that use ecological principles to describe fuel characteristics relevant for emissions calculation. The maps are based on USGS, USDA and USFS data on vegetation distribution. The maps have application for a variety of emissions mapping needs, including use within the WFEIS model for carbon cycle accounting.

Acknowledgements

The research presented was supported through grants from the NASA Carbon Cycle Science Program (Grant # NNX08AK69G to MTRI and USFS), the NASA Applications Air Quality program (Grants #NNX09AP53G to the National Institute of Aerospace, A. Soja, PI), the NASA Applications Wildland Fire program (#NNX12AQ90G to MTRI and USFS), and the NASA Carbon Monitoring Program (Grant #NNX12AM91G to MTRI and USFS).

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Development of methods of calculating the probability of evacuation from unique buildings based on a stochastic approach

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Abstract: Currently, authors develop methods of calculating the probability of escape from unique buildings by the probability of input parameters, namely, the specific rate of burnout, the linear velocity of propagation of the flame of fire load, the number of evacuated people, the rate of people during movement a fire, start of the evacuation. On the basis of a stochastic simulation model that implements the Monte Carlo simulator ´Town Planning Code of the Russian Federation of 29.12.2004 № 190´ was developed by assessing changes in the height of smoke-free zone during the development of a fire in the atrium. Comparison of simulation results with experimental data on the fire in the atrium of the model shows coincidence between calculated and experimental data. The aim of future work is the perfection of the presented model and increase of the number of the model input parameters.

Additional Keywords: Fire safety, unique buildings, evacuation, Monte Carlo simulator, atrium.

Introduction

Under Part 2 of Art. 48.1 ´Town Planning Code of the Russian Federation of 29.12.2004 № 190´, to unique objects are the objects of capital construction (except as provided in paragraph 1 of this article) in the project documentation, which is provided at least one of the following:
1) The height of over 100 m;
2) spans more than 100 m;
3) the presence of the console more than 20 m;
4) The penetration of the underground part (fully or partially) below the level of the planning of land more than 15 m.

In addition to capital construction projects with the above characteristics, it is proposed to consider also objects to the presence of clerestory spaces (the atria). The other large open spaces are, for example, malls, arcades, exhibition centers, malls, galleries, airport terminals and train stations. The term “atrium” is used in the synthesis sense and apply to any of these great spaces.

Atrium space is central to the structure of many social and recreational, cultural, and business buildings. It's safe to say that with the development of construction technologies, improvement of the forms of trade, population growth of large cities, social and technological developments in the design of buildings clerestory spaces, especially in the large public centers will be expanded. According to ´Order of the Ministry of Emergency Situations of Russia 12.12.2011 № 749´, “as the scenario with the worst fire conditions should be considered scenario, characterized by the

most difficult conditions of evacuation of people and (or) the highest growth dynamics of fire hazards, namely fires:
indoor and atrium-type space systems ...”. The evacuation time estimates used to determine the likelihood of evacuation P_{ev}, were produced in a deterministic setting.

These unique buildings have a high fire danger. Some of the reasons are as follows:

•Because of the nature of space-planning decisions during the development of the atria fire burning products with greater than in a typical layout, speed, spread to the upper floors;

•Developed in the height atrium convective column above the fireplace fire has great height, which because of the heavy involvement of the column of air from the environment results in a significant increase in the volume of smoke;

•If a fire, smoke may enter the atrium of the adjoining areas as well as in remote areas along the corridors overlooking the atrium;

•For high-volume atrium and open it in the corridors and galleries of combustion products have a relatively low temperature, which reduces the efficiency of the smoke exhaust system due to low buoyancy of smoke;

•Atriums are usually provided in the buildings crowded with people and are the connecting centers of the communication network the movement of people through the building, and thus, the atrium smoke “cuts” the basic unit of the system of escape routes. By the validity and reliability of estimates of fire risk at such facilities must be brought increased demands and, above all, to assess the probability of escape in case of fire.

In assessing the probability of escape in case of fire dynamics modeling of buildings spread of fire hazards, as well as simulation of evacuation must be probabilistic (stochastic) staging, especially for unique objects for which at present there are no standards for fire safety and to which the full grounds include clerestory space (the atria) located in buildings with a high level of responsibility in terms of providing the required level of fire safety.

Under these conditions, it is proposed that for estimating the time of the evacuation of unique buildings, buildings with clerestory spaces require a probabilistic approach, using simulation. The probabilistic nature of the evacuation time determined by the level in the wild random variation in the number, type and location of combustible materials, the fire location, quantity, location and composition of the evacuees at the time of the fire, a group of mobility, etc. At the same time, in determining the time of evacuation of people in fires of the unique, especially complex of buildings, buildings with massive presence of people is necessary to increase the validity and reliability of the calculations.

In order to solve this problem we are encouraged to use the Monte Carlo method, which combines the physical representation of the success of the evacuation of large (several tens of thousands) of statistical test in one calculation, taking into account a wide range of conditions encountered in specific design fire for a unique multi-level buildings with atriums and for the examination of the quality of design solutions for individual objects on which to supervisory authorities contentious issues arise.

This current project uses methods of collecting baseline data to determine the time of evacuation of people, based on an analysis of the characteristics of the input factors. The selection of the factors used in the procedure is based on the results of studies of the process of evacuation, as well as a series of experiments on real objects in order to identify patterns of the process of movement of people.

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Green roof designs and wildfire: Risks and benefits in the wildland urban interface for fire management professionals

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Abstract:

As green roofs continue to grow in popularity, their appearance in wildfire-prone areas is likely to occur with increasing frequency. Although there is extensive research on fire in the wildland urban interface (WUI) and structure design to minimize fire risk, there has been very little research into how green roof designs may hold up during a wildfire that is threatening structures.

This presentation defines various green roof designs, describes their function and construction, and discusses what particular variables fire management personnel should pay attention to when conducting structure protection operations during a wildfire event. It will also address the critical role that proper maintenance plays in ensuring that green roof designs function to minimize wildfire risks, rather than magnify them.

Additional Keywords: Green roofs, blue roofs, sustainability, green infrastructure

Modeling fire propagation and behavior under various scenarios of extreme conditions for supporting fire management decision-making at the landscape scale under climate change

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Abstract: In Spain, as in other Mediterranean countries, wildfires are causing ecosystems degradation. Climatic change will likely enhance the problem making necessary fire management strategies designed at the landscape-level. In that sense, fire managers need a better understanding of fire responses to changes in vegetation and climate/weather conditions. Fire models, such as FlamMap that was used in this study, are valuable tools. Under the foreseen weather conditions conducive to higher fire risks in the region, changes caused by climate extremes on the vegetation water status are expected to influence landscape-level fire patterns. Vegetation features will interact with major fire propagation drivers, such as wind.

After analyzing the historical series of the Canadian fire weather index, we classified the fire weather conditions in the area in relation to fire risk using a percentile analysis. Based on the historical fire occurrence, 1000 fire ignition points were defined in the area. FlamMap simulations were ran for the current land use-land cover scenario under extreme weather conditions combined with two wind speed scenarios and two fuel moisture scenarios. Preliminary results suggest that vegetation water status and wind conditions, as well as their interaction, will be highly relevant in relation to fire growth and behavior under future extreme weather conditions.

Additional Keywords: Mediterranean landscapes, FlamMap, fuel moisture, wind speed

Introduction

In Spain, as in most northern Mediterranean countries, fires have become a major cause of ecosystems and landscape degradation. The magnitude of the problem will likely be enhanced by climatic change, to which the region is highly susceptible (IPCC 2007), making necessary the implementation of landscape-level designed fire management strategies (Duguy *et al.* 2013). Such efforts require careful planning based on a better understanding of how fire may respond at that operational level to changes in both vegetation (i.e. fuel) and climate/weather conditions. In that sense, fire models such as FlamMap (Finney 2006) have become valuable tools.

Our working hypothesis is that under the foreseen weather conditions conducive to higher fire risks in the future, changes caused by climate extremes (droughts and heat waves) on the vegetation water status will influence patterns of fire spread and behavior at the landscape level.

Vegetation features will interact with major fire propagation drivers, such as wind. Our aim is to gain insight on those interactions applying a fire-modeling based approach in a landscape representative of large marginal lands affected by wildfires in Spain.

Methods

FlamMap incorporates the same fire behavior models as FARSITE (Finney 1998), which we had previously calibrated in a nearby area (Duguy *et al.* 2007). We assembled data on topography and fuels in a binary landscape as required by FlamMap, at 100 m resolution. The fuel-related layers were derived from the 2006 CORINE land use/land cover map.

After analysis of historical series of the Canadian Fire Weather Index (FWI, Van Wagner 1987), we classified the fire weather conditions in the area in relation to fire risk using a percentile analysis: moderate, severe and extreme weather days were classified using the FWI 75p-95p-99p thresholds, respectively. The same FWI thresholds were applied to identify the days with moderate, severe and extreme fire weather conditions in the future, using the FWI projections established by CMCC (http://www.cmcc.it/) after high resolution climate projections performed with the CMCC-Med global General Circulation model and the Regional climate model (CMCC-CLM) for the period (2001-2100), under scenario A1B, in the framework of the EU 7th FP FUME project (http://www.fumeproject.eu/). Three weather scenarios ("Moderate," "Severe," and "Extreme") were then built using the mean values of the climatic variables (temperature and relative humidity) across the corresponding set of future days.

We built two wind speed scenarios. The largest and the smallest wind speeds (35 km/h and, 16 km/h respectively) were fixed considering the 95th and 75th percentiles, respectively, of wind speed values observed in the study area.

Two scenarios of fuel moisture were built. The "Very Extreme" fuel moisture scenario was derived considering the fuel moisture values associated to the largest fires of the study area (≥95th percentile). The "Extreme" scenario was obtained increasing the fuel moisture values to the 75th percentile of the historical fuel moisture values. Finally, based on the historical fire occurrence of the studied landscape (1976-2010), 1000 fire ignition points were set. For all combinations of weather/wind speed/fuel moisture scenarios, 1000 fires were simulated with FlamMap. The outputs selected for comparing the alternative combinations of scenarios are fire size (ha), burn probability (%), flame length (m), rate of fire spread ($m.min^{-1}$) and fire intensity ($kW.m^{-1}$). All outputs were analyzed in ArcGIS.

Results and Discussion

The fuel moisture scenario is an input that clearly affected fire size, burn probability (BP), rate of spread (ROS) and fire intensity (FI) (Table 1). For any combination of weather and wind speed scenarios, the mean values of fire size (MFS) and BP increased as fuel moisture decreased. Mean values of ROS and FI also generally increased.

Under the "Extreme" weather scenario, the decrease in fuel moisture caused increases in MFS ranging from 6 to 23.9%, whereas they ranged from 22.6 to 40.6% under the "Moderate" weather scenario. The same ranges of variation were observed for BP. As for ROS, the decrease in fuel moisture caused increases in mean values ranging from 3.6 to 18.9% under the "Extreme" weather scenario, whereas they ranged from 24 to 29.3% under the "Moderate" weather scenario.

Under the most extreme wind speed scenario (35 km/h), the decrease in fuel moisture caused increases in MFS ranging from 6 to 22.6%, whereas they ranged from 17.8 to 40.6% under the other wind speed scenario (16 km/h). The same ranges of variation were observed for BP. Fire size variations clearly reflect the interaction between vegetation water status and wind speed. While the fuel moisture reduction led to a 22.6% increase of MFS under a wind speed of 35 km/h, the increase was of 40.6% under a wind speed of 16 km/h. Results suggest that the less extreme the weather or the wind speed scenario, the larger the effects on fire spread and behavior caused by a decrease in fuel moisture. The weather conditions prevailing during a fire (especially wind speed) are major fire drivers. If those conditions are already very extreme, changes in the vegetation water status have a smaller effect on fire.

For any combination of weather and fuel moisture scenarios, mean and maximum values of all parameters were much larger under the highest wind speed (Table 1). Mean ROS and mean FI appear to be more sensitive to wind speed changes than MFS. While the wind speed increase caused increases of MFS ranging from 4.4 to 37.8%, the increases ranged from 176.2 to 217% and from 181.8 to 238.6% in the case of mean ROS and mean FI, respectively.

The comparison of the simulations outputs obtained under the “best” and “worse” combination of weather/wind speed/fuel moisture scenarios in relation to fire risk (i.e. “Moderate” weather/16 km/h/“Extreme” fuel moisture and “Extreme” weather/35 km/h/“Very extreme” fuel moisture, respectively) suggests that the expected new weather conditions in the Mediterranean region will have strong effects on patterns of fire spread and behavior. Under the “best” combination of scenarios, 18% of the landscape had a BP larger than 20%. Maximum predicted BP was 32%. Under the “worse” combination, 37.4% and 5.2% of the landscape had a BP larger than 20% and 50%, respectively. Maximum predicted BP was 63%.

Conclusions

Results suggest that the foreseen new weather conditions in the Mediterranean region may clearly alter patterns of fire spread and behavior thus, increasing severity, confirming the hypothesis proposed.

Under the tested extreme weather conditions, fuel moisture and wind speed interacted determining fire size, rate of spread and intensity, but also burn probability across the landscape. This interaction was clearly influenced by the weather conditions prevailing during the fire. The effects of changes in either fuel moisture, or wind speed tended to be weaker under more extreme weather conditions, but generally remained very significant.

Results suggest that larger more intense thus, more severe fires may be expected under the projected extreme future weather conditions and that fire-proneness will tend to increase. This study emphasizes the need for addressing the landscape scale when designing the new fire management strategies that are required under global change. It also highlights the crucial role of fire models as supportive tools for landscape-level fire management decision-making.

Acknowledgements

This work was developed from research conducted under **GRACCIE**, Spanish CONSOLIDER INGENIO 2010 (CSD2007-00067), and EU 7th FP **FUME** project (FP7-ENV-2009-1-243888).

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Table 1. Fire simulations results (SD: standard deviation)

Weather	**Wind speed** (km/h)	**Fuel moisture**	**FIRE SIZE** (ha)				**BURN PROBABILITY**				**FLAME LENGTH** (m)				**RATE OF SPREAD** ($m.m^{-1}$)				**FIRE INTENSITY** ($kw.m^{-1}$)			
			min	**max**	**mean**	**SD**	**min**	**max**	**mean**	**SD**	**min**	**max**	**mean**	**SD**	**min**	**max**	**mean**	**SD**	**min**	**max**	**mean**	**SD**
Extreme	**16**	very extreme	2.47	10514.33	5412.45	2776.42	0	0.55	0.18	0.15	0	6.25	1.84	1.23	0	24	6.3	3.3	0	17723	3366.7	2986.1
Extreme	**16**	extreme	2.47	8806.84	4369.01	2366.21	0	0.47	0.15	0.13	0	6.25	1.69	1.17	0	24	5.3	3.2	0	17430	2924.8	2663.1
Severe	**16**	very extreme	2.47	8841.43	4446.65	2347.91	0	0.48	0.15	0.13	0	5.75	1.63	1.12	0	20	5.4	2.9	0	13849	2671.5	2389.5
Severe	**16**	extreme	2.47	7736.87	3774.27	2078.31	0	0.41	0.13	0.11	0	5.75	1.56	1.08	0	21	4.8	2.9	0	14636	2432.9	2218.13
Moderate	**16**	very extreme	2.47	8342.28	4332.98	2289.73	0	0.47	0.15	0.12	0	5.75	1.61	1.10	0	21	5.3	2.9	0	14541	2571.4	2314.8
Moderate	**16**	extreme	2.47	7094.40	3082.32	1848.52	0	0.32	0.10	0.09	0	5.25	1.43	1.04	0	17	4.1	2.7	0	10878	2069.9	1875.6
Extreme	**35**	very extreme	2.47	14865.86	5650.05	3892.93	0	0.64	0.19	0.17	0	7.25	2.03	1.47	0	37	17.4	8.7	0	26361	9488.4	8001
Extreme	**35**	extreme	2.47	14077.59	5334.71	3712.57	0	0.63	0.18	0.16	0	7.25	2.02	1.50	0	40	16.8	9.3	0	29451	9903.6	8474.4
Severe	**35**	very extreme	2.47	14107.25	5513.44	3831.28	0	0.63	0.19	0.16	0	6.75	1.99	1.45	0	37	16.9	8.5	0	25854	9036.97	7644.6
Severe	**35**	extreme	2.47	13200.37	4775.56	3482.04	0	0.60	0.16	0.15	0	6.75	1.87	1.41	0	35	14.8	8.4	0	24737	8199.4	7035.6
Moderate	**35**	very extreme	2.47	14191.26	5208.06	3686.67	0	0.61	0.17	0.16	0	6.75	1.92	1.41	0	35	15.9	8.3	0	24302	8290.8	7038.8
Moderate	**35**	extreme	2.47	11720.21	4248.73	3183.80	0	0.58	0.14	0.14	0	6.25	1.76	1.34	0	29	12.8	7.4	0	19203	6844.98	5871.3

Protection of settlements from emergency situations caused by vegetation fires

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Abstract:
The number of vegetation fires dramatically increases during severe droughts. Some fires are not suppressed in time, or escape containment reaching large sizes and often creating emergency situations. Analysis shows that both in Russia and abroad the main focus is a passive method of protection of settlements from vegetation fires by means of preventive activities, however, their effectiveness is often not high. To resolve this issue it is not enough to increase technical means, which are incomparable with the might of the fire element. In Russia, this issue is especially acute since the majority of settlements, which can be threatened by vegetation fires are wooden.

In the example of two Siberian settlements burnt by vegetation fires, we analyzed the conditions that can lead to emergency fire situations and the existing methods of their protection. As a result, we developed guidelines for passive and active methods of settlement protection. The active methods imply the use of backfiring, the technology of which with participation of local population is given. To predict possible emergency situations caused by vegetation fires and to predict fire behavior, recommendations are given on creation and use of fine scale vegetation fuel maps on the example of a specific settlement.

Additional Keywords: Wildland urban interface (WUI), passive methods of settlement protection, active methods of settlement protection, backfiring, vegetation fuel maps, Siberia

Introduction

The 2010 fire season in Russia was broadly discussed in mass media In the paper "Lesnaya Gazeta" the authors wrote extensively and specifically about degradation of the forest fire protection in the country and its causes. Some TV programs broadcast interviews with the Russian governmental officials of different ranks (including the emergency specialists). What struck us was the lack of awareness of these officials in terms of active fire management and, moreover, in terms of protection of wildland urban interfaces (WUI) from forest fires. The local population also showed helplessness: they did not know what to do to save their houses when they knew the fire was approaching

The tendency in Russia to only increase technical power when fighting wildfires will not solve the problem: no aircraft can extinguish a fire of high intensity. First of all, we should address the fire science as it was done abroad. Fire behavior prediction systems were created long ago and are being developed further in the USA and Canada. Russia has no such a system yet although there are all prerequisites for this (Sofronova *et al*. 2010). But the senior executives of the Federal Forestry Agency should get interested in funding this project. It is also necessary to improve the available practical recommendations on protection of WUI from emergency wildfire-related situations and to bring them to forest protection specialists' and local population's notice.

Background

WUI protection from wildfires is in the limelight of foreign publications. Fire hazard, relief, fire frequency, and road nets are considered (Camia *et al.* 2002; Lein and Stump 2009). The territory adjacent to the houses within 30-60 m radius is of special concern. According to the model of ignition of buildings from wildfires, the main factor is burning particles (Cohen 2001).

The US, Canada, and Australia consider burning of structures to be the major threat to people, whereas Mediterranean countries consider structures to be shelters since houses there are rarely ignited by wildfires (Caballero *et al.* 2007). After Australia's "Black Saturday" in February 2009, when a number of people died, the following strategy was developed: not to evacuate during a wildfire if it is already late but stay and defend the houses from burning. This strategy would have been possible if a special training for this very situation had been carried out beforehand. The reason to suggest this strategy is the fact that more often people die during evacuation because of untimely warning (Mutch *et al.* 2010).

The idea to turn structures into objects invulnerable to wildfires exists in the US as well. The following approach is even suggested when the fire fighting services do not attempt to stop the approaching fire but let it go through the settlement which had been prepared for the wildfire attack (Cohen 2001). It should be noted that Russian houses in the WUI are mainly made of wood and this approach is impossible to apply there. Thus, the international attention is focused on the passive method of protection of settlements from wildfires by improving the fireproof properties of structures, and by thorough preparation of the territory around each building within 30-60 m radius. It is not taken into account that under extreme weather conditions fuel properties, the character of their burning and fire behavior dramatically change and threaten settlements.

Russia also focuses on the fire preventive arrangement of the territory (Furyaev *et al.* 2000; Ryapolova *et al.* 2003). There are practical recommendations for fire prevention to be used for propaganda among local population but they are unfortunately presented as a list of boring instructions (Glavatsky *et al*. 2006). For local outreach science-popular literature about forest fires is preferable. The lack of such literature is acute in Russia (an example of such literature can be found in M.A. Sofronov and A.D. Vakurov's book "Fire in Forest" (1981) which is a bibliographical rarity).

Our objective was to consider the conditions, which may cause fire-related emergency situations in the vicinity of settlements, and to consider the existing ways of protection to expand and improve them as well as to show their application on the example of the specific settlement.

Results

We investigated two settlements burnt by forest fires: the village Khaya of the Boguchansky raion (Krasnoyarsk region) and the village Ulbugay in the Tunkinsky hollow (Republic of Buryatia) (Volokitina 2002). Analysis of the study results and other fire-related emergency situations near settlements allowed us to come to the following conclusions:

1) Settlements can ignite from both crown and intensive surface fires;
2) A large enough wildfire (over 100 ha) in the vicinity of a settlement can become especially dangerous if the wind changes its direction and turns along fire flank into a wide fire front;

3) Ignitions of structures in settlements directly from the flames of the wildfire are rare since houses and settlements are often surrounded by unburnable areas (fields, gardens, streets, roads, etc.). Usually ignitions of structures occur from burning particles thrown before the fire front. The number of burning particles and the distance of their trajectory depend upon the intensity of the wildfire and the wind speed. According to our observations, intense fires under a strong wind can produce spotting of the vegetation cover (and, consequently, houses) at a distance up to 400-500 m.

Analysis of existing methods of WUI protection from wildfires

When a fire approaches a settlement, some wooden structures catch fire and then the fire spreads to other structures. Therefore, the existing recommendations on protection of settlements (Furyaev *et al.* 2000; Ryapolova *et al.* 2003) from wildfires suggest two groups of activities: 1) fire preventive measures within the settlements to reduce the risk of ignitions and interfere with the fire spread within the settlement; 2) fire preventive arrangement of the territory adjacent to the settlement (a system of fire/fuel breaks) in order to keep the fire at a safe distance away from the settlement.

As an *active protection measure*, suppression of the approached fire edge is suggested by any means. Sometimes "backfiring" is mentioned. Why are the existing recommendations ineffective? In our opinion, the reasons are as follows:

1) Efforts to reduce hazardous fuels around the settlement turn out to be ineffective.
2) An intensive wildfire, especially of large size, easily overcomes fire/fuel breaks, mineralized stripes, roads, etc. at the expense of throwing burning particles before the fire front. The distance can reach 400-500 m under a strong wind.
3) Backfiring, a simple and most effective method of fire edge suppression (including a crown fire) is almost never used in the protection of settlements. Historically, in early 20th century, Siberian peasants were known to have used backfiring to protect their villages from approaching wildfires. Consequently, this method is not new. This method was also considered as optimal in the practical recommendations developed by the Sukachev Institute of Forest "Protection of settlements from emergency situations related to wildfires" (Volokitina 2002).

There are several reasons why backfiring is of limited use. One of them is related to terminological confusion in the Russian literature where for more than a century a practical and safe *backfiring* is confused with a fantastic and dangerous *counter fire* [Leviz 1833; Sofronov and Vakurov 1981).

There is a psychological barrier as well. People are afraid to start burning the forest and supposedly damage it even for the sake of their own houses. They are unaware of the fact that a weak backfire does almost no harm to the forest. On the contrary, it rescues the forest from a devastating fire. There is nobody to explain this to people since the ground forest fire protection employees rarely have practical experience in backfiring.

There are also technical difficulties in arrangement and carrying out of backfiring. To begin with, it is necessary to create a mineralized stripe around the settlement. Its length can reach several kilometers. This takes a lot of time, which is not available when a wildfire is approaching. However, this can be resolved rather easily.

Firstly, it is necessary to create the mineralized stripe around each settlement having a risk of being damaged by a wildfire. This should be done beforehand during fire preventive arrangement of the territory. And this mineralized stripe should be kept ready for use by annually removing litter and grasses so that when there is a warning of an approaching fire it could be immediately used for backfiring. Secondly, such settlements should have volunteer fire brigades familiar with backfiring not only in theory but in practice as well (for example, during prescribed burns).

We have developed a technique how to identify settlements and other objects that can be damaged by wildfires. In the example of the Krasnoyarsk Priangarie we identified the settlements at risk of being damaged by wildfires:

a) Those in the vicinity of the Angara river – Nizhneteryansk, Kamenka, Artyugino, Angarsky, Gremuchiy, Krasnogorievsky, Shiversky, Khrebtovy, Manzya, Pinchuga, Yarki, Boguchany, Goltyavino, Govorkovo, Tayozhny, Karabula;

b) Those in the vicinity of the Chuna river – Pervomaysk, Burny, Osinovy Mys, Novokhaysky, Chunoyar, Oktyabrskiy.

As an example, we made a project for creation of a mineralized stripe for backfiring with the help of a specially made fine-scale vegetation fuel map for the area near the settlement Osinovy May in the Chunsky ranger district.

The recommended mineralized stripe surrounds the settlement from three sides. Its ends merge the Chuna River. The western and eastern parts of the stripe go mainly along forest roads up the valley slopes, and the northern part of the stripe goes along the top of a slope in the cutting.

Technology of backfiring for protection of a settlement from an approaching fire

For the backfiring to be effective it is important to start it timely since the backfire spreads slowly and the wildfire approaches quickly. Therefore, it is recommended to get accurate information about the fire situation in the radius of 10-15 km from the settlement.

When there is a high probability that a large fire can approach a settlement (or another important object), it is necessary to start backfiring immediately. The main objective of backfiring during protection of a settlement is not to suppress the fire but not to let it approach the settlement at a dangerous distance. The wildfire can go around the settlement from one or both sides and continue its spread further.

To carry out a backfire, two groups of no less than 3 people each are organized. Each group should have means of ignition as well as means of fire suppression (shovels, hoes, backpack fire extinguishers). A backfire is usually started at one point on the side facing the approaching fire and then the groups go from this point in the opposite directions and go along the mineralized stripe constantly igniting the surface fuels. One member in each group ignites litter or moss near the edge of the mineralized stripe and the rest walking at a distance behind him and each other member of the group (in a chain) thoroughly monitor the forest floor on the opposite side of the stripe in order to suppress any ignitions from burning particles thrown over the stripe. Later for each 100 m one person is left to monitor the edge of backfiring for an hour (or for 2-3 hours under windy weather conditions).

After the backfire edge measures 5 meters from the mineralized stripe, one can start acceleration of the backfiring. The most simple and safe method to do it is to ignite stripes 5-10 meters each perpendicular to the backfire edge.

After the backfiring is finished, the area between the mineralized stripe and the settlement should be monitored for timely suppression of ignitions from the approaching fire. The monitoring can be done from the roof of a high-rise or via ground patrol. Settlement houses should be periodically checked as well.

Conclusion

The only measure of active protection of WUI from fire-related emergency situations is timely backfiring. For this, it is necessary to identify in advance those settlements which can be potentially damaged by wildfires, and to prepare mineralized stripes for timely backfiring in case of a fire around the settlement for the distance of 200-500 m depending upon the weather conditions and the wind speed. The ground forest fire protection specialists should know the technology of making a backfire as well as the leaders of volunteer firefighting brigades who can effectively provide help of the local population for backfiring. Smoke-jumpers are usually well trained for backfiring but their number is scarce nowadays. Under good coordination it is possible to cope with the situation without attracting resources from the expensive Ministry of Emergency Service. There is no need to hurry up with making new fire breaks everywhere. They tend to be grown with grass and only increase fire hazard during spring and autumn drought. In each specific case, the area around the settlement should be characterized in terms of fire hazard. This will allow the predication of fire behavior, i.e. its spread rate, intensity, and effects. There are necessary elaborations for this (Volokitina *et al.* 2010).

The immediate focus should be on training specialists to use methods of active fire management on the basis of their behavior prediction. So far there is no single university in Russia where such specialists would be trained. There is a lack of highly qualified teachers and up-to-date educational materials in the field of fire science.

Acknowledgements

We are thankful for financial support to Macarthur Foundation (grant #01-116-000) and to Krasnoyarsk Krai Forestry Agency (State Contract 2008-2010).

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