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Introduction to the Proceedings of Third Fire Behavior and Fuels Conference

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Abstract. The third installment in the International Association of Wildland Fire's Fire Behavior and Fuels Conference series was held in Spokane, Washington, October 25-29, 2010. The conference theme was 'Beyond Fire Behavior and Fuels: Learning from the Past to Help Guide Us in the Future'. A total of 203 written contributions are contained within the conference proceedings.

Additional keywords: 1910 fires, case studies, decision support systems, fire ecology, fire history, fire management, fire regimes, fire weather, fuel dynamics, fuel mapping, fuel modeling, fuel simulation, fuels management, fuels treatment, post-fire effects, smoke, wildland-urban interface.

The International Association of Wildland Fire (IAWF) is a non-profit, professional organization founded to promote a better understanding of wildfire, built on the belief that an understanding of this dynamic natural force is vital for natural resource management, for firefighter safety, and for harmonious interaction between people and their environment. The association is dedicated to facilitating communication within the entire wildland fire community and providing a global linkage for people with shared interest in wildland fire and comprehensive fire management. IAWF publications such as the *International Journal of Wildland Fire* and *Wildfire* magazine contribute towards this communication objective as does the proceedings from the various conferences sponsored by the association (http://www.iawfonline.org/proceedings.php). These include the Wildland Fire Safety Summit, Human Dimensions of Wildland Fire Conference, and Fire Behavior and Fuels Conference series as well as other special conference events (e.g. Masters *et al.* 2009).

The first IAWF Fire Behavior and Fuels Conference was held in Portland, Oregon, in March 2006 and focused on 'how to measure success' in fuels management (Andrews and Butler 2006). The second IAWF Fire Behavior and Fuels Conference was held a year later in Destin, Florida, in March 2007 and focused on innovations in technology, management and policy related to the widland fire environment (Butler and Cook 2007). The IAWF is pleased to have the support of the USDA Forest Service to include the proceedings from these first two IAWF Fire Behavior and Fuels Conferences within the present conference proceedings CD.

The third IAWF Fire Behavior and Fuels Conference was held in Spokane, Washington, October 25-29, 2010, and commemorated the 100th anniversary of the 1910 fires in the Northern Rocky Mountains. The theme of the conference was appropriately titled 'Beyond Fire Behavior and Fuels: Learning from the Past to Help Guide Us in the Future'. The 1910 fires were a precedent setting event and have since had far-reaching implications on how the wildland fire community and society as a whole views and deals with wildland fires regionally, nationally and internationally. It seemed only fitting that on the 100th anniversary of this historic event that we reflect on lessons learned from the past as we implement innovative and contemporary best practices with managing wildland fires in the future.

Over 450 participants from several countries were in attendance at the conference in Spokane. A total of 98 presentations covering nearly the full gambit of wildland fire management and science were delivered over the course of four days. This involved opening and closing conference keynote addresses, five plenary keynote addresses, 91 oral presentations delivered within 18 subject matter sessions, 105 poster presentations, and a special panel discussion related to the conference theme (Keller 2010).

The conference also included exhibitor and vendor displays, a film festival, banquet featuring the Wilbur Rehmann Quartet, a fun run and walk in support of the Wildland Firefighter Foundation, a fundraiser for the International Fire Relief Mission, and 12 pre-conference workshops attended by more than 201 people. A description of these activities are given in Robinson *et al.* (2010) which is also included on the conference proceedings CD along with photos taken of various conference activities and a list of registered conference participants.

Many folks contributed to the success of the IAWF's Third Fire Behavior and Fuels Conference, including the registered conference participants. Thank you one and all for a job well done. The Robinson *et al.* (2010) document contains a list of the members of the conference steering and program committees, the session moderators, and conference sponsors and exhibitors. It also includes biographical sketches of all the conference presenters.

The conference presenters were given the opportunity to decide whether they wished to contribute an abstract, an extended summary or a full paper for the conference proceedings. Some presenters have elected to publish fuller accounts of their presentations in peer-review journals such as the *International Journal of Wildland Fire*.

In closing, a special debt of gratitude is in order. In editing these conference proceedings, Dale W. Wade (USDA Forest Service retired), did yeoman-like service for the IAWF.

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The cash value of fire history: an apologia

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Abstract
Fire history belongs with the humanities as much as with the sciences. What fire practitioners mostly want from history, however, are data, lessons, and meaning, all of it coded in ways that speak to operations, or what William James called the ‘ cash value’ of ideas into practice. In the end what historical scholarship can provide is not information or lessons so much as a richer sense of judgment.

Additional Keywords: history as humanities

‘*You must bring out of each word its practical cash-value, set it at work within the stream of your experience*.’
- William James, *Pragmatism* (1907)

Two cultures

By training and temperament I’m a historian. I’ve seen the past, and it works. But by formative experience and long association, I’m also a member of the fire community, which generally shares Henry Ford’s famous dismissal of history as ‘more or less bunk’ and for the same reason. They look to the future. Their historical horizon rarely extends more than three years.

When they do turn to history, they do so for practical wisdom, as a depository of utilitarian knowledge. In particular, they look to history to satisfy three needs. They want data, they want lessons, and they want meaning, and they want it all in a form they can use. They want, in brief, to convert ‘history’ into what the great philosopher of Pragmatism William James called the ‘ cash-value’ of practice.

Data

By their own training, fire practitioners believe that fire management should be a branch of applied science. So they look first for history as a source of data that they can insert into models and prescriptions. If cyberspace can be data-mined, why not the past? In more cartoonish moments they might imagine historian-miners trudging off to dank archives like the Seven Dwarves, whistling while they work at prying out gems of wisdom.

The sad fact is, historical records were not written to satisfy existing models, and they can rarely provide the ready data that the fire community would like. Typically, there is too much or too little, and most of what is preserved is not in a form that can slide into the I/O protocols of computer models. The issue is not simply that historical ore is refractory but that it’s hard to distinguish the precious portion from the gangue. So while history is surely experimental, it is hardly controlled; and while it is sometimes possible to smelt that crude ore into more refined matter, the more usual response is a shrug. The stuff of history is dismissed as anecdotal. Its cash-value is suspect or worthless. We are more likely to use data from the present to reconstruct past events than data from the past to explicate present processes.

Still, if not data, history can help convey an appreciation that the landscapes the fire community confronts are not the result of abstract principles randomly stirred together like pancake batter. The scene looks the way it does because those ingredients came together in a particular order, and not a necessary one. Anyone versed in the history of a place will appreciate that the scene cannot be re-placed (as it were) simply by identifying the critical pieces and processes and beating them together in any sequence. The firescapes before us are historically constructed. Pretending otherwise – assuming that it all can be wiped clean and start over – is delusional and destructive. The Pol Pot theory of environmental management.

Lessons

If data doesn't work easily, then perhaps lessons might. Isn't history mostly stories? Aren't we supposed to learn from experience and draw lessons from the past? But 'lessons' are understood in a peculiar way by the fire community, as part of a technological program in which experience is used to refine tools and sharpen behaviors that function as a tool. History, that is, is imagined to improve our practices and prescriptions in the same way that experience introduces continual improvements into the design of an automobile's U-joint or the procedures for open heart surgery.

In this regard experiences – stories – are deemed interchangeable and universal in the same way that a faulty spark plug or poorly tied diamond hitch are independent of the life-history or psychology of an automobile driver or a mule packer. They are testimonies not tied to temperaments. The U.S. Forest Service has even gathered volumes of such lessons from which the names of individuals have been erased. 'Lessons' thus resemble 'data' in that they exist apart from the actors who create and preserve them. Such a notion will seem odd to historians, but it illustrates again the extent to which the square pegs of a text-based historical scholarship don't fit into the round holes of quantitative models, the demands of bureaucratic schemas, and the urgent need to act.

There is a difficulty in that controlled behavior requires a controlled setting. A garage or an operating room will do; a patch of wildland won't. The other difficulty with lessons, as with data, is that not all of them are equal, and there are too many of them. It is possible to assimilate dozens of fireline experiences, but not hundreds, and as the Web now makes possible, thousands. Lessons stream out of history like embers from a crown fire. There must be a process for filtering, vetting, and editing. Otherwise the past becomes a jumble, or in this case, a digital junk yard in which one might, with persistence, find a rear bumper that will fit the 1936 Ford coupe that one wants to restore, but reduces historical scholarship to antiquarian hobbyism or vocational gossip. Lessons don't by themselves, or when injected into other disciplines, make sense of the past or have the past make sense of the present. That requires judgment.

Sometimes checklists can sort through the clutter. But lists cannot be too long and they have to be memorable. It's possible to remember the Ten Commandments. It's not likely anyone will recall at an instant's notice the litanies of prescribed ritual that fill Deuteronomy. So, too, it's possible to recall the Ten Standard Orders, but not the metastasizing rosters of Watch Outs, What Ifs, and Maybe Alsos or the individual stories that proliferate like Tweets.

That may point to a checklist of stories. But we will still need judgment to match stories with lessons, and lessons with probable fireline experiences. Piles of stories do not make an informing narrative any more than jumbles of words make an essay. Even when organized, words may add up to a dictionary, a useful reference, not a working protocol. We remember instructions better through stories, but flashing stories become banal and unseen, like highway billboards that finally dissolve into a rushing blur of the past.

The lessons of history reveal human character, not natural laws. Their true lessons are such things as the fragility of knowledge, the tenacity of ignorance and fantasy, and the appreciation that wisdom relies on character rather than information. Flawed judgment is more often a source of error than faulty equipment or protocol. Humility matters as much as know-how.

Meaning

This leads to the third expectation, that history can create meaning. Instead of pretending it is a social science or shoehorning it into a technological matrix, this vision accepts – encourages – history's status as a scholarship that deals with values, beliefs, personalities, and idiographic events, and with evidence that doesn't come from controlled experiment, which is to say, it accepts history as part of the humanities. Historians preserve and celebrate the deeds of the clan; but beyond their role as chroniclers and court poets, they are critics who ponder, evaluate, and select. They record a moral universe.

The past becomes usable, that is, not just as data sets or scrolls of lessons but when it becomes informed by judgment. Historians trade in a currency that comes from speaking to those issues of ethics, aesthetics, narrative, and perceived understanding of the world that do not reside in the sciences and in fact can help place those sciences themselves within a social and intellectual setting. (Where did the science come from? Why, in a particular case, choose this science over that one?) Historians provide meaning by comparison and context. They replace certainty with contingency, and positivism with pragmatism. They furnish to policy and practice a historic range of variability, or what might be considered a cone of plausibility.

The concept of a usable past is an old one, not more background babble from postmodernism. It recognizes that just as scientific models rely on boundary conditions, so do narratives. Depending on how it is framed, the same information can yield different outcomes. There is no absolute truth, only working understandings that depend on how you construct the question, how you choose to cut your slice of time, how you select your narrative voice. How you start and end determines your narrative arc, which is to say, your theme and the power of the insights and the conviction it can convey. If you start the American fire story in 1492, you get one narrative, and if you begin in 1910, another. If you start in 1960, you get something again very different. There is nothing new about this idea – Aristotle laid it out more or less completely in his *Poetics*.

Those choices – the way a narrative gets created out of the raw ' blooming buzzing confusion' of life, as William James put it - is the value-added that historians bring to the table. Meaning is not something you pluck out of the past like nuggets. It is made. Physics and philosophy, economics and literature, art and anthropology, all find ways to parse and parcel the intrinsic confusion of the world in ways that make sense and allow practitioners to act. The particular task of historians is to sift through the range of historic variability and transmute its record into usable understanding. The process is not restricted to the provenance of professionals: it's what we all – ordinary people in everyday lives - do with our experiences. The value of scholarly history is that it can bring a more tempered evaluation through a richer sense of context. It stands to vernacular life as the Missoula fire lab does to a backyard burn pit.

I think the American fire community understands and, within limits, welcomes this role for history. With equal measures of pride and perplexity, it recognizes that the most influential document published within the past 40 years did not come out of field or lab but from a book-lined study - a meditation written by a professor of Renaissance literature at the University of Chicago about a forest fire that happened in the Northern Rockies in 1949. This was of course Norman Maclean's *Young Men and Fire*.

Remarkably little changed in the aftermath of Mann Gulch. The tragedy lodged in the memory of Region One and the smokejumper corps, but it affected almost nothing else. Fire research ignited after another blowup, the Soviet Union's first atomic bomb test two weeks later. Fire safety training arrived after the Rattlesnake and Inaja fires burned over two more crews. It's impossible to write a fire history of the United States without reference to the Big Blowup or the cavalcade of conflagrations that swept over the Lake States in the late 19th century. It's entirely possible to write that history without reference to Mann Gulch.

Or it was until 1992. The fire's real impact came only after Norman Maclean published his masterpiece 43 years later. That book, part history, part meditation, helped connect wildland fire to a larger American culture and forced the fire community to reexamine how it practiced its craft and why what it did might matter to anyone else. In Maclean's example the chroniclers and court poets found their voice, for he managed to silence the hall, and then to inspire those who heard him to do their work better. In the quest for cash-value, Norman Maclean won the lottery.

The tree and the flame

Not all historical scholarship pays off so grandly. Much is mundane, or abstract in ways that might appeal only to the guild of professionals. But the same can be said of science. Most studies add little; their real value is to help maintain the community of scientists. Some speak only to a handful of specialists interested in arcane questions intrinsic to the field. Humanity, after all, has successfully managed fire without laboratory data and mathematical models for all of its existence as a species. (In truth, one might identify the breakdown in fire use as the moment when a self-conscious forestry shouldered aside all fire knowledge that was not vetted by formal science.)

The two genres of scholarship follow very different logics. The humanities grow only a little along a cambium fringe. Most of its literature is deadwood, or more properly heartwood, not living but still essential to the structure and physiology of the scholarship. By contrast, science is a flaming front, sometimes wide and sometimes narrow, but active only along that spreading perimeter. Its past is ash and embers. It's possible to read Aristotle's *Poetics* for insights into the nature of tragedy. No one would read his *Meteorologica* as an introduction to earthquakes.

We need both. Science verifies data, while the humanities verify meaning, and it is meaning – that most vaporous of concepts, that least commercial of enterprises – that will ultimately guide practice because we must judge what we do by what we value, and we value only what we can endow with significance. It is through constructed meaning that we assess best practices, decide what is right and proper, and determine what it is we ought to aspire to. Science helps make better pumps and pulaskis. History helps tell us what to do with them. That's worth real money.

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We never saw it coming

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Abstract. In this paper I:1) explore the prevalence of blind optimism, 2) describe some of the cultural practices that sustain it, 3) discuss the organizational structures that both facilitate and discourage it and, 4) reflect on some ways of developing a more balanced vision of best and worst case scenarios. I use lots of varied examples to make my points, but I also try to link the discussion specifically to firefighting as often as possible.

Introduction

What's the worst thing that could happen to you? Can you clearly articulate it? Ten years ago, I suffered an extended illness. Following what was promised to be an uneventful sinus surgery, I developed a series of life disrupting ailments that my doctors seemed unable to diagnose. For over two years, my life was turned upside down. There were more surgeries, specialized treatments, endless medications and tests. And in the midst of it all I asked myself 'What was the worst news the doctors could deliver to me? Cancer … an inoperable tumor … more surgery … more medicine? Or would the doctors remain unable to diagnose me?' Which of these options would be the worst? Frankly, I simply wasn't sure.

Was it just me? Was I the only one who couldn't crystallize the worst? I became curious. So when I returned to work, I decided to informally poll some of my students. First, I asked them: what's the best thing that could happen to you? Their answers were amazingly precise. One person told me, 'The best thing that could happen to me is that Tom and I finish school and get married in June.' Another said, 'To get all As this semester and raise my GPA to 3.76.' Still another said, 'I would become an NBA franchise player in the next 3 ¼ years.'

A few moments later, I asked my students: 'what's the worst thing that could happen to you?' The precision disappeared. They offered very vague, general, answers like 'maybe, death?' 'getting sick,' or simply 'failure.' I was intrigued … so I started casting my net wider looking at people's conception of the worst in a wide array of situations. I looked at research on couples about to marry, parents during pregnancy and stages of child-rearing. I looked at information on people facing key life events: a first sexual encounter, a first job, preparing for old age or widowhood. I looked at decision making in corporate boardrooms and among scientists and engineers. I even examined agencies designed to anticipate and combat disaster.

In the vast majority of settings I found the same thing. Most individuals do not … cannot … envision the worst case scenario, and very often, they don't systematically plan for it. Why? What explains this overwhelming pattern?

Many would frame the problem in psychological terms. Envisioning the worst is frightening, morose, even disabling. Undeniably, these issues are important. But today, I'd like to suggest that broader forces are also at work. I argue that the inability to envision and specify the worst is, in part, a sociocultural phenomenon. Let's call this phenomenon blind optimism – an unbalanced way of seeing the world. In examining a broad array of social situations, I have identified a set of longstanding cultural practices that create a collective tunnel-vision directed to best case scenarios and an accompanying disregard for worst case scenarios.

How prevalent is blind optimism?

I'm here to tell you that it dominates nearly every corner of our lives. Here are a few brief examples from the American experience.[1]

In love …
Despite the fact that as many as 1 in 2 American marriages end in divorce[1], about 85% of Americans define their relationships as 'very happy' or 'pretty happy.' Furthermore, 61% of American teens, a group drastically affected by the high divorce rate, say they expect to be happily married to the same person for life. Perhaps that's why less than 5% of Americans secure prenuptial agreements.

With regard to aging …
85% of Americans 45 and older believe they will be fully functional – i.e. driving, exercising, moving freely until death! And 80% believe that medical science will find cures for what ails the old in their lifetimes! Note too that 75% of Americans believe they will die in their own homes as opposed to an institution and nearly two-thirds believe they'll be able to afford whatever they want. No wonder far less than half of Americans plan for the challenges of old age, i.e. wills, catastrophic health insurance, ample savings, etc.

Blind optimism abounds in the workplace as well …
In the U.S., we have a 1 in 3000 chance of being hurt while on the job or on our way to work. In the larger scheme of things, those are no small odds. Yet in polls, occupational hazards are rarely if ever mentioned as a common worry. In fact, Americans are more likely to believe in extra-terrestrials than they are to believe that they may be hurt at work.

With regard to the economy …
Despite the realities of any particular era, Americans are, in the long run, more likely to feel optimistic than pessimistic about the economy. In 2000-2001, a time that saw a serious downturn in the U.S. stock market, Americans' view of the economy reached an 18 year-low. But within mere weeks of the massive market decline, numerous polls showed that 68% of Americans were optimistic about the economy, both in the short and long-term. The same is true for the present crisis. 2008 presented some of the most serious economic catastrophes in our history. Less than a year later, only 1 in 5 of those polled thought an economic collapse was even possible, and about two-thirds of Americans felt recovery was a given and well underway.

One last area – that of national security …
Despite all our worries with regard to terrorism, blind optimism steers our thinking here as well. Polls show that in the weeks immediately following the 9/11 attack, many Americans worried about additional disasters – an errant plane, an anthrax attack, a dirty bomb. But within two short months, only 13 percent of Americans said they were 'very worried' about being attacked. After the 2009 Times Square bombing incident, only 12% mentioned terrorism as a major concern. Within one short month, that number dropped to 9%. And currently less than one-half of 1% of Americans mentioned terrorism as the nation's most important problem.

I could offer countless other examples of the grip that blind optimism has on Americans and other Western European societies. Blind optimism taints our vision. It dominates the attitudes and behaviors of individuals, as well as policy-making groups. Blind optimism is the rule, not the exception. And those who fail to exercise it are often ostracized as hypochondriacs, neurotics, sad sacks, Debby Downers, or kooks!

Culture

[1]Sources for the statistics cited here can be found in my book, Never Saw It Coming (Chicago: University of Chicago press, 2006). Figures for phenomenon post publication of my book are taken from the Gallup Poll

I've said that blind optimism is a widespread phenomenon. What sustains it? I argue that part of the explanation rests in culture. Specifically, I have discovered that in most groups and communities, certain identifiable cultural practices are at work –practices that, in essence, direct our attentions toward best case scenarios and away from thoughts of the worst.

What are these cultural practices? In my research, I've carefully unpacked three sets of practices that function in this regard. I call them eclipsing, clouding, and recasting. I'm going to describe each practice and use lots of varying examples to illustrate what I mean. Let's start with eclipsing. Eclipsing practices allow community members to distance and hide the worst. These practices are typically initiated by a ritualistic moment of collective avowal, and then, a moment of partitioning or removal. Eclipsing rests on the premise that groups and communities know the worst when they see it, but once acknowledging it, they can and should disattend it or release it from focus.

Communities practice eclipsing in a variety of ways. Banishment represents one example. Banishment, of course is highlighted in myth and scripture. Oedipus was banished to the wilderness for his unspeakable acts of incest. Lucifer was banished to hell for questioning God's supremacy. Judas was banned from the Last Supper for betraying Jesus to the Romans. But of course, banishment is a phenomenon of the real world too. The Greeks and Romans believed banishment cleansed communities of the worst and thus kept people focused on loftier ideals. They preferred it over execution.

In more modern times, the English banished their worst offenders to their colonies. The Russians used the Siberian territories in the same way. In fact, banishment is so effective in hiding the worst from sight that many would prefer to die, viewing death as a way to maintain a 'presence' in the community. Yasser Arafat and Sadam Hussein provide two recent examples of individuals who, when designated as evil and threatened with banishment said they preferred death. For those hoping to maintain political power, life on a perceptual fringe is much less valuable than death in a burst of glory.

Physical seclusion is another means of eclipsing the worst. Historically, asylums hid the mentally ill. Almshouses hid the poor and downtrodden. Prisons hid and continue to hide the worst criminal offenders. In healthcare settings, we still seclude the sickest of patients in out-of-the-way hospital wards or the upper floors of nursing facilities. And we still relegate the worst of moral behaviors (pornography, prostitution, and the like) to out-of-the-way city sectors.

Shunning accomplishes much the same thing, although the practice leaves the door open for re-acceptance. Thus, religious communities such as the Amish or Jehovah's Witnesses shun their sinners until those sinners 'see the light.' The fortunate have been known to shun the homeless on their city streets. Shunning has even been adopted by some new online communities. When the worst are 'out of sight,' the best can monopolize our attentions.

Clouding practices also help us maintain blind optimism. Like eclipsing, clouding strategies involve a ritualistic moment when group members come together and acknowledge the worst. But in clouding, that identification is never followed by disavowal. Clouding practices simply distort the worst, keeping it present, but blurred in its details.

There are two clouding strategies quite common to the perception of quality: impressionism and shadowing. Impressionism mirrors the artistic technique. Rather than explicating details, it supplies only broad strokes of meaning. This unfocused presence makes it difficult, almost futile, for groups and communities to dwell on the worst.

One stark example of impressionism comes from religious communities. Impressionism has been central to Judeo-Christian treatments of two places we might denote as the best and worst of final destinations – heaven and hell. Think of St. John's book of Revelation. John devotes a substantial portion of Revelation's twenty-two chapters, page after page of painstaking detail to descriptions of heaven. We learn of a thrown suspended on a rainbow with 'four and twenty seats' surrounding it, of elders 'clothed in white raiment' with 'crowns of gold.' John tells is of lamps of fire, seas of glass, lions and lambs, beasts with wings, horsemen, books of reckoning, songs and rituals of worship.

John's descriptions of heaven are elaborate and full of color. And they are strikingly more plentiful than the references to hell. Indeed, in describing hell, John provides only brief, vague strokes. In chapter nine, for example, he writes, *'…he opened the bottomless pit; and there arose a smoke out of the pit, as the smoke of a great furnace.'* In chapter fourteen he tells us '*And the smoke of their torment ascendeth up for ever and ever; and they have no rest day nor night.'* John's treatment of hell is noteworthy, both for its brevity and its substance. His descriptions of hell are intentionally hazy, a veil of smoke that hides hell's specific tortures and miseries.

These same distinctions are evident in other theological writings. And it's worth noting that the impressionistic descriptions of hell so common to theological discussions are also evident in artistic renditions of hell. Heavenly scenes tend to be highly detailed. Hellish scenes, in contrast, often present vague images that leave much to the imagination of the viewer. This is a very broad, generalizable pattern.

Shadowing offers another way to cloud the worst. When communities practice shadowing, they spotlight and exaggerate the best, generating a towering image of excellence that casts the worst into perceptual darkness. Lost in the shadows, the worst remains dim, indistinct, and thus, easy for us to ignore.

Often, symbols and rituals help us shadow the worst. Gold medals, blue ribbons, silver cups, and sprays of roses mark the best athletes, cooks, spellers, or beauty queens in a competition. From gold stars on test papers to Nobel, Pulitzer, and MacArthur prizes, from local soccer and little league trophies to World Cups and World Series' rings, awards spotlight the best creating a tower of light that relegates the worst to the shadows.

Finally, recasting – a practice that redefines the meaning of the worst – can establish and maintain blind optimism. Recasting allows a group or community to reconstruct calamity or catastrophe, and render such entities positive, valuable, and critical to collective wellbeing. Make lemons out of lemonade … look for a cloud's silver lining …suffer, it's good for the soul. Inverted and refashioned, stripped of its ugliness, the worst now embodies the vital and noble dimensions of existence. As such, recasted entities remain centered in a group or community's perception.

Some examples. Just recently, BP spokesperson Doug Suttles suggested the oil spill was not a disaster, but a blessing in disguise; he recast the spill as an opportunity. The spill, said Suttles, would allow the oil industry to advance antiquated cleanup technologies

Another example I like: I have been a migraine sufferer for years, and in researching the problem, I was amazed at the positive way medical experts frame migraines. On the one hand, doctors acknowledge that migraines involve 'pain like no other' headache.[2] Yet, many address them as an opportunity in disguise. Holistic guru Andrew Weil[3], for example, writes: *'. . . It is not so bad to let yourself have a headache once in a while. It is a good excuse to drop your usual routines and go inward,. . . . come to accept the migraine this way and see it serving a purpose in your life.'*

Doctor Lawrence Robbins, one of the country's foremost headache specialists, encourages headache sufferers to redefine their pain by employing positive thinking strategies[4]: '*Deep relaxation can change your perception and experience of pain and your response to it. … (it) may also boost your hope and optimism and make you less conscious of your pain. … Learn to focus on the bright side rather than the worst-case scenario.*'

Bringing these ideas to fire.

Those of you dealing with fires aren't just fighting fire. You're fighting a cultural tradition – one that

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[2] See page 17 of Arthur Elkind's book *Migraines: Everything You Need to Know about Their Cause.* (New York: Avon, 1997: 17).

[3] See Pg. 316 of Andrew Weil's book Natural Health, Natural Medicine (Boston: Houghton Mifflin, 1995, my emphasis).

[4] See pages 20 and 37 of Lawrence Robbins and Susan S. Lang's book Headache Help (Boston: Houghton Mifflin, 1995, my emphasis).

eclipses thoughts of fire from people's consciousness, one that clouds the potential causes of fire, and one that often recasts firefighting strategies. Here are three examples of what I mean.

First … in the home. Ninety-seven percent of Americans own smoke alarms. Less than 1/3 of those people regularly change batteries or update those alarms. Note too that less than half of Americans have fire insurance on their homes. What does this tell us? It tells us that the tradition of blind optimism has banished the fear of fire from our minds. We acknowledge that worst case scenario of fire by purchasing the alarm. But we then banish the thought from our minds, meaning we never revisit 'servicing the item that controls our protection.

Now let's turn to wildfires. Who is the farmer who thinks by clearing the land that they are increasing the risk of fire? Yet Steve Pyne's book The Still Burning Bush suggests that is exactly what happens. He writes: *'People begin to slash, drain, grow, loose livestock, or otherwise alter the vegetation in ways that make it easier to combust what, by nature alone, fire could not touch.'* He makes similar arguments for social disorganization or certain migrant patterns. Of course, the problem here is that these actions are defined as progress – as necessary development of a community. But development clouds the issue. Specifically, development relegates the wilderness to the shadows. Development places the wilderness outside the circle of daily attention. And when the wilderness is relegated to the shadows, changes within it are released from attention. Specifically, methods of maintaining or balancing the healthy condition of the wilderness are disattended. Progress overshadows deterioration – even if both are inextricably linked. Progress diverts attentions to the expansion of the new, not the preservation of what the new has replaced.

Finally, there can be a tendency to recast prescribed fires as a solution rather than a potential risk. Unless we take a balanced approach to prescribed fires – a point we'll revisit later in my talk, disaster could await. Karl Weick's analysis of the Cerro Grande fires illustrates the point.

The cultural practices that maintain blind optimism are longstanding and well entrenched.
This means that the culture of blind optimism is not easily changed. Yet, there is hope. I have found that when people … groups … organizations configure themselves in certain ways, those configurations can help to free people from the powerful practices that maintain blind optimism. In such settings – some groups can develop blind pessimism. They foreground the worst, while rendering the best vague and inaccessible.

The importance of group configurations is probably not new to you. Social scientist Karl Weick, who writes frequently about fighting wildfires, contends that the structure in which disasters occur greatly influence our ability to deal with catastrophes. Weick, of course, believes that any group – whether it be a large, complex hospital, a local government, or a small group of fire fighters, can become what he calls a High Reliability Organization (HRO) – that is, a group that successfully anticipates the worst.

Weick offers some principles for becoming a HRO. In my own work, I have found some confirmation of his principles. But I've developed some new ideas as well. My work analyzes large scale events – some that ended in catastrophe like 9/11, the Challenger and Columbia disasters, or the BP Oil Spill. I also look at large scale events that ended well, like the Y2K dilemma, the breakout of the H1N1 flu, or the SARS epidemic. In analyzing such events, I ask: what structures were developed before chaos arrived?

Stories of failure are typically embedded in a strict hierarchical structure. A very mechanistic site similar to what historian Alfred Chandler called the multidivisional or 'M-form' structure.[5] These are strict hierarchies where orders flow from top to bottom with little chance for response or interaction. But success stories are all embedded in a set of interactions, relationships, and exchanges that form a very specific kind of group or organizational structure. I call it a structural web – and I argue that operating within this web can increase one's ability to envision the worst.

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[5] See Alfred Chandler's book Strategy and Structure: Chapters in the History of the American Industrial Enterprise (Cambridge: MIT Press, (1962).

Let me make this a bit more concrete by using an illustrations -- the case of SARS. Then I'll try to translate the lessons of SARS to fire fighting. The saga of SARS began in China's Guangdong Province. In 2002, 305 people, (mostly health care workers), began to show signs of an 'atypical' pneumonia Eventually 5 died. At first, it seemed like a local event that was, at least, contained. Before long, however, it became obvious that the illness we now know as SARS was a global health threat.

How did the disease leave China's borders? During the first three months of the outbreak, an infected doctor from the Guangdong Province carried the disease to a Hong Kong hotel. While there, the doctor contaminated over a dozen guests. As the guests went their way, they took the disease with them, spreading it along international travel routes. Things got even worse when other doctors who had treated the earliest cases in SARS began traveling and carried even more infection.[6]

This chain of events could have triggered massive loss of life. First, the virus responsible for SARS was known for frequent mutations, and upon its emergence doctors knew of no vaccine for its successful treatment. Second, the epidemiology of the disease was poorly understood, and its presenting symptoms were common and non-specific.

Finally, SARS' lengthy incubation period[7] meant that the disease could be widely transmitted before anyone knew they were infected. These three qualities formed a deadly combination. Indeed in contemporary medicine, none of the serious viruses under the scrutiny of medical experts including AIDS, Avian Flu, Ebola, or West Nile virus, meets all of these criteria. Despite the potential for disaster, the SARS story ended amazingly well. By May of 2003, the World Health Organization (WHO) estimated that only 8,098 people worldwide had contracted SARS. And of that number, only 774 died. Now, I don't mean to suggest that 774 deaths are trivial. But when we consider what might have been, the death toll signals an amazing success story.

This success is closely linked to the world health community's truly rapid identification of the disease. Isolated outbreaks began in December 2002, and by April 17, less than five months later, researchers provided the world with '*conclusive identification of the SARS causative agent: a new coronavirus unlike any other known human or animal virus in its family.*'[8]

So what accounts for such rapid action? According to both the WHO and the U.S. CIA, the successful disposition of SARS began with a community 'mindset' – one based on the culture of blind pessimism. I argue that such blind pessimism was related to the structure of the context in which the SARS 'bullet' was dodged.

In the case of SARS, decision-making and subsequent action occurred in the context of a structural web.[9] I argue that this way of configuring people and things disrupts certain cultural routines, freeing people to deviate from the cultural practices that guide behaviors in other contexts.

These webs have several identifying characteristics. First, structural webs contain four components. There is a 'center of operations' – a core to which all of the web's other elements are directly and indirectly linked. In the case of SARS, the WHO functioned as that operational center. A web's center typically subdivides itself, forming 'regional subsidiaries' that enhance the operational center's practical reach by providing it with a mid-level presence.

How does the center determine the number and location of subsidiaries? It isn't based on equal coverage (as is the case in most M-form or hierarchical structures). It is based on need. In the case of SARS, for example, the WHO's central office collected local and national reports on viral outbreaks. The

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[6] World Health Organization. 2003. 'Severe Acute Respiratory Syndrome (SARS): Status of the Outbreak and Lessons for the Immediate Future.' http://www.who.int/csr/media/sars_wha.pdf

[7] The WHO estimates that the SARS incubation period is 10 days

[8] All quotes taken from World Health Organization (2003: 3).

[9] The structural web bears some resemblance to what organizational sociologist W. Richard Scott calls a 'matrix structure.' See Scott's book Organizations: Rational, Natural, and Open Systems, 5th ed. (Upper Saddle River, NJ: Prentice Hall, 2003: 242-244).

WHO then used this information to construct elaborate models on global infection trends. With these trends in hand, the WHO developed subsidiaries that could put it 'on the ground,' in especially hard-hit areas.

In the face of a global emergency, national governments are critical to the enactment of any problem-solving strategy. Thus in structural webs like the one pictured here, regional subsidiaries routinely develop direct links with national divisions. These connections prove mutually beneficial. For the subsidiaries, ties to national governments allow for continuous data collection, helping subsidiaries to better target resource distribution and facilitate timely action. For national units, the contact maximizes nations' problem-solving arsenals. Nations gain the ability to evaluate their circumstances relative to the global stage and fine-tune problem-solving efforts. In the case of SARS, for example, nations who evaluated internal outbreaks vis-a-vis the global community initiated the correct medical protocol more rapidly, and hence, limited their physical and economic exposure.

Local bases form the final and most fundamental unit of a structural web. These bases are the source of all primary information the sites in which hypotheses and assumptions are tested. In the case of SARS, the government agencies, hospitals and clinics in Guangdong, Toronto, or other global cities – represent the local bases.

Now … how exactly do these four components interface and interact? There are five things for us to consider.

1) The nature of a structural web is defined, in part, by the characteristics of its center. In a structural web, the center's powers are limited in scope. The center is guided by a service orientation, It is designed to coordinate both the web's resources and information. This may involve fundraising, resource distribution, data collection and analysis, program design, or innovative research. But in the face of a problem, the center of operation functions to serve and advise rather than to control.

In the case of SARS, the WHO tracked the spread of the disease, It alerted both national and local communities to increased risk; it readied and distributed treatment protocols, consulted with local communities on setbacks and anomalies, and provided worldwide access to global progress reports. These tasks represented cooperative, service oriented action rather than authoritative control. Indeed, the WHO's only act of uncontested power involved the imposition of travel restrictions. But even here, the organization enacted restrictions in consultation with national units and local bases molded with reference to the specific needs of an area.

2) The limited control of operational centers permits significant autonomy among a web's other elements. Each element enjoys some flexibility of action. For example, in the case of SARS, the WHO advised local bases on treatment protocols, but each local base had the freedom to alter that protocol in accord with its own special needs. .

3) The characteristics described thus far could hardly be possible if structural webs were not themselves porous bodies. By that, I mean that people, goods, information, and other resources flow across these webs with relative ease.'[10] In the case of SARS, successful resolution required medical practitioners to regularly interface with public health authorities. Public health authorities, in turn, interfaced with both community leaders and residents. The flexible boundaries between these various local bases made it possible to coordinate productive action. The porousness of international boundaries necessarily increased as well, enabling governments to quickly exchange medical personnel and information. Nations who rapidly brought SARS under control shared their methods, their personnel, even tissue and blood samples with nations at the onset of an outbreak. Such exchange is credited with the rapid identification of the coronavirus that triggered the epidemic.[11]

4) Porous boundaries encourage easy movement. This, in turn, affects the communication patterns

[10] See Robert Wuthnow's book Loose Connections: Joining Together in America's Fragmented Communities. (Cambridge: Harvard University Press, (1998: 5-6; 59).

[11] Note that the WHO often facilitated such exchanges

that characterize structural webs. Structural webs display what we might call multidirectional communication patterns. Information in the web moves both vertically and laterally, and flows through the web reciprocally rather than uni-directionally. One unit says something, others answer. Orders don't emanate from on high and funnel down in one direction. This style of exchange gives structural webs a certain transparency, keeping problem-solving efforts public, traceable, and, for the most part, void of secrecy.[12]

Multidirectional communication was quite evident in the treatment of SARS. In their efforts to contain outbreaks and hasten recoveries, local bases such as hospitals, public health agencies, and local governments 'compared notes' – openly and frequently – on the practical aspects of clinic setup, treatment tactics, and methods of quarantine. Similarly, the WHO's various regional subsidiaries regularly communicated with regard to the international movement of the disease. In this way, regions 'in the thick' of an outbreak could share information with those whose problems had just begun.
Note too that communication in the SARS structural web was not confined within rank. Information traveled from center to periphery and vice versa. Such vertical exchanges often flowed through the established links – local to national to regional to center. But often, one element might leap-frog over others to establish direct communication with a distant destination – i. e. a local base might contact the WHO directly or vice-versa.

5) Finally, structural webs are defined by the type of information in which they trade. And the information that binds the elements of the web is typically formal knowledge. We can think of formal knowledge as a set of explicit beliefs about the way in which elements of the world work. These beliefs form a script for action that is highly articulated and self-consciously invoked. But while explicit and conscious, formal knowledge is also constantly contested and amended. Unlike tradition or common sense, the dynamism of formal knowledge corresponds to the flexibility of the web.

Where would the fight against SARS have led without a flexible, well articulated foundation? The ability to consider all possible sources and mutations of the virus, the capacity to amend hypotheses with information garnered in new outbreaks – this stance was critical to the ultimate (and rapid) discovery of the disease's unique etiology. Recognizing the potential for change and diversion freed members of the SARS web to consider unconventional solutions and avenues of action.

How does all of this related to you?

Let me suggest some issues to think about as you try to answer that question.

1) When you think about the 'players' in your field, who does your field of operations contain? Is the U.S. Park Service or U.S. Forest Service involved? Are they your core? Are there regional offices that control policy and resources? What units are on the ground? How do local authorities come into play? The answers to these questions are important because they will help you understand how to best build a structural web if it does not already exist.

2) Is the core of your system service oriented or control oriented? Is the level of control loose of strict? The service stance seems critical to a system's effective disaster preparedness. If it doesn't dominate right now, what changes would be necessary to elevate the service stance?

3) Do the players in your system all have some degree of autonomy – i.e. can you make strategy

[12] Indeed, when elements of a web fail to communicate openly, they are admonished by the other components of the system. China suffered such a fate in the early days of the SARS disaster. The CIA's Office of Transnational Issues reports that the world health community gave China 'low marks' for attempting to hide early outbreaks of the disease. Similarly, Taiwan was admonished for its reluctance to report a second wave of outbreaks in May 2003. See U. S. Central Intelligence Agency. 2003. '*SARS: Lessons from the First Epidemic of the 21st Century: A Collaborative Analysis with Outside Experts*.' Pages 7-8; http://www.pdhealth.mil/downloads/cia_sars.pdf.

decisions in the field? Can you quickly access needed resources? This kind of autonomy appears critical to anticipating worst cases and effectively fighting them.

4) Are the boundaries between the players in your system porous? How easy is it for you to communicate with other players in your sphere local crews with regional offices … local crews with citizen groups or local governments or police. Are other players open to dialogue? Again – this is critical to success.

5) How does information travel in your sphere? Does it move freely from core to periphery and back again? Can you communicate laterally or do you relay information through some central headquarters?

6) Finally, are you trading in tradition or formal knowledge? Do you fight fires in certain ways because it has always been done that way or do you visit and revisit current strategies looking for pros and cons based on actual experience?

All of these issues are related to successful preparation for and fights against worst case scenarios.

Some Parting Ideas

If blind pessimism helps us to envision the worst, should we work toward institutionalizing it in all groups and communities? Doing so might certainly minimize worst-case scenarios in our lives … but, perhaps, at a dangerous cost.

Many contend that blind optimism fuels not only a community's survival, but its energy and growth. Imagine, for example, the changes to U.S. history had our population been unable to regain optimism and hope after the plague of 1900, the Great Depression, or 9-11. Consider the fate of any nation's labor force if workers became riveted to the probabilities of injury. Your occupation is certainly centrally involved in that idea. And could families survive if their members could not re-embrace life after the death of a spouse or a child?

Clearly, blind optimism is critical to the stability and flourish of individuals and communities. Thus rather than looking for ways to establish blind pessimism … at the cost of optimism, we would do better to explore a path toward balanced or symmetrical vision …to provide an equal 'presence' for best and worst … an optimism tempered with caution.

Symmetrical vision: the prescription seems easy – almost obvious. But achieving it presents a challenging task. It will require re-orienting most groups and communities' ways of seeing – ways sustained by longstanding cultural practices that make blind optimism seem 'natural' rather than constructed. Knowing this, I suggest three specific steps that could initiate movement toward symmetrical vision.

Step 1: Acknowledge the centrality of blind optimism

Obvious … yes. But according to those who have successfully instituted the type of large-scale cultural change I am advocating the step is crucial. The leaders of MADD, for example, site acknowledgement of a drunk-driving problem as key to subsequent efforts to enact both legal reform and cultural change. Similar arguments are being made among those seeking responses to global warming. Until we acknowledge the elephant in the room, we simply cannot address it.

Where does blind optimism exist for you? Do you see yourselves as immune to injury? Do you see every fire as controllable? What is your Achilles heel in this regard? Identifying that point is central.

Step 2: Let's broaden our notions of evaluation.

The best and worst are typically treated as opposite 'faces' of the same 'coin.' That approach can be quite useful for certain evaluative tasks. But in many cases best and worst are often distinct elements rather than opposites.[13] Remember my students' descriptions of best and worst case scenarios? The 'worsts' were never polar opposites of the best. Indeed, in experience, best and worst often represent two distinct categories.

In evaluating of quality, we must add a new tool to our conceptual arsenal. I advocate the development of a ‘separate but equal’ strategy – one that would allow us to simultaneously consider a variety of quality dimensions. When we consider the best and worst as distinctive and independent, we open ourselves to considerations of quality that we might otherwise have missed.

Consider, for example, the development of asbestos and other insulation materials. In creating it, manufacturers defined best and worst as polar opposites. The best insulations retained heat or cooling and deflected noise. The worst insulations failed to meet those goals. In the marketing of housing insulation, no one anticipated that the worst case scenario might involve something completely different. No one considered that asbestos might be toxic or that insulation foams, because of their appropriateness for nesting, might attract destructive rodents to a house. Had manufacturers considered worst cases as distinct rather than the flip side of the best case coin, some of these results may have been anticipated.

The best case scenario of fighting a fire is likely extinguishing the fire. But is the worst case failing to extinguish fire … or something else? Maybe the worst case is having the fire spread to certain healthy areas as opposed to moving toward unhealthy ground that begs for a controlled burn. Maybe damage to a small portion of developed area might make a large area safer for long term inhabitance. I am not a fire expert, but you are and these are questions that should be considered.

Step 3: If symmetrical vision is our goal we would do well to consider the structural settings in which cognitive and cultural change are best implemented.

Earlier, I suggested that structural webs provide the necessary flexibility to support new evaluative practices. Thus, symmetrical vision, as a viable cognitive alternative, may have to be initiated in such settings. Now, to be sure, we cannot realistically reconfigure every decision-making context to create such a structure. Yet, in this setting, it may be that local and regional firefighting groups are small enough to reconfigure themselves in helpful ways. The configurations of the places in which we think and reason and decide and see influence what we think and how we reason, what we decide and see.

I think I’ll stop there. Thanks for your attention.

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[13] Elsewhere, I have written that the forced imposition of conceptual continua in considerations of social phenomena can lead to flawed perceptions of social processes and events. See my article, ‘. ‘Individualism Pro Tem: Reconsidering U.S. Social Relations.’ Pp. 135-171 in K. A. Cerulo (ed.), Culture In Mind: Toward A Sociology of Culture and Cognition.. New York: Routledge, 2002).

The 1910 fires in Alberta's Rocky Mountain and Foothill Regions

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Abstract

Fire history studies are an important tool for understanding the role previous fire events played in structuring todayǿs landscape. The year 1910 was a monumental year for wildfire events in the northern U.S and Canada. These fires had a profound influence in setting forest fire fighting policy that still has implications today. While the ecological and societal effects of the 1910 fires have been studied closely in the U.S., little research has been done on the magnitude of these fires in Canada until recently. By 1910 the forest services in both western Canada and US were still relatively new and untested agencies. Although the Dominion Forestry Branch had been created before its American counterpart, it was lagging in administrative structure as a result of the vast area for which it was responsible. In 1872 the *Dominion Lands Act* was passed in Canada which enabled the federal government to set aside public land as ǲtimber landsǳ and, later, Dominion Forest Reserves in order to create timber revenue and protect watersheds, valuable streamflow and timber. This laid the parliamentary cornerstone for the protection of timberlands from sale and fire while enabling orderly harvesting (Murphy 2007). It led in 1910 to the creation of the Rocky Mountains Forest Reserve (RMFR), which was later to be expanded and divided into the Athabasca, Brazeau, Clearwater, Bow River, and Crowsnest Forests.

Over three million acres burned across the Northern U.S. that year, making 1910 one of the worst fire seasons on record for the U.S. (White 1985). The major loss of life and acreage as a result of the fires deeply impacted American policy on conservation and fire management as well as social attitudes towards wildfire (Egan 2009). The weather conditions for Alberta in 1910 paralleled those of the Northern States. The 1910 fires were monumental both in terms of the area burnt and subsequent development of forest fire policy in the Dominion Forestry Branch. Our study defines the scope of the 1910 fires in Alberta and examines the evolution of Dominion forestry and fire protection in the context of the 1910 fire events. Evidence from local histories, newspaper articles, historical reports, survey photographs, and recent fire history studies were used to evaluate the extent of the 1910 fires in southern Albertaǿs Rocky Mountains and foothills regions. The references to the 1910 fires in Alberta were organized by fire events within, or in proximity to, the Dominion Forest Reserves. Results show that the fires in 1910 consumed close to 300 000 ha (~0.7 million acres) of forested land in southern Alberta in the Sheep, Highwood, Elbow, Bow, Ghost, Porcupine Hills, and Oldman River regions. Comparatively smaller fires occurred in the Rocky Mountains (Banff) Park region. Other smaller fire events also occurred further north in the Athabasca, Brazeau, and Clearwater forests. The loss of timber on the forest reserves and damage done to the prairie and ranch lands in the Foothill regions surpassed other recorded bad fire seasons.

The social impacts of the 1910 fires were keenly felt in the communities south of the Bow River and in the Crowsnest Pass. The fires that threatened the communities of the Crowsnest Pass reinforced public concern about wildfire, and led to increased public expectations for improved governmental fire control. The establishment of the Rocky Mountains Forest Reserve in 1910 reflected the emergence of a new era in western Canadaôs fire fighting policy. Examining the 1910 fire events in Alberta provides a basis on which to deepen our understanding of how those events influenced forest fire policy and social attitudes towards wildfire, and those events still reverberate through contemporary policy and values.

Additional keywords: 1910 fire history, U.S. and Canada forestry, fire policy

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The Climate of the Big Blowup

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Abstract
Two gridded spatial climate datasets (PRISM and 20th Century reanalysis) are used to examine the climate leading up to and during the August 1910 Big Blowup. An anomalous cold and wet winter was followed by an anomalous warm and dry spring that began in March. The dry conditions continued throughout the summer, accelerating a short-term drought. Geopotential height (500 mb) anomalies from the 20th Century reanalysis further support the occurrence of the surface anomalies. The dry and warm conditions lead to anomalous high fire danger indices in July and August. Though August was anomalously cool, a vigorous cold front along with the very dry fuels contributed to the Big Blowup on August 20-21.

Additional keywords: Climate, Northern Rockies

Introduction

The fire season came early for the northern Rockies in 1910. Following a cold and very wet winter, March turned extremely warm and dry as if a switch had been flipped. April 29 saw the first wildfire in the region, and fires continued to start through July facilitated by persistent dry weather, though the number of fires was to yet overwhelm the Forest Service. In early August, however, numerous fire reports began coming into District headquarters in Missoula, Montana as the drought continued, and the number of fires now did overwhelm firefighting resources. On August 19 forest Supervisors thought they finally had the upper hand, but then on August 20, a vigorous dry cold front with very strong winds swept through the region generating what over the next two days (August 20 and 21) became known as the Big Blowup. By the time season ending snow put out the last flame, over 1,700 fires had killed 85 people, injured scores more, destroyed several towns, and burned more than 3 three million acres of private and federal land.

How extreme was the climate of the Big Blowup? Weather reports from the region were sparse in the early 1900s. In 1910, there were only five U.S. Weather Bureau stations that more or less represented the northern Rockies. Today, two gridded datasets allow for a more detailed and spatially complete climate analysis of the 1910 fire season, including both surface and upper air. The first of these for the surface is PRISM (Parameter-elevation Regressions on Independent Slopes Model), which provides 4-km monthly gridded precipitation and temperature for 1895 to the present for the conterminous U.S. (Daly *et al.* 1994). From PRISM additional drought related indices can be calculated such as the Standardized Precipitation Index (SPI; McKee *et al.* 1993) and the Palmer Drought Severity Index (PDSI; Palmer 1965). SPI can be integrated over any time span that has a sufficient number of months; for example, it can be shown as a 1-month index, or integrated over 12 months. The second dataset is the 20th Century Reanalysis[1] (Compo *et al.* 2010). This dataset provides surface and upper air global gridded atmospheric circulation patterns from 1871 to the present.

Fire and Climate in the Northern Rockies

Westerling *et al.* (2003) showed that increased fire activity in the northern Rockies is preceded by several months of substantially dry precipitation anomalies (Fig. 1). Three to four years prior to a larger fire year tend to be wet, followed by 1-2 years of moderately dry conditions leading up to the fire season. Stated another way, antecedent climate of dry winters and warm springs leads to a longer fire season window, and of course a dry summer allows for more fire during the peak of the fire season.

Morgan *et al.* (2008) examined regional fire extent in relation to temperature and precipitation anomalies, equatorial Pacific El Niño/La Niña conditions, and the Pacific Decadal Oscillation (PDO). The largest fire totals across the region occur when the spring is warm and dry, and summer is also dry (Fig. 2), but summer temperature is less influential ranging from normal to warm. Neither El Niño nor La Niña shows a strong signal in the region. There is a tendency for the larger fire total to occur during a positive PDO phase, but the three largest events occurred with neutral PDO. The largest circle with the red arrows corresponds to 1910.

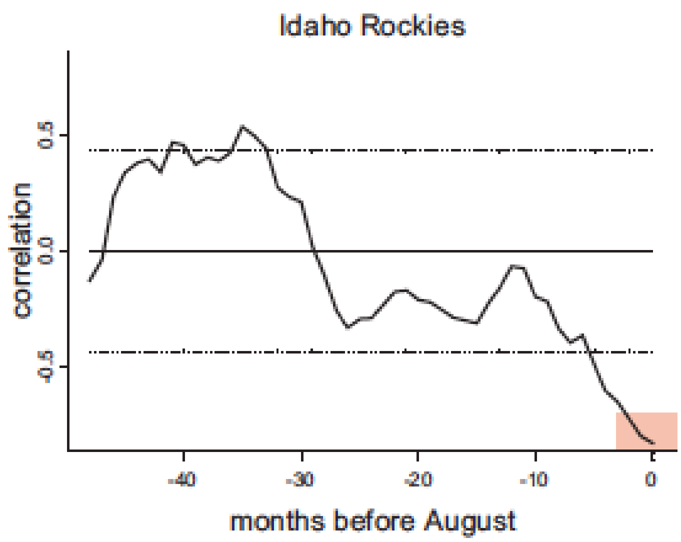

Fig 1. Idaho-Rockies region precipitation lag correlation with August. Positive correlation represents wet anomalies, and negative values dry anomalies. From Westerling *et al.* (2003).

[1]Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ (2010) The Twentieth Century Reanalysis Project. Unpublished manuscript on file Desert Research Institute, Reno, NV.

Fig. 3 shows an antecedent temperature and precipitation analysis from Kolden *et al.* (2010) for the Selway-Bitterroot Frank-Church River of No Return Wilderness area (green area in Idaho on the map). Histograms of composite maximum/minimum temperature and precipitation anomalies are given for antecedent conditions from January through October of the fire year. Red bars denote statistically significant large (> 400 ha) total area burned years. Warm and dry July and August months especially stand out, but it is also of interest to note that warm minimum temperature anomalies dominate nearly all year long. In other words, warm minimum temperatures have as an important role in the season outcome of total area burned as does the maximum heating of the day.

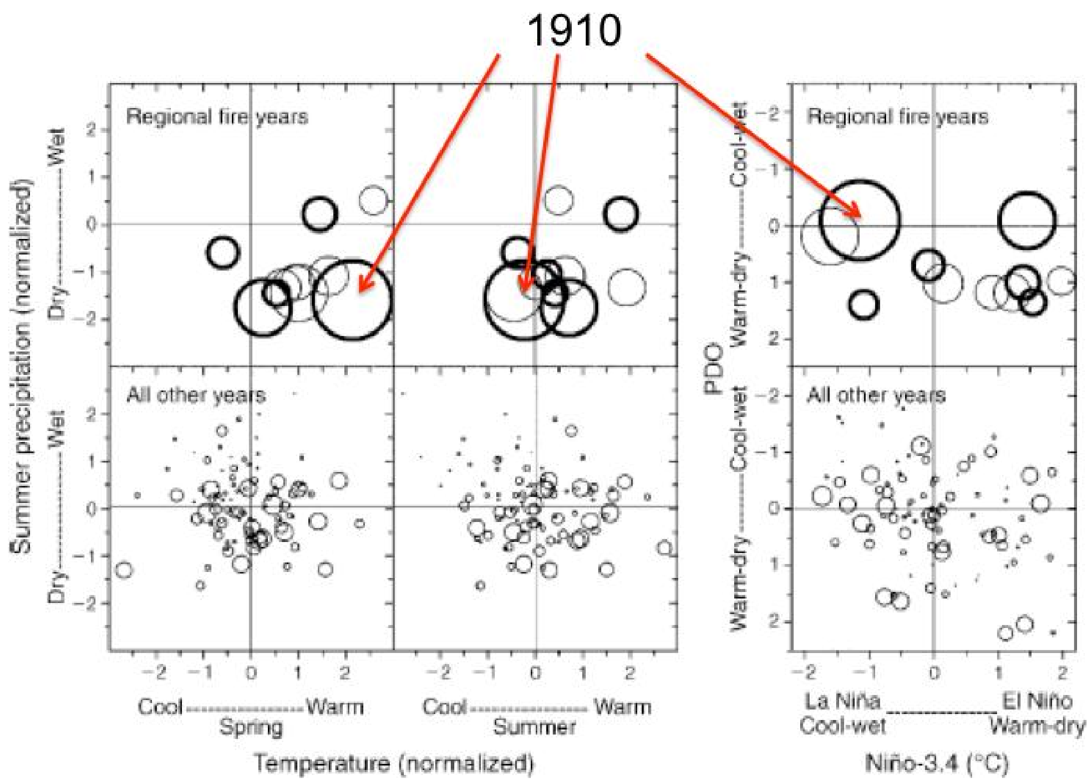

Fig. 2. Regional fire years in the northern Rockies in association with precipitation and temperature anomalies, and El Niño/La Niña and PDO conditions. Size of circle indicates magnitude of area burned in the region for the year. Red arrows highlight 1910.

The 1910 Season

The winter of 1909-1910 was very cold and wet across the northern Rockies. Heavy snows occurred in both November and February (Fig. 4). These two months dominated the PDSI and the 12-month SPI drought indices for several months. In fact, the 12-month SPI did not show drying until September, while the PDSI began indicating drought by June. However, the monthly precipitation anomalies in Fig. 4 show anomalous drying beginning in March and persisting through August, though both April and May were near average. Hence, the drought leading up to

August 1910 was short-term (6-months) rather than a long-term event. Noteworthy here is that despite a very wet winter, the rapidly accelerated drying from spring through summer was sufficient to substantially dry even heavy fuels.

The switch in climate between February and March was quite remarkable, not only in precipitation, but also in temperature. February was one of the coldest months on record, and March and April switched to become two of warmest months on record. In fact, temperature records for Missoula, Montana (March 16-20, highs of 66-70°F and lows of 40-43°F) and Wallace, Idaho (April 18-25, highs of 80-91°F) still stand in the record book today.

Fig. 5 shows January through August 1910 percent of normal precipitation across the western U.S. based on 4-km PRISM data. In February, the northern Rockies were very wet, but quickly began drying out in March. This monthly drying was quite substantial in June through August.

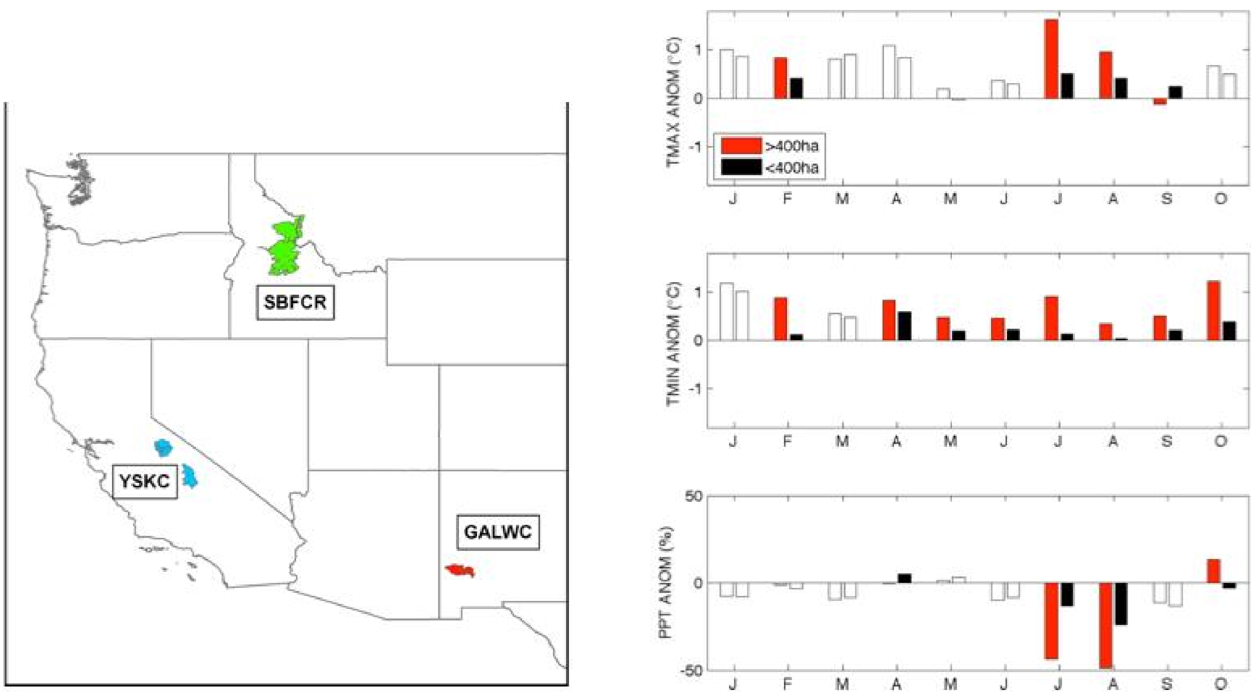

Fig 3. Composite monthly maximum temperature, minimum temperature and precipitation anomalies for large (>0.4 ha) (red) and small (<0.4 ha) (black) fires in the Selway-Bitterroot Frank-Church River of No Return Wilderness area (SBFCR). Time period shown includes antecedent conditions from January, the year prior to fire through October the year of the fire. Statistically significant differences at the 95% confidence interval are denoted by filled bars.

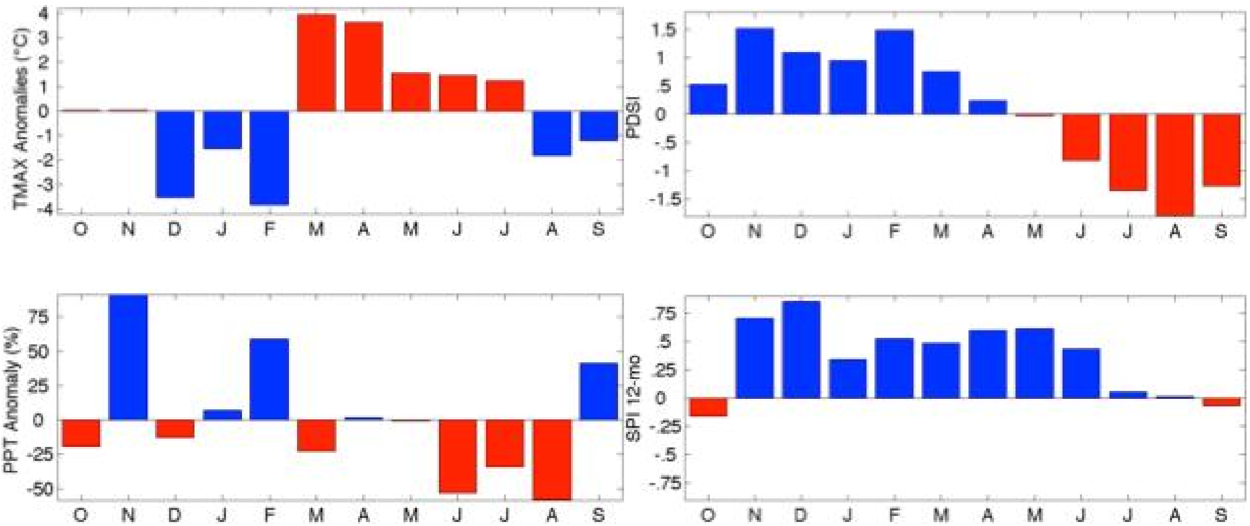

Fig. 4. Monthly maximum temperature and precipitation anomalies, and PDSI and 12-month SPI index values for October 1909 through September 1910 for the northern Rockies region.

Fig. 6 shows January through August 1910 departure from normal (°F) temperature across the western U.S. based on 4-km PRISM data. February was very cold across the entire western U.S., but suddenly switched to very warm across the same area in March. The warm pattern continued through April across the northern Rockies and much of the West. The rest of the months leading up to August continued mostly above normal, though much less in magnitude compared to March and April. However, August was quite cool for the month overall across the northern U.S.

The warm and dry conditions throughout the spring and summer were well reflected in fire danger indices. Fig. 7 shows the energy release component (ERC), burning index (BI), and the 100- and 1000-hour time lag fuel moistures calculated for the northern Rockies region. The dark grey band indicates the daily interquartile range and the light grey bands the daily 5th and 95th percentiles; the blue line shows daily values for 1910. The light and dark red dashed lines indicate the seasonal 90th and 97th percentiles, respectively, based on an 1895-2008 period of record. The major jump in values in March is especially noticeable, and record values occurred in August.

Comparing to Other Years

How unique was the 1910 season from a climatological perspective? In Fig. 8, the year 1910 is contrasted with five of the next largest ranked fire seasons in the northern Rockies by comparing 5-year composites of 6-month SPI. The composite years include 1919, 1988, 1994, 2000 and 2007. The 5-year composite of 6-month SPI is the left map, and August 1910 is the right map. While the five largest fire years were substantially dry, they were not as dry as the period leading up to August 1910, the largest fire year on record in the northern Rockies.

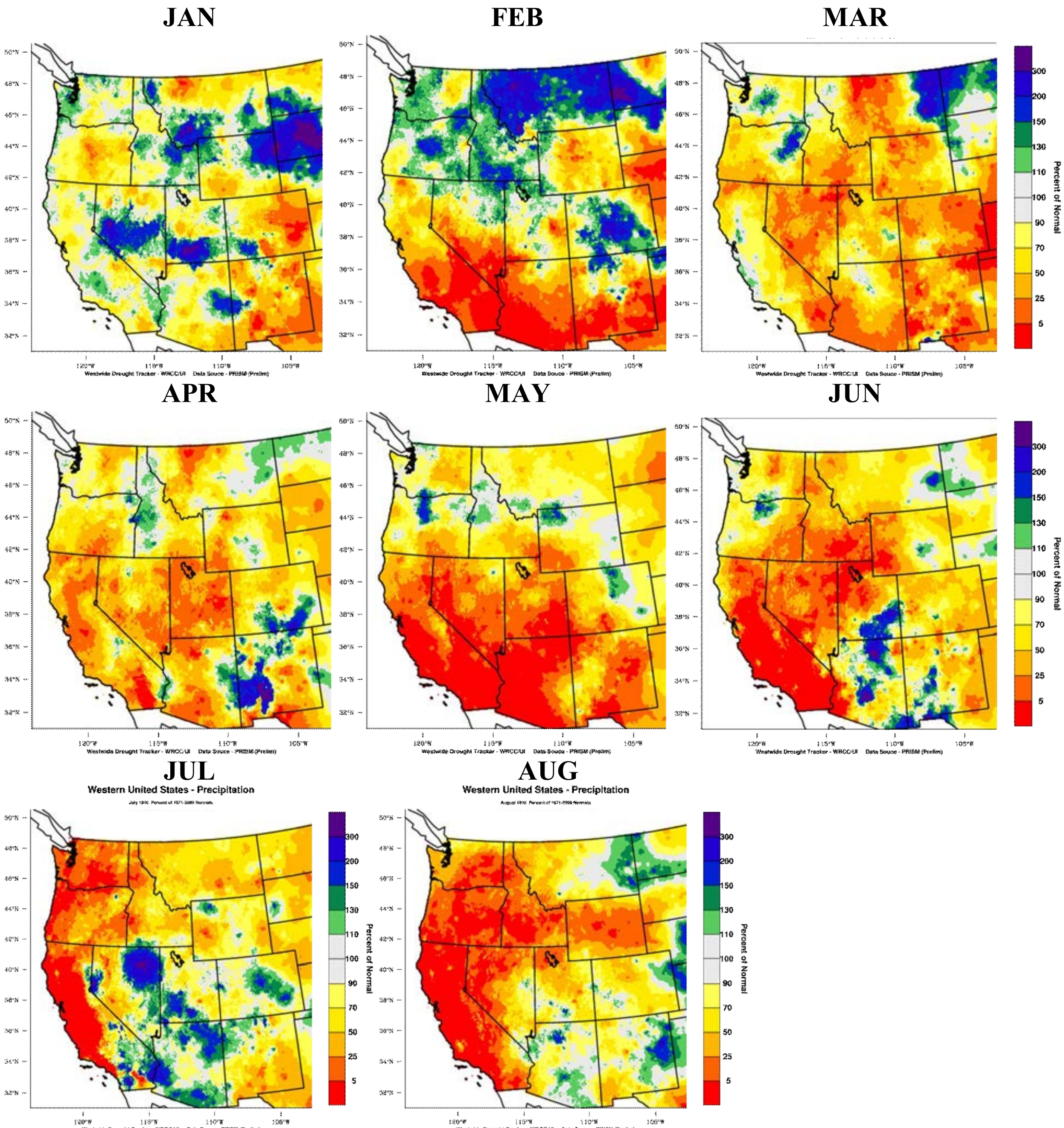

Fig. 5. January through August 1910 percent of normal precipitation across the western U.S. based on 4-km PRISM data.

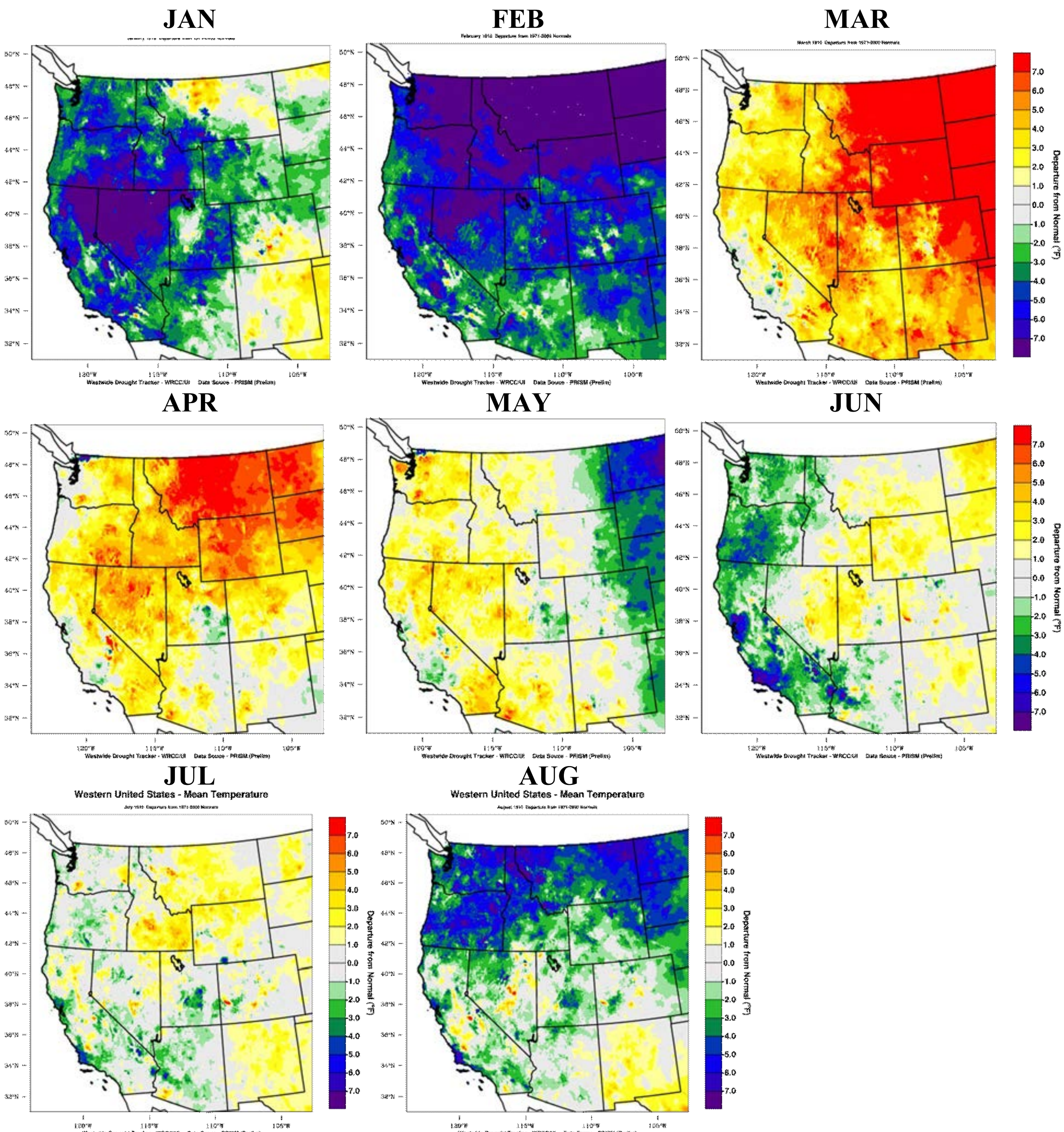

Fig. 6. January through August 1910 departure from normal temperature across the western U.S. based on 4-km PRISM data.

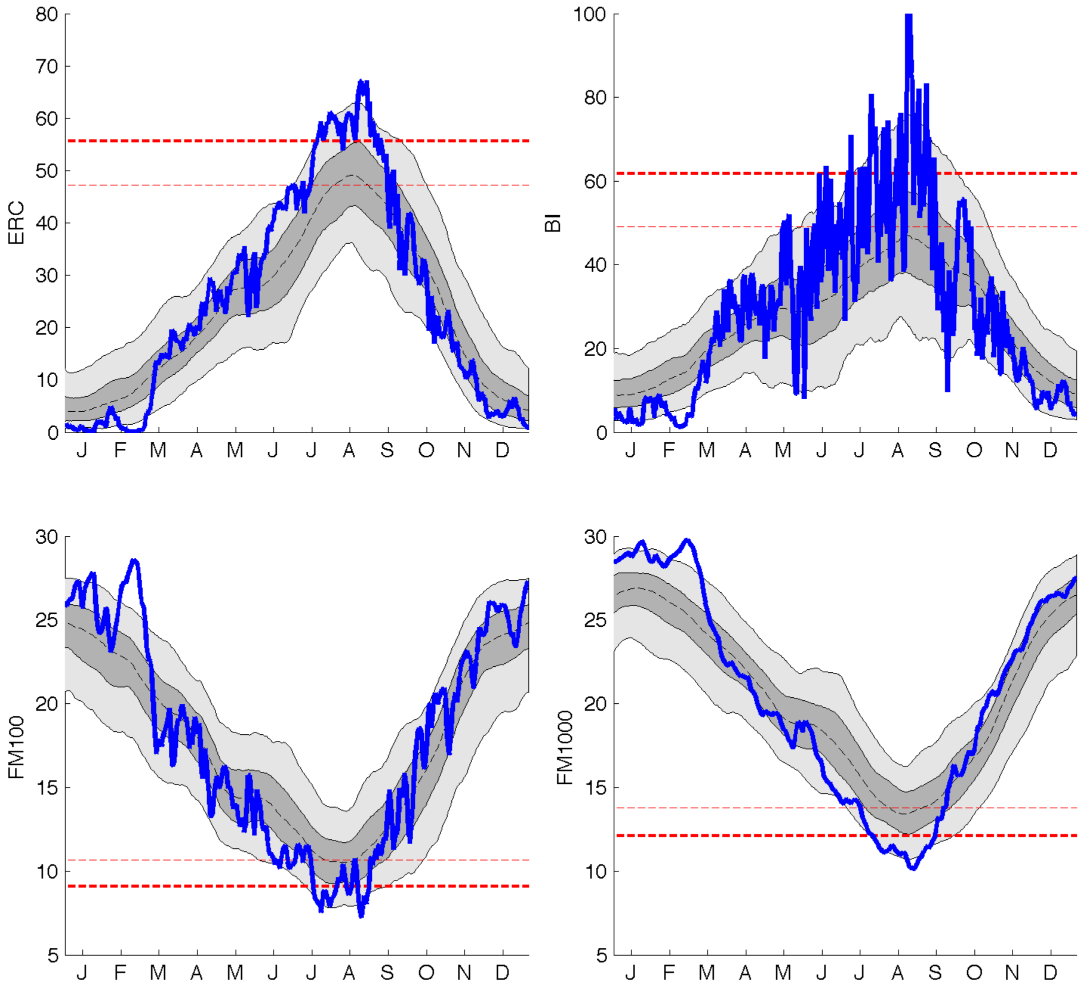

Fig. 7. Daily fire danger indices in 1910 for the northern Rockies region. The dark grey band indicates the daily interquartile range and the light grey band the daily 5th and 95th percentiles; the blue line shows daily values for 1910. The light and dark red dashed lines indicate the seasonal 90th and 97th percentiles, respectively.

Fig. 9 shows 500 mb height anomaly patterns from the 20th Century Reanalysis dataset. The left maps show the 5-year composites of 1919, 1988, 1994, 2000 and 2007, and the right maps show 1910. The top row shows the March through May spring season months combined, and the bottom row June through August summer season months combined. During the spring season in 1910, a substantial ridging (high-pressure) pattern (positive height anomalies) is seen across much of U.S. In fact, the spring saw notable fire activity in the Great Lakes region as well as the western U.S., consistent with the height anomaly pattern. While the composite years also show a ridging pattern across much of the central and western U.S., it is not nearly as strong as 1910. During the summer season for the composite years, the ridging pattern strengthened over the western U.S., but is non-existent in the 1910 summer season. Recall from the temperature maps above that though the summer season was generally above normal in June and July, it was not exceptionally warm, and August was substantially below normal in temperature. The lack of dominating high-pressure across the West in August lead to the cold month, and also allowed for strong dry cold fronts to cross the northern Rockies, such as what occurred on August 20-21.

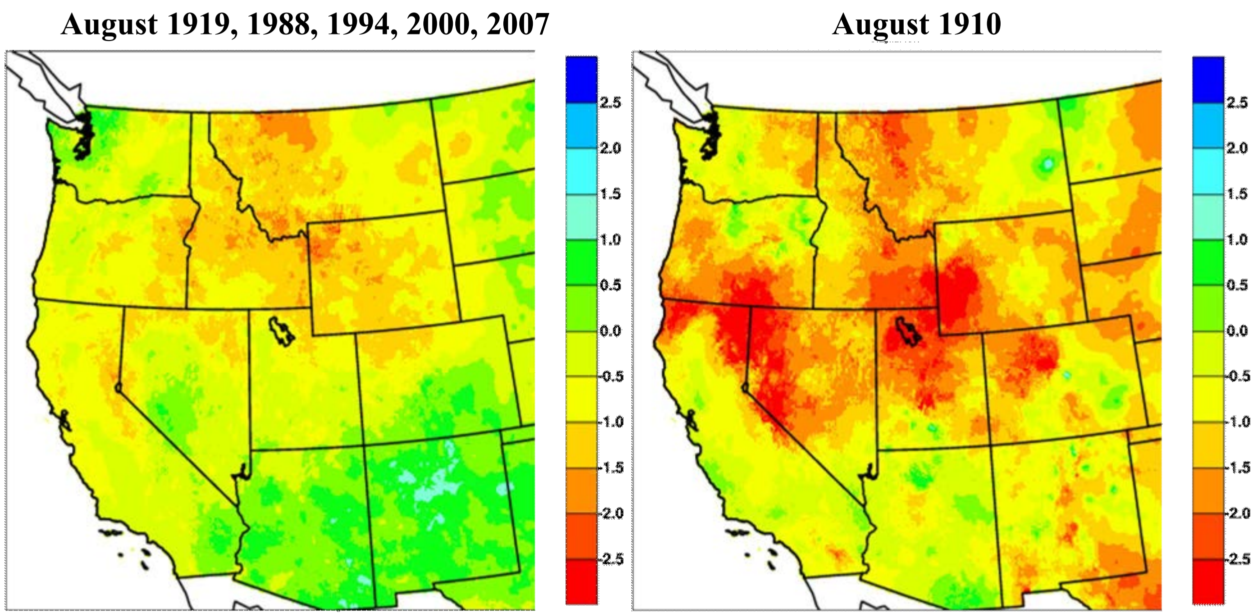

Fig. 8. August 6-month SPI for the 5-year composite (left) and August 1910 (right). Composite years are 1919, 1988, 1994, 2000 and 2007.

1910s of the Future

Four the six largest annual burn totals in the northern Rockies have occurred basically during the past two decades (1988, 1994, 2000, 2007). Global climate models (GCMs) suggest a generally dry pattern across the northern Rockies and Northwest by mid-21st Century. Fig. 10 shows the change in the June-August summer season precipitation (inches) based on simulations of future climate from 13 global climate models. The difference shown is for mid-Century years 2046-2065 versus 1971-2000. The period 2046-2065 is predicted to be drier in the summer months by 1-2 inches in the northern Rockies compared to what was observed in the latter three decades of the 20th Century. More extreme events (including both dry and wet anomalies) are expected as a result of climate change. This and the more general drier conditions could easily make the 1910 fire season repeatable on more than one occasion in the 21st Century.

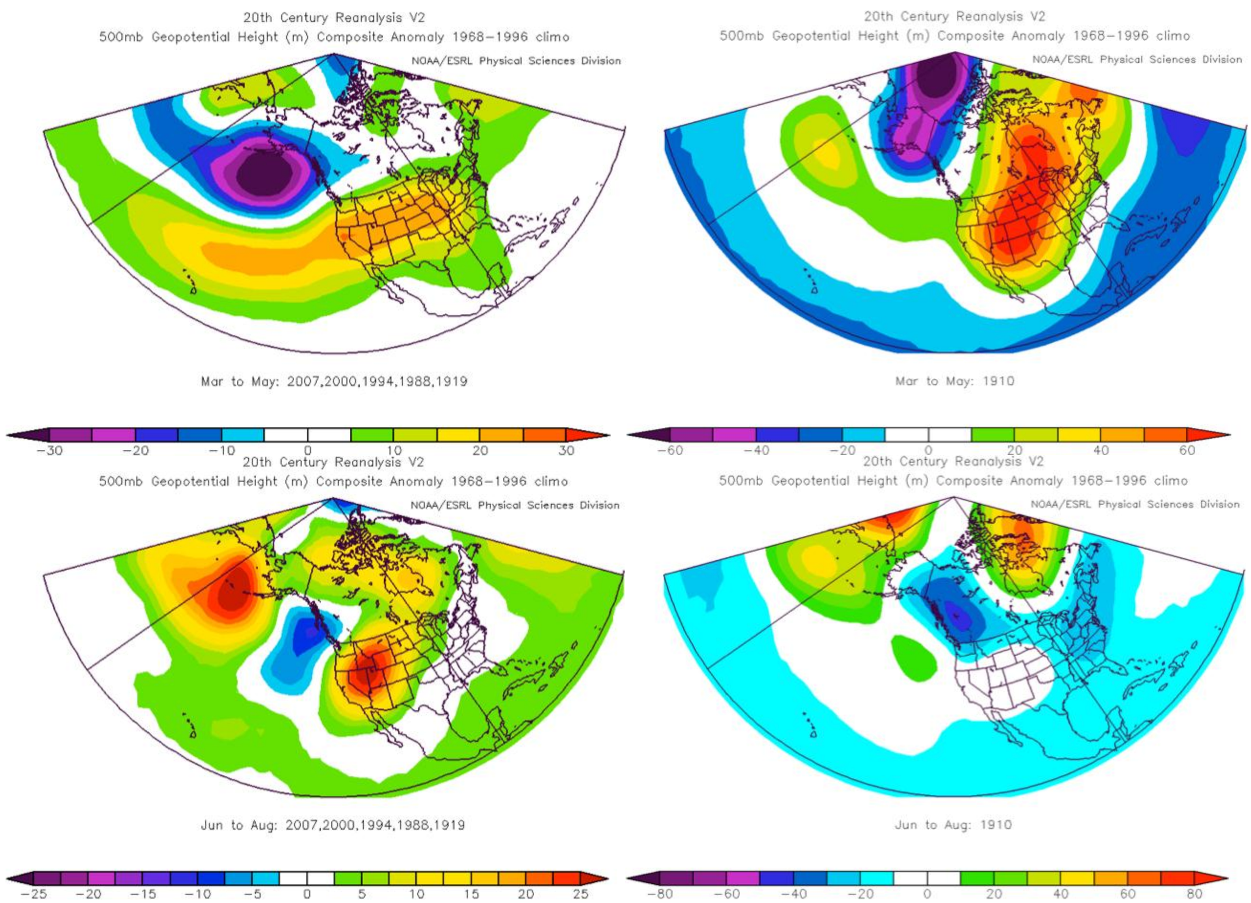

Fig. 9. 500 mb geopotential height (m) anomaly patterns for composite years 1919, 1988, 1994, 2000 and 2007 (left maps) and 1910 (right maps). The top row is the March through May spring season, and the bottom row the June through August summer season. Map and data source: NOAA/ESRL Physical Sciences Division 20th Century Reanalysis.

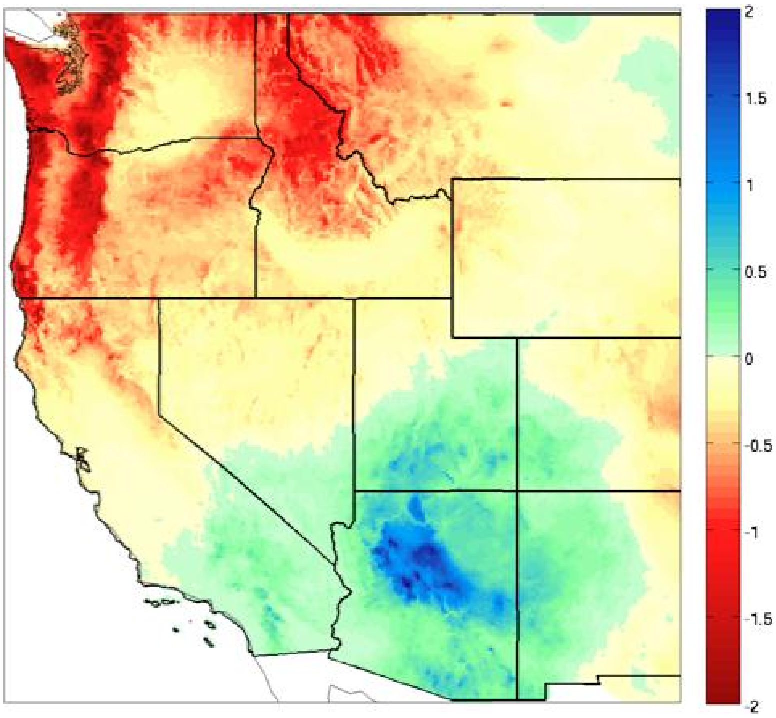

Fig. 10. Change in the June-August summer season precipitation (inches) based on simulations of future climate from 13 global climate models. The difference shown is for mid-Century years 2046-2065 versus 1971-2000.

Summary

The 1910 Big Blowup took place in part due to short-term drought from March through August, and much above normal temperatures during the spring. Except for August, which was cool, the summer temperatures were only slightly above normal. Lightning caused some fires in the summer of 1910, but many were from human ignitions. A major dry cold front substantially contributed to Big Blowup given the very dry fuels. Key climate highlights for 1910 include:

- Winter 1990-1910
  - Anomalously cold; wicked cold spell in February
  - Above normal precipitation (November-February)
- Spring 1910
  - March-May very warm; below normal precipitation
  - No long-term drought; short-term drought going into summer
- Summer 1910

- Critically dry; acceleration of short-term drought
- Temperatures slightly above to near normal (but very cool August)

Acknowledgements
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The Confluence of Weather and Climate Stressors Contributing to the Big Burn of 1910

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Abstract
Anecdotal evidence suggests that the confluence of weather and climate stressors contributed to the fires across the Idaho panhandle and western Montana during the summer of 1910. The 20th century reanalysis project data was used to reconstruct the synoptic meteorology and examine the respective influence of these stressors. Despite neutral drought conditions going into June, the summer of 1910 was exceptionally dry and accelerated the drying of 1000-hr fuels resulting in above normal Energy Release Component (ERC) values from June-August. However, several recent summers have seen ERC values far higher than 1910. The summer of 1910 also featured an unusually large number of dry cold fronts, most notable the capstone event of 20-22 August when a vigorous cold front passed across the Canadian Rockies sustaining an alignment of the surface pressure gradient and upper-level winds for a 48-60 hour period. This combination of forces resulted in strong winds, low relative humidity, and the near record Burning Index (BI) values that fostered fire growth. We conclude that the strength and longevity of this late season wind event concurrent with critically low fuel moistures was the dominant meteorological factor that allowed the large areal coverage of the fires.

Additional keywords: Northern Rockies, Fire Danger

Introduction

Anecdotal data is often discarded in scientific studies. However, despite such data not being collected through the scientific method, anecdotal data provides invaluable information that inspires scientific inquiry. Much of what we know about the fires of 1910 has been documented in qualitative form. Reports of epic drought, winds and fire behavior are therefore challenging to contextualize, particularly given recent large wildfire seasons for which hard data exists. We'd like to assess whether the climate and weather of 1910 was historically significant, or whether anecdotal data exaggerated or embellished the events that transpired.

Area burned in 1910 across the Northern Rockies remains a long-standing modern day record (Morgan *et al*. 2008). We hypothesize that large-scale climate-forcing played a dominant role in synchronized fire activity. Today's seasonal fire predictions are based primarily on recent fire seasons and antecedent conditions. Would we have been able to predict the fire activity of 1910 using modern day predictive capacity, or was the 1910 fire season novel in terms of its meteorological conditions? A thorough quantitative analysis of the 1910 season may help to better understand the sensitivity of area burned to prolonged moisture stress and extreme fire weather (e.g., Bessie and Johnson 1995).

Regional large fire seasons have historically altered national fire management policy. From a fire management perspective is has been argued that the combination of fuel treatment and fire suppression would prevent megafires on par with 1910. However, without a quantitative understanding of the biophysical factors at work that year, such arguments are mere conjecture. Have we withstood more severe drought and fire weather in recent seasons? Or, were the events that transpired in 1910 truly unprecedented in the historical record? Our ability to answer these questions hinges on being able to quantitatively contextualize the 1910 fire season and provide added insight into the prediction of fire seasons.

Data and methods

Reliable high spatial and temporal meteorological observations did not exist in 1910. Daily and even hourly surface observations were recorded at several sites across Washington, Idaho and Montana during 1910. However, such observations are suspect due to biases from nonclimatic factors including instrumentation quality, incorrect station siting and human error (Jones and Wilby 2010). Higher quality observations from National Weather Service Historical Climate Network and Cooperative stations (COOP) provide spatially incomplete data for primary variables of temperature and precipitation, and lack information on atmospheric dynamics that are important in gaining a full understanding of synoptic meteorology. Surface based meteorological observations were in limited use prior to World War II, and frontal analysis was not routinely conducted until the 1940ŝ in the United States. The United States Weather Bureau (precursor to the National Weather Service) created hand drawn maps of mean sea level pressure; however efforts to digitize these maps suggested that the data was of poor quality and furthermore limited by stations reporting in real time (e.g., Williams and van Loon 1976).

Given the interest in contextualizing the synoptic meteorology during the 1910 fire season to recent observations for which a more spatially and temporally complete set of metrics exist, we examined data from the 20th century reanalysis project (Compo *et al*. 2011). Global three-dimensional reanalyses have been used extensively in meteorological and climatological studies; however previous reanalysis datasets extend back only to the advent of the modern radiosonde record in 1948. Compo *et al*. (2011) developed a novel reanalysis dataset that extends the record back to 1871 by assimilating only surface sea level pressure and monthly sea surface temperature and sea ice distribution into an atmospheric model. The result is a 6-hourly three-dimensional global gridded dataset that covers over a centuryŝ worth of synoptic meteorological conditions. We acquired 6-hourly fields of surface temperature, near surface (.995 sigma) wind velocity and relative humidity, accumulated precipitation, as well as 300hPa wind velocity, mean sea level pressure (MSLP) and 850hPa relative humidity from 1895-2008.

To further bridge the gap between the spatial resolution of the reanalysis and the spatial resolution needed to assess surface meteorological conditions and fire danger, we employed the Multivariate Adaptive Constructed Analogs (MACA) statistical downscaling methodology (Abatzoglou and Brown, unpublished manuscript). This downscaling method utilizes a high-resolution (8-km) gridded observational record of data from 1979-2009 (Abatzoglou and Brown 2009) and a weather-typing approach to project synoptic-scale meteorology from the 20th century reanalysis to local scales. The resulting product is an 8-km gridded meteorological dataset covering the Northern Rockies from 1895-2008 that includes the primary meteorological elements (temperature, humidity, winds, precipitation, insolation) needed to calculate fire danger using the United States National Fire Danger Rating System. We calculated Energy Release

Component (ERC), 1000-hour fuel moisture and the Burning Index (BI) using fuel model G (dense conifer stand with heavy litter accumulation) given its widespread use by regional fire management (Brown *et al*. 2004). To compliment the spatially explicit analysis, we aggregated the data to the perimeter of Northern Rockies fire atlas recording area in Idaho and Montana west of the Continental divide (e.g., Morgan *et al*. 2008).

Anecdotal data of the 1910 fire season is suggestive of a number of dry cold fronts that affected the Northern Rockies. While a definitive definition of dry cold front is lacking, they are generally associated with the dynamics of a frontal passage (e.g., strong winds and a shift in wind direction) in the absence of substantial precipitation. In lieu of defining dry frontal passages, we utilized the National Weather Service Spokane Weather Forecast Office's criteria for wind advisories as a proxy for strong summertime wind events (personal communications, NWS Spokane Weather Forecast Office). The criteria require a sea level pressure gradient exceeding 20hPa between Portland, Oregon and Kalispell, Montana or 15hPa between Yakima, Washington and Lethbridge, Alberta. We interpolated MSLP from gridded reanalysis to the locations of these four sites and counted the frequency of wind advisory days during each fire season, defined herein as 1 July to 15 September.

Results

Unlike recent large fire seasons in the Northern Rockies, temperatures during the summer of 1910 were not above normal, and were instead marked by significant intraseasonal variability associated with the large number of days meeting wind advisory criteria (12 days in total, tied for largest on record with 1914 and 1996). However, consistent with other large fire seasons, the summer of 1910 was extremely dry with the cumulative precipitation over the entire summer being in the bottom decile on record. The largest cumulative summer precipitation (1 June onward) deficit occurred on 21 August, with the study area having received less than 50% of the median precipitation for that date. These dry conditions, following the warm spring allowed for above normal ERC from the beginning of June through the end of August (Fig. 1a). Region wide ERC values topped 97th percentile values on 20 July and sustained extreme fire danger until 23 August. However, we note that while ERC was high during 1910, other large fire years such as 1988 and 2007 experienced higher ERC values and sustained extreme fire danger over a longer time period.

A series of wind events affected the Northern Rockies in August after the onset of the short term drought and extreme fire danger conditions from late July onward. Observations from COOP stations and the downscaled data suggest these events brought nominal precipitation, thus doing little in the way of increasing 100 or 1000-hour fuel moistures. A synoptic disturbance migrated southward from the Yukon into British Columbia, Canada on 19 August 12Z (5am PDT) increasing the east-west pressure gradient between the Oregon-Washington coast and interior Montana. By the 20 August 12Z the pressure gradient strengthened (Fig. 2a) to advisory criteria resulting in a strong southwesterly flow, referred to as a "Palouser" over the study area (Fig 3a). The alignment of the zonally oriented upper-level jet streak just north of the study area coupled with surface pressure forcing to intensify winds across the northern Panhandle of Idaho. ERC values for 20 August were above the 97th percentile across the entire study area, with most of the area in the panhandle of Idaho about 20 points above normal.

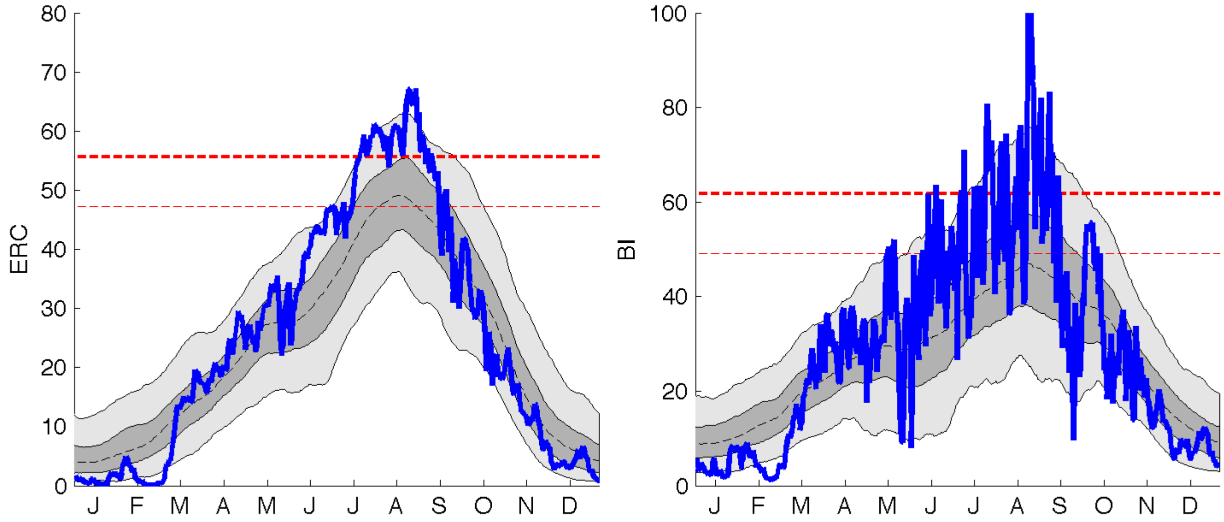

Fig. 1a-b: Time series of daily ERC (left (1a)) and BI (right (1b)) aggregated over the study area. The blue line shows the value for 1910. Climatological normals filtered with a 21-day moving average are depicted by the light grey envelop (5-95th percentile), the dark grey envelope (interquartile range) and the dashed line (median). The two horizontal dashed lines depict the 90th and 97th percentile value calculated from the entire period of record (1895-2008).

The synoptic ingredients allowed the strong dry winds to continue for the next 48-60 hours. On 12Z of the 21st, the development of a blocking pattern over the North Pacific further strengthened the upper-level flow across northern Idaho. This occurred with the passage of the frontal system, as noted by the shift in the wind direction to a more westerly direction (Fig 3b). Subsidence associated with cold air advection behind the front allowed for the downward mixing of momentum and dry air into the boundary layer further adding to fire behavior. Sustained winds of 30mph (13.5 m/s) were estimated for most of the Idaho panhandle and western Montana and limited overnight relative humidity recovery (Fig. 3b). Conditions on the 22nd were fairly similar, although winds were slightly weaker across the major conflagrations (Fig 2c; Fig 3c).

Finally, by the morning of 23 August (12Z), the bulk of the energy had moved out of the northern Rockies. Substantial increases in lower-tropospheric humidity, along with much cooler temperatures associated with the northerly flow into the region dramatically reduced winds and fire danger (Fig 2d; Fig 3d). While anecdotal reports stated that precipitation fell (some as snow) across the area, both the downscaled output at COOP observations show nominal precipitation for a few locations in northwestern Montana. However, the strong change in surface temperature was evident by noting a drop in temperatures by over 15°C between the 19th and the 23rd.

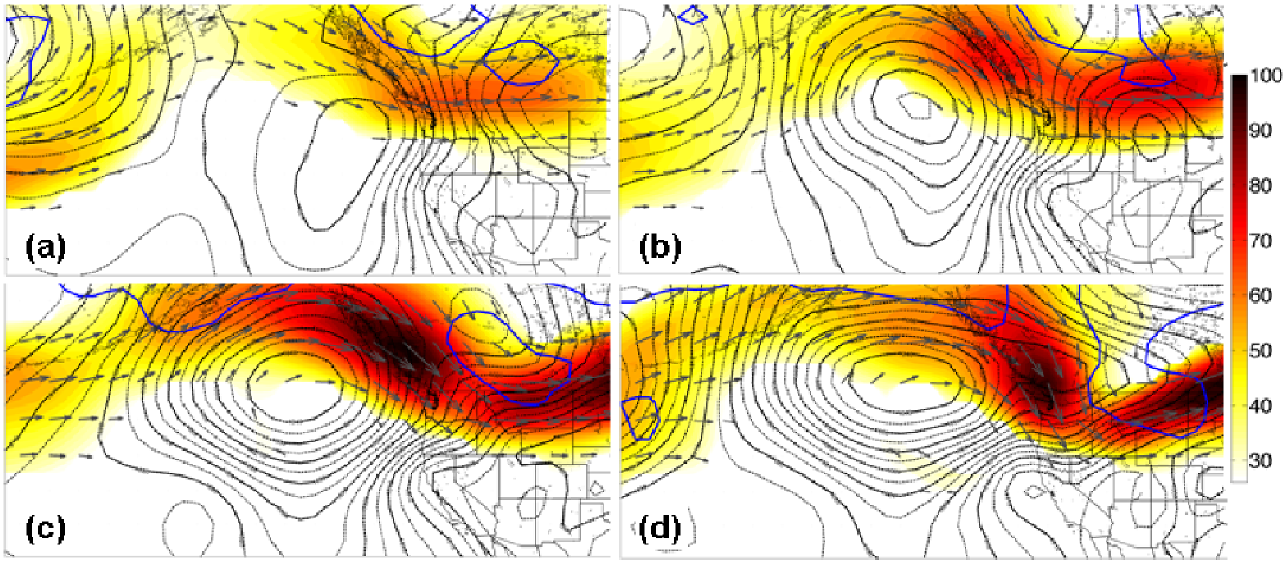

Fig. 2a-d: Synoptic weather maps at 12Z for (2a) 20 August, (2b) 21 August, (2c) 22 August, and (2d) 23 August. Black lines show isobars of mean sea level pressure (contour interval 2-hPa), vectors and shading show the 300hPa wind vectors (only winds exceeding 30mph or 13.5 m/s are shown) and isotachs (units: mph), and the blue line shows areas where the 850hPa relative humidity exceeds 75%.

While these results confirm the anecdotal evidence of the big blow up, our results do not support stories of ósustained hurricane force windsó. However, the combination of coupled fire atmosphere dynamics, channeling of flow through topography, and turbulent downbursts in the moderately unstable air (Haines index values of 4-5 were observed throughout the event) may have resulted in localized winds for short time periods exceeding 74mph (33 m/s). Our 114 year dataset suggests that daily wind speeds have been stronger in subsequent years, for example both 7 September 1988 (Canyon Creek Fires and other Yellowstone Fires, (Bushey 1989)) and 1 September 1967 (Sundance Fire, (Anderson 1968)). However, the BI (a proxy for flame length) during the big blow up was historically significant. Although the highest BI on record occurred during 7 Sept 1988, BI values for the three-day period 20-22 August were the highest three-day period on record (Fig. 1b).

Although the summer of 1910 was exceptionally dry, the lack of extended warm spells akin to recent large fire seasons clearly made 1910 a unique year. We suggest the late-season ócapstoneô event on 20-22 August 1910 was the dominant factor that accounted for a majority of the area burned. The high frequency of cold front passages in conjunction with elevated ERC likely resulted in an above normal number of dry-lightning ignitions that united in the fire complex during the strong late-season wind event. Our analysis suggests that the frequency and intensity of wind events increases from August into September. The number of active fires, fuel moisture and timing of season ending or fire slowing precipitation events with respect to these wind events is a critical component not currently accounted for in climate-fire relationships.

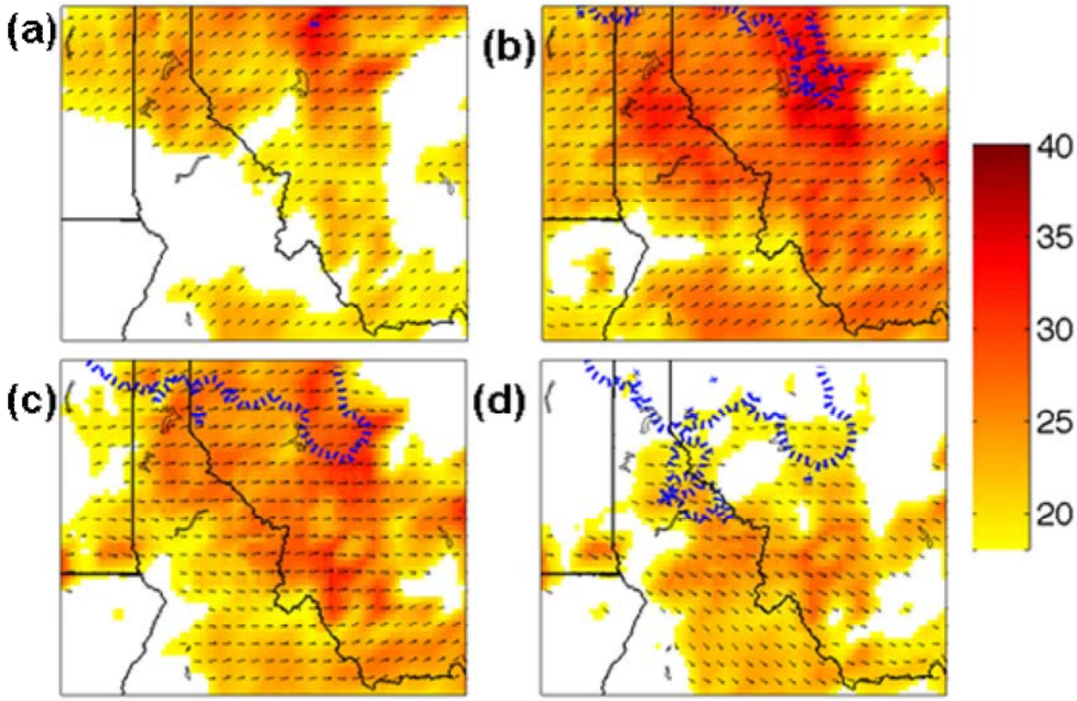

Fig. 3a-d: Daily average wind vectors for (3a) 20 August, (3b) 21 August, (3c) 22 August, and (3d) 23 August. Wind speeds greater than 18mph (8 m/s) shaded. The blue outline denotes areas where the minimum relative humidity exceeded 35%.

Concluding remarks

Our analysis supports anecdotal data suggesting the wind event during 20-22 August 1910 was unprecedented in terms of its persistence and timing at the end of a dry fire season. Over the 114-year record examined, BI values were the highest three-day period on record, with only 7 September 1988 having higher values than those seen on 21 August 1910. Despite relatively normal temperatures during the summer of 1910, the warm spring and implied early snowmelt, in conjunction with very dry summer conditions enabled high fire danger to persist into late August. The ́perfect stormô of numerous active fires, dry fuels, and the late season prolonged capstone wind event provide solid support for the consortium of weather and climate stressors driving the fires of 1910. Furthermore, while we have experienced more severe moisture deficits in the recent modern fire management era, a prolonged wind event like that of late August 1910 has not occurred since.

Acknowledgements

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An Assessment of Climate and Fire Danger Rating in the Northern Rockies During the 1910 Fire Season

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Abstract:

The 1910 fires of western Montana and northern Idaho have received much publicity in the popular media but little scientific attention regarding the factors that contribute to fire behavior and fire danger. Here we present information surrounding the weather, and reconstructed measures of Palmer Drought Severity Index (PDSI), Keetch-Byram Drought Index (KBDI), Energy Release Component (ERC), and Pacific Decadal Oscillation (PDO) during the 1910 fire season in the northern Rockies. KBDI and ERC were used to assess local and regional fire danger related to fuel conditions while PDSI and PDO were used to examine regional and continental scale measures of drought in 1910 in the northern Rockies. Reconstructed measures of PDSI clearly illustrate the drought conditions during the months leading up to and during the 1910 fire season. However, measures of PDSI for the month of August were more severe in contemporary fire seasons such as 1919, 1934, 1988, 2000, and 2003 and over a much broader geographical extent. KBDI trends illustrate the early season dryness that occurred in 1910. However, KBDI trends where higher and a month earlier in 1934, while 1988 and 2000 were more severe later in August in comparison to 1910. KBDI values during the period July-October were also much higher in 2003 than those for the same period in 1910. We compared calculated ERC values from 1910 to contemporary fire seasons to display and compare the 1910 season to other recent extreme years in the northern Rockies. Similarly, measures of ERC were higher in 1910 from May to mid-July when compared to 1988, 2000, and 2003. However, these years had higher ERC values from mid-July to October. An examination of PDO indicates a relatively cool (negative phase) period in 1910, especially when compared to the period 1980 to the present. Finally, many eyewitness accounts describe the winds during the blowup of August 19-21, 1910 as “hurricane” or “cyclonic in nature”. However, we examined available hourly wind data recorded at Weather Bureau Offices operating in the region at the time and found that peak recorded wind speeds during this period ranged from 20-26 mph. The exception being Lewiston, Idaho which recorded peak wind speeds on these dates ranging from 38-42 mph.

The 1910 fire environment of western Canada

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Abstract
The purpose of this paper is to describe the prairie, boreal and cordilleran fire seasons in Canada in 1910. Historical Canadian newspaper accounts and meteorological observations from the Lakehead west to the Pacific were amassed in an attempt to delineate critical fire danger periods in these distinct fire environments during 1910. This historical information points to the extents and severity of the 1910 seasons, where extreme fire danger collided with rapid settlement of the Canadian west. In many cases, 1910 fire environment conditions remain unprecedented but provide useful examples of fire potential for current Canadian fire management organizations.

Introduction

In 1910 western Canada was linked by rail and wire, having all the modern convienecies, including daily newspapers. Western Canada was not a blank place on the map, but was instead known throughout the world as a prosoperous region, open for business. Little has changed today. However, despite sharing a fire season which became legend in the United States, the 1910 fire season in western Canada has remained an unknown quantity to modern fire management practitioners. This paper attempts to illuminate this significant fire season in western Canada.

Methods

Fire occurrence information from 1910 was mined from on-line newspaper accounts available from the Alberta Heritage Digitization Project (http://www.ourfutureourpast.ca/). The historical sources of this on-line resource include the Calgary Daily Herald, Edmonton Daily Bulletin, Lethbridge Daily Herald, Morning Albertan, and the Red Deer Advocate. Fire articles were captured in digital format and archived by publication source and date. A fire database was then created from these articles. Reporting was understandably inconsistent but at a minimum, the 1910 fire database included the location of the fire and the date of the fire event. When available, information related to fire cause, weather, behavior, suppression, size, and losses was also included. Digital maps at various scales (1:50K, 1:250K, 1:1000K), available on-line from Natural Resources Canada (http://geogratis.gc.ca/), were used to locate place names contained within the fire articles. The small scale maps were especially useful for determining fire locations in this large study area, with similar scale maps available for adjacent regions in the United States from the University of Texas (http://www.lib.utexas.edu/maps/imw/). Once the fire location was confidently placed on the maps, the location was converted into latitude and longitude using Google Earth (http://www.google.com/earth/index.html).

Adjusted historical climate data for Canada (monthly mean of daily maximum temperature and monthly total of daily precipitation with trace correction) was obtained on-line from the Climate Research Division, Science and Technology Branch, Environment Canada (http://ec.gc.ca/dccha-ahccd). These data incorporate a number of adjustments to original station data due to changes in instrumentation, observing programs and station relocations. Documentation is available on-line (c.f. Vincent and Mekis 2009; Vincent *et al.* 2002). Canadian anomalies for 1910 monthly maximum temperature (°C) were calculated for about 40 locations, while 1910 monthly precipitation anomalies (%) were calculated for about 60 locations. Similar data from neighboring states was obtained from the United States Historical Climatology Network (http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html), with about 100 monthly maximum temperature anomalies and 80 monthly precipitation anomalies calculated. These two independent data sets were combined without consideration for their origin, providing a cross border view of climate anomalies.

Observed daily precipitation (mm) for 153 weather stations in operation during the 1910 fire season in western Canada were obtained on-line from the Meteorological Service of Canada, National Climate and Information Archive (http://www.climate.weatheroffice.gc.ca). These data was obtained in order to determine relatively rain-free periods conducive to fire initiation and spread. Days with reported rain less than 0.6mm were considered as having no rain, which conforms to the Canadian Forest Fire Weather Index (FWI) system, where less than 0.6mm rainfall is assumed to have no effect on the Fine Fuel Moisture Code (Van Wagner 1987). Unfortunately, the complete hard-copy record of meteorological observations from the network of stations in western Canada in 1910 was unavailable. These observations include twice daily observations of temperature, relative humidity, wind and precipitation, which could have been used to determine FWI codes and indices required for fire behavior prediction.

Results

Newspaper accounts during the 1910 fire season.provided information for 130 fires in western Canada and 88 fires in the neigbouring states. The location of these fires is shown in Fig. 1. Maps of annual, seasonal and monthly maximum temperature and precipitation anomalies were generated to dilineate anomalous regions of heat and drought. The spring and summer maximum temperature and precipitation anomalies are provided here for interest (Fig. 2). Observed daily precipitation records for 153 western Canada stations were transformed to depict rain free periods from March through October.

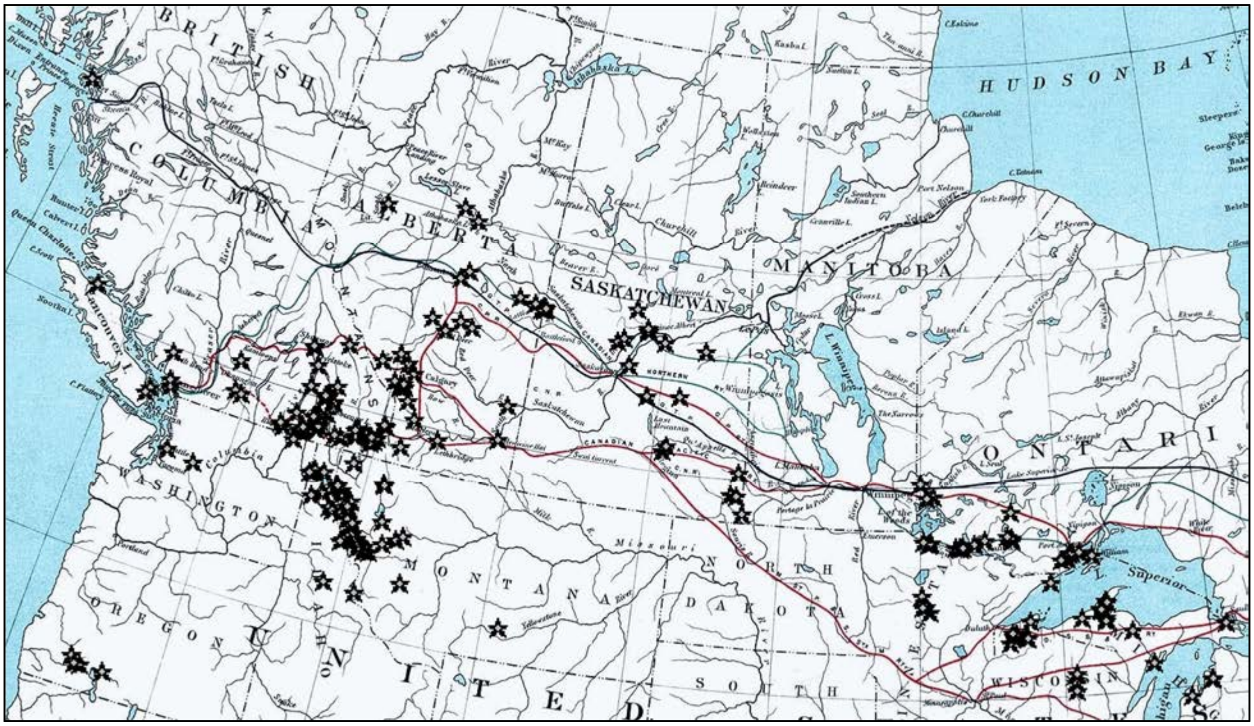
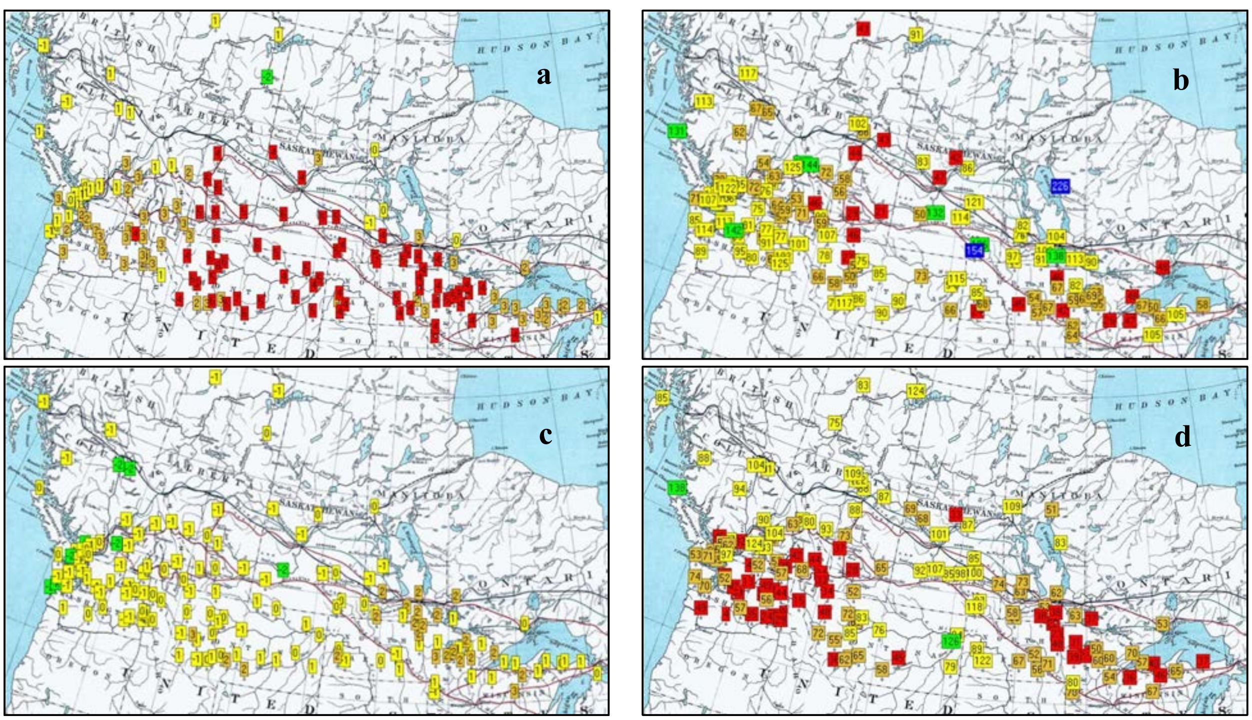


Fig. 1. 1910 Fires



Figs. 2a-d. 1910 Spring and Summer Maximum Temperature (°C) and Precipitation (%) Anomalies (a = spring maximum temperature, b = spring precipitation, c = summer maximum temperature, and d = summer precipitation).

During 1909, it was much warmer than normal in Washington, along with near normal precipitation. In most of western Canada and from North Dakota east, it was colder than normal, with cold increasing from west to east; the coldest temperatures were found in the Great Lakes region. Precipitation was high in western Montana, part of the prairie region of Saskatchewan, and the Great Lakes region. The droughtiest areas were central British Columbia, southern Alberta, and the parkland ectone across central Alberta and Saskatchewan.

The winter of 1909/1910 brought continued warmth in Washington, with near normal precipitation. To the east and north, it was cooler than normal, with it being much cooler in a swath from Montana to Michigan. Precipitation in this cold swath was generally greater than normal, with wetter areas in western Montana, and western North Dakata/southern Manitoba. Less precipitation was recorded in parts of eastern Manitoba, Minnesota and Wisconsin. A dry winter was evident across the western Canadian prairies and BC. The northwestern Canadian boreal region was also dry, but with near normal temperatures.

After a cold winter from the cordillera to the Great Lakes, March was hot. In fact, the heat of March 1910 appears unprecedented in the instrumental records, with temperatures up to 13°C above normal. Record heat resulted in early melting of the winter snowpack, which was near normal in the Pacific Northwest and below normal across British Columbia, Alberta and Saskatchewan. March was wet along the coast, in portions of Idaho, along the railway through the Canadian Rockies, and across southern Saskatchewan to Lake of the Woods. March drought is evident for much of the northern US from Montana to northern Michigan, the BC Interior, and the western Canadian Prairies north through parkland and boreal.

March heat continued in April. The warmest temperatures occurred east of the Rockies. Precipitation deficits are evident through the central cordillera, western prairies and parkland. The first reported fires for 1910 come from Canadian prairies in southern Saskatchewan at Watrous, Gainsborough and Moosomin on April 6. This early season stretched into Alberta, with “*prairie fires*” burning for a week along the Red Deer River near Medicine Hat. Another prairie fire swept about 10 square miles southwest of Calgary on April 12, burning two ranches.

By mid-April, the southern foothills and central parkland area of Alberta were fully involved, with fires reported west of Claresholm in the Porcupine Hills, Pincher Creek, NW of Cochrane, Red Deer, Vermilion and Lloydminster. The most significant fires included the Porcupine Hills fire (19,000 acres), two Red Deer area fires (30,000 acres), and the Vermilion Fire (64,000 acres). The rash of fires near Lloydminster was also significant as they resulted in the successful prosecution of six offenders, with the hope the fines would “*act as a deterrent to culpable carelessness in the future*”. Fires also burned at this time in southern Saskatchewan, with reports from Regina and Redvers.

Significant fire activity continued in the later part of April, with fires reported in Saskatchewan at Aberdeen, the Pia Pot Indian Reserve, and Wynard. In Alberta, fire occurred at Fort Saskatchewan, Kitscoty, near Stettler, and at Athabasca Landing. The large fire at Athabasca Landing was “*raging along the Athabasca below the mouth of Lesser Slave River in the large spruce belt*”. This fire was the result of abandoned campfires during the winter months.

In areas east of Alberta and Montana, the incredible spring heat in March and April eased in May. However, May was still warm in much of southern Alberta and across the cordillera of British Columbia, Washington, Idaho and western Montana. Much of the western cordillera also remained dry, which was a continuation of April drought. In the Great Lakes region, May resulted in dry conditions, a change from the damper than usual April. Only parts of southwestern Montana and southern Saskatchewan showed centres of above normal precipitation. Fire activity continued in the news.

On May 4, "*a prairie fire*" near a packing plant on the outskirts of Edmonton Alberta caused concern. In British Columbia, the first fire activity of the season was reported in early May, with fires at Princeton, Nicola, Similkameen and in the west Kootenays. In the Kootenays, "*tremedous bush fires*" were burning at Salmo on May 5. Government Agent Teetzel from Nelson, along with 20 fire fighters, went by rail to aid in the suppression effort. Assistance from Trail was unavailalbe as a "*bush fire*" was occupying the attention of all available men there.

During the second week of May, fatal fire struck the boreal forest of Saskatchewan, where "*four Indians were burned to death in their camp about fifteen miles south of Kinistino*". Other reports from "*many points in the Prince Albert District*" include fire at Chellwood, Blaine Lake, Sturgeon Lake, Appleton, and at Skipton. Fire also impacted forests in Prince Albert National Park (Weir & Johnson 1998).

Forest fires were reported in the Lake States during this week as well. On May 9, fire near Grand Marais Minnesota "*swept through the territory six miles west of here*". Near Calumet Michigan, "*fires about Alliston, South Range, and Baltic*" were suppressed by forest rangers and volunteers. Fires burning in northern Wisconsin "*broke out anew*" on May 16, "*fanned into fury by strong winds off Lake Superior*". These northern Wisconsin fires were in the vicinity of Lake Nebaw, Solon Springs, Delta, Cusson, Brule, Blueberry and Mapleton. Rain in northern Minnesota on May 16, easing the situation at Bemidji, Walker, Laporte and Wilkinson. The fire at Bemidji was being fought by "*hundreds of citizens, soldiers and forest rangers*".

On May 23, a fishing schooner in British Columbia "*steered a perilous passage through Johnstone Strait*" owing to a forest fire "*believed to have originated in a logging camp on the mainland and to have spread across the straits to Graham Island*".

Towards the end May, fire swept a large portion of the Canadian Northern Railway in the Saskatchewan/Manitoba border area. Logging camps, mills, rolling stock and timber were lost in the fire, which extended from "*Crooked River to Bannock, fifty miles in length*". Another report places the fire from Tisdale Saskatchewan to Mafeking Manitoba, while the last report indicates fire damage was greatest at Mistatim Saskatchewan, with the fire burning on both sides of the railway, "*extending back two to two and half miles and forming a strip thirty miles in length*".

The final fires of the month occurred on May 30, with three fires near Priest River Idaho. The fires originated in "*some slashings about seven miles from here on the West branch*". "The sixty men and two women who lived there succeeded in escaping to Priest River".

June was cold in much of British Columbia and coastal Washington. Further inland, near normal temperatures characterized the month in the rest of Washington, Idaho and western Montana. Droughty conditions persisting in this region, as well as further north in southern BC and Alberta. The east slope of the Rockies in Alberta and Montana was 2-3 °C warmer than normal. Pronounced warm and dry conditions characterized the Great Lakes region.

On June 1, "*prairie fires*" were "*running wild on all sides of Medicine Hat*" in Alberta. By mid-June the fire situation near Athabasca Landing was back in the news, where fire "*driven by a terrific gale leaps Athabasca River*". The burned area was "*fully 200 miles long by 20 miles wide*". It was confirmed that the fire was "*started by frieghters during the winter*".

By mid-June, fires hit the Great Lakes region in Ontario. Fire threatened the Kaministiqua Power Company power plant, which supplied power to Fort William and Port Arthur, covering 15,000 acres in the Conmee, O'Connor and Papnoonage townships. "*Dozens of settlers*" were rendered homeless, with men "*weary almost to exhaustion with days of ceaseless efforts to fight the fires*". There was also a fatility when a women "*was smothered in the burning of her own home while her husband was away with other settlers fighting the flames*". Later this month, fires were reported at Mine Centre, Steep Rock, Bear's Pass and other points. "*Millions of dollars worth of damage has been caused by forest fires in the Atikokan district*" with fire burning in the red pine, jackpine and white pine forests "*practically all the way from Atikokan to Fort Frances and in some places runs to a depth of fifteen miles from the CNR tracks*". Fires also burned between Fort Frances and Rainy River.

July across western Canada and the neigboring states was near normal or slightly above normal in terms of temperature. The precipitation patern was another matter, however. The cordilleran drought of southern British Columbia/Alberta, eastern Washington, Idaho and western Montana intensified and spread to include coastal Washington and British Columbia Another pocket of drought was evident in the Great Lakes region.

After a June hiatus in reporting, fire in the Lake States were once again in the news in early July. Fire destroyed the homes of settlers near Cornuicopia Wisconsin but was extinguished by a "*heavy downpour*". The extent of Wisconsin fires was described as "*the burned area extends about 50 miles north of Prentice and is about 40 miles wide between Stanley and Thorpe. Twentyfive villages in the burned district narrowly escaped destruction. The homes of more than 100 families were burned*". Michigan was also hard hit, with fires near Sault Ste. Marie fire on both sides of the stage road, with a stage coach "*racing over a mile through a lane of fire*". Ontonagon was threatened, with Boyne City, Orville and Haller also in danger. Cedar River was in the path of two fires and fires were also burning in Delta county. Fire in the Great Lakes region continued later in July, with fires raging in northern Wisconsin (Kaniwa, Heinman, Winterberg, Bloomville), northern Michigan (Negaunee), near Kenora in Ontario (Kenora, Winnipeg River, Ostersund), and in the Rainy River region along the Ontario/Minnesota border. At Rainy River on July 20, it was reported "*Bush fires are within half a mile of the town, which is in the greatest peril*". Engines, apparatus and fire fighters were dispatched from Baudette Minnesota, Fort Francis Ontario and Winnipeg Manitoba. The Minnesota resources were recalled on July 22 as fire was also threatening the American side. By July 23, about 1000 men were fighting fire at Rainy River, with the aid of a high pressure water system. Rain fell this day, diminsihing the danger from the fires burning along the Canadian Northern Railway. RH Campbell, superintendent of forestry in Ottawa, placed blame for the fires on right-of-way maintenance, indicating the railway had done nothing to "*clear the right of way of this menace*".

By mid-July, large fires were burning in the east slopes of Alberta, through the Crownest to the Kooteney's in British Columbia and across western Montana. In the east slopes of Alberta, fire was reported 20 miles from Priddis, SW of Calgary. A detachment of Mounties responded, putting in "*seven hours in the saddle, doing almost 80 miles*" in their round trip. Chief of Dominion Fire Rangers Margach also responded with 20 men. This fire was later reported to have been burning since the last week of June. "*Another alarming fire is raging in the government timber limits at the source of the Elbow River*". Fire was also reported west of High River, on Willow Creek 40 miles west of Nanton, near the headwaters of Sheep Creek and NW of Cochrane. At least two of these east slope fires were human caused, with the fire at Willow Creek caused by fishermen and the fire west of High River caused by a surveryor laying out a timber limit. Drought was evident with Chief Ranger Margach reporting "*many streams that have not been known to be dry for the past twenty years have not a drop if water in the this summer*". The most extreme danger of the month likely occurred on around July 14 and July 24. On July

23, the Priddis fire was ó*burning fiercely*ö and ó*burning over a territory thirty miles wide across the face of it*ö. A fire at Banff the next day was successively contained to 10 acres and according to an on-site account by Colonel James Walker, RNWMP, ó*if the citizens of Banff had not turned out almost to a man and worked heroically to check the fire which started on Sunday afternoon, the results would have been very disastrous*ö. A change in the weather also helped check the east slopes fires in Alberta, with rain reported on July 29 and 30: ó*the splendid rain of Friday night and Saturday morning, while not suffecient to entirely extinguish the forest fires in the foothills, checked their progress and there is very little danger of their spreading during the next few days*ö. No further reports concerning these Alberta fires was found in the newspapers.

In the Crownest of British Columbia a report indicated ó*the bush fires and lumberman are clearing out the Crow's Nest*ö. Large fires burned near Michel, Elko, Jaffray, Baines Lake, Wardner, Cranbrook, Loco, Moyie, and Kitchener. All of these fires were burning along the railway where extensive slash in the vicinity of timber camps and railway were identified as the source of many problems.

Further west in the Kootenayös, the mid-July fire bust was particularly intense. Fatalities resulted: ó*The dead bodies of four victims of the forest fires that are raging in the vicinity of Sandon and Kaslo were found today* (July 18) *in the tunnel of Lucky Jim mine, where they had sought shelter from the intense heat and smoke*ö. A fifth victim was found the next day. At least 34 large fires burned throughout the region, centred around Nelson. July 16 was perhaps the worst burning day of the month when the fatalities occurred on the Kaslo River: ó*the fire had travelled in twenty minutes about three miles*ö with ó*burning trees, uprooted or broken by the fierce wind, completely filled the air*ö. Government Agent Teetzell cancelled all fire permits at this time, and was of the opinion ó*that 75 percent of the fires now in progress were the result of clearing fires*ö. British Columbia Premier McBride sent word to Kaslo ó*to extend all aid to all requiring it, and has also empowered the fire wardens to engage every man available for the work of fighting the flames*ö. By the last week in July, ó*advices to Premier McBride declare that the forest fires are extinguished throughout the province*ö. Fire reports from the Kootenayös did indeed diminish after this, however another fatility occurred near Trail in early August when a firefighter was killed by fire-weakened timber. Fires also burned near Rossland, Wyndell, and Renata in early August.

Thirteen forest fires were reported raging in mid-July in western Montana, with hundreds of men fighting them. Fires were reported in the Couer DöAlene, Lolo, Clearwater, Bitterroot, and Missoula forests. ó*The town of Whitefish is in the centre of forest fires which are sweeping the mountain sides*ö. Over 300 men were fighting fire on the Kootenay National Forest on July 17, with a number of fires reported on the Flathead reservation. By July 20, the town Ryan Washington on the Columbia was ó*reported to have been wiped out by a forest fire*ö which covered ó*a tract 15 miles long and seven miles wide*ö. The situation eased towards the end month, when it was reported on July 24 that ó*heavy showers during the last forty eight hours have checked the great forest fires that were threatening towns of Washington, Idaho, Montana and British Columbia and for the present practically all danger is passed*ö. No further reports of fires in this region were found until early August.

Fire activity on the Pacific coast was also reported in July. On July 20, fires were burning between Lake Washington and Sammamish east of Seattle. In Canada, a fire on Salt Spring Island was reported to cover an area of 1200 acres and a fire at Cobble Hill on Vancouver Island was reported to be under control. At about this same time, officers of the steamship Dolphin ó*told* *of a tremendous forest fire, a hundred square miles in extent*ô burning in Howe Sound. Coastal fire activity continued in August and September.

August was cooler than normal, with the exception of the Lakehead region, which had near normal temperatures. The pattern of August precipitation shows two main drought areas: the cordillera south of the international border and the Lakehead region. Drought conditions in the Canadian cordillera eased, especially in the east slopes of Alberta. Drought conditunued in the Nelson region, east along the Crowsnest, and along the south coast of British Columbia.

In early August, it was reported fires in the Flathead Valley were the worst in history. On August 8, there was some encouraging news concerning suppression efforts in western Montana and Idaho, however, there were also reports of large fires burning along Big Creek, in the Bitterroot and Clearwater forests, at Seeley Lake, and on the outskirts of Missoula. The next day, August 9, President Taft authorized the use of troops to fight fire in Montana, Idaho, Washington, Oregon and California. Conditions continued to deteriorate during the second week of August, with 7 distinct fires burning on the Flathead Indian Reserve and critical conditions reported on the Couer dôAlene national forest. Suppression efforts became desperate by August 15, with ó*hundreds of pounds of dyamite*ô exploded at Wallace Idaho in the hope of inducing rain. The next day, American troops were in Canada, on their ó*roundabout railway route*ô from near Tacoma to the Colville reserve. On August 19, it was reported that ó*forest rangers and settlers are working day and night in the Couer d'Alene region, Idaho, where three towns have been threatened*ö. On Monday, August 22, the news broke concerning the events of the weekend with the following headline: ó*Hundreds Burned*ö. Reporting was comprehensive, with articles from western Montana and Idaho occupying the attention of the Alberta newspapers for the rest of the month.

In Canada, fire burned near White Rock British Columbia in August. This fire, reported in September, was ó*smoldering since August 2*ö. Another coastal fire occurred on Wales Island, north of Prince Rupert, on August 13, where ó*a bush fire, fanned by a west wind, burned five miles in less than an hour and a half*ö. In the Great Lakes region, fires were reported near Fort Francis at the end of the month. Fires here were located at Rainer Minnesota, as well as in Ontario at Fort Francis, Leaslee and Crozier. Another fire further north was located at Ignace.

September was cooler than normal in much of the cordillera, with the coolest temperatures found along the east slopes of the Rockies in Alberta and Montana. The Great Lakes region experienced near normal temperatures. The drought in the cordillera was releived for the most part, although drought conditions continued in SE Washington and along the lower Fraser River in British Columba. A pocket of drought appeared along the Saskatchewan/Manitoba border and the Great Lakes region continued with below normal precipitation, especially in the Lake States.

The only September report of fire comes from the Delta district on September 14, between Vancouver British Columbia and Blaine Washington. This report may be related to the August White Rock fire.

The next reported fire comes from the Rainy River region in early October. On October 5, just west of Baudette Minnesota ó*a bad fire which has been burning in the bush to the south for several days was today fanned into a dangerous activity by a strong wind from the south and swept down on the railway village of Graceton on the Canadian Northern Railway system*ö. This large fire with a 25 mile front ó*destroyed*ô Graceton and ó*threatened*ô Williams. The next day it was reported four Graceton people were missing, with two hundred men fighting the fire. Disaster struck Baudette and Spooner on October 7, when the ó*Great Forest Fires Wipe Out Two Minnesota Towns*ö. Comprehensive reporting of this large fire event continued for a week.

Discussion

The 1910 fire season followed more than a decade of economic boom in western Canada, prompting Prime Minister Wilfred Laurier to speculate "*The 19th century was the century of the United States. I think we can claim that it is Canada that shall fill the 20th century*" (January 18, 1904, Canadian Club of Ottawa). The immigration policies of the Laurier government resulted in the population of the prairie provinces rising from about 400,000 in 1901 to 1,300,000 in 1911, while at the same time, British Columbia's population jumped from 179,000 to 392,000 (Hardy 1959). Immigration in western Canada was fueled by rapid industrialization and urbanization in eastern Canada, the United States and Europe. Factories required raw materials and food for the workers. Advances in agronomy, including the development of early-ripening spring wheats (Red Fife, Marquis), pushed the viability of farming into the northern prairies and aspen parkland. Beef, lumber, fossil fuels, and minerals were also in demand, with existing and new infrastructure quickly carrying products to market. The Canadian Pacific Railway was completed in 1885, spanning western Canada from Port Arthur on Lake Superior to Vancouver on the Pacific. By 1910, the competing Canadian Northern Railway had reached Edmonton, aiming for a more northern route to the Pacific at Prince Rupert. Branch lines criss-crossed the prairies and portions of the cordillera. Telegraphs and telephones linked the country, allowing rapid communication and coodinated transportation. This economic and settlement boom in western Canada occurred during unusually favourable climatic conditions, where proxy tree-ring precipitation suggest settlement occurred during one of the wettest periods of the last 500 years (Watson & Luckman 2006).

The climate of the era was not uniform however. In the southern Canadian Cordillera, the 1900-1909 decade was the wettest decade in about 300 years, with 1900 appearing to be the most spatially extensive, extremely wet year post-1700 (Watson and Luckman 2004). This early 20th century wet period appears more severe in the eastern portion of the Canadian Cordillera, which corresponds to high flows in the North Saskatchewan, South Saskatchewan and Saskatchewan River basins (Case & MacDonald 2003; Watson & Luckman 2005). The incomplete decade from 1906 to 1910 also ranked as the wettest during the 20th century in the North American prairie pothole region (Millett *et al.* 2009). Further east in Ontario, drought characterized the years leading up to the 1910 fire season, beginning in about 1905 (Giardin *et al.* 2006*a*, 2006*b*). In northwestern Ontario, prolonged drought from 1906 to 1915 appears unmatched in the preceding century (St. George *et al.* 2009). Furthmore, extreme low tree growth in 1910 was well beyond any other negative growth anomalies observed since 1783. It therefore appears the 1910 fire season was preceded by persistent wet conditions in the cordillera and across the prairies, but distinctly drier conditions the Great Lakes region. Antecedent climate, however is not necessarily a factor in the appearance of large fire years (Heyerdahl *et al.* 2008a, 2008b, Morgan *et al.* 2008). Instead, large fire years tend to be more dependent on warm and dry conditions during the fire season.

The 1910 fire season in western Canada is noted for the incredible spring warmth and spring and summer drought (Fig 2). The role played by large scale climate patterns like El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) in 1910 appears somewhat confused. NOAA's Earth System Research Laboratory (http://www.esrl.noaa.gov) data indicates winter ranked 19th, spring 18th and summer 5th in the ranked La Niña extreme years from the Southern Oscillation Index (SOI) record, 1896-1995. Regarding PDO, a cool PDO regime prevailed from 1890-1924 (Mantua & Hare 2002). In much of western Canada, these ENSO and PDO conditions do not normally favor large fire years (Shabbar & Skinner 2004; Skinner *et al.* 2006; Meyn *et al.* 2010). There is similar evidence from further south in the United States (Hessl *et al.* 2004; Heyerdahl *et al.* 2008a, 2008b; Morgan *et al.* 2008). On the other hand, some evidence for large fire years synchronous with La Niña and cool PDO in British Columbia and the southern Rocky Mountains in the United States. (Fauria & Johnson 2006; Schoennagel *et al.* 2005). Regardless of the above, the 1910 fire season in western Canada occurred during La Niña/-PDO, exhibiting a very warm and dry spring, followed by summer drought with near normal temperatures. These unusual climatic conditions of 1910 resulted in large area burned in western Canada.

Alberta newspaper articles provide evidence for large area burned in coastal British Columbia, southeastern BC, the east slopes of Alberta, the prairies and aspen parkland/boreal ecotone of Alberta and Saskatchewan, and in the Great Lakes forests of Ontario. The initiation, duration and appearance of critical fire periods within the fire season in each of these relatively distinct areas can be deduced using daily records of precipitation, as long sequences of rain-free days have a high correlation with area burned in Canada (Flannigan & Harrington 1988). Fig. 3 shows rain-free periods for select Canadian stations in 1910.

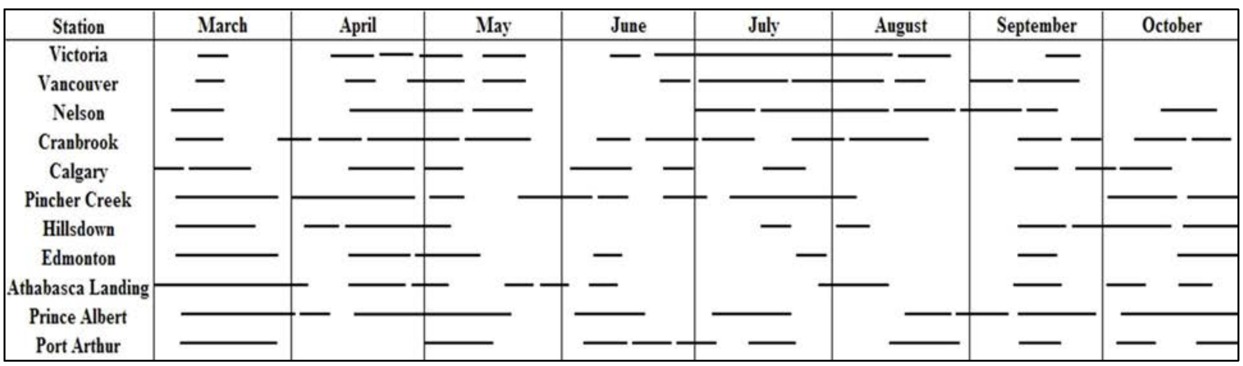


Fig. 3. Rain-free periods, 1910**.** Lines represent sequences of rain-free days, with a minimum period of seven days.

A summary of fire events by region shows close correlation to critical fire periods at the various stations. Large fires burned in coastal British Columbia on May 23 (Johnstone Strait), July 20 (Vancouver Island/Howe Sound), August 2 (Vancouver), August 13 (Prince Rupert) and September 14 (Delta). Representative stations are Victoria and Vancouver. In southeastern British Columbia, represented by stations at Nelson and Cranbrook, large fire events occurred on May 6 (Salmo/Trail/Princeton/Nicola), July 15 (widespread around Nelson and through the Crowsnest), and August 2 (Rossland/Trail/Wyndell/Renata). The large fire events in the east slopes of Alberta occurred on April 17 (Porcupine Hills/Pincher Creek) and around July 15 (Ghost River/Elbow River/Priddis/Sheep River/Highwood River/Willow Creek). Calgary and Pincher Creek are the representative stations. The large aspen parkland/boreal ecotone region is represented by stations at Hillsdown, Edmonton, Athabasca Landing and Prince Albert. Large fire activity occurred on April 16 (Vermilion/Red Deer/Hillsdown), April 30 (Athbasca Landing), May 8 (Prince Albert), May 26 (Mistatim) and June 11 (Athabasca Landing). The Great Lakes region, represented by Port Arthur, had large fire activity on June 13 (Port Arthur), June 25 (Atikokan), June 29 (Devlin), July 20 (Rainy River/Kenora), August 27 (Fort Francis) and October 7 (Rainy River).

The dates provided above relate to the first reports of the various fires and can be assumed close in time to fire ignition. The origin of the fires are likely both human and lightning, although lightning was not mentioned as the cause in any of the reports. Instead, the majority of the fire causes were reported as caused by railway, industry, clearing, recreation, or were incendiary in origin. Itǿs likely some lightning fires burned at the same time as many of these fires in the main summer lightning season. However, much slash was accumulated in the vicinity of booming railway, logging, and mining operations, with ample opportunity for accidental or intentional ignition. Further, the success of the influx of settlers depended on clearing and breaking land for agriculture, with the intentional use of fire an obvious benefit. Relatively unlimited human ignition dominated the 1910 landscape, clashing with fuel moisture never before experienced by most residents. Numerous, large, uncontrolled fires resulted.

Conclusion

With the exception of the fires burning in the east slopes of Alberta, the focus of recent research (Annand & Arthur, Rogeau this conference), little documentation concerning the 1910 fires in western Canada exists. Barring similar fire history research in the rest of western Canada, determination of 1910 fire extents will continue to become cloudier with reburns, landscape change and other losses of evidence. The value of understanding historical fires should be obvious. Fire management relies on forecasts and predictions to guide management actions. Tools which aid forecasts and predictions are developed and tested with historical conditions. Without comprehensive histories, forecasts and predictions may be unreliable as they could fail to take into account the full range of possible outcomes. Based on the simple approach taken in this paper, it appears it would be worthwhile to consider the history of the 1910 season in western Canada in future fire forecasts.

Ackowledgements

I thank Marty Alexander, the American expatriate fire scientist with an exemplary record of service to Canada, for encouraging me to investigate the larger extents of the 1910 season.

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Fire-Scar Formation Processes in Mixed Conifer Forests in the Sierra San Pedro Mártir and Sierra Nevada

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Abstract:

Little is known about the probability of fire scar formation. In this study we examined all mixed conifer trees for fire scar formation in a 16 ha watershed that burned as part of a wildfire in July 2003 in the Sierra San Pedro Martir (SSPM), Mexico. In addition, we examine the probability of fire scar formation in relation to the previous fire interval in forests in the SSPM and Sierra Nevada. Within the 16 ha SSPM watershed 1647 trees were assessed (100% census) for new fire scars. The SSPM wildfire burned around the base of 78% of the trees but only 8% of the trees developed a new fire scar. While the years from tree germination to first fire scar could potentially represent a fire-free period, there is clear evidence from this study that the inclusion of this interval when computing fire statistics is not justified. When the time since previous fire was <10 years, 10-30 years, and >57 years, the probability of rescarring was approximately 0.05, 0.5, and 0.75, respectively. In areas where fires are frequent (< 10 years), fire-scar derived fire frequencies will likely underestimate true fire frequency, at least in forests that are similar to those studied here. This has important connections to inferences made from fire scar studies.

Fire regimes of Alberta's southern Canadian Rockies and important fire years

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Abstract

A compilation of province wide fire occurrence statistics (1961-2002) revealed that each natural subregion has a unique fire regime signature. With a particular focus on the Rocky Mountain and Foothills Natural Regions, detailed fire regime studies indicated that terrain, fuel continuity and lightning distribution were three lead contributing factors that differentiate these fire regimes. The compilation of fire history information from different regions unveiled that large fire events shared similar fire years. It is estimated that fifteen periods of severe drought conditions have occurred between the 1840's and 1940's. Other important findings from fire history data collection in the Foothills and Montane Natural Subregions of Alberta were the short fire-return-intervals and the mixed severity burning that took place historically. Under prolonged fire suppression, it is clear that current forest conditions for some regions are now severely departed (by up to 200%) from historical ones, which is greater than what was first expected.

Additional keywords: mountains, foothills, fire history, severe droughts, historical fire interval, fire-free interval, fire return interval

Introduction

Since the early 1980's a number of fire history and fire regime studies have been completed in the Southern Canadian Rockies of the Province of Alberta. Over the years, fire history data has been collected from the Montane Ecoregion of Jasper National Park (Tande 1979, Rogeau 1999a), Peter Lougheed Provincial Park (Hawkes 1980), Banff National Park (White 1985, Rogeau and Gilbride 1994, Rogeau 1996a), Jasper National Park (Parks Canada unpublished data circa 1989), Kananaskis Valley (Johnson and Larsen 1991), Spray Lakes Recreation Area (Rogeau 1994), Waterton National Park (Barrett 1996), Forest Research Institute landbase - formerly the Foothills Model Forest (Rogeau 1996b, 1997, Andison 2000), the Whitegoat and Siffleur Wilderness Areas and portions of the North-Saskatchewan Valley (Rogeau 1999b), Spray Lake Sawmills FMA and Kananaskis Country (Rogeau 2004, 2005, 2006), and Forest Management Unit R11 (Rogeau 2009, 2010a, 2010b). As a general rule, time-since-fire maps were produced using fire polygon data for landscapes dominated by a stand replacing fire regime, whereas landscapes dominated by a mixed fire regime, largely found in the Montane, front ranges and in the foothills, were assigned Mean-Fire-Return-Intervals from point location data. Having participated in the data collection and analyses of many of these studies, I would like to take this opportunity to spread the word that many agencies have kept their wood sample cross-sections (cut at ground level) and these are available for research purposes.

Fig. 1 shows the outline of known fire history in the Rocky Mountain and Foothills Natural Regions of Alberta. The zone covers a total of 42,662 km^2 area. From the Continental Divide, which corresponds to the Alberta-British Columbia border, the zone varies in width from 15km to 175km. At its extremities, the fire history zone covers nearly 500 km in length.

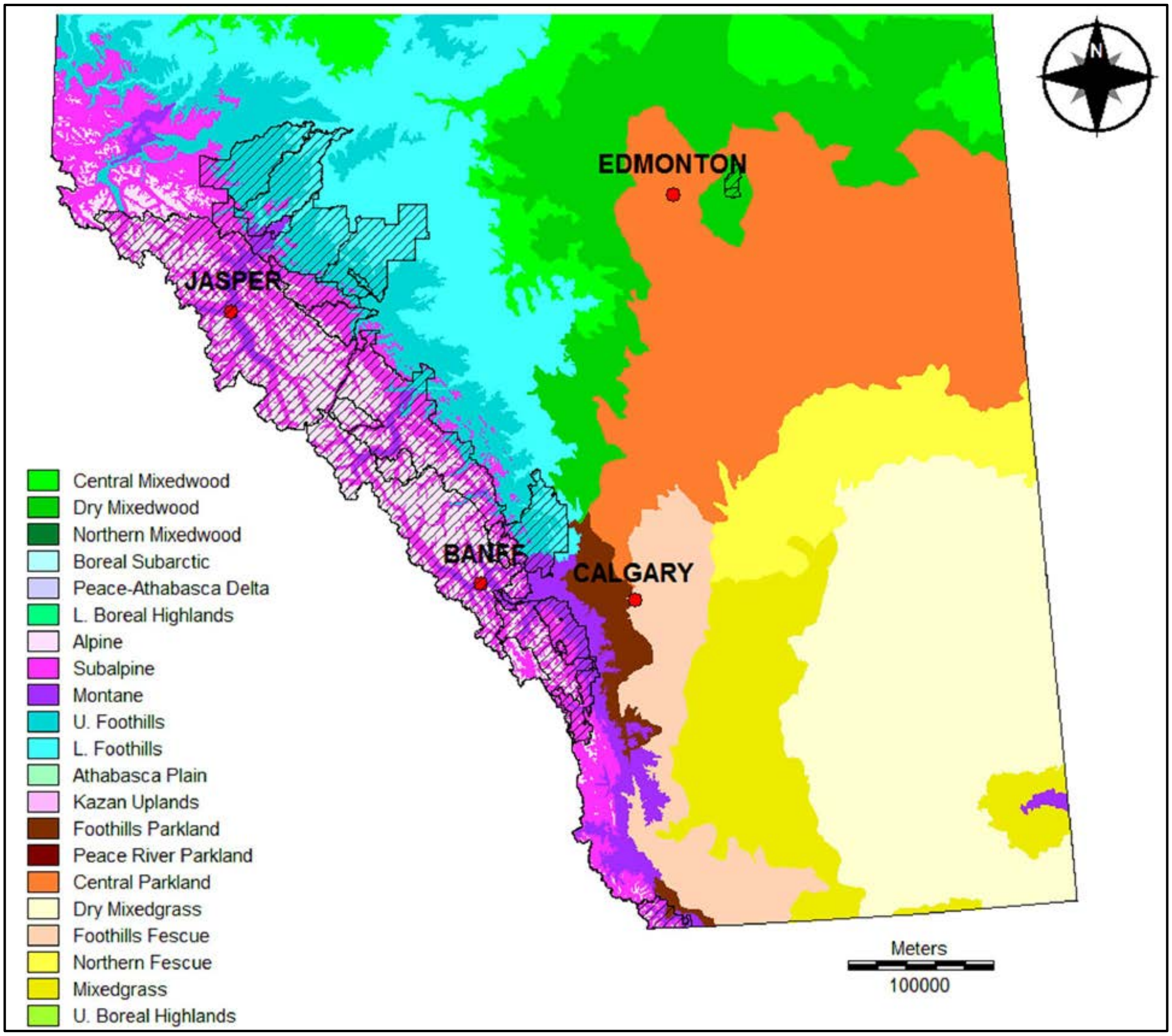


Fig. 1. Zone of fire history data in the Rocky Mountain (Alpine, Subalpine, Montane) and Foothills (Upper and Lower Foothills) Natural Regions of Alberta.

Fire regimes of Alberta

A fire regime study necessitates documenting a large number of parameters. In summary, fire history studies involving field data collection can provide information on historical fire intervals and fire cycles, and their spatial variation. In addition, Governmental fire occurrence data sets can be used to evaluate the lead fire cause (lightning vs anthropogenic), season of occurrence and area burned by cause, mean fire size, and the spatial distribution of probabilities of ignition.

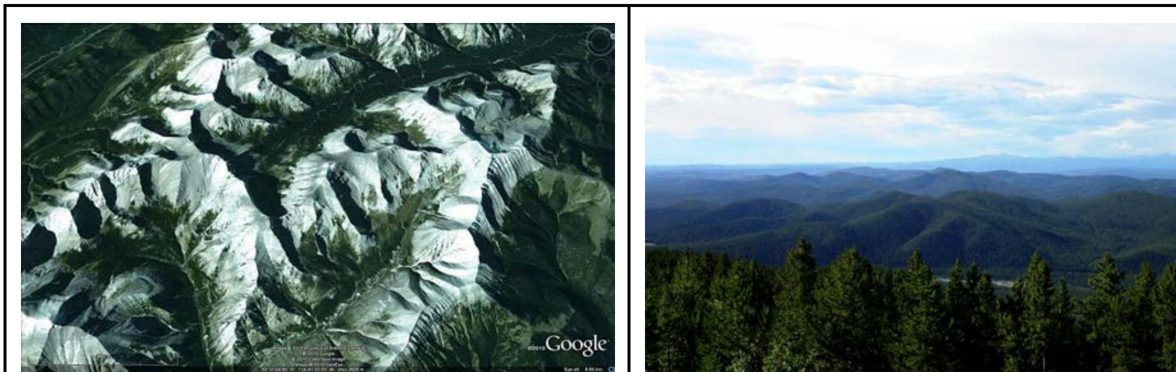
Lastly, historical fire intensities and severities can be documented with the use of old aerial photography and historical photographs from early surveyors (http://mountainlegacy.ca/).

It has been found through a province wide study that made use of fire occurrence statistics collected between 1961 and 2002, that each Natural Subregion has its unique fire regime signature (Tymstra *et al.* 2005). Natural Regions and Subregions are partitioned and stratified according to climate, dominant vegetation, soil and physiographic features (Natural Regions Committee 2006). Very much like the fire behaviour triangle: topography, climate and fuel, these three components not only dictate fire behaviour on the ground, but they were found to capture sets of fire regime conditions.

The focus of this paper is to outline the main differences in the fire regime between the Rocky Mountain and Foothills Regions.

Rocky Mountain and Foothills Fire Regimes

A number of parameters influence the fire regime of each region. Differences in topography and fuel cover play a significant role in determining fire size and fire spread patterns. As shown in Fig. 2, watersheds of mountain landscapes are bound by rocky ridges that break-up the fuel cover, whereas vast extents of continuous fuel exist in the Foothills. The lower elevations of the Foothills imply a longer fire season that can start as early as April. A similar fire season length is found in the Montane Subregion of the Rocky Mountains due to lower elevations, but Subalpine regions can be snowbound well into June. Table 1 presents an itemized description of the Mountain and Foothills fire regimes, while the following sub-sections describe in greater details some of these differences.



a) b)

Fig. 2. a) Rocky Mountain Subalpine type landscape, b) Foothills type landscape.

Table 1. Prevailing environmental and historical fire regime characteristics of the Rocky Mountain and Foothills Natural Regions.

Variables	Rocky Mountain		Foothills
	Subalpine	Montane	Upper Foothills
Vegetation	100% coniferous	>85% coniferous	>85% coniferous
Topography	Rugged, >1600m	valley bottoms 1400m - 1600m	Rolling - mountainous < 1400m
Fuel continuity	broken-up by rocky ridges	forest broken-up by dry meadows	continuous
% lightning-cause fires	25 to 45%[a]	10%	55%
Avg. fire size (ha)	400 to 800	1300	1300
Seasonality	Jul. - Sept.	Apr. - Sept.	May - Sept.
Fire cycle (yrs)	80 to 250[b]	45	40
Mean-Fire-Return-Interval of significant fire events	n/a	5 to 45	50
Fire intensity	stand replacing	partial to full stand replacement	partial to full stand replacement
Fire severity	high	mixed	mixed

a: varies according to location
b: highly variable according to historical land use and fire frequency of the area

Fuel continuity
Fuel continuity is closely related to the expected range of fire sizes. Rugged Rocky Mountain landscapes bound by rocky ridges, which create a discontinuous fuel cover, tend to see smaller size fires and a lower overall burn area. In comparison, Foothills landscapes with their partial to fully continuous forest cover, are associated with larger size forest fires and greater overall burn area. In a recent study including both Mountain and Foothills landscapes (R11 FMU, Rogeau 2009), it was found that historical fire severity, number of fires and time-since-fire, were best explained by fuel continuity over valley orientation and Natural Subregion. This information was recorded on a watershed basis using 1950 aerial photography.

Complexity of the vegetation mosaic
The vegetation complexity in terms of variety of stand ages, intricacy of forest patches and stand structure was very different historically between the Subalpine and the Montane or Foothills landscapes (Fig. 3). Lower fire frequencies, longer fire return intervals and higher fire intensities observed in the Subalpine Natural Subregion tend to produce a landscape that is

largely dominated by full stand replacing fires. The clear landscape fire boundaries are easy to outline even centuries after the fire and exhibit an overall forest age mosaic that is relatively homogeneous. In comparison, both the Montane Subregion of the Rocky Mountains Natural Region and the Foothills Natural Region, historically saw frequent fire activity, with repeat burning at 5, 10, 15 or 20 year intervals. This level of fire activity kept the fuel load low, which produced mixed severity burns, which in turn created a high level of intricacy in stand structure and overall patchiness of the forest. Today in these same forests, as a result of fire suppression, forested stands have become much denser with an increased fuel load. Burning intensities and patterns are now expected to be reminiscent to those found in the Subalpine Subregion.

a) b)

Fig. 3. a) example of Subalpine vegetation mosaic of low complexity, b) very complex vegetation mosaic typically found in the Montane and Foothills.

Lightning activity

Another important difference between these fire regimes is the lightning / anthropogenic fire ignition ratio. The east side of the Rocky Mountains lie in a lightning strike shadow (Wierzchowski *et al.* 2002), which is a zone that sees very few lightning strikes (Fig. 4). Due to the orographic effect of the high mountains along the Continental Divide, lightning storm patterns track to the east and tend to form away from the mountain ranges. A compilation of lightning strike data from 1990 to 2004 show a density of less than 5 strikes/year per 100 km^2 (only positive polarity strikes were considered for this exercise as there is a stronger relationship between those and actual fire ignitions). Fire regime studies of this region (Rogeau 2004, 2009) have shown that there is not a strong correlation between the density of lightning strikes and the number of lightning-caused fires. However, low strike density zones are always associated with zones of rare lightning-fire ignitions. In summary, the likelihood of lightning fires remains very low in the Subalpine and Montane regions, and is significantly greater in the Foothills (the Lower Foothills being more lightning-fire prone than the Upper Foothills).

By deduction, regions that are not prone to lightning-caused fires, but that historically saw much burning activity, were greatly influenced by traditional land use, as well as first explorers and land settlers. To maintain the ecological integrity of these fire driven ecosystems, it is thus well justified to utilize prescribed fires to offset the departure in fire regime conditions that have been documented (Rogeau 2008, 2010).

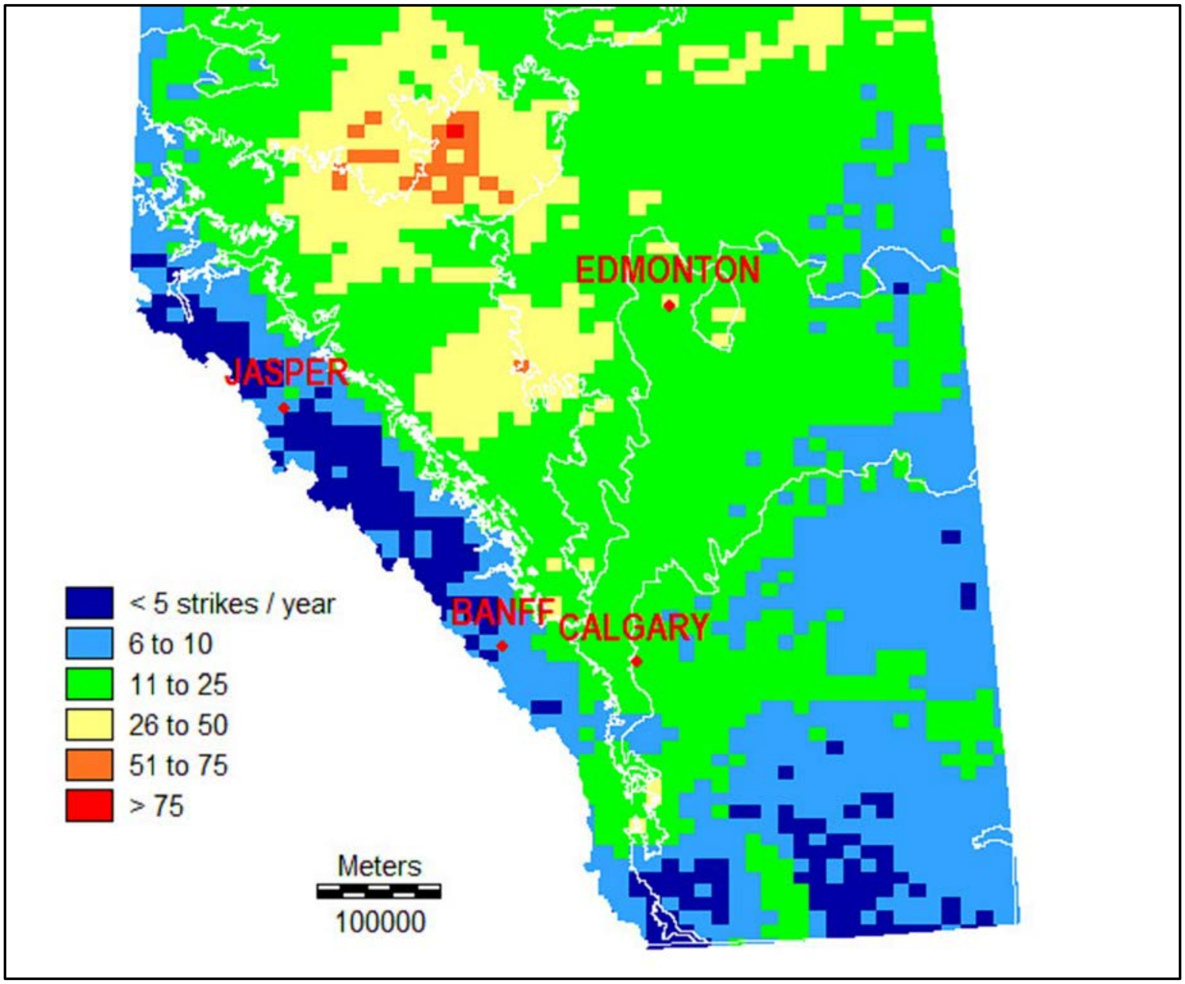


Fig. 4. Yearly average positive lightning strike density distribution (10 km x 10 km grid cells) in Alberta.

Effect of topography

In mountain landscapes another important factor that influences the spatial variation in fire frequency or fire return intervals is topography. Elevation, aspect, valley size and orientation, and distance from the Continental Divide, all individually affect the probability of burning of a forest stand. Rogeau *et al.* (2004) determined that these four variables can explain up to 64% of stand age distribution in the Subalpine Subregion, and up to 70% in the Montane Subregion[1]. Other topographic elements that were not tested, but appear to contribute to fire distribution patterns in the mountains are valley width and valley headwaters. Combined together, all these topographic elements become powerful indicators of where old growth forests (fire refugia) and younger aged forests are expected to persist.

[1] When this study was conducted, fuel continuity was not considered as a topographic variable. But as previously noted, it would appear that fuel continuity also contributes significantly to fire distribution.

Significant fire years between 1830 and 1950

Most fire history studies, listed in the Introduction, repeatedly identified the same fire years. These important fire years, which involved all Natural Subregions: Subalpine, Montane, Upper and Lower Foothills, had to be associated with severe drought conditions. Judging from the area burned and the number of fires encountered on this broad landscape, it would appear that some of these fire years were as severe, if not worse, than 1910, which has been documented as one of the worst fire seasons in the history of the forest service. The list of significant fire years documented are: 1843 - 45, **1848 - 50**, **1863 - 64**, 1867 - 68, **1869 - 70**, **1875 - 77**, 1885, **1888 - 89**, **1994 - 96**, 1909 - 10, 1913 - 15, 1917 - 19, 1924 - 25, 1927 - 29 and, **1934 - 36**. In bold are those fire years that were potentially worse than 1910.

While many more fires have occurred on numerous other years, those fire events were more localized and of smaller dimension. Interestingly, it would appear that when a severe drought occurs and ignition is available, that a greater part of a broad landscape could burn ćall at onceô within a fire season.

Departure of Fire Regime Conditions

Historical photographs and fire history data revealed the severity of fire regime conditions departure in both the Montane and Foothills landscapes. Historically, the Mean-Fire-Return-Interval of significant fire events was ten years, generating a fire cycle[2] of 40 years. Due to effective fire suppression over the last 80 years, two fire cycles have been skipped, which corresponds to a departure of 200% in fire regime and ecosystem conditions. Fig. 5, dating from 1895, is a representation of historical conditions. Multiple fires at short intervals can be identified in this landscape of immature trees. Such photos explain why many lodgepole pine trees cut for fire history purposes hide internal fire scars (Fig. 6) that occurred on trees that were anywhere from 4 to 20 years of age at the time of scarring. The low fuel load resulting from back to back burning produced fires with intensities low enough that many saplings could actually survive. Today, these landscapes are composed of a dense and continuous forest cover as per Fig. 2b.

[2] The fire cycle is the number of years it takes to burn an area equivalent to the size of the area of interest. During one cycle, some areas may burn more than once and others may not burn at all.

Fig. 5. Example of historical Montane landscape. Photograph taken in 1890 by James J. McArthur while surveying in the Bow Valley (Mount Yamnuska in the background). (source: http://mountainlegacy.ca/)

Fig. 6. Internal scars are occasionally found on landscapes of mixed fire regimes and low fire intensities.

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Fire Regimes in Mexico

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Abstract:

Mexico is a country with high species and ecosystem diversity, and where fire has become one of the top priorities in forest management policy. However, current management fire management practices are still centered in firefighting and fire suppression. To ensure that the ecological conditions that gave rise and maintain the high diversity of species in Mexico is maintained, it is important to incorporate information on the natural fire regimes in fire management programs. Here, we analyze information available on the main terrestrial ecosystems of Mexico to suggest what the likely fire regimes were for each one of them.

Fire History in Pine Forests of the Mogollon Biotic Province Central East Arizona

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Abstract:

Fire history was reconstructed from fire-scarred conifers using tree-ring dating methods (dendrochronology). Ponderosa pine and mixed-conifer forest sites were sampled. This is a unique pyrogeographic region due to the Mogollon Rim, a 300 meter escarpment rising above the desert that runs from northwestern Arizona to southeastern New Mexico, influencing monsoon lightning, climate and fire interactions. Fire histories were cross-dated and mapped at 10 sites and evaluated in context of historical land-use records. Comparative fire-regime statistics were calculated and the relative extent of past fire events inferred. We collected 278 fire-scarred samples from ten sites and cross-dated 210 for analysis (75.5%). Fire events were recorded at relatively frequent intervals at all sites prior to land-use changes beginning in the late 19th century (e.g., post-1880 settlement, grazing, logging, and farming).

The ponderosa pine sites (8) recorded relatively fine to intermediate extent fire events (i.e., ≤ 20% of the fire-scarred trees) with mean fire intervals (MFIs) ranging between 1-3 years, and extents estimated to range from one tenth to several hundred hectares. Relatively broader-extent fire events (i.e., ≥ 20% of the fire-scarred trees) were also recorded between sub-sites (MFIs = 3-11 years). Mixed-conifer forest sites (2) in comparison show fire regime changes several decades later in the early 20th century. Frequent fires were recorded prior to this change, however, fine to intermediate extent fire events were not as frequent (MFIs = 2-4 years) or as spatially variable as ponderosa pine sites. Relatively broader-extent fire events (≥ 20% fire-scarred trees) had MFIs of 5-8 years and synchronous inter-site fire events with MFIs of 15 years. These relatively more extensive fire events, in both forest types, likely spread beyond the study sites into adjacent forest stands and vegetation communities covering many square kilometers.

Fire frequencies were unusually high compared to many fire histories in the Southwest U.S. High concentrations of monsoon-lightning activity around the Mogollon Escarpment combined with diverse landforms and vegetation may explain these frequent and highly variable fire regime patterns. Past fire-use by local Apache may have also altered fire regimes at times and places.

This research suggests the spatial influence of fire was extremely variable and that relatively fine-, medium-, or broader-extent surface fires occurred almost every other year at these sites. These fire regime attributes indicate the profound role fires had in shaping past landscape patchiness and ecological resilience. This wide variability in fire frequencies and extent should facilitate the use of wildfire and prescribed fire to meet resource management objectives in the ponderosa pine and mixed-conifer forests of the Mogollon Province.

The Potential Impacts of Native American Land-use on Fire and Forest Structure in the Lower Klamath River Region, California

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Abstract:

Our study tests the hypothesis that Native Americans in the Klamath Mountains of northwestern California significantly influenced forest composition and structure through the extensive use of fire. Most vegetation change and paleo-fire studies in the region have been conducted at high elevations (>1500m) well removed from Native American settlement sites and focus on climate change as the primary factor controlling forest change. Our project examines two low elevation lakes, Fish Lake and Lake Ogaromtoc, that are within ~3 km of historically documented Native American settlements, but are still far enough away that evidence attributed to burning by Native Americans should only be recorded if these populations were manipulating the landscape well beyond the Klamath River corridor. We use pollen and charcoal analysis to reconstruct vegetation change and paleo-fire history. Fire scars are used to verify the charcoal record and examine the seasonality and frequency of fires. Past Native American influences are evaluated by analyzing whether past vegetation changes and fire occurrences are consistent with regional climate reconstructions or whether the timing of vegetation change and fire occurrences are more consistent with shifts in Native American regional occupation and land use. Preliminary evidence indicates that the two lake sites exhibit different fire patterns that may be attributable to changes in Native American land use and occupation. This research has implications for land management activities conducted within historic Native American territories. If Native Americans were burning regularly beyond their immediate settlements it could mean that forests at the time of contact reflect a human-modified landscape and not a landscape shaped by climate alone. Such a conclusion could reshape our ideas regarding pre-settlement reference conditions and help to better inform management decisions made in landscapes with a legacy of Native American fire use.

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Incorporating Fire Behavior into Evacuation Plans

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Abstract:

More communities are being asked to make decisions regarding evacuation. Programs such as Ready, Set, Go are being advanced throughout the nation where residents are asked to prepare for a wildfire and make plans regarding evacuation.

However, community-wide evacuation plans usually do not integrate the pre-planning of expected fire growth patterns and spread rates. We promote the use of fire behavior modeling - coupled with information on population density and traffic levels - to improve the decisions evacuation planning agencies make.

Fire behavior modeling can offer insights to the consequences of the timing of evacuation decisions. The decision regarding the extent and location of evacuation is also aided with fire behavior modeling. These decisions balance the desire to avoid disrupting the community needless, with the desire to ensure all can evacuate safely without being placed in harm's way.

In one project in Napa we based evacuation recommendations on the results of FARSITE under two scenarios, varying weather conditions and ignition locations. We included road network, location of residences and other buildings to determine recommendations for evacuation routes along with recommendations for temporary refuge. We developed time-and distance-based transportation models to identify preferred and alternate evacuation corridors. We also defined and applied network accumulation models to inventory, queue, and route evacuees using private and public transportation via the safest and fastest routes, without overloading the transportation system.

The case study illuminated the value of fire growth and spread patterns. For example, we found the timing of the decision to evacuate to be more sensitive, since rapid fire growth and/or poor traffic and access conditions could preclude evacuation options and promote a shelter in place strategy. It also bolsters the necessity for education of the community and practice of the emergency response plan, since this analysis identifies specific routes and intersections that are more appropriate and others that would be better avoided.

Cerro Grande Fire, Lessons Learned

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Abstract:

I just published my book "Inferno by Committee" which examines the land use history, land management history and the fire management history of the Cerro Grande (Los Alamos) Fire of 2000. This was a National Park Service prescribed fire that went awry and burned onto US Forest Service lands and then into Los Alamos, New Mexico, home of the nuclear weapons lab at Los Alamos National Laboratory.

At the time of the fire, federal agencies were operating under the 1995 National Fire Plan which proved to have serious holes and omissions revealed to receptive policy makers by Cerro Grande. The Cerro Grande Fire was perhaps the most investigated fire in recent history because there was so much controversy in professional circles about exactly what went wrong. Ultimately a Board of Inquiry was convened and that investigation resulted in an honest understanding of the fire's problems. The hasty and self-serving investigations ordered by the USDOI in an election year, and those done by the US Forest Service were then discounted.

The Cerro Grande Fire ended up having a major impact on national fire policy and the way prescribed fires are planned and implemented. Though there were no fatalities associated with Cerro Grande, the fire is estimated to have cost $1 billion in property losses and costs to agencies including the US Department of Interior.

I propose to offer a review of the prescribed fire and its management and then the suppression efforts that followed its declaration as a wildfire and then the main federal policy changes that came from the lessons learned at Los Alamos.

Exploring the Meanings and Significance of Living with Wildfire in the Rural West: Preliminary Research Findings on the "Lived Experience" of Everyday Interactions between Firefighters and WUI Community Members

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Abstract:

Federal agencies such as the Forest Service and BLM manage wildfire according to agency policies and fire management plans, and they communicate with rural Western communities living with wildfire through a variety of formal channels and media. However, frontline agency employees like the seasonal firefighters who work and live in local communities also represent these agencies, interacting on-the-ground with residents and communicating with them about fire management activities, direction and assumed responsibilities. Responses to hazardous fire situations in the WUI, moreover, can pose significant risks to these firefighters; pressures for them to protect people, homes, and communities likely will increase, even while requiring that they accept new, ever-increasing risks accompanying medical emergencies, structure fires, and other hazardous situations. In addition, these employees often quickly communicate fire-related information (e.g., current wildfire activity, planned prescribed burns, and fire restrictions), and concerns by residents and firefighters alike can be exchanged: thus, these employees can serve educational and public relations functions as they share information about and explanations of fire-related and other local agency management activities, such as forest health or recreation planning. What are the expectations of local community members and agency managers, as well as firefighters, concerning responsibility for community protection, in particular? And what job-related hazards and actions are perceived by community members, as well as on-the-ground employees, to be reasonable, allowable and acceptable in helping achieve desired community conditions? Here we report some initial findings of this research: what the "lived experience" is of everyday interactions between firefighters and WUI community members; what they suggest are the perceptions, attitudes, and expectations of firefighters and residents alike concerning wildfire risks, the need for property protection, and other agency functions; and what the consequences and impacts of these interactions are. Our research is providing insights into a number of issues raised by current and potentially expanded job functions of frontline employees. We suggest the ramifications of our findings for new forms of training and education for firefighters who directly interact with residents of rural western communities, provide for their well-being, and work to help achieve desired community conditions.

The Relative Effectiveness of Fuel Treatments Versus Other Wildfire Risk Mitigation Strategies in a Coastal Wildland-urban Intermix Area on the Pender Islands, British Columbia, Canada

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Abstract:
Community wildfire protection plans often contain a long list of recommended risk mitigation strategies yet local governments have limited budgets to allocate towards risk mitigation. How can communities know which risk mitigation strategies they should focus their limited resources on? In this presentation, I describe how strategic landscape-level fuel treatments were found to be less effective at mitigating wildfire risk than other proposed risk mitigating strategies being considered by local government agencies on the Pender Islands. As part of my Masters research at Simon Fraser University I developed a wildfire risk assessment model and used it to evaluate 5 risk mitigation strategies being considered by local government managers. The evaluation found that strategic landscape-level fuel treatments produced no measurable reduction in wildfire risk, however, fuel treatments associated with a residential FireSmart strategy were found to be very effective. Reducing human-caused fire ignitions was found to be the most effective risk mitigation strategy. FireSmarting residential homes and properties as well as improved evacuation in evacuation problem areas were also very effective strategies for reducing wildfire risk. I then look at the implications for risk mitigation recommendations, suggesting that the Pender Islands community wildfire protection plan focus recommendations on those that reduce human-caused ignitions and protect values at risk. These results are relevant to community wildfire protection planning in all wildland urban intermix areas, particularly coastal wildland-urban intermix communities.

The Wildfire Management Overlay and the Victorian Black Saturday Fires

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Abstract:
In Victoria, Australia a land use planning control is implemented to reduce the impact of wildfire on new development. This control is know as the Wildfire Management Overlay (WMO). Areas of high forest fire risk are mapped and designated in local planning schemes as the WMO. The purpose of this control is to identify areas where the intensity of wildfire is significant and likely to pose a threat to life and property. Development in these areas which is likely to increase the number of people in the overlay area must satisfy the specified fire protection objectives for water supply, access, vegetation management and buildings and work. Development applications subject to the overlay must be referred to the relevant fire authority, the Country Fire Authority (CFA) for approval before a permit is issued.

A key strategy of the WMO is to require vegetation management to reduce the chance of direct flame contact and potential level of radiant heat. Buildings are then designed and constructed to contend with the modelled radiant heat and ember attack. To calculate the distance required to avoid direct flame contact and radiant heat ignition of the proposed building, the flame length in the vicinity of the site is derived from modelling fire line intensity based on site conditions and set weather parameters. The distance at which radiant heat flux will be $29kW/m^2$ is then calculated using Leicester 1987. This distance is then added to the calculated flame length to determine the setback distance required between unmanaged vegetation and the proposed building.

Following the catastrophic February 2009 Victorian Fires (Black Saturday) a review was undertaken of dwellings lost in key fire footprint areas. Specifically, a statistical analysis was undertaken comparing house loss for dwellings referred to the CFA with overall losses. Amongst other things, the results show a significantly lower percentage of loss for those dwellings which had been referred to CFA.

This presentation will outline the WMO requirements; the CFA's approach to modelling radiant heat and determining vegetation set back distances and the process and results of the statistical analysis undertaken following Black Saturday. Changes and improvements made to the control as a result of Black Saturday and the associated Royal Commission, including the process for designating subject areas, will also be discussed.

The Howling Prescribed Natural Fire – long-term effects on the modernization of planning and implementation of wildland fire management.

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Abstract
Wildland fire management policy and practices have long been driven by the occurrence of significant events. The Howling Prescribed Natural Fire in Glacier National Park in 1994 is a prime example of a significant historical fire event that provided the impetus for program changes and modifications that modernized wildland fire management at the local, regional, and national levels. During the management of this fire in the midst of numerous wildfire suppression complexes, factors such as resource availability, internal and external concerns, and long-term situational awareness became increasingly important. Glacier National Park and National Park Service (NPS) fire management leaders were forced to develop and apply innovative methods to assess the long-term situation, ensure adequate resources were available to manage the fire, put ground-breaking planning and operational activities into practice, and confirm with both internal and external audiences that desired objectives would be achieved. This paper chronicles how the Howling Prescribed Natural Fire framed the development of wildland fire use as a strategic direction, influenced the development of planning and implementation procedures, demonstrated the value of fire presence in vegetation and landscape-scale land management, shaped long-term public opinion, and yielded lasting effects on wildland fire management policy.

Additional keywords: fire policy, wildland fire use, Glacier National Park, fire history.

Introduction
Throughout the history of wildland fire management, program growth and development has not followed a steady course, but has more often been driven by the occurrence of significant events. Such events can occur with positive outcomes that reveal inefficiencies in policy, procedures, and practices or have negative outcomes which bring immediate, focused attention generating program and policy reviews, updates, or changes aimed at minimizing or eliminating any potential reoccurrence of such negative outcomes.

Historically significant wildland fires where objectives were not achieved or where extreme negative outcomes occurred have garnered much attention and observation. These types of events often represent instances of failed planning and implementation actions, or resulted from cascading circumstances yielding undesirable outcomes. Review and attention to these fires frequently become an impetus for major changes. In other cases, fires have been managed in a manner that, while receiving much less attention, provide examples of situations where desirable outcomes occurred and lessons learned led to improvements in organizational procedures, practices, and policy which markedly strengthened capability, accomplishments, and performance.

The Howling Prescribed Natural Fire in Glacier National Park, Montana, in 1994, is a significant historical event where objectives were successfully accomplished and attention was localized. While the fire was relatively unheard of and did not gain regional or national prominence, it eventually had profound effects on the fire management program at local, regional, and national levels. This fire provided the beginning for multiple changes and modifications to the prescribed natural fire program, influenced subsequent policy reviews and modifications, and established a foundation for efforts that would modernize wildland fire management.

Setting the stage

Wildland fire management policy direction in effect in 1994 originated after the 1988 fire season with implementation beginning in 1989-1990. This policy clearly stated that all fires were either a prescribed fire or a wildfire. Prescribed fires were composed of two types: management ignited prescribed fires and prescribed natural fires (PNF). Prescribed natural fires were in every way, a very subordinate part of the total program, only managed on selected units under Forest Service and NPS jurisdiction, and subject to a number of constraints on implementation. During this time, management of many prescribed natural fires was strongly questioned by groups both internal and external to the agencies. Management of fires was limited by fire activity and resource availability constraints. As a result, managers were often forced to make innovative decisions and put ground-breaking planning and operational activities into practice to realize management opportunities. From such activities it was apparent that the fire management program was not operating at its highest level of efficiency; in fact, by 1994 many instances of policy inflexibility and undue constraints, lack of program adaptability, and incomplete guidance were evident.

Agency direction limited prescribed natural fire implementation to a small number of administrative units with funding allocated to the specific units; emergency fire suppression funds were not allowed to be used for these fires. Consequently, available funding for PNF implementation often limited the number and extent of potential fires, and sometimes, was completely exhausted for a particular unit before the height of the fire season.

Regional and national preparedness levels had been developed, which at the time, also constrained PNF implementation. Specific wording found in preparedness level (PL) 4 (the next to highest level) stated that initiation of new PNFôs and management ignited prescribed fires would be suspended. At PL 5 (the highest level), all directions from PL 4 would continue and all PNFôs and management ignited prescribed fires would be suppressed with no further implementation or planned ignition. This direction markedly constrained PNF prospects, especially during those periods where ecologically significant fires could occur in fuel or condition limited ecosystems and in higher elevation areas having short windows of opportunity.

Regional and national prioritization procedures also presented limitations to program implementation as all PNF events essentially received by default, a lower priority designation than suppression actions. This resulted in an inability to obtain additional resources beyond what was locally available, and served as cause for frequent decisions to suppress fires. Even in situations where there were low demands for firefighting resources for suppression actions, the allocated funding scenarios made it extremely difficult to obtain additional resources due to costs and lack of non-reimbursable agreements for management situations, and at times, mobilization of additional resources was not supported due to the lack of interagency funding charge codes.

In 1994, hot, dry conditions developed across much of the northwestern United States creating high early season fire danger. Wildfire activity began sooner than usual and intensified as the summer progressed; by late July, fires were growing quickly in numbers and size. As fire activity escalated, support from other fire management agencies began to waiver, and pressure was given to NPS managers to suppress the Howling PNF. In addition, a wildfire in 1988, the Red Bench Fire, had burned very near to where the Howling PNF was located. Public opinion of PNF was mixed with those in the local area having the Red Bench scenario still fresh in their minds. Additionally, the Little Wolf Fire to the west of Glacier NP was putting up smoke and had the potential to threaten the town of Whitefish. So, as the Howling PNF progressed through the season, NPS managers were faced with a variety of challenges, including increasing internal and external concerns, which threatened successful implementation of the PNF.

The Howling Prescribed Natural Fire story

On June 23, a thunderstorm ignited a fire in the North Fork of the Flathead River area on the west side of Glacier National Park. The park had an approved Fire Management Plan that allowed use of multiple strategies to manage wildland fires and this fire fell within a natural management area. Based on current and short-term weather forecasts and expected fire behavior, managers declared the fire a PNF and prepared a fire situation analysis (FSA), the required NPS planning document for managing prescribed natural fires. Initially, little fire activity was observed, and by August 4, after six weeks of unchecked burning, the fire, named the Howling PNF, had grown to only 1 acre in size.

Despite the small size and minimal fire activity to date, park managers became concerned about managing a potentially large, uncontained fire while fire suppression activity demands were markedly increasing on numerous wildfire complexes, both locally and throughout the northwest. The first of several significant decisions was made when the park superintendent determined that park staff could not make the necessary commitment to the Howling PNF for its duration in light of escalating wildfire activity. He told NPS national office leaders that the current strategy might continue only if an outside organization could be provided to the park for planning and implementation support. This was, at this time, an unusual request. Virtually all previous prescribed natural fire management had been completed by local units with local personnel. It was assumed that administrative units having prepared fire management plans identifying PNF as a management strategy would have the capability and depth to plan and implement all fires within their own organizations.

The park superintendent felt that, without meeting certain conditions, his decision space would narrow and likely be channeled toward suppression. Support in the form of a dedicated incident management team staffed with non-park personnel was requested to establish goals, accomplish detailed planning, provide focused attention to public information, and implement management operations, including close and aggressive monitoring. This request was viewed nationally with some skepticism, but the situation surrounding this fire was recognized as well outside historic experience. The unique nature of this situation and high potential for an ecologically significant management fire where few had occurred represented considerations of such importance that it was agreed to assemble a dedicated incident management organization to manage the Howling PNF.

A small incident management organization was established with NPS personnel and provided to Glacier NP. During the course of the fire, the team updated the FSA, addressed the current situation, long-term situation, management objectives, values to be protected, special resource concerns, management actions to achieve objectives, and contingency actions. Contingency actions were of special importance because the increasing magnitude of the local, regional, and national fire situation was placing growing demands for firefighting resources elsewhere and making them unavailable for the Howling PNF. As a result, it was necessary for the team to have enough resources on-site to implement all defined contingency actions.

As the summer progressed into August, management of the Howling PNF escalated in scale as additional fires in the same area took on more importance (Fig 1). Several other fires throughout the park were being managed by park personnel. One fire, the Starvation Creek Fire, near the Canadian border, was being suppressed and managed by an organized incident management team. By late August, management of this fire transitioned to the Howling PNF management organization. Two additional fires, the Adair2 and Anaconda Fires, started very near the Howling PNF; these fires were not managed as PNFĉs, but as wildfires under a confinement strategy because of high potential for elevated costs, damage to park resources, and risks to firefighters. Responsibility for management of these fires was added to the Howling PNF management team. By late September, the Howling, Adair2, and Anaconda fires had burned together, control actions on the Starvation Creek Fire had been completed, and management of this complex of fires transitioned back to the park. The team organization created for the Howling PNF managed it on-site for 75 of the 138 days of its duration as well as having management responsibility for three other fires. Snow fell in late October ending the fire situation. The general location of the Howling PNF and other fires managed by the management team is shown in Fig 1.

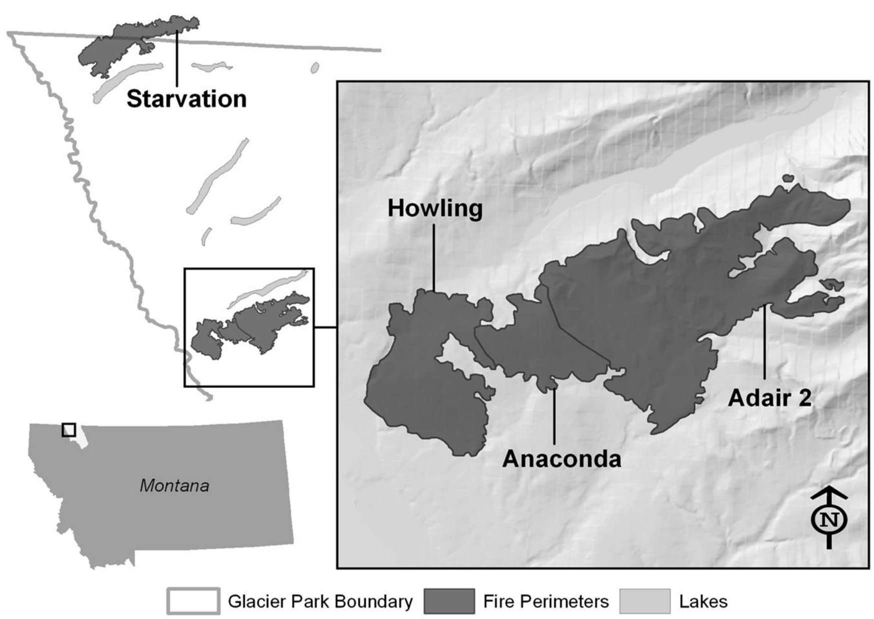

Fig1. Howling PNF ï general location, final perimeter, and perimeters of adjacent wildfires.

Impacts of the Howling Prescribed Natural Fire

Decisions and actions implemented during the Howling PNF set the stage for sweeping changes in the wildland fire management program. This fire demonstrated a need for a flexible policy that promotes appropriate management of fire for maximum protection of societal infrastructure as well as the use of fire for ecological objectives, where appropriate. Lessons learned were compiled into recommendations that could improve future management activities for complex, long-duration wildland fires (Zimmerman *et al*. 1995). These recommendations were focused on the PNF program in general but made specific reference to management organizations, program limitations, dedicated PNF resources, and consistent use of risk assessment tools. Nearly all of these recommendations have been implemented; many had immediate effects while others had delayed impacts, but all substantially influenced federal agency wildland fire management policy and continue to do so (Fig 2). These changes advanced overall program effectiveness and modernized fire management (Zimmerman and Lasko 2006, Zimmerman and Sexton 2010). Program areas influenced include: fire policy; establishment of dedicated fire use resources; wildland fire use and long-duration fire planning and implementation procedures; establishment of new positions and qualifications; operational implementation procedures improvement; and definitions and implementation of long-term risk assessment procedures (Fig 2). Many of these changes were the impetus for subsequent policy changes, revised fire review protocols, and updates to operational clarification (Fig 2).

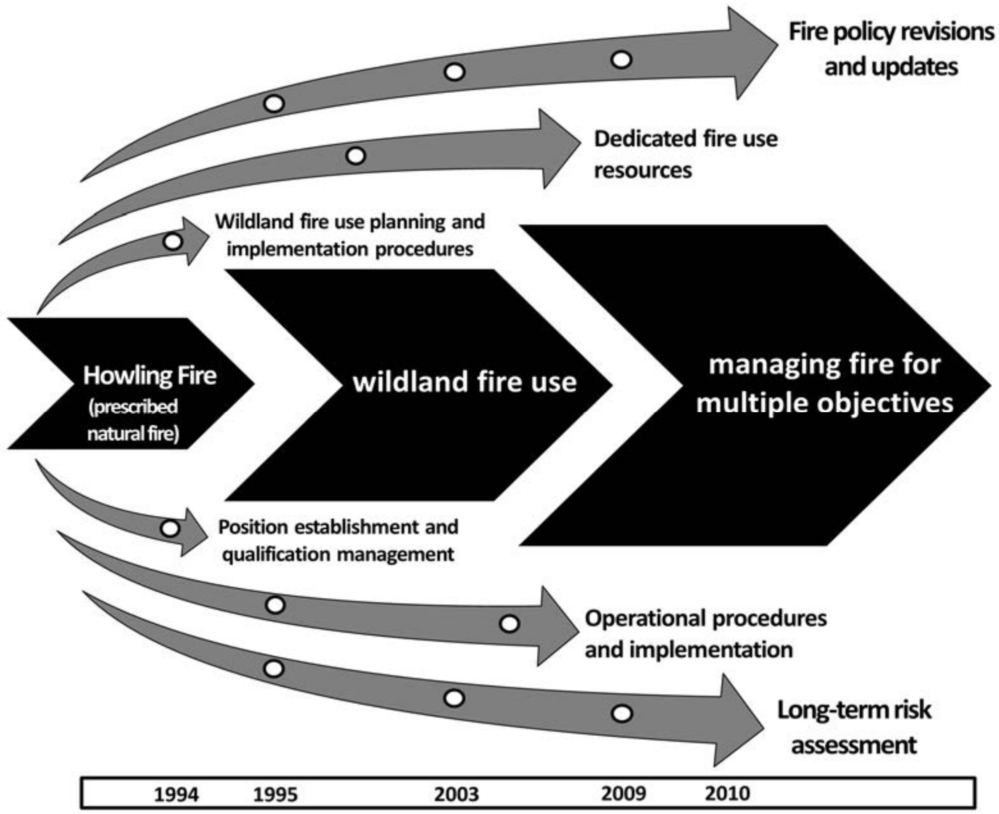

Fig2. Areas of wildland fire management program policy, procedures, and direction influenced by the Howling PNF.

Program policy, procedures, and direction influenced by numerous situations and decisions from the Howling PNF within program areas shown in Fig 2 are described below.

Wildland fire management policy revisions and updates

Following several catastrophic occurrences during suppression actions and organizational inefficiencies associated with managing fire for resource benefits, national leaders recognized current fire policy needed to be updated. A national review took place and resulted in several key policy changes. The 1995 Federal Wildland Fire Management Policy addressed many components of wildland fire program management, but the Howling PNF and others like it served as incentives to develop a more comprehensive wildland fire policy. This policy direction specifically addressed the role of fire as a natural disturbance and moved fire planning toward integration with resource management (Lasko 2010). Prescribed natural fire was eliminated as a fire type and natural wildland ignitions were no longer categorized as part of prescribed fire. All fires were now either wildland fires or prescribed fires. In 2003, another policy review and update broadened fire management program capacity to better balance fire suppression with ecosystem sustainability. Then again in 2009, a policy modification removed the distinction between wildfire and wildfire use.

Lessons learned from the Howling PNF influenced the 1995 policy review, and to some degree, the 2003 and 2009 modifications and updates. Outcomes helped improve understanding that policy must provide flexible and responsive direction, be adaptable, and incorporate emerging knowledge, technology, and science without unnecessary constraints (Zimmerman and Sexton 2010). Specific policy modifications include:

- Improved accountability for long duration fire events managed for resource benefits (1995, 2003, 2009 policy direction).
- Shift from wildfire and prescribed fire to wildland fire (1995 direction).
- Shift from PNF as a strategy to wildland fire use (1995 direction) (van Wagtendonk 2007).
- Wildland fire use eliminated as a separate entity or fire type and consideration of all fires as wildfires (2009 direction)
- Creation of fiscal procedures that facilitated the use of wildland fire for resource benefits (1995 direction).
- Change in preparedness level wording to support better resource allocation and incident prioritization (supplemental direction after 1995).
- Greater advocacy and support for wildland fire use as a strategy for achieving land management objectives (1995, 2003) (Zimmerman and Lasko 2006).

Establishment of dedicated fire use resources

The need for and establishment of formal management organizations to manage complex fire situations in remote areas that require a high level of resource protection and small numbers of resources became increasingly important during the late 1980s and early 1990s. But management capabilities were often confounded by the inability to consistently obtain resources to implement necessary management actions.

Managers of the Howling PNF decided to establish a dedicated management organization with necessary contingency forces to plan and implement operations for this fire. This type of organization, essentially mobile tactical resources, did not formally exist prior to this fire and other options were not usable for this type of situation due to commitments to suppression actions.

Management implications of this decision were increased awareness of the value of having dedicated prescribed fire resources for planning, oversight, and implementation on prescribed natural fires and later, for wildland fire use events. Without pursuing this effort, it is very likely that the Howling PNF would have been suppressed at a small size; but instead this decision created the foundation for establishing organized management teams and small crews which became a major part of wildland fire management and have evolved into the current Wildland Fire Management Teams and Wildland Fire Modules.

NPS developed a Prescribed Fire Management Team program and a Prescribed Fire Module program in 1995. These resources were designed to provide dedicated fire use resources that would not be compromised in availability by fire suppression demands. Four specific Prescribed Fire Management Teams (PFMTs) and four specific Prescribed Fire Use Modules were created. Teams transitioned in name from Prescribed Fire Management Teams to Interagency Fire Use Management Teams and today are either Wildland Fire Management Teams or Type 2 Incident Management Teams. Modules originated as Prescribed Fire Support Crews, then became Prescribed Fire Modules, Fire Use Modules, and are now known as Wildland Fire Modules. Modules currently number 31, generally consist of 6-10 firefighters and are managed by four federal agencies as well as non-federal cooperators.

Wildland fire use and long-duration fire planning and implementation procedures

Prior to 1995, fires in national forests were required to have a Prescribed Natural Fire Burn Plan completed while fires in national parks were required to have a Fire Situation Analysis completed. At this time, no other federal agencies were involved in PNF management. These were two distinct processes for managing PNFôs and led to some inefficiency and sometimes, redundancy. It eventually became clear at all management levels that successful application of wildland fire depends on detailed planning from land and resource management plans to fire management plans and the translation of this information into specific implementation action planning and decisions (Zimmerman and Sexton 2010). After the 1994 fire season, the following planning and implementation procedures were adapted:

- Creation of the Wildland Fire Implementation Plan (WFIP) as a single process for use on all wildland fire use events, replacing the Forest Service Prescribed Natural Fire Burn Plan and the NPSô Fire Situation Analysis, and unifying these agenciesô planning processes.
- Development of the Wildland and Prescribed Fire Implementation Procedures Reference Guide (1998) and Wildland Fire Use Implementation Procedures Reference Guide (2005) (USDI/USDA 1998, 2005, 2006) which unified wildland fire management agency planning and implementation policies.
- Development and use of the Wildland Fire Decision Support System (WFDSS) to provide the most detailed and comprehensive planning and implementation system for post-ignition fire management decisions. Implementation of WFDSS in 2009 replaced the WFIP and Long-Term Implementation Plan (LTIP) processes (Pence and Zimmerman,2011).

Definitions and implementation of long-term risk assessment procedures

In every wildland fire situation, managers are confronted with uncertainty about the fire situation and potential effects. The need to assess long-range fire conditions to support fire management decision-making and reduce uncertainty has been steadily increasing over several decades and the active fire situation in 1994 strongly reinforced the need for, and value of such assessments (Mutch 1998, Bradshaw and Andrews 1998).

During the Howling PNF, the local, regional, and national situation combined into a scenario where firefighting resources were scarce, multiple fires were in need of support, and timely decisions had to be made on prioritization and resource allocation. There was a strong belief that the situation was not conducive for management of prescribed natural fires and that all fires should be suppressed. In order to defend the decision to manage the Howling PNF, it was necessary to show that the Glacier NP fire situation, while clearly expected to worsen over the course of the summer, could be managed without adding to the demands for suppression resources.

In response to this need, a variety of decision analysis techniques were employed to acquire and illustrate the long-term situation for the Howling PNF area. Predictions of how the fire could behave were obtained using fire behavior prediction tools (Rothermel 1993). Estimates of the probability of rare fire spread and season ending events were obtained through the Rare Event Risk Assessment Process (RERAP) (Wiitala and Carlton 1993). Relative fire danger conditions and trends in fuel moisture conditions were shown through interpretation of satellite vegetation data (Burgan and Hartford 1993). Long-term fire growth estimates were made using the Fire Area Simulator (FARSITE) model (Finney 1994). This information was provided to decision makers at the local and regional levels and was crucial to decision making that facilitated continued management of the Howling PNF. In addition to providing information to managers, assessment information was useful in communication with the public. In particular, photographs taken from a lookout helped address public concerns over smoke and clarified that much of the local smoke was being produced by wildfires outside the park and not the Howling PNF.

The direct management implications of these efforts for long-term risk assessment clearly illustrated the value of information acquisition and analysis to decision makers. Prior to the modeling and weather analysis there was concern amongst park managers that the Howling Fire could eventually make its way to park headquarters and the West Glacier entrance. Without this modeling and weather analysis support, it is very likely that a completely different decision would have been made. But because decision makers put traditional thinking aside and based their decision on data presented rather than listening to the subjective cries of control-only advocates, the concept of utilizing natureœs match to achieve resource benefits under specified conditions originally approved for the USFS Southern Region in 1967 as the Designated Controlled fire (DESCON) concept, for the NPS Sequoia-Kings Canyon NP in 1968, and for the White Cap Wilderness Fire Management Plan in the USFS Northern Region in 1972, was proven a viable policy during a severe fire season. As a result, fire assessment efforts were completed more frequently after 1994 for a variety of purposes across a range of spatial and temporal scales. Specific risk assessment advances that have followed the Howling PNF include:

- Definitions of fire risk assessments. Rothermel (1998) grouped fire assessments into three principal areas: evaluation of possible growth of large escaped wildland fires, regional fire assessments, and assessment of prescribed natural fires (now categorized as wildfires managed for resource benefits). Zimmerman *et al*. (2000) further defined Rothermel's groupings into: individual fire growth projections, long-term risk assessments, and long-range fire assessments.
- Implementation of Long-Term Risk Assessment procedures. Long-term risk assessments became the staple for long duration fires, provided much greater accountability, reduced uncertainty, and markedly supported decision making. As a result, long-term risk assessments, institutionalized over subsequent years, were/are an integral component of:
    - Wildland Fire Implementation Plan (1998 - 2009) (USDI/USDA 1998, 2005, 2006).
    - Long-Term Implementation Plans (2007 – 2009) for long duration wildfires.
    - Wildland Fire Decision Support System (2009 - ?) (Pence and Zimmerman,2011).
- Implementation of Long-Range Fire Assessments: Long-range fire assessments developed into specific assessments of seasonal severity, seasonal duration, and demands on firefighting resources for large areas, generally on a state or regional scale. These assessments incorporated a variety of analytical techniques and processes to provide reliable information to decision-makers and were used extensively for specific purposes in subsequent years (Hilbruner *et al*. 1998*c*, 1998*b*, 1998*a*; Zimmerman *et al*. 1998).
- Inclusion in training curricula. Long-term risk assessment information was incorporated into multiple regional and national training courses within the national interagency wildland fire management training curriculum. Training courses containing information directly or indirectly stemming from the Howling PNF include:
    - S-491, National Fire Danger Rating System,S-492, Long-Term Risk Assessment,S-493, FARSITE
    - S-495, Geospatial Fire Analysis Interpretation and Application
    - RX-590 Long-Term Fire Behavior Analyst (incorporated into S-590 in 1998),
    - S-590, Advanced Fire Behavior Interpretation,
    - National Park and Wilderness Fire Management Training (NPWFM)(later incorporated into S-580),and
    - S-580, Advanced Wildland Fire Use Applications (later incorporated into S-482, Advanced Fire Management

Applications).

Establishment of new positions and qualifications

In response to a need to define command oversight and support for wildland fire use, several new positions were established and others were modified or expanded in scope. Positions established or revised include:

- Fire Use Manager (FUMA), which later evolved into a multi-complexity position with a Type 1 (FUM1) and Type 2 (FUM2) level available. The 2009 policy direction caused this position to transform into a Strategic Operational Planner (SOPL).
- Fire Effects Monitor (FEMO).
- The Prescribed Fire Behavior Analyst (PFBA, then later, RXBA) transformed into the Long-Term Fire Behavior Analyst (LTAN).

Qualifications for each position and position task books to document experience and currency were created and incorporated into the interagency qualifications system. The training courses above were modified or created to support the positions and provide knowledge, skills, and abilities to trainees.

Operational implementation procedures improvement

The Howling PNF illustrated the disparity in prioritization and resource allocation associated with wildland fire management under the 1989 fire policy. Suppression efforts were supported by cooperative interagency activities and a sophisticated dispatch mobilization system, given consistently high priorities, and provided rapid firefighting support. Conversely, PNF and fire use actions received a consistently low priority classification and did not receive necessary resources, even though time commitments for holding and support resources may have been well-defined, of short duration, and potential benefits of the fire were significant. Numerous operational procedures were modified after 1995 that facilitated more equitable management of wildland fires. These include:

- Regional and national prioritization processes considered all fires based on objectives and situation.
- Reworded preparedness levels placed no restrictions on management of fires.
- Hazard pay entitlement was gained for appropriate wildland fire use events.
- Wildland fire use events became classified as emergency events and were provided specific fiscal codes.

Advancing use of naturally ignited wildland fire to accomplish resource benefits

In Glacier NP, the Howling Fire is a vivid example of how a single event influenced future management decisions and actions and encouraged the active management of future wildland fires for resource benefit. Pre- and post-Howling PNF management fire history clearly show how management activity accelerated after the Howling PNF (Fig 3). This increase occurred on a national scale as well. The transition from PNF to wildland fire use brought expanded fire management accomplishments (Zimmerman and Sexton 2010) with expansion from a wilderness only program to one that spans all land-use situations (Zimmerman *et al*. 2006).

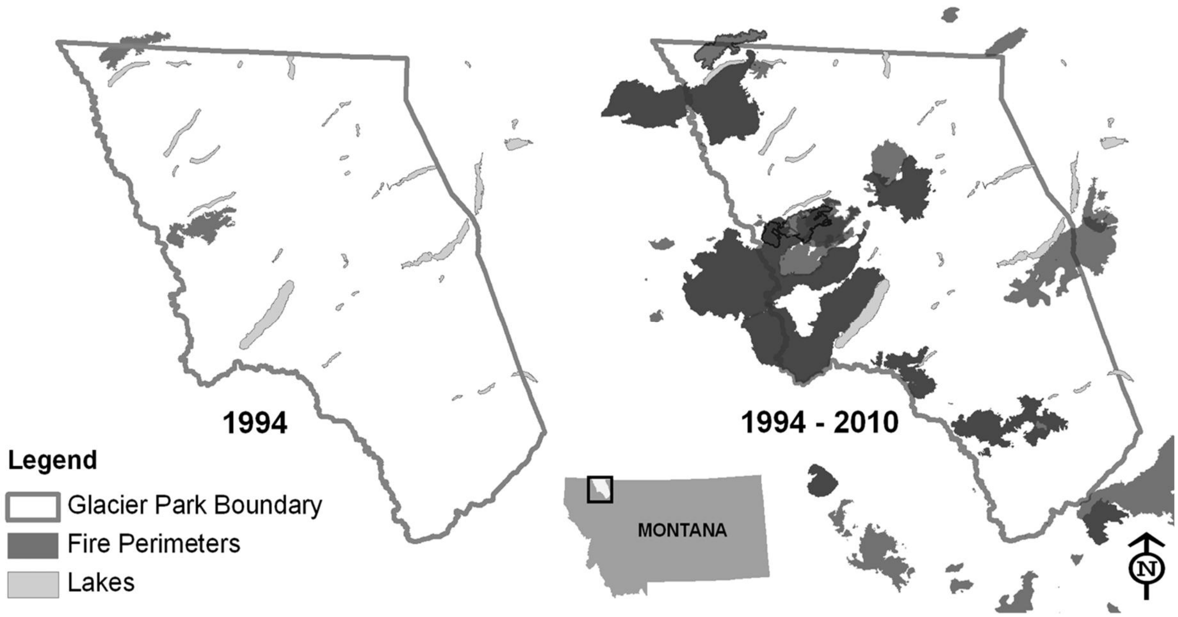

Fig 3. Glacier NP fire history showing PNF fires in 1994 and all long-duration fires from 1994 to 2010.

Summary

Programmatic growth and change in response to lessons learned are critical to improved organizational efficiency. As wildland fire management continues to evolve, management challenges, risks, program complexity, associated demands, and needs to use fire to accomplish beneficial objectives will continue to escalate. The Howling PNF demonstrated the potential to implement management actions for resource benefits and suppression actions simultaneously and manage fires successfully within a wide range of fire danger and fuel moisture conditions; a situation not previously accepted as an option in the range of strategic responses. Fire management leaders were forced to develop and apply innovative methods to assess the long-term situation, ensure adequate resources were available to manage the fire, put ground-breaking planning and operational activities into practice, and confirm with both internal and external audiences that desired objectives would be achieved.

Because of these decisions and actions, this fire is a foremost example of a significant historical event that provided the impetus for substantial fire management program changes. Leveraging lessons learned from these types of events is vital to influencing improvements in organizational procedures, practices, and policy and ultimately promoting greater organizational efficiency, and strengthened capability, accomplishments, and performance.

The outcomes from the Howling PNF served to modernize wildland fire management at the local, regional, and national levels. Numerous changes to fire policy, planning processes, and risk assessment tools and procedures emerged from management actions, decisions, lessons learned, and successes from the Howling PNF, and set the stage for fire management policy and procedural changes to create a more flexible policy.

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The role of a long term assessment in management of the North Fork Complex, 2009

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Abstract
The North Fork Complex Wildfires in northeastern Oregon in 2009 provided an opportunity to manage large, long duration fires in a safe and cost-effective manner, in an area not currently being managed for the use of fire to achieve resource benefits. A long term fire assessment helped managers and line officers select a course of action that resulted in a fire that was safer, less expensive, and more consistent with wilderness objectives than a direct attack option. The long term assessment accurately predicted the effect of an unusual early August rainstorm on the fires, the likelihood that the fires would spread to private lands by the end of the season, and the remaining length of the fire season, and also characterized the weather events that would lead to significant fire growth periods. The risk assessment gave managers the confidence that they needed to manage the fire with local resources for more than 60 days as it covered more than 5660 ha (14000 ac) of national forest.

Additional keywords: Blue Mountains, wilderness fire, case study

Introduction
The fire season of 2009 in northeastern Oregon started with a cool and wet early June, but an extended drying spell resulted in fire danger indices that ran well above average through the month of July. On August 1-2, a typical mid-season lightning episode started numerous fires on the southern portion of the Umatilla National Forest (UNF) and adjacent private lands.

Six fires were started by lightning in the North Fork John Day Wilderness on the North Fork John Day Ranger District of the UNF, and were staffed soon after being reported on the morning of August 2. While all of the fires were staffed with initial attack crews, the fires outside of the Wilderness were given a higher priority, as they threatened homes and other structures and private timberlands. As a result, two of the fires in the Wilderness area continued to grow, and suppression efforts on a third were abandoned when it became apparent that the growing fires would overrun it. Within 36 h of fire start, two fires in the Wilderness had grown to over 80 ha in dense conifer forest.

A type 2 Incident Management Team (IMT2) assumed management of the North Fork Complex on the morning of August 4. Their first efforts were aimed at controlling the most accessible fires, and following the initial success their attention turned to the more remote uncontained fires in the Wilderness. The team initially evaluated the feasibility of direct control of these fires, and realized that this strategy would mean significant use of type I crews, helicopters, and logistical support. The team and the local unit managers then began evaluating a much less direct, longer duration strategy.

Soon after the IMT2 was ordered, the local unit also requested a long-term fire assessment team (LTAT). This team, with skills in fire behavior analysis, long term fire modeling, fire operations, and planning, was developed in the Pacific Northwest to support local units with fire decision support tools and products, and provides local managers with rapid fire assessments to help make sound fire management decisions in the first few days of large fires.

Soon after the IMT and LTAT were in place and working, an unusual rainfall event occurred across eastern Oregon and Washington. This precipitation event was unusual in its timing, amount, and duration. August 6-7 is the statistical peak of local fire season based on energy release component. August is the driest month of the year, and the 5.25 cm of recorded rainfall made this a very rare event. The storm duration of 28 h is easily two to three times the normal precipitation event duration for August, based on weather records from several nearby RAWS sites. This event created a puzzle, and perhaps an opportunity, for the local fire managers; the fires were at least temporarily checked in place, so the managers had some time to develop a strategy to manage the fires if and when they resumed spreading.

This paper will describe the analyses completed by the LTAT and how the long term assessment and management plan contributed to a successful outcome as the North Fork Complex of wildfires was managed until the season-ending weather event 60 days later. A successful outcome in this case is defined as one that protected firefighter and public safety, was cost-effective considering values at risk and the costs of managing the fire, and appropriately managed risk of damage to natural resources and improvements on both private and public lands.

Location

The UNF is in the Blue Mountains physiographic providence in northeastern Oregon and southeastern Washington State (Fig. 1). The North Fork of the John Day (NFJD) River is a dynamic drainage with steep heavily timbered slopes. Fuel models in the vicinity of the fire are dominated by timber models 8, 9, and 10, with minor representation of models 2 (grass understory) and 5 (brush) in recently burned areas and open pine stands (Anderson 1982; Rothermel 1983).

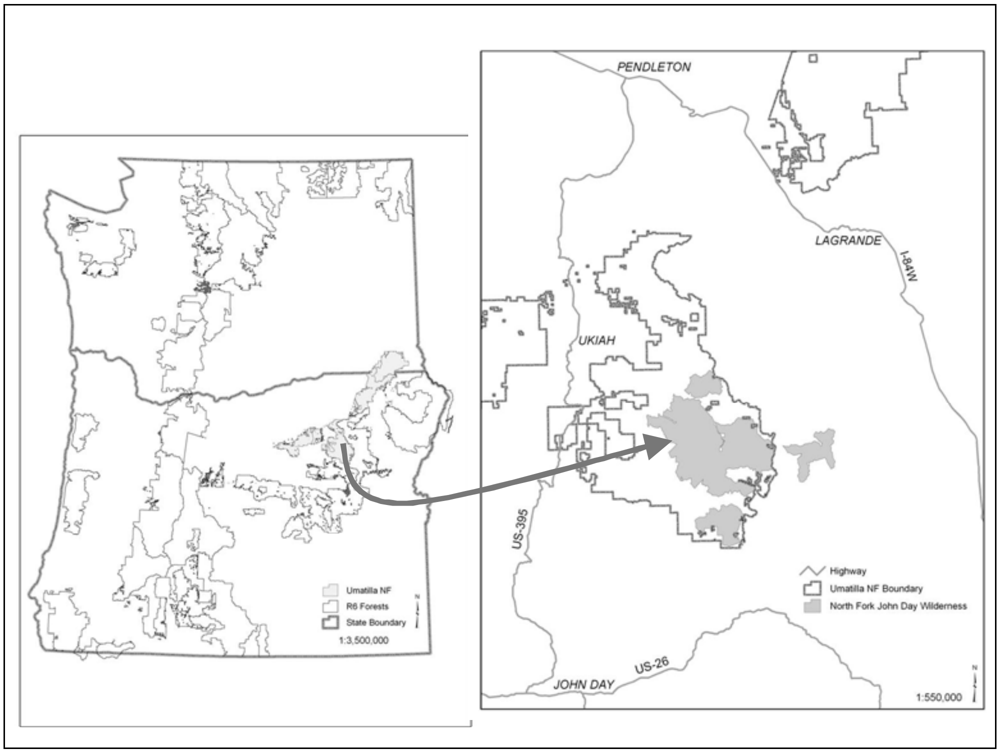

Fig 1. Location of the Umatilla National Forest and the North Fork John Day Wilderness in northeastern Oregon.

The climate of the UNF is relatively arid, being located at the far eastern edge of the rain shadow created by the Cascade Mountains. Winters are influenced by moist maritime air masses, and at the upper elevations precipitation falls as snow. Summers bring dry continental air masses, with long periods of fair dry weather interrupted by thunderstorms. Annual precipitation can reach 100 cm at the higher elevations. Annual drying starts in the spring, with the peak of fire season in the first two weeks of August. Daily weather during fire season generally brings maximum temperatures of 21-31ŬC, minimum relative humidity of 17-29%, and wind speeds of 1.8ï 2.7 m s^{-1}.

The NFJD Wilderness Area is made up of four separate congressionally-designated Wilderness Areas on the UNF and the adjacent Wallowa-Whitman National Forest. The 34000 ha unit on the NFJD River is the largest of the four units, and is managed by the NFJD District of the UNF. The NFJD River lies at the center of this unit, and the Wilderness Area is a forested canyon aligned roughly NW-SE on both sides of the river. Elevation ranges from 975 m on the river to almost 1830 m on the ridge tops.

The NFJD Wilderness is managed by the UNF primarily for backcountry primitive recreation, where natural processes, including fires, will be the primary forces affecting natural resource conditions without ñendangeringò adjacent lands (USDA 1990 p.4-138). While unplanned fires are not currently managed with an explicit objective of improving resource conditions, fire managers do place a lower priority on suppression of wilderness fires. They consider cost-effectiveness, safety, and minimizing suppression-related resource damage as important objectives for managing these wildfires.

Wildfires, most ignited by lightning, occur every year in this Wilderness unit. Fire history records show that about half of this unit has burned in 9 large (>400 ha) wildfires over the past 20 years, much of it by stand-replacing fire in mature lodgepole pine (*Pinus contorta* Dougl.) and mixed conifer forests (Fig. 2). The older burns form a continuous lower hazard fuel bed to the east and north of the NFJD River. Portions of the previous wildfires have regenerated into dense young lodgepole pine of 2.5-5 m tall with very little fine surface fuels, but with increasing accumulations of large diameter material as the trees killed by fire fall.

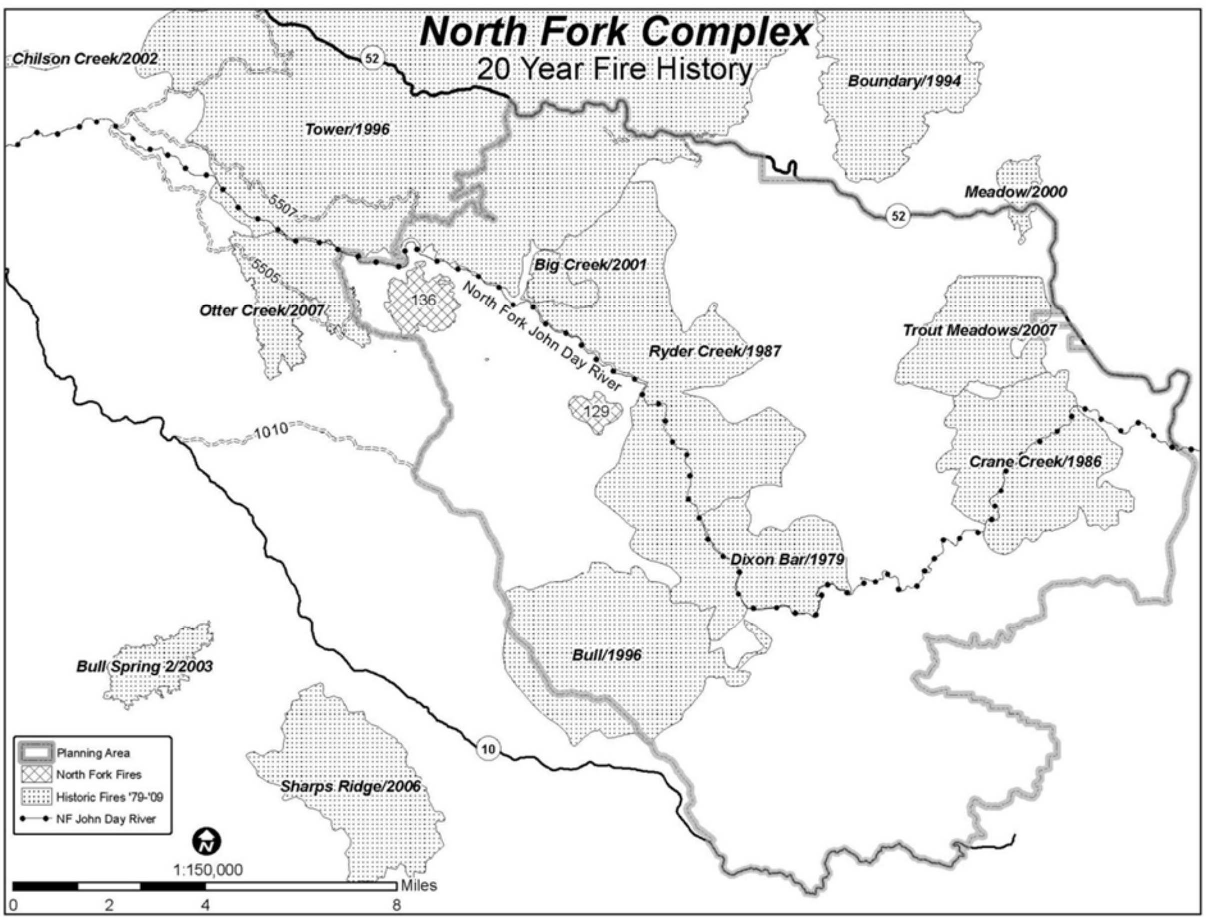

Fig 2. North Fork John Day Wilderness and recent wildfire history in the vicinity. Fires 129 and 136 are shown as of August 6, 2009.

Key questions

After the unusual rain of August 6-7, local fire managers and the incident management team provided the long term assessment team with some key questions, the answers to which would help fire managers make critical decisions regarding future management of the North Fork Complex fires. These key questions included:

- What is the short term prognosis for fire growth, given current weather and fuels conditions?
- How long will the fire season last, and where will the fire spread by the end of the season?
- What values or points of concern are most at risk of being reached by the fire?
- What events are associated with periods of large fire growth, and how frequent are these events over the course of the season? How can these fire growth events be anticipated?
- How will the areas burned in the past 20 years affect fire behavior, if the fire reaches these areas?
- What actions should be taken now to manage these fires, and what actions should be considered in the future? What ñtriggersò should be used to indicate action is needed?

Methods

The long term assessment team uses historical weather and fire data, short-term and seasonal weather forecasts and projections, and vegetation and fuels data to conduct their assessment of fire spread probabilities and the risk that fire presents to identified natural resource values and infrastructure. The foundation of this work assumes that no further fire suppression would occur on a wildfire, and then attempts to predict what would happen by the end of the fire season if fire spread was left unchecked. While fires are rarely managed this way, the evaluation provides a baseline from which to plan and prioritize work to slow or stop fire spread.

The team retrieved historical weather and fire occurrence records via the Kansas City Fire Access Software (KCFAST) website (USDA 1997), for 15 Remote Automated Weather Stations (RAWS) in the Blue Mountains. The Case and J Ridge RAWS, located closest to the fires and in the same elevation range, were used for most analyses. Case RAWS is located 15.3 km west of the fire area, and the J Ridge RAWS is located 27.6 km northeast. The Realtime Observation Monitoring and Analysis Network (ROMAN) was used to evaluate hourly weather records in 2009 and recent years, in an attempt to identify weather patterns associated with known fire growth events.

The team used Fire Family Plus (ver. 4.0.2) to evaluate weather records and develop and analyze fire danger indices (Andrews 2003). Three standard National Fire Danger Rating System (NFDRS) indices were used to evaluate seasonal severity ï Energy Release Component (ERC) and 100-hour and 1000-hour timelag fuel moisture (Deeming 1997).

We used the Rare Event Risk Assessment Process (RERAP) ver. 7.01 (USDA 2006; Wiitla 1994) to evaluate the conditional probabilities that a free-burning fire traveling a straight line route would reach a point of concern before the end of season, with fire spread starting at several dates through the fire season. We used the UNF Gradient Nearest Neighbor fuels data to describe fuel models in the fire vicinity. Values at risk in the vicinity of the fire were identified by the local federal and state managers.

We also used the Fire Spread Probability (FS-Pro) spatial modeling tool from the Wildland Fire Decision Support System (WFDSS). Simulations of 7, 14, and 30 day duration were analyzed in order to evaluate the probability of fire spread across the landscape. The simulations were initiated from the August 9 fire perimeter. Forecast weather values were used for the first six days of each simulation, and the remainder of the simulation used climatology data from the Case RAWS using the time period of 1985 through August 2009. Fuels data were from the LANDFIRE rapid refresh national standard data layer, which uses a set of 40 fuels models (Scott 2005).

Results

Short term prognosis for fire growth

After the rain of August 6-7, the fires in the NFJD Wilderness were essentially checked ñin placeò at an estimated 212 ha in size. The local unit managers were interested in knowing the effect of this rainfall, especially since they had an Incident Management Team in place that was developing plans to manage this fire. Managing the complex of fires with this team was costing $200,000-400,000/day.

The specific questions related to the weather event that the Long Term Assessment Team considered were:

1. Was the rainfall event significant enough to call it a season-ending event?
2. How long until normal burning conditions resume?
3. How long until problem fire behavior returns?

To evaluate the effect of this precipitation on fire danger indices, the team searched the weather records from 15 RAWS sites in northeastern Oregon. We attempted to find rainfall events of similar amount and/or duration with similar timing, and intended on evaluating the rebound in Energy Release Component and the modeled large fuel moisture. Although we could find no events that matched the 2009 situation perfectly, we were able to learn enough from these records to make some educated forecasts for the recovery in burning conditions.

Previous analysis of actual large fire growth and daily fire danger by the Umatilla National Forest shows that large fire growth is associated with ERC levels at or above the 80th percentile. Using the Fire Danger Projection function of Fire Family Plus, we estimated that it would take 14 days of normal August drying weather before the fire danger indices would reach the average value for the date, and about 35 days to reach the 80th percentile ERC. Fig. 3 displays the actual ERC for the entire 2009 fire season, and shows that the ERC did reach the average level in 14 days (August 20), approached the 80th percentile in 20 days (August 26), approached it again in 27 days (September 3), and finally crossed the threshold in 42 days (September 21) on the way to a late-season peak on September 28.

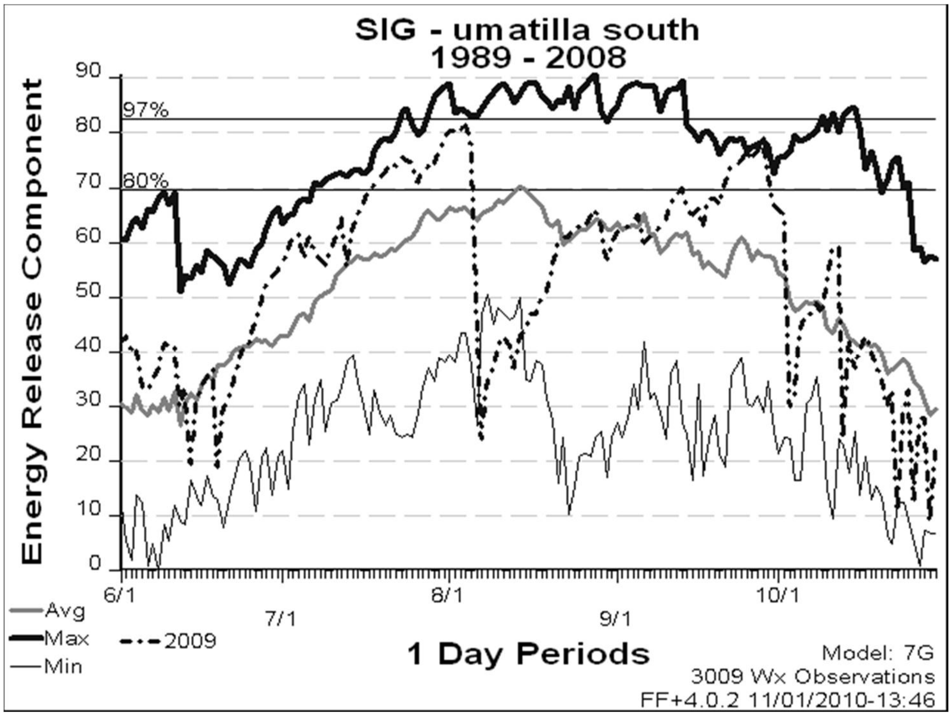

Fig 3. Energy release component, the usual fire danger index in eastern Oregon, for the fire season of 2009 plotted against the daily low, average, and high value recorded during the period 1989-2008.

Remaining length of season

The LTAT has adopted a method of predicting season ending dates that relies on a trigger (rainfall) that results in a drop in fire danger indices from which the indices do not recover by the end of the fire season. In the case of the North Fork Complex, we used 20 years of RAWS data from the J Ridge RAWS site, evaluated with the help of Fire Family Plus and RERAP. We defined season ending date as the first date after August 1 when more than .63 cm of rain fell over a 3 day period, followed by a drop in the Energy Release Component to below the 50th percentile ERC value, and from which the ERC subsequently did not rise above the 80th percentile value the remainder of the calendar year. The derived dates for the 20 years in the record are then used to develop a waiting time distribution of season-ending dates.

This sort of criteria is useful because it is both 1) tied to a weather event that depresses fire danger, and 2) considers the fire danger index the remainder of the season. It does not use fire occurrence data for two main reasons. First, fire occurrence data relies on fire start date. With large fires burning for weeks or months, fire growth days have little to do with fire start dates. Second, a substantial number of fires in the record are human-caused late season fires, started by big game hunters during periods when fire danger and fire spread are low.

The waiting time event curve generated by these criteria is shown in Fig. 4. Based on this analysis, we demonstrated that 50% of the past 20 fire seasons were over by September 15, and

90% were over by October 2. For 2009, we then considered the Climate Prediction Centersô (CPC) 30 and 90 day outlook for temperature and precipitation probability, and recommended that managers anticipate a later than average season end date based on these forecasts.

The highest ERCs of the remainder of the season occurred in late September, with more than a week of ERC values above the 80th percentile accompanied by significant daily fire growth (Figs. 3 and 7). The 2009 season actually ended on October 3, with a cold front and over 1.2 cm of rain over a 3 day period. ERC dropped below the 50th percentile, and although it rebounded, it never again reached the 80th percentile large fire threshold. This season ending date was 57 days after the completion of the long term assessment, approximately the 90th percentile date for season-ending ï validating our prediction that a late season was more likely.

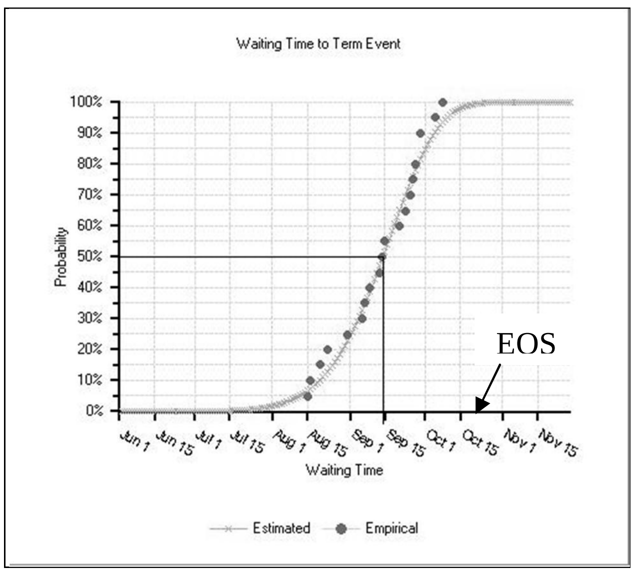

Fig 4. Waiting time distribution of fire season-ending dates, based on 20 years of data from the JRidge RAWS. 50% of fire seasons are over by September 15, and 90% by October 1. In 2009, the fire season ended on October 3 (EOS 2009).

Fire spread toward points of concern

Local fire managers were concerned about fire spreading towards (and eventually reaching) any of three private land parcels (Fig. 5), thus potentially burning privately-owned timber and improvements. The Camp Creek area is 4 km northwest and across the NFJD River, with managed forest lands, roads, and areas burned by the Tower Fire of 1996. The Forks Guard Station is 6.1 km north of the NFJD River, where fire spread would be through the 1996 Tower Fire. Granite is a small community located 8.7 km from the fire area, and fire spread in this direction would be through areas burned in 1987 and 1979 wildfires. The FS-Pro assessment indicated little risk of fire spread to these parcels within 14 days (less than 5% probability).

We used the edge of previous wildfires or the river as starting points for fires spreading towards the private land parcels. The analysis included four assessment start dates. Using RERAP, we evaluated the likelihood that free burning fire would reach these parcels before the end of the season (Table 1). The RERAP assessment essentially sets up a ñraceò between a spreading fire and the approaching end of season. The LTAT and local managers believed that spotting across the NFJD River would occur at some point and four assessment start dates spread over a typical fire season duration would provide decision makers with the most information. The later in the season this spot fire occurs, the later the race begins, and the lower the chance the fire reaches private land by end of season (15% chance if it crossed the river on September 1, for example). In our assessment, the area most at risk was the Camp Creek area, and we predicted a 40% chance that a free burning fire, initiated from a spot fire across the NFJD River on August 10, would reach the private land before the end of the season.

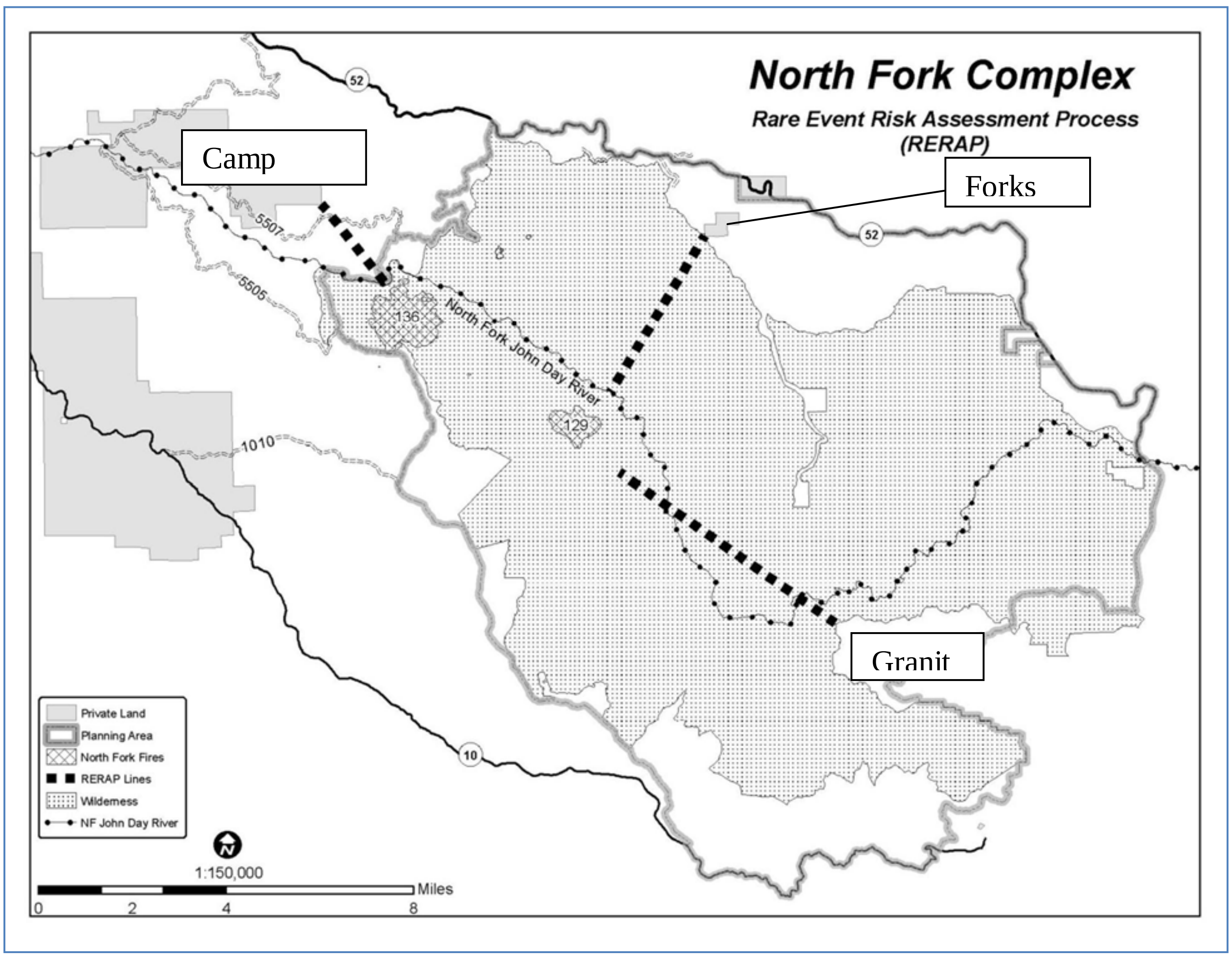

Fig 5. Private land parcels as points of concern in the proximity of the North Fork Complex, and the assumed path of fire spread required for fire to reach these parcels.

Table 1: Risk Assessment for likelihood that fire would reach any of several private land parcels, given spread initiated on four different dates through the fire season.

Assessment Date (2009)	Total Risk (%) Camp Creek	Total Risk (%) Forks GS	Total Risk (%) Granite
August 10	40	8	11
August 20	27	4	7
September 1	15	2	3
September 15	7	1	1

Over the course of August and most of September, the fire did not cross the NFJD River. The local fire managers considered the natural barrier created by this river as an important control feature for much of the season, and took actions to reduce the downhill rate of spread and fire intensity close to the river. Fire crews constructed ñcheck linesò to slow fire spread as the fire approached the NFJD River closest to the Camp Creek assessment line, and used helicopters on several occasions to drop water on the downhill edge of the fires.

The fire did spread into the young lodgepole pine forest resulting from past burns after September 1. By this time there was little threat to private lands and no actions were taken other than monitoring. The RERAP assessment indicated only a 2-3% chance that a fire reaching the old burns on September 1 would reach private lands by end of season.

On September 28, the fire did cross the NFJD River on the far southeastern side of the fire. Based on the remaining length of season and the short term weather forecast for cooler and wetter weather, local fire managers chose to take no direct action other than to monitor fire spread and to notify hunters in the area.

Fire growth events and frequency

Typically, large fires in western forests gain most of their growth on relatively few days during the fire season, with modest or even minimal fire growth on most days. Often in the intermountain west, a large midsummer high pressure ridge will result in conditions favorable for large fire growth across broad areas for a period of a few days. The specific conditions that have strong association with past large fire growth on the southern portion of the UNF include high temperatures, atmospheric instability, and poor overnight humidity recovery, creating favorable conditions for very low daytime fuel moistures.

As part of the assessment, the LTAT evaluated three recent large fires in similar fuel types in the area to discover what weather events could be associated with large fire growth days: the Tower Fire (1996), the SharpsôRidge Fire (2006), and the Trout Meadows Fire (2007). The team concluded that large fire growth days were well associated with high temperatures and low humidity after a period of extended drying. Table 2 displays fire weather conditions during two periods of significant growth of the Tower Fire (1996); what should be noted are the low 100hr and 1000hr fuel moistures which indicate extended drying, poor overnight humidity recovery (maximum relative humidity below 40%), and high ERC values (above the 80th percentile value of 68). Historical observations of the Tower Fire on August 25-26 described a northeast wind, an unusual wind direction in this area which is usually associated with a strong high-pressure ridge.

Table 2. Fire weather conditions during two periods of rapid fire growth, Tower Fire, 1996.

Attribute	August 16	August 25-26
100hr fuel moisture (%)	5	5
1000hr fuel moisture (%)	8	8
ERC	77	80
Maximum overnight humidity (%)	33	29

The Sharpôs Ridge Fire in 2006 experienced decreasing overnight humidity from August 17 through August 21 and rapid fire growth occurred on August 20, 21, and 22. The Trout Meadows Fire grew rapidly on its start date of August 4, 2007 after a period of decreasing maximum overnight humidity each night from July 30 to August 3 (USDA Forest Service 2009).

A review of the shape of large fires over the past 20 years on the North Fork Ranger District shows that large fires tend to grow in all directions, indicating little influence of general winds. The team evaluated historical wind records at several RAWS, and concluded that frontal passage winds are not a significant component of the fire weather environment in the vicinity of the North Fork Complex (Fig. 6). Case RAWS near the fire complex shows few high wind speed occurrences known to drive fire growth. This is contrasted with the Alder RAWS, 150 km north-northeast of the fire area but also on the Umatilla NF, which shows both higher wind speeds and a dominant wind direction associated with frontal weather passages.

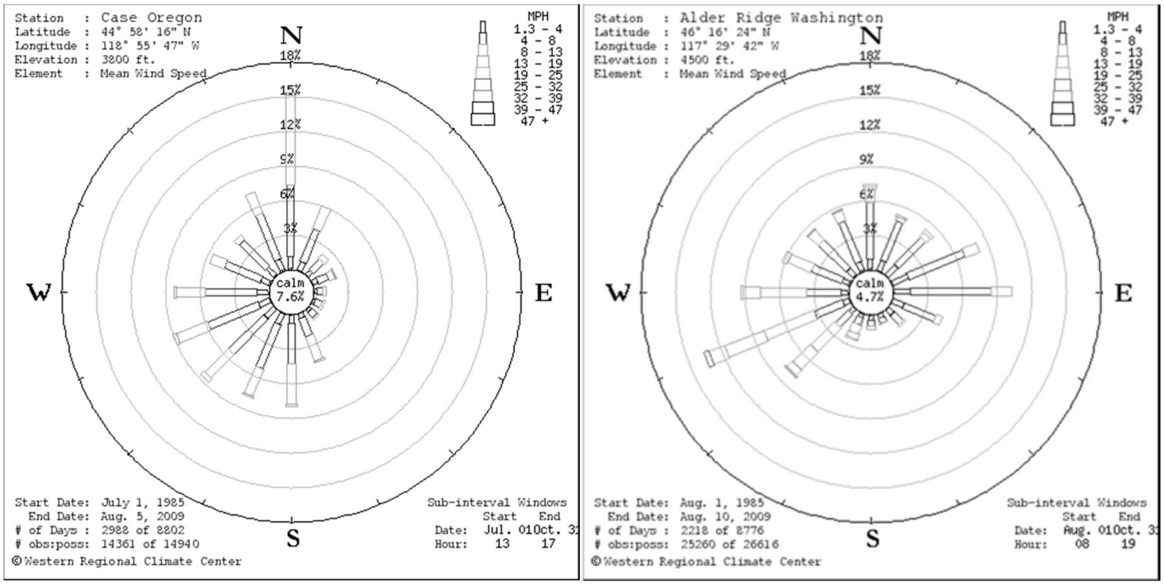

Fig 6. Windroses for Case and Alder Ridge RAWS for the August-October daytime burn periods.

The LTAT analysis recommended that poor nighttime humidity recovery (below 40%) be used as an indicator of potential fire growth days when it is accompanied by a high ERC value. The team predicted that local fire managers should expect an average of 7 nights of poor humidity recovery per year between July 15 and September 30. Using a threshold value of <35% humidity, two or three days per year can be expected during the same period.

The 2009 fire season actually saw 6 nights of overnight humidity recovery below 40% between July 15 - October 3, and 2 nights below 35%. However, after August 2 there were only two nights with humidity recovery below 40%, and only night below 35%.

Poor overnight humidity recovery was associated with fire growth days on the North Fork Complex. Fire growth was not calculated every day during the 60 day life of the fire, but only when the fire was mapped with infrared imagery (Fig. 7). Fire managers tended to request an infrared image after the most active fire growth days (M. Johnson, North Fork Ranger District Fire Management Officer, pers. comm.), and the dates of the fire mapping tend to follow periods of poor relative humidity recovery. Therefore, we conclude that fire growth days tended to follow nights of poor humidity recovery.

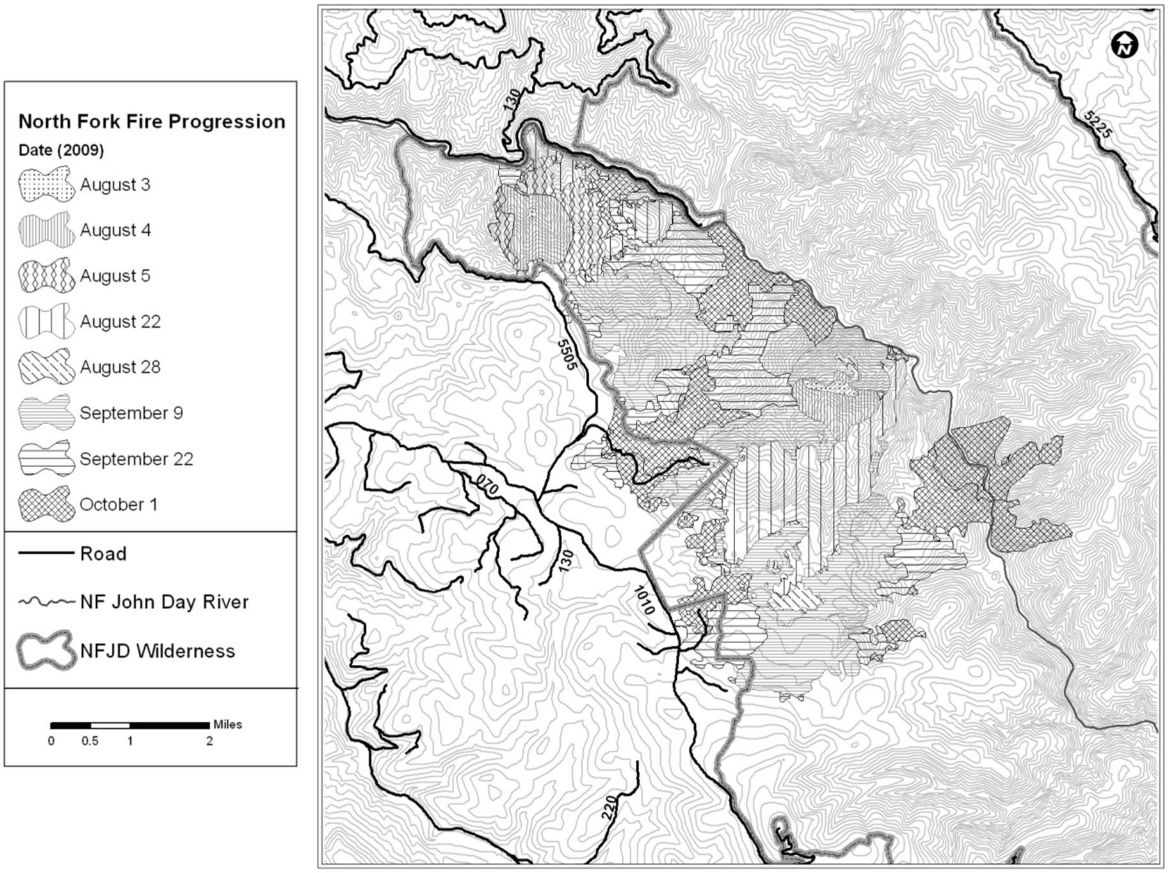

Fig 7. Fire Progression Map, North Fork Complex, Umatilla NF 2009

Table 3 displays the known fire perimeter each time the fire was mapped with infrared imagery, and the observed overnight humidity recovery on the previous night as recorded at the Case RAWS. The average overnight humidity recovery for the period of August 1-September 30 was about 70%, and the predicted number of poor humidity recovery nights during the fire season, based on the average of 20 years of records, was about right. In hindsight, it appears that the recommended threshold for predicting periods of active fire growth (<40% humidity recovery) was conservative, as active fire growth days followed nights of humidity recovery below 55%.

Table 3. Overnight humidity recovery preceding days of known fire size, as mapped from infrared imagery

Date	Maximum humidity (%)	Fire size (hectare)
August 6	48	534
August 28	53	1372
August 29	52	1530
September 2	58	1813
September 9	46	2480
September 13	44	3420
September 22	33	4363
October 1	39 (on September 28)	5612

Location of fire at end of season

The core question for this analysis is: where will this fire be at the end of the season if fire managers take no action to inhibit spread? The direction and distance of fire spread is a function of fuels, weather, and topography, and the interactions between the three. Given even perfect information about fuels and topography (which is not possible), the fire spread predictions will always be probabilistic in nature because of the uncertainties of weather.

We use the Fire Spread Probability tool (FSPro), as part of the Wildland Fire Decision Support System (WFDSS) to evaluate the probability of fire spread over a given period of time. FSPro uses both forecasted weather and climatological values over the time period of the simulation, and for this assessment we used forecasted weather for the first 6 days. We ran both 14 day and 30 day simulations, and assumed barriers to surface fire spread at the NFJD River, Forest Roads 5505 and 1010 (southwest of the NFJD Wilderness) and the two-year old Otter Creek Fire to the west. Modeled fires were still allowed to spot over these barriers.

The average fire size projected by a 14-day FSPro assessment was 2926 ha, and the 50th percentile fire size for the same period was 2244 ha. Actual fire size on August 28 (18 days) was 1356 ha. The average fire size projected by a 30 day run was 7904 ha, and the 50th percentile size was 4864 ha. Actual size on September 9 (30 days) was 2452 ha. Because 30 days was not likely to be the end of the season (Figure 4), the team did not use this 30 day progression to predict whether any particular points were likely to be reached by fire before the end of the season. Rather, the team used the FS-Pro probability map to indicate which direction(s), if any, the fire was most likely to spread. In general the probability map showed fire spread in all directions, with no dominant direction. This indicted that the general southwest flow was not likely to drive fire growth and that wind events like cold front passages were not frequent enough or strong enough to dictate spread direction.

Discussion

The rainfall event of early August provided fire managers with an opportunity to evaluate several courses of action. They considered a conventional direct attack approach with crews constructing handline in the NFJD Wilderness area with logistical and operational support by helicopters; the incident management team estimated that this approach would have cost about $9.2 million to implement. The rainfall had created fire behavior conditions that favored the success of this approach, but local managers rejected it due to costs, safety, and natural resource concerns.

Instead, they chose an approach that created a roughly 5600 ha ñboxò within which to manage the fires, created by past burns, a river, and a road system. Such an indirect approach is becoming more common on National Forest fires, especially for wilderness fires, as it takes advantage of existing fuel breaks and roads to ñbring a fire outò of the wilderness where it can be suppressed more safely and with the use of equipment. This approach also allows fire, as a natural process, to play a role in management of these wilderness areas. In the case of the North Fork fires, the IMT in place estimated that taking this indirect approach and implementing it would cost about $7.6 million.

While the rainfall event gave managers an opportunity to study options, it also created uncertainty ï for example, uncertainty about when and if fuels would dry enough to allow fire to spread towards the indirect boundary or to allow fuels along the boundaries to be intentionally burned. The selected approach called for patience, and a commitment to taking action only when necessary. As a result, less than 10% of the prepared fuel break alongside roads outside of the Wilderness was ignited during the course of the fire season in order to control fire spread.

The fire eventually burned for 65 days, finally ending spread on about October 5. The final cost for management of the North Fork Complex was about $5.2 million ($967/ha burned), of which $2.9 million was spent in the first 11 days. Daily cost to manage the Complex with Type III or Type IV organizations ranged from $2,000 to $10,000/day (compared to the daily cost of the Type II organization of $200,000-400,000/day).

The Forestôs previous analysis of fire danger indices has revealed an important threshold for large fire growth. The use of 80th percentile ERC continues to successfully distinguish the active fire days from the really large and potentially dangerous fire growth days. Further study by the Forest of overnight humidity recovery values and trends associated with actual fire growth may lead to another useful rule of thumb, which can be easily measured, that could be used in both strategic and operational decision making.

The most important role that the long-term assessment played may have been the confidence it gave local fire managers in their selected course of action, knowing that they used the best available information to make a reasoned choice for management of these fires for the duration of the fire season. They knew which portions of the fire perimeter presented the greatest threat to values at risk, and they were able to anticipate active fire days. Even when the large ñboxò was breached by the fire, they had confidence that there was minimal risk to private lands, which allowed them to monitor the fires and wait for the end of the season to eventually stop fire spread.

Personnel staffing the North Fork Complex of wildfires experienced no significant injuries or accidents. While there is no way of knowing how many injuries or accidents would have occurred if a more aggressive or direct fire-fighting strategy would have been selected, the exposure (likelihood of an accident) would have been higher with more use of aircraft and more direct line construction, and the consequences of injury could have been greater given the difficulty of quickly moving personnel into and out of the fire location.

Concluding remarks

The Forest Service is committed to supporting line officers that consider a variety of options for management of fires through the long term. We recognize that while taking this approach results in fires that may be safer, and better for the land, the fires are also bigger, last longer, are fatiguing for local managers, and could even be more expensive when viewed in the short term. There is also risk ï and the long term assessment gives them better information upon which to base these decisions.

Not all long term assessments will end up in decisions to manage fires to be bigger or longer duration. Sometimes the LTA validates the decision to stay aggressive and as direct as possible, and sometimes burning conditions, resource availability, or access leave no options other than to manage it as a big fire. And sometimes we have a choice. Providing the decision support for an informed and reasoned choice is the goal of a good long term assessment.

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The Dome Wildland Fire of 1996; Challenges in Predicting Extreme Fire Behavior

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Abstract
On April 25th, 1996 the Dome wildland fire, started from an abandoned campfire, on the Santa Fe National Forest in New Mexico, United States. Fire danger indices for the month of April were at record high levels. The fire weather forecast for April 26th, indicated that temperatures would be slightly cooler, with less wind than the previous day, a Haines Index of 3 (low) and the National Fire Danger Rating System indices showed the Burning Index dropping to 39. The fire behavior forecast and briefing provided the morning of April 26th, indicated the possibility of extreme fire behavior but a crown fire was not predicted. During the morning of April 26th, fire behavior was moderate with flame lengths less than 3 feet. At about 3:30 pm, the Dome fire exploded into a major conflagration dominated by crown fire. In an after action review of fire weather conditions, the Haines Index had actually increased from a level 3 to a level 5, from the morning into the afternoon of the 26th. Predicting the transition from surface fire to crown fire can be very difficult, especially during the initial stages of a fire, when information can be quite limited.

Additional keywords: fire behavior, crown fire, flame length, Burning Index, Haines Index

Introduction

On April 25th, 1996, in mid-afternoon, the Dome fire, started from an abandoned campfire in the Jemez Mountains, on the Santa Fe National Forest in the State of New Mexico, United States. The fire spread east onto Bandelier National Monument, lands administered by the National Park Service. The fire was named 'Dome' after the lookout tower located two miles to the west of the point of ignition, on a mountain peak named St. Peters Dome.

Topography in the fire area is very rugged with deep canyons and high mountains. Elevations in the area range from about 7,000 feet to 8,400 feet. The main topographic feature is Capulin Canyon and the San Miguel Mountains. Major peaks in this area include St. Peters Dome and Boundary Peak. The Rio Grande River is located four miles to the east of the fire at 5,300 feet elevation. The city of Los Alamos is located about six miles to the north of where the fire was kindled.

The predominate vegetation in the fire area consisted of mixed conifer timber, primarily Pinus ponderosa (ponderosa pine), Pseudotsuga menziesii (Douglas fir) and Abies concolor (white fir), along with scattered stands of Populis tremuloides (quaking aspen). Timbered areas were either open with an understory of grass and small shrubs or very dense with heavy ladder fuels and thickets of pole size trees. The lower elevations and drier sites are dominated by brush including juniper (various species), and Pinus edulis (pinyon pine).

The pure stands of ponderosa pine in the area are typical of National Forest Fire Lab (NFFL) fuel model 9, which is long leaf pine litter. Fire spread is typically in pine litter with occasional jackpots of heavy woody material which contribute to spotting and torching. The mixed conifer stands of pine and fir in the area are typical of NFFL fuel model 10, a timber over story with heavy downed woody fuels. Brush fuel types in the fire area consisted of mostly pinyon, juniper and oak with scattered grass understory, typical of NFFL fuel model 5. With low wind speeds fire spread is fairly slow in this fuel model. There was also a significant loading of downed logs on mesa tops from a 1950's wind event that influenced fire behavior on the Dome Fire.

In April of 1996, northern New Mexico was in a moderate to severe drought as measured by the Palmer Drought Index. The Tower remote automated weather station (RAWS), located six miles to the east of the fire received scant rainfall in the months prior to the Dome Fire, with less than an inch of rain before April 25th. Both live fuel moistures and dead fuel moistures were extremely low, due to drought conditions. National Fire Danger Rating System (NFDRS) indices for the energy release component (ERC) for the Tower RAWS set records for much of March through April of 1996, based on historic weather observations from 1964 to 1996, with values well above the 90th percentile for much of that period.

When the initial attack crews arrived at the fire location at 3:00 PM on June 25th, the fire was 2 ½ acres in size. The Dome fire was active all night of the 25th into the morning the 26th, spreading mainly to the east into Capulin Canyon and along the main ridgeline that defines the San Miguel Mountains. During the evening of June 25th a Type II incident management team (team) was ordered, and they took control of the fire, the next morning, at 0600 hours. The team prepared an incident action plan (IAP) for April 26th, and a briefing was given to all staff early that morning. The IAP included a fire behavior forecast, prepared by a fire behavior analyst (FBAN) which articulated the possibility of extreme fire behavior but never predicted crown fire activity.

Fire weather forecasts for the Dome Fire were obtained from the National Weather Service (NWS) in Albuquerque, New Mexico. The fire weather forecast, issued at 8:35 am, for April 26th, indicated there was an upper level ridge of high pressure over New Mexico, with a mostly sunny and dry day expected. Temperatures in the mountains were expected to be in the mid 70's, with winds north to northwest winds at 15 to 25 mph. The air mass over the Dome fire on the morning of the 26th was dry but relatively stable and the Haines Index (Haines 1988) was calculated as a 3 which indicated very low potential for large fire growth. However this prediction did not represent actual conditions by mid day on the 26th, when the late afternoon balloon sounding indicating cooler air aloft associated with a passing disturbance spread over the fire area, which quickly destabilizing the air mass, increased the Haines Index to a 5.

From the morning into early afternoon of the 26th, fire behavior was moderate with flame lengths generally less than 3 feet and low spread rates. At 1300 hours a weather observation was taken at the Dome lookout tower at 8400 feet, and the winds were very light and variable which seemed abnormal for the early afternoon hours. At approximately 1400 hours a spot fire was discovered, next to Forest Road 142, on top of the main ridge. The spot was a couple of acres in size and was burning in a open stand of mature ponderosa pine, mostly backing with flame lengths less than 2 feet. Fire crews in the area responded quickly and contained this fire.

The winds were in the fire crews favor most of the morning and early afternoon of April 26th because they were very light and blew out of southwest, which carried fire brands mostly into the burned area. Sometime in early afternoon the winds began shifting to a more west/northwest direction. At 1500 hours the northwesterly winds increased 3-4 miles per hour at the Tower weather station, which was also noticed by the firefighting crews on the scene. The relative humidity dropped to about 9% around the same time. The 20 foot winds for the two closest weather stations never exceeded 12 miles per hour, on that afternoon. The changing wind direction caused fire brands to be carried into unburned areas instead of into the black. Fire activity started to increase as flames pushed hard against road 142 and the main ridge line of the San Miguel Mountains.

The afternoon of April 26th, at around 3:30 pm, the Dome fire exploded into a major conflagration, and by late that evening had spread to 4,150 acres. Fire behavior was extreme and several crown fire events occurred, pushed by westerly winds with spread rates estimated at 1 to 2 miles per hour. The surface fire moved in conjunction with the crown fire. Three ‘20 person’ fire crews and two engine crews moved into safety zones and escaped with one minor injury.

The fire perimeter map for the end of the day on the 26th shows an elliptical fire shape and indicates the fire spread generally from the northwest to the east and southeast towards St. Peters Dome. Topography appears to have played a minor part in affecting fire spread direction. An analysis of the fire behavior on April 26th, using the fire behavior and fuel prediction system called BehavePlus (Andrews 2007), indicates a crown fire spread rate of ½ to 1 miles per hour. Surface fire spread rates prior to the fire blowup were approximately 500 feet per hour which jumped to 1000 feet per hour as the winds picked up and the atmosphere became more unstable.

The fuels, weather and topography changed very little from the 25th to the 26th. The weather was cooler and less windy on April 26th compared to April 25th and the NFDRS indices showed a decrease in the energy release component (55 decreasing to 51). The only major difference between the two days was the Haines Index. The Haines Index on April 25th was a 4 (low potential for large fire growth) and on April 26th was a 5 (moderate potential for large fire growth). Cooler air aloft associated with a passing disturbance spread over the fire area on the 26th, increasing the Haines Index to a 5, and quickly destabilized the air mass, but no significant drying occurred that afternoon. National Weather Service fire weather meteorologists, Kerry Jones and Bob Berkowitz, reviewed the data from that week and determined that the Haines Index was the most critical weather factor.

Based upon observations and an analysis of fire behavior, the Dome fire may have been ‘plume dominated’ during the afternoon of April 26th. Ground observations and photos taken of the convection column appear to show a plume dominated fire for the first part of the crown fire run, then show the smoke column shearing off.

The next several days the Dome Fire was very active with periods of extreme fire behavior. Fire crews flanked the fire on the north and south sides burning out along road systems and trails, allowing the fire to move to the east where natural barriers and low fuel loading helped slow or stop the fire spread. The fire was finally contained at 16,468 acres.

Conclusions

Predicting wildland fire behavior is a challenging task in the best of circumstances. The FBAN often faces a tough job of gathering environmental variables, obtaining an accurate map of the fire perimeter, then selecting a fire behavior model that will provide accurate, relevant and timely results. Data can be erroneous, missing or outdated, plus there are limitations to the fire behavior and fire weather models. Fire danger indices were at record levels during the Dome Fire which added to the challenge of predicting the initiation of a crown fire event.

The tools available to predict transition to crown fire and associated spread rates were very limited, in 1996. That has changed in the last several years. Fire behavior software now can model the transition to crown fire and crown fire spread rates, with the critical inputs being crown base height and foliar moisture of the conifer trees. Even with improved fire modeling software, there are still many challenges in predicting crown fire events. Accurate and timely fire weather and fire behavior observations, and gathering of fuels information is essential. The Haines Index is not an input in fire behavior models, but during large fires it needs to be carefully tracked and used with other tools and on-site observations to evaluate the potential for large fire growth.

During high fire danger periods, even subtle changes in environmental conditions can ignite extreme fire behavior, which is what happened on the Dome Fire. Changing weather conditions, such as frontal passages, wind direction, temperatures and humidity need to be carefully monitored. These changes may not be readily visible to the firefighter on the ground, making escape routes and safety zones, even more important. Hence the importance of fire crew supervisors having a good knowledge and training in fire behavior.

On large fires the importance of obtaining on-site fire weather forecasting from an incident meteorologist (IMET) is critical. The IMET can provide weather forecasts, and briefings tailored to the specific fire environment and be a ready source of information for the FBAN.

A fire behavior analyst has to rely on his/her own personal judgment using an appropriate set of tools when preparing a fire behavior prediction. The fire behavior prediction for any given day, is only a starting point, and needs to be reevaluated by fire line personnel throughout the day. Actual fire behavior and environmental conditions, have to be closely monitored on each division, and tactical fire operations adjusted as needed, to insure safety of personnel.

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Reconstructing the spread and behaviour of the February 2009 Victorian Fires

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Abstract
This paper summarises the methodology involved in reconstructing spread and behaviour of nine large-scale bushfires that burned across the state of Victoria, Australia in an event known as Black Saturday on 7th February 2009. The methodology uses a fire isochrone approach that integrates the latest remote sensing technology with field observations of the Black Saturday fires to characterise the rate of spread, fire intensity, energy release, convection column, and spot fire dynamics during the various phases of their development.

Fire reconstruction was based primarily on indirect evidence from remotely sensed data such as digital aerial photography, satellite imagery and high-resolution Doppler radar. Additional sources of data included: point-based ground observations like photographic and video images, statements and submissions to the Bushfires Royal Commission, and field interviews with local residents. Detailed weather station data also aided interpretation of fire behaviour and convection column behaviour. All data, particularly local residents' photographs and home videos were compared against all other existing data layers and ranked for spatial and temporal reliability.

Fire line scans paired with ground and aerial photographs aided the estimation of initial spread lines and the location of early spot fires. Patterns of fire spread in the intervening periods were interpreted from patterns of fire severity on aerial photography and then linked to times and positions from remote sensing, Doppler radar and field observations.

Using the methods described, fire isochrone maps were created for each fire showing spread through the landscape associated with a level of spatial and temporal confidence. For most sections of the fires, isochrones were drawn within a spatial and temporal accuracy of ± 200 m and ± five min. Predominant spread mechanisms and associated smoke plume behaviour were also described in each fire period.

The study also revealed that fire behaviour variables and their equations, such as rate of spread and fire line intensity, do not adequately describe the complex fire processes found in the Black Saturday fires. Three phases of energy release were identified on most fires — spot fire building, coalescence, and dissipation, which affected convection column and spotting behaviour, as well as local wind fields.

Additional keywords: Fire reconstruction, fire behaviour, methodology, fire isochrones, case study.

Introduction

Fire behaviour reconstruction involves collecting details of when, where, how and by what process a fire moves through the landscape. This reconstruction is based on a detailed assessment of the landscape terrain, vegetation and fuels, seasonal fuel conditions, and fire weather on the day. Accurate information about the location of actively spreading perimeters and sporadic spot fires and identification of the propagating mechanism are key components to the analysis. Without detailed observations, complex fire behaviour events such as mass spotting and merging of multiple fire fronts can make fire reconstruction difficult. It is nearly impossible to construct the exact moment to moment detail of a fire through a landscape owing to the dynamic temporal and spatial variation in fire combustion processes, flame behaviour and spotting events. However, reconstruction is useful for approximating fire behaviour within a given time, any time between 5 minutes to one hour, depending on the detail and accuracy of fire observations. As stated by Simard *et al.* (1983):

> '*Trying to understand the behaviour of all large fires with individual case studies is like trying to understand a movie by individual frames chosen at random. Each fire is only a single observation of a complex process, and many observations are needed before patterns begin to emerge. Despite the complexity, however, careful examination of even a single fire can yield insights into the underlying physical processes that control large fire behaviour*.'

On 7th February 2009, several small to large scale fires erupted across the state of Victoria following years of extended drought and a period of severe fire weather. Victoria had been experiencing the longest heat wave on record, with temperatures above 40°C lasting over a week; the temperature in Melbourne exceeded 43°C for three consecutive days for the first time since records were created (Victorian Bushfires Royal Commission 2010). Of the fifteen fires on the day, the eight largest fires consumed 430,000 ha of forest and grassland, claimed 173 lives and destroyed thousands of homes. The event came to be known as 'Black Saturday' and followed in the footsteps of historical damaging fire events in the state such as Black Thursday (6th February 1851, 5 million hectares, 12 lives), Black Friday (13th January 1939, close to 2 million hectares, 71 lives) and Ash Wednesday (16th February 1983, 210 000 hectares, 47 lives) (Victorian Bushfires Royal Commission 2010).

Case studies and analyses have been prepared globally and ultimately contributed to the current level of understanding of forest fire behaviour and its impact on fire fighter safety, suppression tactics and quantitative fire prediction (Alexander and Thomas 2003a, 2003b). Within the state of Victoria, fire behaviour analyses have been completed in various fuel types and in multiple formats (Billing 1983; Rawson *et al.* 1983; Watson *et al.* 1983; Billing 1987; Buckley 1992a, 1992b, 1993, 1994; Bartlett 1993; Chatto *et al*. 1999). Most studies provide a chronological summary of events, photographs, maps, descriptions of fuel and weather conditions, and interpretations of fire behaviour. A standard methodology for reconstructing fire behaviour generally does not exist with only some general guidelines and discussion available (Alexander and Thomas 2003b). Interestingly, very few large destructive fires (LDFs) are studied in detail, which points to an important gap in fire research of fire behaviour at the landscape scale (Alexander and Thomas 2003b).

Understanding bushfire behaviour under extreme fire conditions is the key to improving agency and community awareness and fire preparation and response. By committing time and resources to reconstructing the fires' events after their occurrence, by compiling and comparing multiple sources of information, much of the detail of spread, intensity, and energy release can be reassembled. Using a methodology that combines a range of spatio-temporal information, the Victorian fire reconstruction project aimed to uncover the details of fire spread and convection column dynamics of the larger and more destructive fires of 7th February. This knowledge obtained is then transferred into fire knowledge databases and training courses to assist fire managers dealing with future LDFs.

This paper outlines the methodology used to reconstruct multiple fires from the Black Saturday event. A discussion is presented detailing underlying methodological issues associated with the fire isochrone approach and proposes adaptations to this approach that may better characterize fire dynamics and convection column behaviour.

Background

The Department of Sustainability and Environment (DSE) initiated the Black Saturday Fire Behaviour Reconstruction Project in June 2009, following the events of the 7th of February. The project was supported by multiple agencies and research organisations, including the Country Fire Authority (CFA), Parks Victoria, the Bushfire Cooperative Research Centre, 2009 Victorian Bushfires Royal Commission (VBRC), Victoria Police (VICPOL) and the Australian Commonwealth Scientific and Research Organisation (CSIRO). This project was recognised as being a landscape scale assessment of fire spread and behaviour, was distinct from the detailed fire investigations into the fire origins and deaths being conducted by VICPOL, and was conducted with support from the Country Fire Authority (CFA), the Bushfire Cooperative Research Centre (BCRC) and the Australian Commonwealth Scientific and Research Organisation (CSIRO).

The geographical location and extent of the fires under study are presented in Fig. 1. Most of the large fires align in a north-westerly fashion associated with strong winds driven by a pre-frontal heat trough.

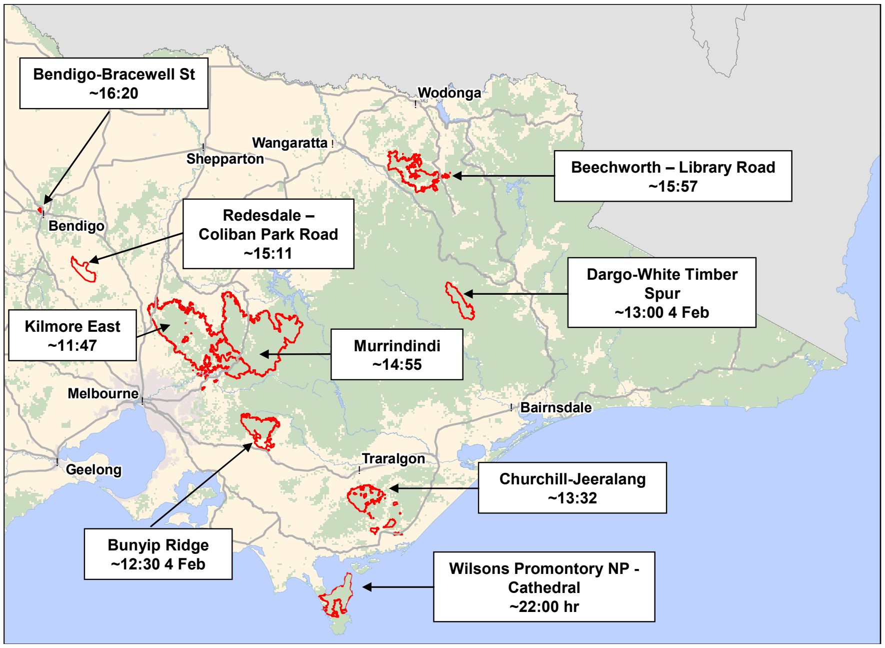

Fig. 1. Location of Black Saturday fires in Victoria

Details of the cause, extent, and type of vegetation burnt in each of the nine fires are summarised in Table 1. The reconstruction project focused on the first 24 hr of fire spread for each of the fires, spanning the fires' rapid movement under strong north-westerly winds followed by a cool south-westerly change.

Terrain and fuel interactions at the landscape level played an important role in determining the final extent and severity of the fires. The forests consumed by these fires consisted primarily of species associated with mass ember spotting events, which were exacerbated by dry seasonal conditions superimposed by extreme surface weather temperatures, low humidities and strong winds.

The combination of more rugged terrain, dense forest cover, long unburnt fuels and full exposure to the power of the winds contributed to the larger extent of the Kilmore East and Murrindindi fires. The Dargo- White Timber Spur fire was substantially smaller in extent due to the presence of younger fuels along parts of the montane Dargo plateau and less exposure to pre- and post- trough winds. The Bunyip-Ridge Track fire moved from more flammable forest into less cured grasslands; the Churchill- Jeeralang fire originated in plantation covered rugged terrain but moved into less flammable forest as it moved south-easterly, reducing the overall length of north-eastern perimeter exposed to the post-trough winds. The Redesdale- Coliban Park Road fire was much smaller in extent related to the large amount of grassland and active suppression on the northern flank. The Bendigo-Bracewell Street fire was situated on the urban edge of the city and burned a smaller area as it moved through the mosaic of low grass and forest fuels wedged in between peri-urban and mining areas. The Beechworth- Library Road fire spread was restricted by a mix of forest and grassland, as well as strategic fuel management along its flanks. The major outbreak following the south-west wind change was principally on privately owned pastures and forests in the Mudgegonga- Bruarong locality.

Table 1. Fires under study in the reconstruction project.

Fire Name	Cause	Final Size (ha)	Vegetation
Murrindindi	Not yet determined	148,453	Native forest, pine plantation and grassland
Kilmore East	Electrical failure	125,383	Native forest, pine plantation and grassland
Beechworth- Library Road	Electrical failure	33,577	Native forest, pine plantation and grassland
Bunyip Ridge Track	Lightning	26,200	Contiguous and remnant native forest and grassland
Churchill- Jeeralang	Deliberately lit	25,861	Pine and eucalypt plantation, native forest and grassland
Wilsons Promontory National Park - Cathedral	Lightning	25,200	Native heathland, shrubland and forest
Dargo – White Timber Spur	Lightning	13,807	Contiguous native forest
Redesdale – Coliban Park Road	Not yet determined	7,086	Grassland, remnant forest and eucalypt plantation
Bendigo- Bracewell Street	Deliberately lit	341	Disturbed woodland, shrubland and grassland

The fires were preceded by multiple years of below average rainfall and a period of severe fire weather. The vegetative fuel array across the Victorian landscape was suffering from heat stress and drought conditions brought on by seven to ten heat-wave days in Victoria. Dry sclerophyll forests on more exposed aspects had extremely low live fuel moisture content and increased rates of litter fall. Productive wet sclerophyll forests (usually unavailable to burn) also experienced wilting, plant senescence and decreases in live fuel moisture content, effectively doubling the fuel load available to burn amongst the forest structure[1]. Based on a detailed fire climatology reconstruction conducted by Gellie *et al.* (2010), the 2008/09 fire season was identified as being as severe as past fire seasons with large destructive fires which occurred historically in Victoria in the 1897/98, 1925/26, 1938/39, 1982/83, 2002/03 and 2006/07 seasons. The Black Saturday fires also occurred after a thirteen year drought that contributed to deep drying of the soils and vegetation. All historical LDFs were associated with the combination of heat-waves on top of very dry seasonal landscape conditions Gellie *et al.* (2010).

Following two weeks of heat-wave conditions, a continental heat trough drew in dry air from across central and northern Australia as a cold front and associated low approached from the west, to the south of the Great Australian Bight. On the 7th February, temperatures up to 47°C

[1] Gellie NJH, Gibos KE, Mattingley G, Wells T, Salkin O (2010a) Reconstruction of the spread and behaviour of the Black Saturday fires; the first 24 hours. *Research Report No 80 (in progress).* Victorian Department of Sustainability and Environment.

and humidities as low as 10% were experienced across much of central and eastern Victoria. Along with these very dry and hot conditions, turbulent and gusty winds averaging 45 km hr^{-1} (peak gusts up to 80 km hr^{-1}) were measured at the surface, reflecting the deeply mixed boundary layer conditions (up to 5000 m vertically deep) (Bureau of Meteorology 2009). For one hour after the change, similar wind speeds (between 40 and 45 km hr^{-1}) gusting to 80 km hr^{-1} were measured at coastal and near-coastal weather stations. Further away from the coast, the winds tended to be less strong soon after the change and ranged between 30 and 35 km hr^{-1} with gusts up to 55-65 km hr^{-1} (Bureau of Meteorology 2009). The modified Haines Index of 12 (original Haines Index of 6) indicated that the atmospheric conditions on the day were extremely unstable, which assisted in the formation of pyro-convection above the largest and most intense fires. Pyro-convection was at its peak following the south-west change as long flanks became head fires and released massive amounts of energy into convection columns.

The fire reconstruction process

The reconstruction process for this project was cyclical and iterative. From this, a fire reconstruction map and tables of fire spread and behaviour were produced from the available sources of information on each fire (Fig. 2). The GIS evidence was collated from first actual plots of the fire spread and activity documented by incident management teams (IMTs), as well as airborne fire line scans and second, from a range of evidence that could be assembled in a Geographic Information System (GIS). The latter source of evidence was based on the inputs required to deduce fire behaviour at a landscape scale, including landscape terrain, vegetative-fuels, disturbance history, seasonal climate and hourly fire weather obtained from weather stations.

The project relied on field evidence from personal and group observations of fires. This ranged from agencies' or local residents' photographs and video footage, to submissions and police statements to the VBRC, as well as information sourced from internet web-sites and reports. In addition to these direct sources of evidence, other evidence came from sources such as the BCRC, who had, prior to the start of the project, systematically collated field evidence on patterns and directions of leaf freeze, locations and numbers of houses lost and the effects on local communities (Victorian Bushfire Research Taskforce Report 2009). All of this information was assessed for validity, referenced in a geographical format and assigned an associated time.

Different types of data were used to infer different fire behaviour characteristics. Fire perimeters were best estimated from line scans, satellite data, post-fire aerial photography, digital photographs, video and Doppler radar imagery. Flame height and depth were best estimated from fire line scans, photographs and video clips and interpretations of severity patterns in post-aerial photography. Convection column dynamics were best read from photographs and video clips. In most cases, energy release was determined by viewing the Doppler radar imagery and calculating a rate of spread and fireline intensity from the fire isochrone map.

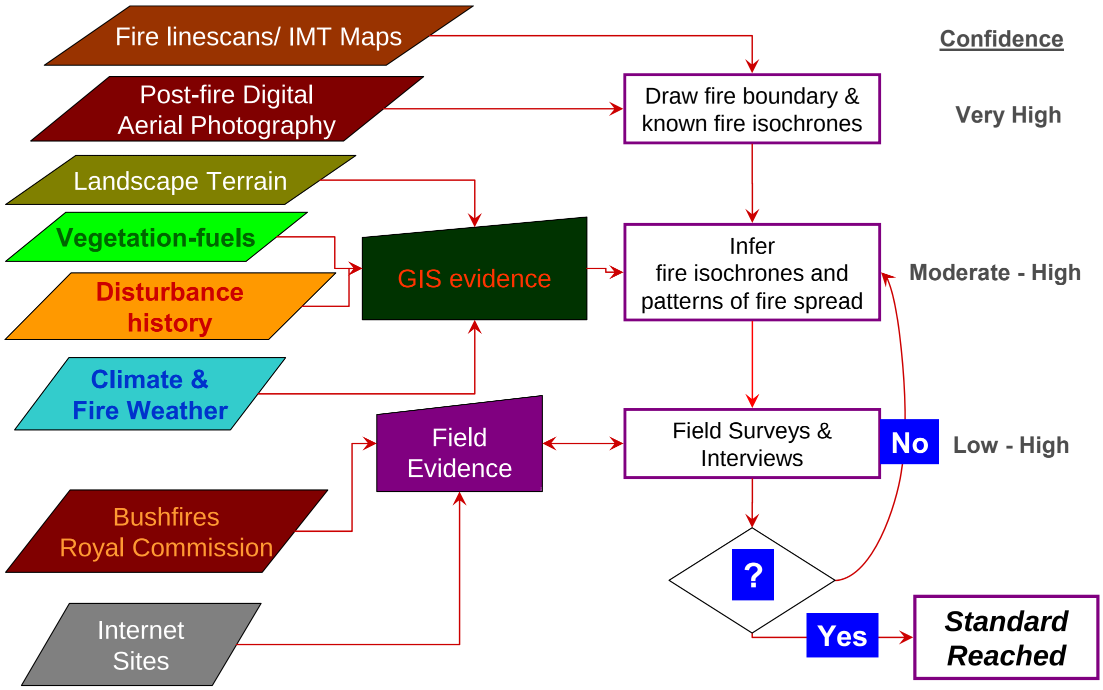

Fig. 2. Fire reconstruction process

The final boundary and the known spread locations were first drawn on a GIS as a first step to act as a base reference to drawing the inferred fire isochrones and patterns of fire spread in the second step (first and second box in middle section of Fig. 2). Fire isochrones[2] were drawn on maps using individual interpretations of fire severity patterns on the post-fire digital aerial photographic image and a plethora of triangulated local observations from the field evidence. The interpretation of inferred fire isochrones and patterns of fire spread was reliant on a fire behaviour analyst's high level of knowledge and skill of fire behaviour in the different forest types burnt in the Black Saturday bush fires, as well as skills in interpreting fire spread and behaviour from ground or aerial photographs or video images, from a variety of different viewer vantage points.

A draft map would then be prepared, which would prompt questions about where the critical spatial and temporal gaps in the knowledge of fire spread were. Potential candidates for interview were then identified, based on their location relative to the fire spread, their local knowledge, and the degree of fire impact on their persons and property. Upon obtaining agreement with them to undertake interviews, field interviews were then scheduled in two or three day blocks to maximise efficiency in field effort. Upon completion of the field survey, summary reports of fire spread and behaviour observations were recorded and related to photographic or video evidence. The new evidence would then be entered onto the GIS evidence and related back to the fire isochrone map, which was then reinterpreted and reworked to develop a new version of the map.

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[2] A fire isochrone is a line indicating the location and time of occurrence of a fire perimeter on a map. It connects points of known fire behaviour at certain times and displays the progression of a fire from its origin to its final area.

Data collection and organisation

The GIS and field-based evidence required a system for storing and maintaining the plethora of information: airborne imagery (fire line scans, pre and post fire digital aerial photography), satellite imagery, Digital Terrain Models, fuel and fire spread models, climate and weather data (daily and hourly weather data, Doppler radar, aerological diagrams, drought indexes), fire and government agencies (Incident Action Plan maps, situation reports, radio logs, equipment GPS tracking system logs, police statements, leaf freeze data), media (emergency call logs, mobile phone information) and local residents (photographs and video).

Information was collected as it became available and centrally stored on a shared network drive, dedicated specifically for fire reconstruction and related projects. The original information was stored on a separate computer dedicated to fire reconstruction and updates were made from their onto the shared computer network drive. It was very important to record details of the location and timing of photographic images and video recordings, if known, as the indicated time linked to the file was often in error or simply did not exist. Referencing software like Endnote® and RefWorks® was used to manage a growing collection of historical scientific literature and technical reports. The final collection of data for the Black Saturday reconstruction project approached 300 articles of historical literature, 250 transcribed interviews, 40 gigabytes of post-fire digital photography and over 60 gigabytes of video clips.

Data were spread across multiple agencies and had various levels of accessibility. Information involved in police investigations was difficult to obtain, and often key spread details were censored from public view. The longer the time since the fire, the more difficult it was to obtain personal logs, recollections and Incident Management Team (IMT) documents.

Prior to commencing the analysis, the context in which the fires occurred was investigated. Temporal climate, weather and fire potential datasets were collated and considered. Long and short term weather data were downloaded and used to analyse local weather patterns and predominant wind flow, and to calculate values of Soil Dryness Index (SDI), FFDI, GFDI, as well as other fire danger rating indexes, such as the Canadian and Fosberg FWI (Fosberg 1978, Van Wagner 1987). Synoptic charts for the days leading up to the event were filed and studied, along with aerological diagrams showing atmospheric conditions. Information about fuel load and structure was collected using existing fuel hazard models (Hines *et al.* 2010), notes from historical literature and technical reports, and local field observations. Local land use and fire histories were assembled and site visits made to observe nearby unburned fuels. Three-dimensional terrain models were used to assess local topographical conditions and their effect on fire spread and behaviour, such as fire crowning, convection column development, and spotting.

To assemble and interpret all the sources of information for this process necessitated a team approach, drawing on a team of five personnel from DSE, Parks Victoria, and a Masters graduate from the University of Toronto, Canada. A principal fire behaviour analyst in the team provided the overarching interpretation of fire spread and behaviour on all the fires. The rest of the team helped organise the field surveys and interviews, as well as undertake some of the more detailed local fire reconstruction on some of the fires. Having team members from multiple agencies proved invaluable for accessing data and connecting to fire ground personnel. Many additional interviews and contacts were made by each team member coordinating with agency staff either involved with or close to the location of the fires.

Team members also had a strong understanding of the vegetation and fuel types in Victoria and how individual eucalypt species affected spotting and crowning behaviour. Fire weather analysis skills were also valuable including the ability to estimate and interpret the Grass and Forest Fire Danger Indexes (GFDI and FFDI) (McArthur 1967, Luke and McArthur 1978); to interpret and interpolate weather at the fire from the nearest weather stations; and to understand the effects of atmospheric conditions, such as atmospheric stability and moisture, at the surface and in other levels of the atmosphere on fire and convection column behaviour. In addition to this knowledge, cartographic skills were developed amongst the team to cater for the demand for cartographic maps, oral and poster presentations and fire spread animations for a wide range of audiences, including rural communities, agency presentations, and submissions to the Victorian Bushfires Royal Commission.

Drawing final perimeters

For each fire, the first step was to draw the final perimeters of the main and associated spot fires. Digitised IMT maps, post-fire aerial photography and Landsat TM data were the best sources for these initial fire interpretations. However, the accuracy of the IMT maps varied from case to case and often indicated positions different than that visible in the post-fire digital aerial photography (Fig. 3). The quality of IMT maps can range from quick estimations of location jotted on a map, to detailed point by point trails recorded on GPS units used during a ground scout of the perimeter. Similarly, post-fire digital photography can also be misleading, especially in relation to areas burnt with a lower intensity fire and those with bare ground or dark underlying soils, bearing close resemblance to burnt areas.

Differences between the IMT map and aerial photograph perimeters may also be explained by differences in the intensity of fire behaviour; the individual on the ground may have mapped areas of milder fire behaviour that were not visible within the resolution of the digital aerial photograph. Although the photography used in this project had 0.15 m resolution, stitching and stretching together of the photos across scale of the landscape covered by these fires may produce some hidden unknown spatial errors.

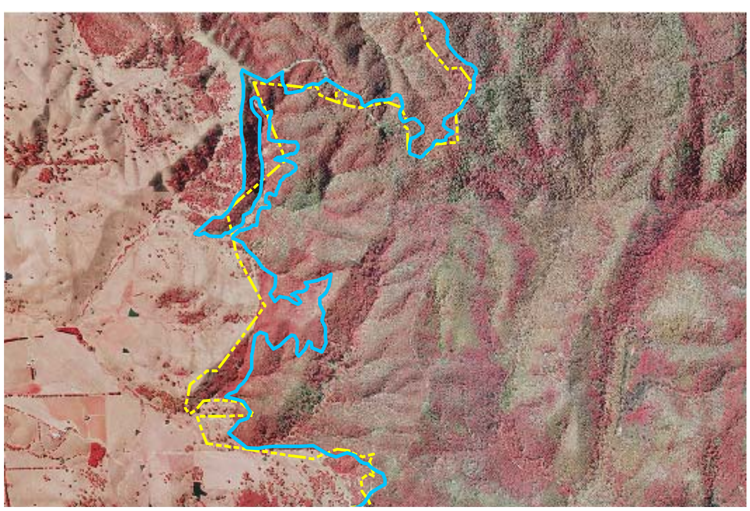

Fig. 3. Delineation of the final fire boundary of the Murrindindi Fire using IMT maps and post-fire digital photography

Unburnt areas were also delineated using the same data sources (Fig.4). Fine-scale information at the individual property level was often better collected from interviews of locals rather than directly interpreted from the images. Sometimes areas appeared to be burned in the aerial photograph but other evidence suggests they did not. In these cases, the area may have burned at a later time, some days after the original run of fire, or the very dark soils imitated the appearance of burned ground.

(a) (b)

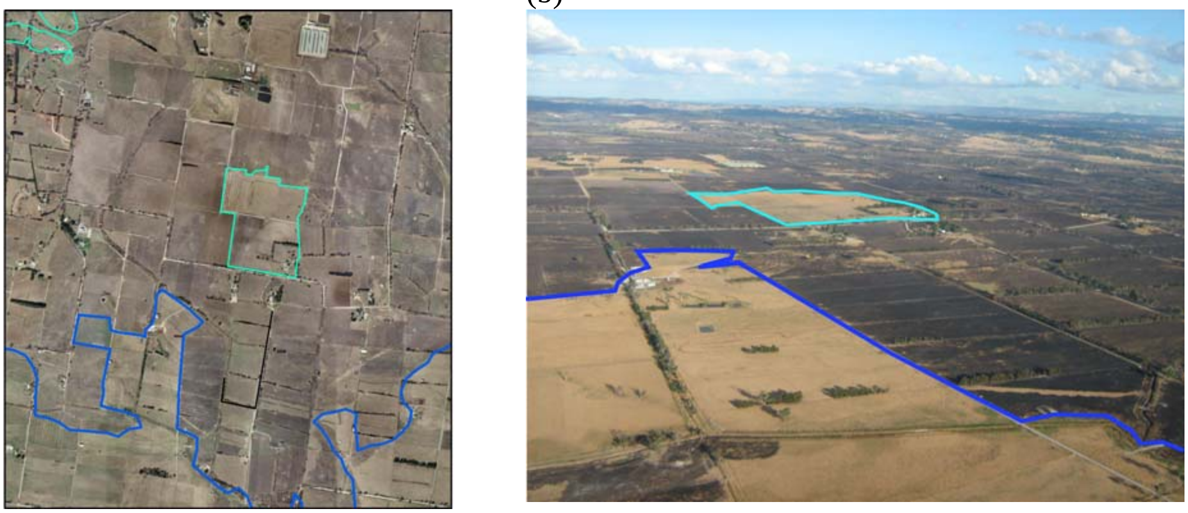

Fig. 4 Unburnt areas inside the burnt area within the Bunyip Ridge Track fire area: a) Post-fire digital aerial photograph showing a black area in the paddock enclosed by turquoise line that could be interpreted as being burned. (b) Photo from aircraft suggesting that the paddock enclosed by the turquoise line remained unburnt. (Photo credit: DSE, Noojee Office)

Drawing known isochrones

As a primary source of evidence, line scans were associated with the highest temporal and spatial accuracy of all the data sources used in the project. However, spatial accuracy was often not ideal. Due to the high speed upper level winds associated with the Black Saturday fires, the aircraft was often forced to capture the line scan image under highly turbulent flying conditions. If the plane was moving as the image was taken, the result is often a skewed and misaligned representation. In addition, the ortho-rectification technique used a digital terrain model (DTM) at a mapping scale of 1:250,000, which in complex terrain did not correctly align the edge or shape of the fire to the underlying terrain. Images were imported to Google Earth and the image was rectified manually using the simple image stretching tools provided. By and large, the fire line scans were accurate to within 50-100 m, depending on terrain and flying conditions.

Because of the nature of the Black Saturday events, there were very few line scans for each of the fires related to the lack of availability of equipped fixed-wing aircraft and the height and density of smoke plumes, in some cases reaching up to 12,000 m. The isochrones drawn from the scans provided a base reference from which to make future inferences. Line scan images were layered over post-fire digital aerial photographs in the GIS environment and used to draw isochrones and spot fires (Fig. 5). The line scans also helped inferences about mass spotting events, the width of the active combustion zone, and the shape of the overall fire and internal fire fingers and spot fires.

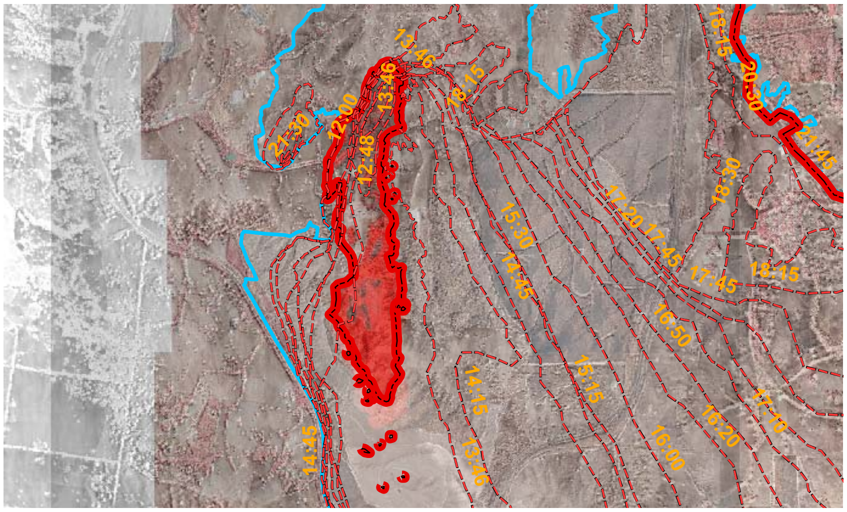

Fig. 5. Using fire line scans to delineate a fire isochrone from the Kilmore East Fire

As well as fire spread information, fire line scans can portray fire intensity and combustion zones, as evidenced in Fig. 6. The current imaging technology used in airborne fire line scans provides a relative difference between areas heated by the fire and the surrounding unburnt or cooled areas, rather than measuring absolute temperatures. Thus, zones of flaming, flaming and smoldering, and smoldering combustion cannot be distinguished using the current fire line scan technology. These measurements would provide more accurate estimates of fire line intensity and energy release, which are critical factors in fire convection column dynamics.

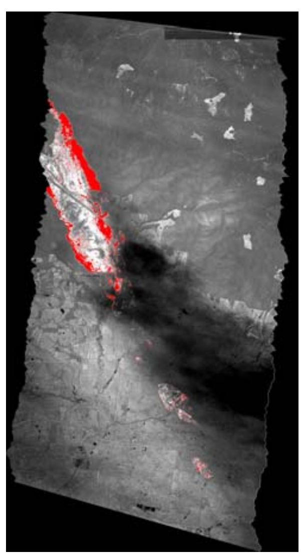

Fig. 6. Infrared line scan image showing convection column shadowing (1437 hrs 7th February, Bunyip Ridge Track fire).

Drawing inferred isochrones

Once all of the known isochrones and final perimeters were drawn on the GIS map, inferences were drawn about the fire spread in between the known fire spread locations, including spot fires. The process of drawing inferred isochrones was complex and heavily dependent on the availability of certain types of information. It involved tedious cross-referencing amongst data layers and constant updating of line information as new evidence was discovered.

It is difficult to describe the exact techniques used to infer isochrones on the map as it varied greatly across different sections of the fires. It usually began by using the post-fire digital aerial photography to build a general overview of intensity and fire movement in the area. This was then supplemented with any knowledge of local suppression crews working in the area who were then either interviewed or their statements and log books retrieved from the Bushfires Royal Commission submissions. This was often enough to sketch a rough line on the map or at least identify a general area burning at a specific time. The accuracy of this line was improved as additional interviews were conducted and the point evidence from those interviews, such as photographs, video and GPS tracks from fire equipment, was assessed. A level of confidence was always associated with each line to track the improvement process.

A three-dimensional terrain model, such as the simple representation used in Google Earth® software, was frequently used to locate points of evidence in the landscape. For example, if the location of the origin of a photograph was unknown, horizon profiles and other local landmarks could be used to estimate the position and orientation of the photographer (Fig. 7). Google Earth® was also useful for triangulating the locations of multiple sources of point evidence and the position of the fire within them by lining up fields of view across the landscape. Once a general position of the fire perimeter was determined, the accuracy of the isochrone was enhanced using interpretation of local fire severity from the post-fire digital aerial photography and satellite imagery, together with corresponding local observations.

In many cases, the time and date recorded with each photograph or video clip was incorrect. Many cameras were neither reset for daylight saving time nor had date and time settings set correctly, making it very difficult to determine the exact time the photograph or video clip was taken. The correct time was then corroborated with other information available at that location, such as information collected from other field interviews or from examination of written evidence and submissions prepared by VICPOL, CFA, and DSE for the VBRC. Cross-referencing each observation with those nearby became an important part of the validation of the fire isochrones to ensure that the fire reconstruction process had captured correctly the nature of the fire behaviour at those locations.

Fig. 7. The use of Google Earth to pinpoint fire activity on a photograph taken during the Beechworth- Library Road fire. Top: Photo taken at the corner of the Myrtleford-Mudgegonga Road and Carrols Road North looking at the fire moving up over and behind Clarry Murray's Hill (photo credit: R. Lay). Bottom: Google Earth view of the same location.

At some point on each fire, the fire reconstruction process ceased once a sufficient standard had been reached across the whole fire, based on the goal of the project to draw fire spread lines at intervals between half an hour to an hour to within an accuracy ±200 to 500 m and ±5 min. This was achieved across most of the fires and in some cases exceeded where a detailed sequence of photographic observations made it possible to map the fire spread every 5 to 10 min. This was particularly important when a series of spot fires developed ahead of the main fire front, followed by mass coalescence of spot fires soon afterwards. Here the detailed mapping was crucial to understanding how quickly the fire progressed into a three dimensional fire tied closely to the atmosphere. The process of drawing inferred isochrones thus varied across the length and breadth of the fire based on available data and the number of accurate field observations.

Conducting field surveys and interviews
Field interviews were conducted with local residents and suppression crew members to obtain detailed descriptions of fire behaviour in specific areas. The selection of interviewees had to be

done carefully for several reasons. First, a number of fire agency personnel, bushfire brigade members, and local residents had been previously interviewed by the police task force and research organisations' connected with the BCRC immediately following the fires. Second, some were still traumatised by the day's events and could not recall the events on the day objectively and accurately. In these instances, statements or submissions to the Victorian Bushfires Royal Commission were already available online, which reduced the time spent on field interviews and were invaluable for aligning chronologies of spread events with the information collected on field surveys. Sometimes it was necessary to follow-up with individuals in key locations or with good recollection of incidents. Additional field interviews were often needed to bridge data gaps and confirm assumptions.

Often, specific sections of the fires were targeted for interview at the same time, with multiple site visits completed in one or two days in the same area. The interview process varied in length across individuals, but generally lasted between one and two hours. Generally, multiple interviews were scheduled in a single area, often through word of mouth amongst residents and through CFA brigades and DSE teams. During the interview, individuals were encouraged to draw fire locations on paper maps as well as directly into the GIS on a laptop computer. It was important, especially with local residents, to focus the interview on strictly fire behaviour observations, rather than on the efficiency of suppression operations. Questions about the time of arrival of the fire front, flame height, observation of spot fire behaviour and intensity of surrounding fire generally provided good insight into the events at their location. Interviews provided additional information on fuel condition including paddock grass type and conditions, such as dominant grasses, state of curing, and recent grazing management, fuel loads in nearby bush and observations of wilting and senescence of understorey or eucalypt overstorey, and increased seasonal litter fall in forests due to drought and/or heat waves. Many individuals took photos from their properties, noted times of critical events and even collected local weather data. The interview process was time consuming, but the information provided by local residents often surpassed the quality provided by those attempting to suppress the fire. Some individuals had been heavily traumatised by the events of these fires, so it was important to remain sensitive to their stories and maintain an air of compassion at all times, regardless of the quality of information they were providing.

To link the field survey data with the fire isochrone map, a spatio-temporal reference was needed for each individual observation, incorporating spatial and temporal accuracy and reliability for each of the observations. First, following interviews, notes, arrows indicating direction of travel and delineation of unburned areas were sketched on the post-fire aerial photographs layer within the GIS environment (Fig. 8). Not all interviews required this level of detailed cartography, but it became very useful for recording complex fire movements at the local landscape scale. Often, a stand-alone GIS environment was taken along to interviews on a laptop, so that individuals could place their observations directly on the map.

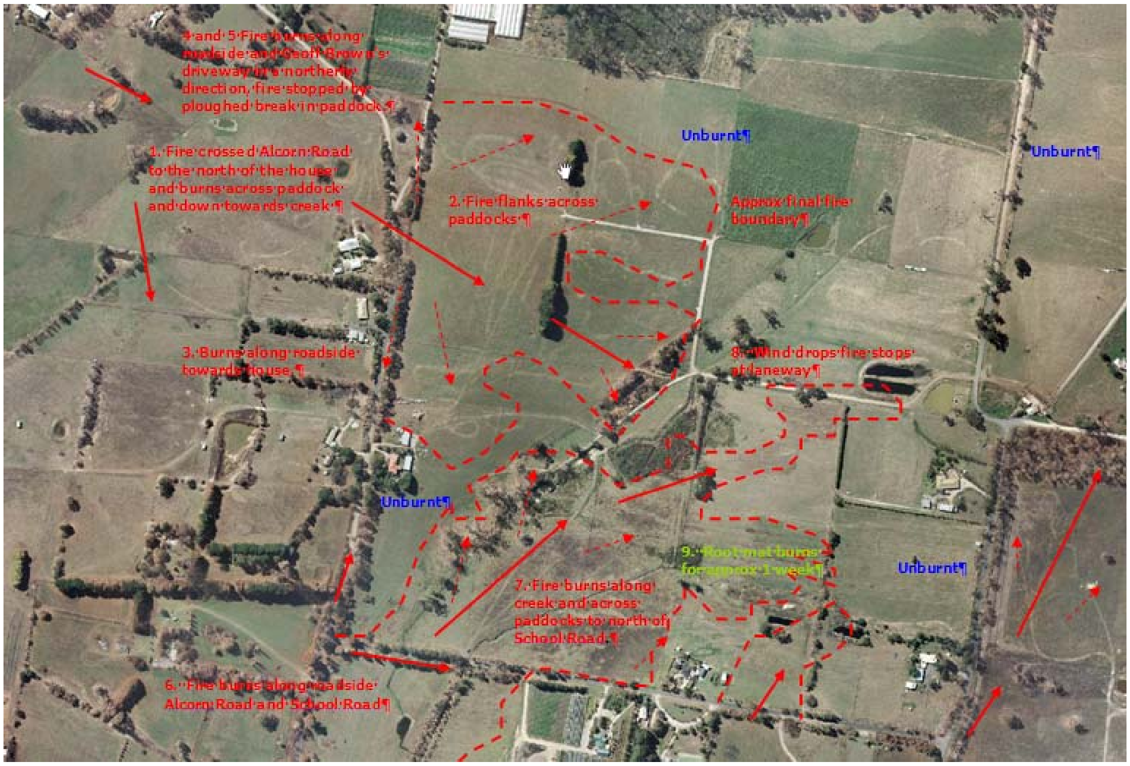

Fig. 8. Example of ArcMap image showing details summarised from interviews on the Bunyip-Ridge Track Fire.

A storage system was needed to organise components of these interviews as well as the final isochrone data layer. A detailed attribute table within the isochrone file was created in ArcMap® GIS (Fig. 9), with fields indicating time, information source, level of confidence and accuracy. These fields were filled in as lines were drawn on the map in an effort to track information used to make inferences. By identifying which piece of media was used to make each interpretation, simplified searches for certain photographs and videos were substantially decreased. It was also used to help determine and validate times and locations of the photographic and video evidence, as well as document the validity of individual pieces of information.

Attributes of Isochrones.Fmapint.Beechworth

FID	Shape *	Id	Date_	Time	Fmap_class	Source_inf	Conf_level	Date_Time	Spat_Accur	Temp_Accur	Notes
168	Polyline	0	8/02/2009	17:10	3	Line scan 07/02/2009 1710 hrs	Very High	20090208 1710			
169	Polyline	0	18/02/2009	02:30	4	Dave McDonald	High	20090208 0230	+-200m	+-30min	Interview with David McDonald
170	Polyline	0	8/02/2009	11:00	5	Doug Connors	Moderate-High	20090208 1100	+-200m	+-60min	Needs to be validated
171	Polyline	0	8/02/2009	18:25	4	Doug Connors	Moderate-High	20090208 1825	+-100m	+-30 min	Refer to Doug Connors photos
172	Polyline	0	9/02/2009	17:10	5	Local brigade observations	Moderate	20090209 1700	+-200m	+-60 min	Needs to be validated
173	Polyline	0	12:00:00 A		0		Undefined				
174	Polyline	0	8/02/2009	18:25	5	Inferred NGellie	Moderate	20090208 1825	+-100m	+-60min	Needs to be validated
175	Polyline	0	8/02/2009	16:45	5	Doug Connors	Moderate-High	20090208 1645	+-500m	+-30min	Needs to be validated
176	Polyline	0	8/02/2009	08:00	5	Doug Connors	Moderate-High	20090208 0800	+-200m	+-60min	Needs to be validated
177	Polyline	0	8/02/2009	02:30	6	Local Obs-Rosewhite Valley	Moderate	20090208 0230	+-20m	+30 min	Photos John Sweeney
178	Polyline	0	8/02/2009	01:30	7	Chirs McCracken photo	High	20090208 0130			
179	Polyline	0	8/02/2009	02:30	5	Inferred - previous fireline	Moderate-High	20090208 0230	+-500m	+-30min	C McCracken
180	Polyline	0	8/02/2009	13:30	5	Doug Connors	Moderate	20090208 0230	+-500m	+-60min	Needs to be validated
181	Polyline	0	8/02/2009	16:30	5	Andrew Cross	High	20090208 1630	+-500m	+-15min	
182	Polyline	0	8/02/2009	11:00	4	Chinese satellite	High	20090208 0230	+-50m	+30 min	Needs to be validated
183	Polyline	0	8/02/2009	00:05	7	Local obs and photographs	High	20090208 0005	+-500m	+-2 min	Based on Andrew Cross, Rod Ley, and Lindsey Easterbroo
184	Polyline	0	8/02/2009	00:30	4	Inferred-NG	Moderate	20090208 0030			
185	Polyline	0	8/02/2009	00:30	4	Inferred-NG	Moderate	20090208 0030			
186	Polyline	0	7/02/2009	20:45	6	Inferred-NG	Moderate-High	20090207 2045			
187	Polyline	0	8/02/2009	00:30	0	Photos-J Sweeney	High	20090208 0030	+-100m	+-10min	Also based on Andrew Cross obs
188	Polyline	0	8/02/2009	00:30	0	Photos-J Sweeney	High	20090208 0030	+-100m	+-10min	Also based on Andrew Cross obs
189	Polyline	0	7/02/2009	04:00	0	K McPherson	Undefined	20090208 0400	+-500m	+-30min	
190	Polyline	0	8/02/2009	12:30	5	Colin-local sawmiller	High	20090208 1230	+-500m	+-30min	Fire crossed first grid at 12:30 pm
191	Polyline	0	8/02/2009	01:30	5	Colin-sawmiller	High	20090208 0130	+-200m	+-30 min	Started by lightning at ~00:30
192	Polyline	0	8/02/2009	12:30	5	Andrew Cross Interv 30/06	High	20090208 1230	+-200m	+-10min	
193	Polyline	0	8/02/2009	14:30	5	Andrew Cross-interview	High	20090208 1430	+-500m	+-15min	

Record: 1 Show: All Selected Records (0 out of 197 Selected) Options

Fig. 9. Example of an attribute table for the isochrone layer of the Beechworth- Library Road Fire.

As part of this system, the level of confidence for fire isochrones and spot fires was incorporated into the attribute table. A simple subjective assessment of the level of accuracy and reliability was assigned to each, based on a six point scale, ranging from Low-Moderate, Moderate, Moderate, Moderate-High, High, and Very High. The confidence rating was based on the type of information used and the ease to which fire isochrones or spot fires could be drawn on a map. For instance, fire isochrones based on fire line scans were assigned a Very High rating, those derived from airborne photographs or IMT maps were given a High rating, and for fire isochrones inferred from a variety of indirect and direct evidence, such as post-fire digital photography, were assigned a Low-Moderate or Moderate, depending on the ease of interpretation. This served two purposes. Firstly, it made it easier to locate original interpretations and improve them as new information arrived. Secondly, it helped to identify areas on the map where additional information was needed to fill gaps in fire spread and improve descriptions.

Discussion

In terms of rates of spread, the fire isochrone approach is an extension of the rate of spread concept which has dominated fire science in the past five decades. Rate of spread is essentially determined by measuring the distance and time taken to spread between two successive fire isochrones. For much of the Black Saturday fires, the estimated rate of spread is a crude approximation of the spread process under wildfire conditions. For instance, the overall progression of the fire is assumed to be the rate of spread of the fire. In fact, the actual fire spread should be based on the spread rate of the individual spot fires burning within a fire's footprint, leaving out the unburnt areas in between the spot fires. These unburnt areas then burn out in a later time period. This detail is important if we are to move from simple empirical fire spread equations developed back in the 1960s by McArthur (McArthur 1966, 1967), which assumed a fire growing as a series of uniform ellipses.

Rate of spread is a key factor in estimating Byram's fireline intensity (Byram 1959), the simple estimation of rate of spread using fire isochrones may lead to significant errors in the equation:

$$BFI = HWR \qquad \text{Equation 1}$$

where I is fireline intensity (kW m^{-1}), H is the effective heat content of fuel (kg m^{-2}) adjusted for moisture losses, W is weight of fuel consumed per unit area in the active flaming zone (kg m^{-2}) and R is the rate of spread of the fire (m sec^{-1}).

In bomb calorimetry studies, H has been estimated to be between 18.5 and 22.5 MJ kg^{-1} for dead and live eucalypt leaves (Pompe and Vines, 1966) under free oxygen conditions. Assuming a rate of spread based on the overall advance of the fire is 2.0 m sec^{-1} (120 m min^{-1}), a value of H equal to 18.5 MJ kg^{-1} under low moisture conditions, and a value of W equal to 3.5 kg m^{-2}, the value of BFI is estimated as 129,500 kW m^{-1}. This value of BFI is classified as extreme fireline intensity. BFI here is assumed here to be a measure of the peak amount of energy produced by the flaming fire front, based on H.

However, the incomplete combustion evident in large mass fire behaviour can also affect the amounts of H and W. Byram (1959) considered that the effective heat yield, H_{eff}, was in effect convective energy (~65-85% of H) that took into account radiant (~14-30%) or conductive (negligible) energy losses. H_{eff} is a variable amount depending on the type of fuel being consumed and the burning conditions (Wooster *et al.*, 2005). The effective heat yield (H_{eff}) here is assumed to be 0.65 times H, based on energy balance studies of combustion of grassland savannah fuels (Freeborn *et al.*, 2008), yielding a value 13.1 MJ kg^{-1} for dead eucalypt leaves. Combustion efficiency is defined here as:

$$\chi = \frac{Heff}{H} \qquad \text{Equation 2}$$

The value of χ=65 percent is lower than that obtained under free oxygen laboratory conditions by Santoni and Morandini (2010), whose values lay between 81 and 88 percent for pine needles. However, Babrauskis (2006) obtained values of χ=70% in his studies of flaming combustion of small Douglas-fir small trees (*Pseudotsuga menziesii* (Mirb.) Franco). Similarly Madrigal *et al.* (2010) reported values of Heff being 44 to 81% that of H in Mediterranean fuels, suggesting an average 30% reduction in χ. Using a H_{eff} value of 13.1 MJ kg^{-1} and a value of 0.99 times W and a value of 1.7 m sec^{-1} for average rate of spread of individual spot fires, yields a value of 75,000 kW m^{-1}. This estimated value is 57 percent of the above BFI value of 129,500 kW m^{-1}, based on maximum values of H, W, and R. Thus, to take account of the varying χ under the variety of field combustion conditions under field fire conditions, Equation 1 could be replaced with:

$$BFI = \chi HWR \qquad \text{Equation 3}$$

The field value of BFI may be further reduced by incomplete combustion of fuels under severe wildfire conditions because of unburnt hydrocarbons in pyrolysates escaping above the flames, the lack of oxygen available during intense combustion, leading to partially consumed live and dead fuels, which in turns creates black smoke, indicative of increased soot and production of carbon monoxide (CO). This leads to an unknown quantity of pyrolysates from the combustion of W escaping unburnt. Thus, the extreme values of BFI being advanced in the literature for the Black Saturday bushfires require further validation using remote sensing tools, such as fire radiative energy (FRE) (Wooster *et al*., 2005), airborne fire linescans (Riggan and Tissell, 2010), or high resolution Doppler radar[3].

In addition to the fine dead- and live- fuels involved in flaming combustion at the fire front, there are other phases of fire combustion, such as flaming and smoldering, as well as glowing and smoldering, that continue after passage of a fire front (Gellie *et al.* 2010). These phases can be readily identified in infra-red line scans (Riggan and Tissell 2010), based on temperature zones. As well as residual bark and fine dead fuels, coarser woody debris and duff material contribute to the ongoing release of energy. A combustion zone is thus created behind the fire front, depending on the type, size, and configuration of fuel particles engaged in stationary combustion. At present, none of this residual fire combustion is accounted for in estimating fire intensity. The fire isochrone approach will thus have to be modified to take account of this (Fig. 10). Advances in airborne line scanning using infrared can now quantify fuel consumption rates, residence time, rates of spread, fire line intensity, and energy release (Riggan and Tissell 2010).

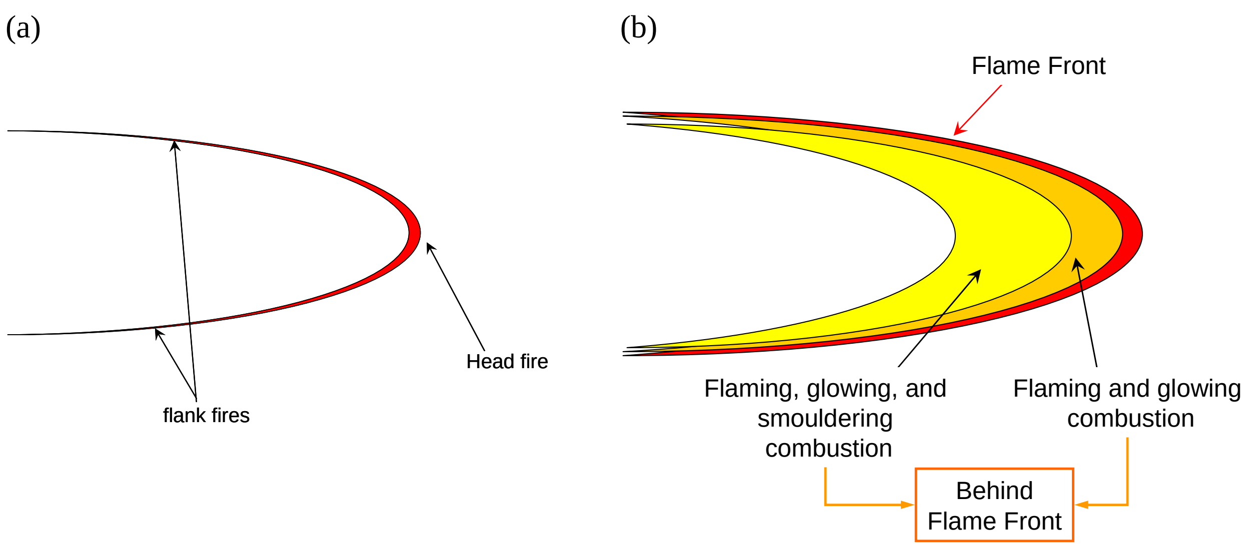

Fig. 10. Current (a) and future enhancements to fire isochrone shapes to take account of combustion zones around a fire perimeter

The concepts of rate of spread and fire line intensity have been extended to estimate the energy release of recent historical fires, including the recent Black Saturday fires, where fire isochrones have been mapped[4]. Energy release (W) around the total perimeter of a fire is based

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[3] Gellie and Bannister, 2010, unpublished data – Analysis of energy release of 2009 Black Saturday fires using high resolution Doppler radar.

[4] Harris S, Anderson W, Kilinc M, Fogarty LG (2010) The relationship between the power of fire and community loss and implications for developing a bushfire severity scale. *Research Report (in progress).* Victorian Department of Sustainability and Environment.

on equations derived from Catchpole *et al.* (1982), using rate of spread of the head, flank, and back fires, BFI at the head of the fire, and the shape of an ellipsoid or other geometrical shapes (Fig. 11). The four diagrams (a-d) capture most of the common energy release scenarios where a south eastern run of fire driven by a north westerly wind changes over to a north easterly run after a south westerly wind change. It becomes imperative that the three variables, rate of spread, BFI, and fire line perimeter(s) are estimated correctly for energy release to be accurately. The additional energy release from other fuels burning after the passage of a fire front would need to be added to the energy release from the flaming combustion around the perimeter, and hence to the heating and buoyancy of air in a fire's convection column.

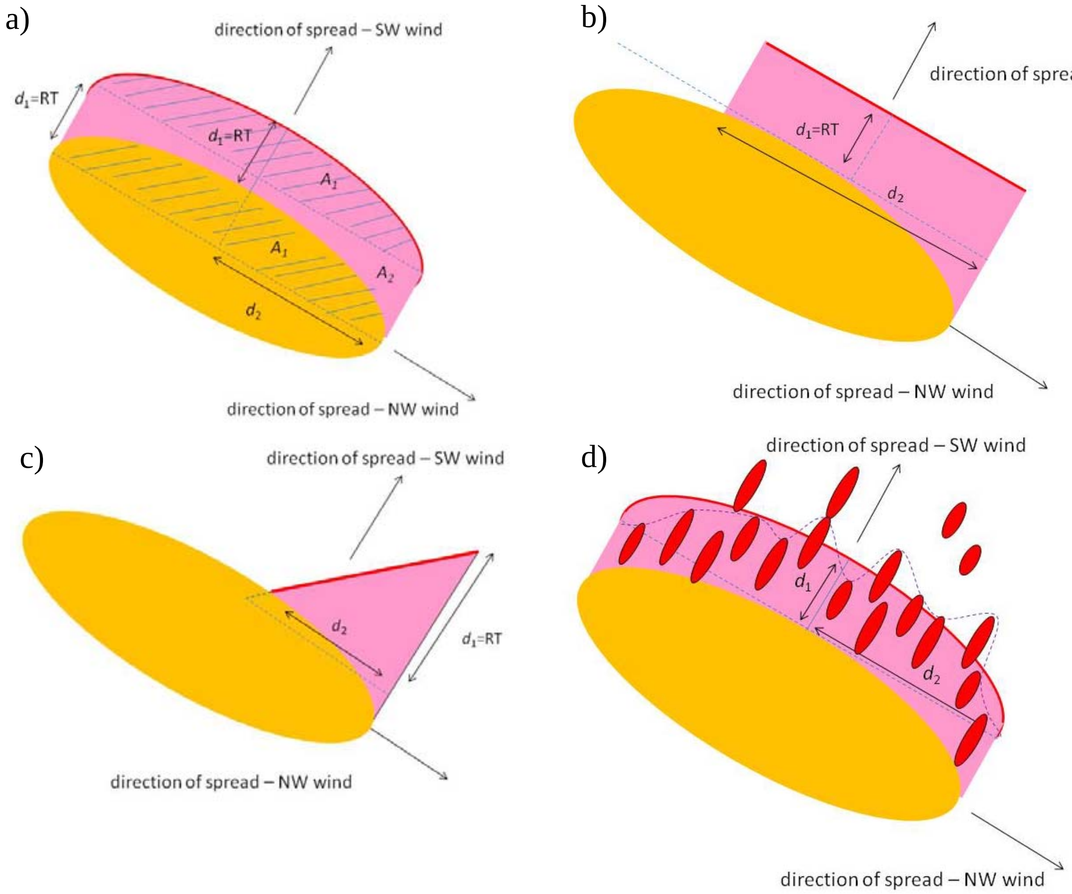

Fig. 11. Representations of calculations for energy release of large destructive fire events. a) Elliptical shape derived from Huygen's principle for estimating energy release based on a 90 degree wind change. b) Rectangular shape for estimating energy release for a partial blow out. c) Triangular shape for estimating energy release for a partial blow out. d). Multiple spot fires burning out within an immediate period after a 90 degree wind change.

Note: In the diagrams, d1 represents the length of the minor elliptical axis, d2 the length of the major elliptical axis, R the rate of spread and time T. For detailed equations and explanations see Harris *et al* . (2010, in prep.).

The estimation of rate of spread, combustion efficiency, and fireline intensity are important not only for accurately estimating energy release in these cases, but also for estimating convection column characteristics such as height, density, and power of the fire over the power of the wind (Byram 1959). These characteristics are important for assessing potential for medium to long distance spot fires, the effect of a fire column on ambient wind fields, and eruptive fire behaviour following changes in wind direction due to heat troughs or cold fronts. In any fire scenario, rate and duration of combustion are critical factors in determining a fire's rate of spread and intensity at any point around its perimeter. The very low fuel moisture contents, steep forested terrain, and strong turbulent winds on Black Saturday produced intense combustion rates associated with attached flow of flames and low angled smoke plumes. Combustion rates slowed as live fuels became engaged in combustion, producing darker red rather than orange flame color and darker, denser smoke columns related to incomplete combustion (Byram 1959). At these times convective energy would increase as the vertical plume energy overcame the horizontal wind kinetic energy either at relatively short time scales (several minutes) on the smaller fires to longer scales (hours) on the largest fires, such as Murrindindi and Kilmore East.

The process of fire spread in the forest fires on Black Saturday could be described as occurring in three phases: (1) spot fire building – rapid laying out of spot fires, aided by the strong turbulent furnace-like winds and landscape terrain; (2) coalescence of spotfires – strong dense vertical pyro-convection in smoke plumes dominating over the wind's horizontal kinetic energy; and (3) dissipation of pyro-convection – associated with further medium to long distance spot fires, with middle and upper winds coming down to the surface.

In the first phase, a series of short to medium distance spot fires spaced 500 to 2000 meters apart are laid out, establishing quickly under the influence of the ambient turbulent heated winds. If the terrain was configured as a series of ridges at right angles to wind direction, this exacerbated the spotting process producing more spot fires at longer distances, between two and three km downwind of the main fire front. This resulted in accelerating the fire seven to twelve kilometers ahead, even though most of the area in between remained unburnt.

In the second coalescence -intensification phase, individual spot fires developed into larger fires, sometimes merging with other spot fires nearby. Where spot fires landed at the base of ridges with moderate to high relief, fires actively crowned uphill (Gellie *et al.* 2010a) which contributed to quickly developing and strongly rising convection columns. When the fires were fully established, a mature convection column would form (Fig. 12a). While this was happening, forward and sideways spread of the fire slowed as the result of inward flow from entrainment or air ahead of the fire and along its flanks. On a post-fire digital image, zones of lower fire severity corresponded to the peak of this intensification phase. If sufficient energy was produced during this intensification phase, a pyrocumulus cloud formed. On the Kilmore-East and Murrindindi fires, pyro-cumulus lasted for several hours as the result of crown fires at the base of their convection columns. Longer distance spotting only occurred during this phase if the fire's convection was overridden by the wind.

In the third phase, energy release from these intense plumes was either interrupted or slowed, usually when the fuel within the burning area was mostly consumed and often coinciding with the fire reaching the top of a main ridge system or a plateau. During this time, longer distance spot fires were initiated between six and fifteen kilometres downwind, usually associated with ribbon bark embers from moister eucalypt forest types becoming detached from the column and being carried downwind in the strong dry windy air aloft. The transition to a wind-driven smoke plume occurred quickly (Fig. 12b), sometimes within five to ten minutes. As the upper air winds came down to the surface, the flank fires spread out sideways more quickly than in the second phase leading to spot fires on the flanks, (the spot fire accelerating near the front left hand corner of the fire in Fig. 12b). Energy release at this point increased along the flanks as there was no central convection column to restrain their lateral movement. The rise and fall of energy release within a smoke plume may last for as long as several hours while the fire weather is sufficiently severe and there are sufficient vertical discontinuities in terrain relief, energy release pulses from active crown fires, the main fire or fires coalesce with smaller spot fires on flatter terrain (Wade and Ward 1973), or the fires spread onto fuel types with lower and shorter energy release rates, such as grassland.

The process of fire spread would be repeated until either a wind change occurred, or the fire ran out from forest into grassland, or when the combined effects of higher fuel moisture contents and lower wind speeds associated with the passage of the cool change gradually reduced energy release. In the first case, mass spot fire ember fall-out along a north-easterly flank would create an eruptive energy release associated with the newly created series of head fires. In the second case, scattered spot fires would emerge downwind after the collapse of the fire's main convective centres leading to fingers of fire to run more or less independently. In the third case, the convection column would maintain its energy release until late in the evening even while fuel moisture content increased and the winds moderated.

(a)

(b)

Fig. 12. Energy release influencing convection column dynamics on the Churchill- Jeeralang Fire. (a) intensifying convection column at ~1445 hours and (b) temporary collapse at~1452 hours (seven minutes later). Photo credit: James Wilson

The preceding discussion of fire spread and energy release observed on the Black Saturday fires revealed a more complex suite of spread and spotting mechanisms than have hitherto been described in most fire reconstruction studies, with the exception of Chatto *et al.* (1999). Where there was sufficient information to support this more detailed fire reconstruction, we have attempted to characterise the patterns of fire behaviour at a more detailed level of spot fire behaviour, rather than drawing elliptically shaped broad fire isochrones. This was made possible by the advent of detailed post-fire digital photography, which accurately captures the fire severity footprint. From this footprint, spot fire development, fire coalescence, and eruptive fire behaviour along flanks can be interpreted with varying levels of confidence. While this level of interpretation might be considered conjecture, many times during the fire reconstruction, the interpretation of fire behaviour at this detail level was supported by independent evidence from photographs, video clips, and field-based observations.

Using an enhanced fire isochrone approach, the fire spread and behaviour of nine large destructive fires on Black Saturday have been characterised to varying degrees of accuracy and reliability in this study. Studying several rather one fire has several advantages. First, ideas about fire spread in one fire, could be translated to another, where there were significantly less detailed observations in the latter. Second, each of the fires traversed a different landscape with different landscape vegetation and disturbance mosaics, which provided insight into the effects of vegetation and fuel management on fire spread and behaviour[5]. Third, the additional fire behaviour information from nine fires can be used for generating different fire scenarios under Black Saturday conditions in planning for LDFs in Victoria and elsewhere in south eastern Australia.

From our studies, more sophisticated fire behaviour models can be developed and validated using the characterisations of fire behaviour and convection column dynamics analysed here. As the project progressed, it also identified deficiencies and data gaps in existing knowledge of local forest and grassland fuels, including definitions of forest fuel structure, estimates of fuel loads and understanding of fuel availability related to moisture stress in vegetation (Gellie *et al.* 2010b). Increased knowledge of forest fuels and their seasonal dynamics is critical for understanding fire behaviour dynamics under extreme fire conditions.

Conclusions

The fire reconstruction study approach outlined in this paper provides a new innovative approach for developing landscape scale studies of fire behaviour on LDFs in Australia and potentially, throughout the world. The fundamental concept of the fire isochrone, while satisfying the immediate purposes of fire construction outlined here, needs further refinement to reflect the varying combustion conditions on both unplanned and prescribed fires.

Our modified fire isochrone approach has revealed more complex patterns of fire behaviour than hitherto have been described. To further our understanding of the dynamic processes involved, research into fire combustion and energy release during a running fire would reveal more about the relationships between vegetation-fuel, fire behaviour, and convection column dynamics under extreme fire conditions. The insights provided by Byram (1959) in his studies of fire combustion and convection column dynamics could be advanced with the technology available today to probe in real time these fire processes. In addition, his concepts of fire combustion zones, fire line intensity, and power of the fire could be further refined and better quantified to predict convection column and spot fire behaviour.

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The Chakina Fire and the Spotting Problem: A Case Study in using Geospatial and Non-geospatial Fire Behavior Models to Assess Spotting Potential

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Abstract:
The Chakina fire, occurring in Alaska's Wrangell-St.Elias National Park and Preserve in the summer of 2009, presented a unique case study for the application of several fire behavior modeling applications in assessing spotting potential. The lightning-caused Chakina fire was managed for multiple objectives and was active from early July through early September, burning more than 50,000 acres. The primary management concern for the Chakina fire was the potential for it to spot across the Chitina River into areas designated as Full Protection within the Alaska Interagency Wildland Fire Management Plan. As such, three analysis questions needed to be addressed. First, what was the minimum wind speed and associated direction that could produce spotting across the 200 – 400 meter wide Chitina River? Second, what was the probability of that event? Third, what were the spotting probabilities associated with increasing wind speeds and changing wind directions? These questions were addressed using a variety of geospatial and non-geospatial fire behavior modeling programs (Behave Plus, WFDSS Short Term Fire Behavior, Near Term Fire Behavior and FSPro). As might be expected, the different models produced slightly differing results. In general, Behave Plus indicated that lower wind speeds were required to produce spotting across the Chitina River than was indicated by the geospatial fire behavior models. Additionally, FSPro, traditionally viewed as a long term fire behavior modeling application, demonstrated utility as a means to assess spotting potential in a short, 1-3 day timeframe.

Fire Regime Condition Class: Concepts, Methods, and Applications

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Abstract
Since the late 1990s, the Fire Regime Condition Class (FRCC) ecological assessment method has provided natural resource managers with field- and Geographic Information System based tools for interpreting the ecological status of lands in relation to natural conditions. For biophysical settings (BpS) within the U.S., FRCC assessments compare current fire regime and vegetation traits to those that existed historically. Percent departures from historical reference values determined by modeling are classified as follows. FRCC 1 represents ecosystems with low (0-33%) departure, indicating conditions that are still likely within the historical range of variability (HRV). FRCC 2 represents ecosystems that exhibit moderate (34-66%) departure, and FRCC 3 indicates ecosystems that exhibit high (>66%) departure from reference conditions. The purpose of this paper is to describe FRCC methodology, associated tools, and user support as provided by the National Interagency Fuels, Fire, and Vegetation Technology Transfer (NIFTT).

Additional keywords: characteristic condition, fire regime group, FRCC Landscape, FRCC Mapping Tool, FRCC Software Application, FRCC on-line certification, present natural range of variation (PNRV), succession class, stratum, uncharacteristic condition.

Introduction
During recent decades, interest in maintaining or restoring terrestrial ecosystems has grown among land managers in the U.S. For example, increasing fire sizes, severities, and suppression costs in many regions has spurred widespread interest in restoring fire adapted ecosystems. In the policy arena, several General Accountability Office reports between 1994 and 2002 (e.g., U.S. GAO 1999), the Cohesive Strategy (U.S. Forest Service 2000), the National Fire Plan (2001), and the Healthy Forest Restoration Act of 2003 (HFRA 2003) all called for restoring ecosystems impacted by long term fire exclusion and other land use activities. Such policy and statutory directives led to the first coarse-scale effort to evaluate the ecological status of fire regimes and associated vegetation (Hardy *et al.* 2001; Hann and Bunnell 2001; Schmidt *et al.* 2002). Because those initial data were too coarse to be useable for local management purposes, the National Interagency Fuels Coordination Group (currently known as the NWCG Fuels Management

Committee) established the FRCC Working Group in 2002 and charged it with developing an assessment method that would be applicable to any biophysical setting (BpS), and that would have mid- to fine scale applications (such as for watersheds and individual stands). An additional goal was to develop a basic assessment method that would be readily useable by managers, which would help them fulfill agency planning and reporting requirements. Accordingly, the first FRCC Guidebook was produced in 2003 (Hann *et al*. 2003).

Over the past seven years, the guidebook has been revised and updated several times by the National Interagency Fuels, Fire, and Vegetation Technology Transfer team (NIFTT). NIFTT ecologists, along with collaborators such as The Nature Conservancy and the LANDFIRE program, have conducted extensive testing and have incorporated user feedback to help validate and improve the FRCC assessment methodology. The topic of this paper is to describe fundamental concepts and methods contained in FRCC Guidebook Version 3.0 (Barrett *et al*. 2010). In addition, we will describe some of the typical applications of FRCC assessments conducted to date.

FRCC Concepts & Methods

FRCC is an ecological measure that rates the current status of major ecosystem traits relative to historical conditions. A key tenet is that pre-Euro-American conditions reflect the best approximation of ecosystem sustainability, because those so-called ónatural ó ecosystems evolved to dynamic equilibrium over thousands of years. That is, the historical range of variation (HRV)(Morgan *et al*. 1994; Landres *et al*. 1999; Swetnam *et al*. 1999) for a given BpS serves as an important baseline for evaluating ecosystems. Although the present natural range of variation (PNRV) also can be a useful concept (Swetnam *et al*. 1999), few data currently are available for reliably predicting ecosystem traits in response to climate change and other largely hypothetical factors (Millar and Wolfenden 1999; Running 2006; Westerling *et al*. 2006). Note, however, that reference condition models used for FRCC assessments (described below) can always be adjusted in the future if necessary.

Quantifying reference conditions.

In FRCC methodology, BpS reference condition models (Rollins *et al.* 2007) provide the basis for comparing historical to current conditions. Fire regime input data for both the reference and current periods consist of: 1) central tendency metrics for fire frequency (i.e., mean fire interval [Romme *et al.* 1980]) as determined by fire history studies, field surveys, or expert opinion, and 2) stand replacement severity (i.e., percent topkill in the dominant overstory) as estimated by modeling and expert opinion. Central tendency estimates, rather than value ranges, form the basis for reference condition modeling and FRCC assessments because precise empirical estimates of HRV are lacking for most BpS types in the U.S. In addition, a fire regimes classification consisting of five broadly defined fire regime groups serves as a general framework for modelers and FRCC users (Table 1).

The vegetation data used for FRCC assessments consists of composition metrics (mean percents) for discrete seral stages called succession classes (S-Classes). A simple conceptual framework consisting of five or fewer S-Classes was used during state-and-transition modeling with the Vegetation Dynamics Development Tool (Beukema *et al.* 2001). During model development, professional literature and expert opinion were used to document successional pathways and associated timeframes in the absence of disturbance and after recurrent disturbances such as by fire, insects, disease, and other factors. Many models to date have used a standard óS-box ó(S-Class) conceptual framework consisting of early-to-late successional stages with open versus closed overstory canopies (Fig. 1). However, the final schematic varies substantially among the many models developed to date.

Table 1. Fire regime group classification used for FRCC assessments (modified from Schmidt *et al*. 2002).

Group	Frequency (yr)	Severity	Severity description
I	0 ï 35	Low / mixed	Primarily low-severity fires replacing <25% of the overstory (but can include mixed-severity fires that replace up to 75%)
II	0 ï 35	Replacement	Primarily high-severity fires replacing >75% of the overstory
III	35 ï 200	Mixed / low	Generally mixed-severity (but can include low-severity fires)
IV	35 ï 200	Replacement	Primarily high-severity fires
V	200+	Replacement / any severity	Generally high-severity fires, but can include any severity type

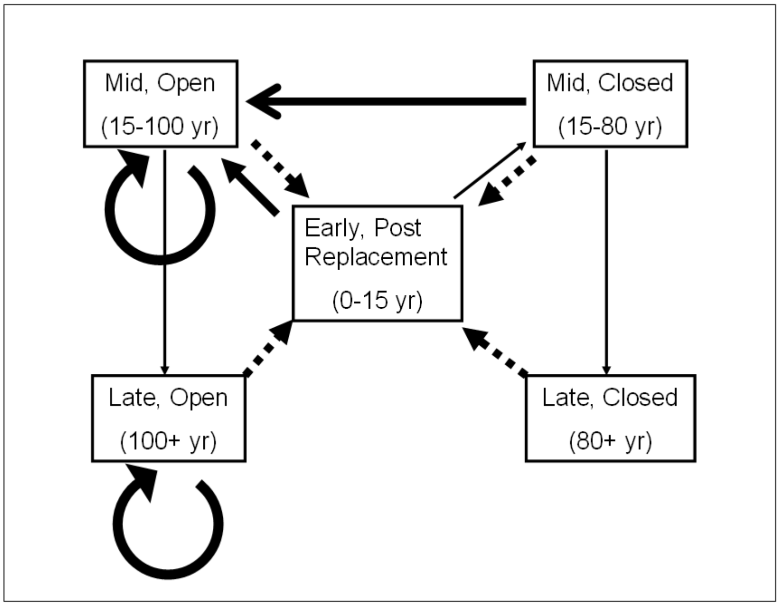


Fig. 1. Deterministic 5-box model illustrating successional pathways and approximate timeframes for a hypothetical forested BpS during the reference period. The model depicts successional pathways in the absence of disturbance (light solid lines) and post-fire successional pathways (heavy solid lines represent mixed severity fires; heavy dashed lines represent replacement fires).

After establishing the conceptual framework for a given BpS, modelers used VDDT to conduct multiple Monte Carlo simulations to determine: 1) mean percents for each S-Class, and 2) fire frequency probabilities according to severity type. As described below, these outputs provide the basis for comparison to current S-Class compositions and current fire frequencies and severities, which are determined from field surveys, local data on file, expert opinion, or from Geographic Information System (GIS) geospatial layers such as the LANDFIRE Succession Classes layer (available from www.landfire.gov).

Although FRCC users can develop their own reference condition models, most assessments to date have been based on previously built default models. Between 2003 and 2009, several sets of reference condition models for all biophysical settings in the U.S. were produced by NIFTT and by numerous ecologists working under the auspices of LANDFIRE (Rollins *et al.* 2007). Specifically, after an initial set of models had been created by ecologists known as the FRCC Working group, refinements occurred during the LANDFIRE Rapid Assessment, and LANDFIRE National and Refresh phases. Because those LANDFIRE efforts increased the number and quality of reference condition models for the U.S., users should keep that refinement process in mind when considering which models to use for assessments. Note that written descriptions for the above models can be downloaded from www.frcc.gov and www.landfire.gov.

Assessing departure & condition classes.

The first step during FRCC assessments is to stratify the analysis area according to major BpS types (also called "Biophysical Strata") (Fig. 2). Since FRCC is primarily a landscape-scale metric, assessment areas must be large enough to include the full range of variation in characteristic succession classes and fire regime traits for each BpS. For example, sub-basin assessment areas would be appropriate for areas historically dominated by large stand replacement fires (Regime Group V) because fire generated patches generally are extensive. Conversely, subwatershed-size assessment areas might be acceptable for areas dominated by frequent low severity fires (Fire Regime Group I).

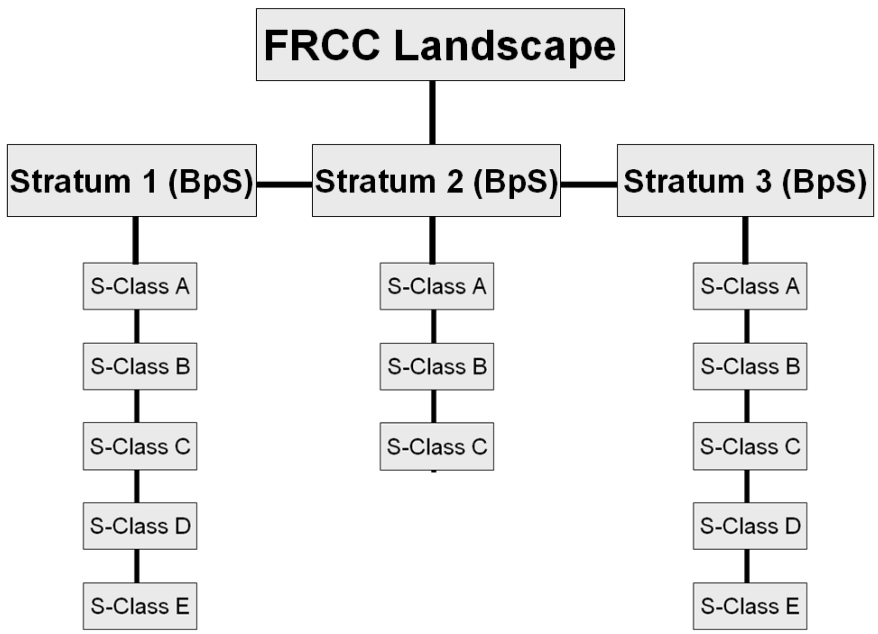


Fig. 2. Hierarchical relationship between FRCC assessment units. Note the varying number of characteristic S-Classes among the three BpS Strata

The FRCC assessment method determines ecological departure based on longstanding algorithms that compute mathematical similarity (Clements 1934; Mueller-Dombois and Ellenberg 1974). For example, departure for the vegetation component of a given BpS can be evaluated by comparing reference versus current percents for each S-Class (Table 2). Note that the S-Class data for the current period can also include any uncharacteristic classes that, by definition, did not exist historically (such as terrain currently dominated by exotic plants). Similarly, the algorithm for the fire regime component first evaluates fire frequency and severity as separate entities, then computes an overall departure for the regime by summing then averaging those two outcomes (Table 3).

Table 2. Departure algrorithm for vegetation component of a hypothetical BpS Stratum.

Succession Class	Reference Amt. (mean %)	Current Amount (mean %)	Similarity (smaller value)
A: Early	15	5	5
B: Mid, Closed	5	55	5
C: Mid, Open	10	5	5
D: Late, Open	60	10	10
E: Late, Closed	10	25	10
Totals:	**100**	**100**	**35**
Vegetation Departure (100 minus Sim. sum):	**65%**		

Table 3. Departure algorithm for fire regime component of a hypothetical BpS Stratum.

A. Regime Variable	B. Reference	C. Current	D. Departure Pct. (1 - [smaller / larger]) * 100
Frequency (*mean, yrs*)	20	100	80
Severity (*mean, %*)	30	80	63
Regime Departure (Sum of column D / 2):	**72%**		

After the vegetation and regime departures have been diagnosed for a given BpS Stratum, as shown above, the next step is to compute an overall departure for the Stratum by averaging the two values. Thus the stratum departure for the hypothetical example above would be 69 percent.

The final step for each Stratum is to classify the departure outcome according to one of three condition classes:

1) *FRCC 1*: Low (0-33%) departure from HRV central tendency;
2) *FRCC 2*: Moderate (34-66%) departure from HRV central tendency;
3) *FRCC 3*: High (67-100%) departure from HRV central tendency;

The three condition classes above were broadly defined, in part, to help mitigate the absence of actual HRV data. In addition, this quantitative classification represents a practical application of the qualitative FRCC definitions originally described by Schmidt *et al*. (2002) (Table 4).

Table 4. Qualitative condition class definitions (Schmidt *et al.* 2002).

Condition Class	Description	Potential Risks
1	Fire regimes are within an historical range, and the risk of losing key ecosystem components is low. Vegetation attributes (species composition and structure) are intact and functioning within an historical range.	Where appropriate, these areas can be maintained within the historical fire regime by treatments such as fire use.
2	Fire regimes have been moderately altered from their historical range. The risk of losing key ecosystem components is moderate. Fire frequencies have departed from historical frequencies by one or more return intervals (either increased or decreased). This results in moderate changes to one or more of the following: fire size, intensity and severity, and landscape patterns. Vegetation attributes have been moderately altered from their historical range.	Where appropriate, these areas may need moderate levels of restoration treatments, such as fire use and hand or mechanical treatments, to be restored to the historical fire regime.
3	Fire regimes have been significantly altered from their historical range. The risk of losing key ecosystem components is high. Fire frequencies have departed from historical frequencies by multiple return intervals. This results in dramatic changes to one or more of the following: fire size, intensity and severity, and landscape patterns. Vegetation attributes have been significantly altered from their historical range.	Where appropriate, these areas may need high levels of restoration treatments, such as hand or mechanical treatments, before fire can be used to restore the historical fire regime.

In addition to Strata-scale metrics, departure and condition classes can also be derived for the landscape and stand scales. The Landscape FRCC output is computed by aggregating the various Strata outputs according to an area-weighted average formula (Table 5). That is, each stratum departure is multiplied by the percent of the landscape, then the area-weighted departures are summed to yield a departure value for the entire Landscape. Finally, the Landscape departure value is classified according to one of the three FRCC condition classes.

Table 5. Landscape Departure/FRCC algorithm for hypothetical assessment area.

Stratum No.	A. Stratum Departure (%)	B. Stratum Percent of Landscape	C. Stratum Weighted Departure (A x B / 100)
1	72	25	18
2	55	70	39
3	31	5	2
	Landscape Departure (Sum of Column C):	**59%**	
	Landscape FRCC:	**2**	

Finally, stand FRCC is derived by evaluating only the vegetation component of each BpS. (The term "stand" here merely refers to an individual S-Class; also note that a method for computing fire regime departure at the S-Class level has not been devised to date.) The first step in the stand algorithm is to compute a percent difference value by analyzing the current amount of a given S-Class in relation to its reference amount, based on one of the following formulas:

*If (Current S-Class < Reference S-Class) then % Diff. = ([curr-ref]/ref)*100*

or

*If (Current S-Class ≥ Reference S-Class) then % Diff. = ([curr-ref]/curr)*100*

The percent difference outcome is then classified according to one of five relative amount classes ranging from *Trace* to *Abundant* (Fig. 3). And finally, the relative amount outcome is classified according to one of three Stand FRCC classes as follows: 1) Stand FRCC 1 applies when the relative amount class is *Trace*, *Underrepresented*, or *Similar*, 2) Stand FRCC 2 applies when the relative amount class is *Overrepresented*, and 3) Stand FRCC 3 applies when the relative amount class is *Abundant*.

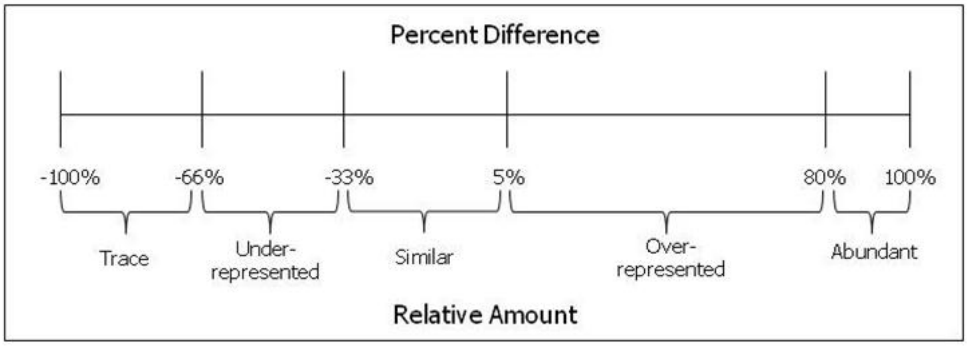


Fig. 3. Percent Difference/Relative Amount scale for determining Stand FRCC.

The stand relative amount and condition class metrics can be useful for project design, and for evaluating treatment effectiveness after an initial assessment has occurred. In addition, the Stand FRCC metric can help managers satisfy agency reporting requirements, such as those in the National Fire Plan Operations and Reporting System (NFPORS) or the Forest Service Activity Tracking System (FACTS). (For more details on how to use stand-scale metrics for reporting purposes, see FRCC Guidebook version 3.0 [Barrett *et al.* 2010]).

In summary, FRCC assessments can be used for documenting ecological trends at multiple scales. Note that FRCC is *not* a fire hazard metric. However, indirect inferences about fire risk can sometimes be made after examining fuels data in tandem with FRCC data (Hann *et al*. 2003; Zimmerman 2003; Williams 2004; Laing *et al*. 2005).

FRCC assessment types

FRCC Guidebook version 3.0 describes several techniques and tools for deriving FRCC. Users who prefer to conduct ground-based field surveys can use the Standard Landscape Method and associated data forms and manual calculations. Although the FRCC field method is less spatially specific, more time consuming, and inherently more subjective than the GIS-based method described below, field surveys make maximum use of local expert knowledge and ground truthing. Note that the FRCC field method can be facilitated by using the FRCC Software Application (available from www.frcc.gov). This user-friendly software automates data summarization and graphing, which is particularly useful for processing large amounts of data between various projects over time. A second way to conduct FRCC assessments is to use the GIS-based Standard Landscape Mapping Method, which is more spatially specific than the field survey method described above. To date, NIFTT has developed several versions of the FRCC Mapping Tool, which is an ArcMap extension available at www.frcc.gov. Although that approach requires basic familiarity with how to use GIS software, the tool allows users to assess FRCC for much larger geographic areas than is possible with ground-based surveys, and input and output data are derived through less subjective means. Unlike previous versions of the software, which could evaluate only the vegetation component of the FRCC algorithm, the recently released FRCC Mapping Tool version 3.0 can now process vegetation and fire regimes inputs in the same manner as the Standard Landscape Method described above. In addition, the tool can provide 13 output layers describing Landscape-to-Stand scale departure and condition classes.

FRCC applications.

FRCC data have been generated for various planning purposes to date, ranging from national to local scales. For example, successive phases of the LANDFIRE program have produced a number of downloadable geospatial layers depicting coarse scale FRCC vegetation departure and closely related themes across the U.S (Fig. 4). Such outputs presumably are less accurate than those produced by local assessments, in part, because coarse scale assessments summarize data across very large reporting units such as ecological subsections (ECOMAP 1993; Cleland *et al*. 1997; Rollins *et al*. 2007). As a result, coarse scale FRCC outputs are useful mainly for national to regional-level planning rather than for local project planning. Examples of national FRCC applications include summarization of broad trends, and for funding allocation within the Ecosystem Management Decision Support model.

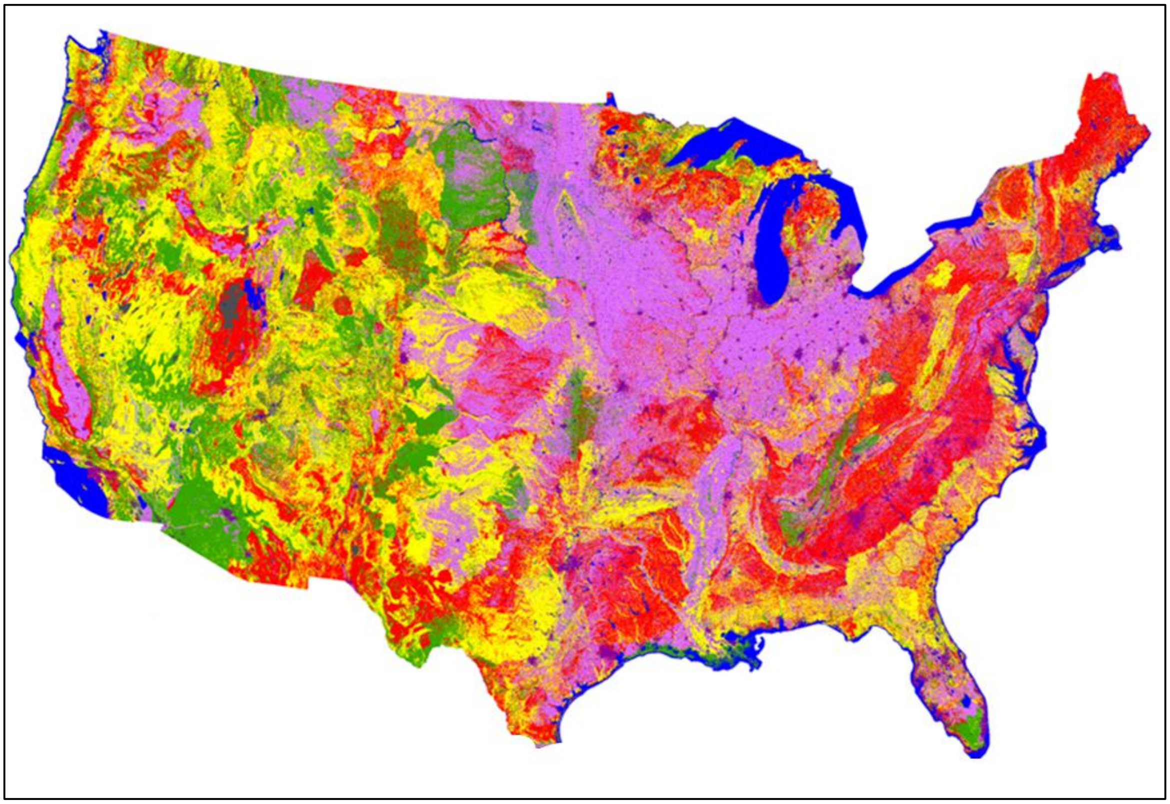


Fig. 4. LANDFIRE National FRCC geospatial layer depicting vegetation departure across the conterminous U.S. As of 2010, FRCC 1 (*green polygons* [low departure]) comprised 20 percent of FRCC classes, FRCC 2 (*yellow* [moderate departure]) comprised 46 percent, and FRCC 3 (*red* [high departure]) comprised 34 percent (non-FRCC polygons represent non-vegetated terrain or urban- and agricultural areas).

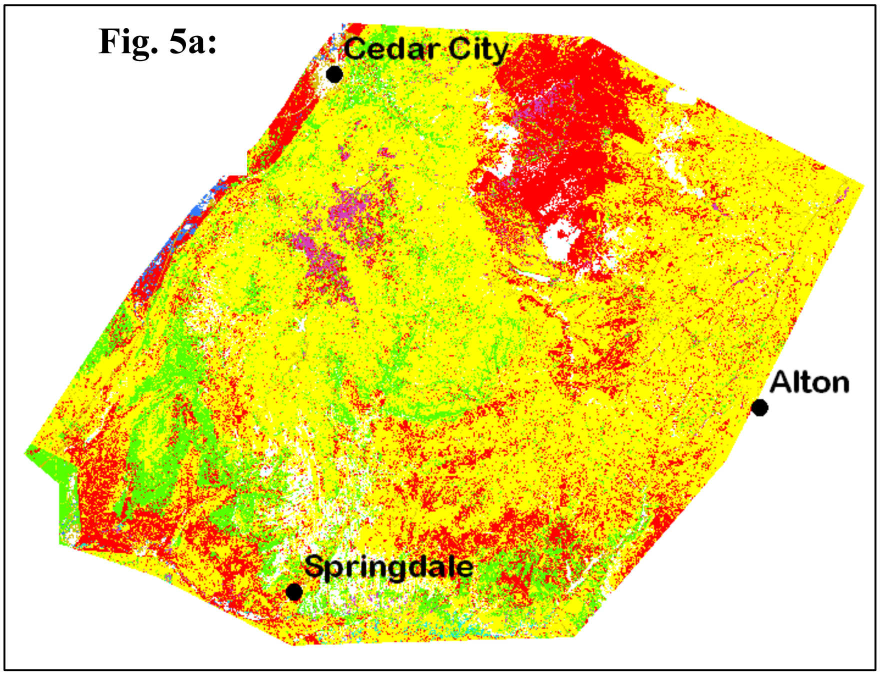
The FRCC Mapping Tool also has been used to conduct many mid scale assessments. (Note again, however, that assessments conducted before 2010 reflect only the vegetation component of the FRCC algorithm.) For example, ecologists in several U.S.D.A Forest Service Regions have conducted GIS assessments to document vegetative trends for individual national forests and ranger districts (for example, see *A Comparison of Fire Regime Condition Class (FRCC) Assessments in Multiple Scales in the Pacific Northwest* by T. DeMeo, in this Proceedings). Similarly, the Nature Conservancy has conducted local-to-regional scale FRCC assessments for multiple LANDFIRE Application Projects and other areas (e.g., Provencher *et al*. 2008; Provencher *et al*. 2009) to evaluate data accuracy and assist conservation planning. Finally, some federal agencies require a summarization of FRCC in Land Use Plans and Fire Management Plans.

As described earlier in this paper, FRCC assessments can also be conducted for relativelysmall scale units. Landscape, Stratum, and Stand level outputs for subwatershed-to-subbasin units can be used for project-level planning, and can help satisfy agency policy and reporting directives. For example, personnel with the USDI Bureau of Land Management in the Western U.S. use FRCC to identify BpS types and individual seral stages that might benefit from land treatments. USDA Forest Service Ranger District personnel, often with assistance from NIFTT and other ecologists, on the Salmon, Ozark-St. Francis (Shlisky *et al*. 2004), Gila, Pike (Hann and Strohm 2003), Hiawatha, and Flathead National Forests and have conducted FRCC assessments to help guide project-level planning and evaluate conditions at the stand and BpS scales.

Recently, planners on the Silver City Ranger District, Gila National Forest (NM) used the FRCC Mapping Tool to assess ecological conditions for the Signal Peak Landscape Assessment. Departure- and condition class data for individual BpS types and stands helped identify areas that could benefit from management treatments to improve ecological conditions while simultaneously reducing wildfire hazards. For instance, densely stocked ponderosa pine (*Pinus ponderosa*) stands rated as *Abundant* in the Relative Amount layer were targeted for thinning in order to alter successional trajectories toward characteristic open-grown conditions. Conversely, stands rated *Trace*, *Similar*, or *Under-represented* were targeted for prescribed burning to help maintain the standsô current status as FRCC 1.

Summary

FRCC is a scale-dependent metric that can be used for various analysis and planning purposes. To understand the scale-sensitive nature of FRCC, consider the following comparison of local versus national-scale FRCC outputs for an approximately million-acre assessment area in southwestern Utah (Fig. 5). Fig. 5a shows output generated by the LANDFIRE National mapping project when vegetation composition was summarized according to the areaôs surrounding ecological subsections and then óclipped ó to the assessment area. In contrast, Fig. 5b shows results when vegetation composition was summarized according to subwatershed-to-subbasin reporting units within the assessment area itself. Presumably, results from the latter type of analysis are more useful than the LANDFIRE National FRCC outputs for documenting local conditions and for project-level planning.



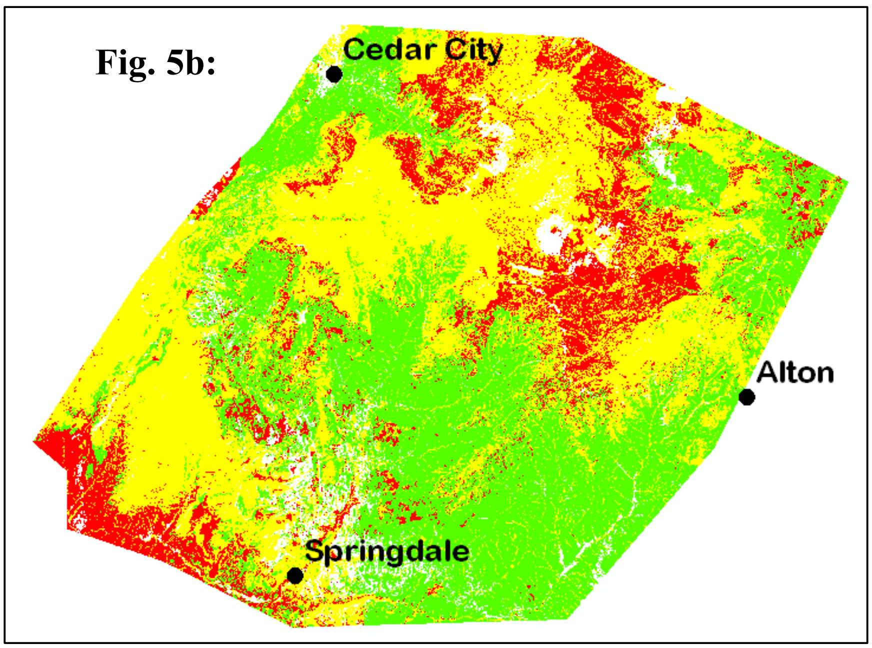


Fig. 5a-b. FRCC outputs for a million-acre area in southwestern Utah when LANDFIRE vegetation data were summarized according to different scales (*green polygons* = FRCC 1; *yellow* = FRCC 2; *red* = FRCC 3).

A final caveat for FRCC Mapping Tool users is that such assessments cannot be used to compare current versus historical landscape patterns in terms of patch sizes, shapes, and other traits. The departure algorithms analyze only S-Class percent composition and relative amountð not spatial arrays. This limitation is well illustrated by the so called ócheckerboard óland ownerships that occur in many areas of the Western U.S. For example, in the Swan Valley of northwestern Montana and along the Montana/Idaho border near Lolo Pass, widely varying logging practices among adjacent 640-acre (259 ha.) parcels have produced pronounced geometric patterns within landscape mosaics (Figs. 6-7). Yet the effects of such habitat fragmentation (Weins 1989; Lord and Norton 1990; Meffe and Carroll 1997) might not be apparent in FRCC outcomes (Fig. 7). Therefore, supplementary data from such sources as fire history maps, historical photographs, land survey records, or wildlife habitat assessments might be useful for developing a more accurate interpretation of current landscape conditions.

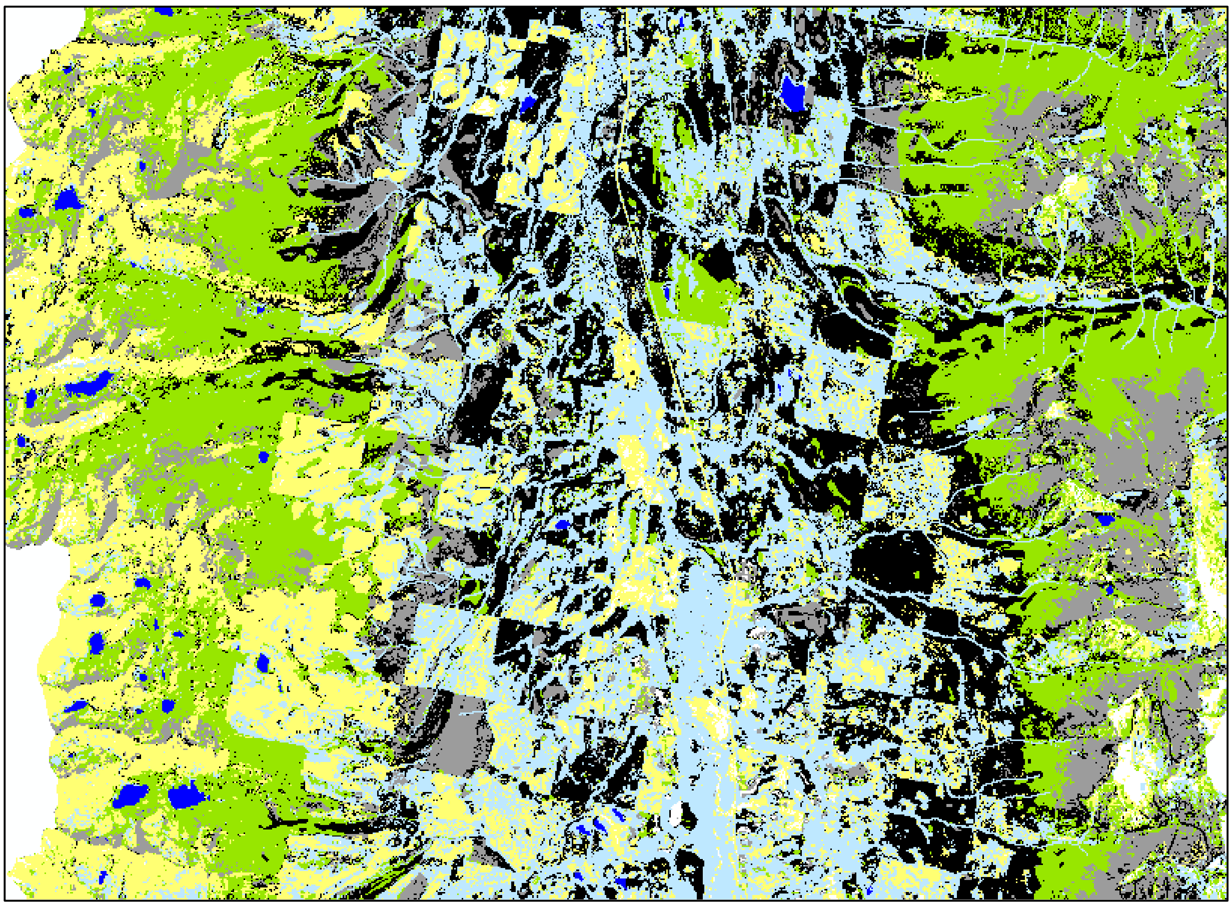


Fig. 6. GIS depiction of LANDFIRE succession classes (unlabeled) for an approximately 15,000 acre (6070 ha.) portion of the Swan Valley, northwestern Montana.

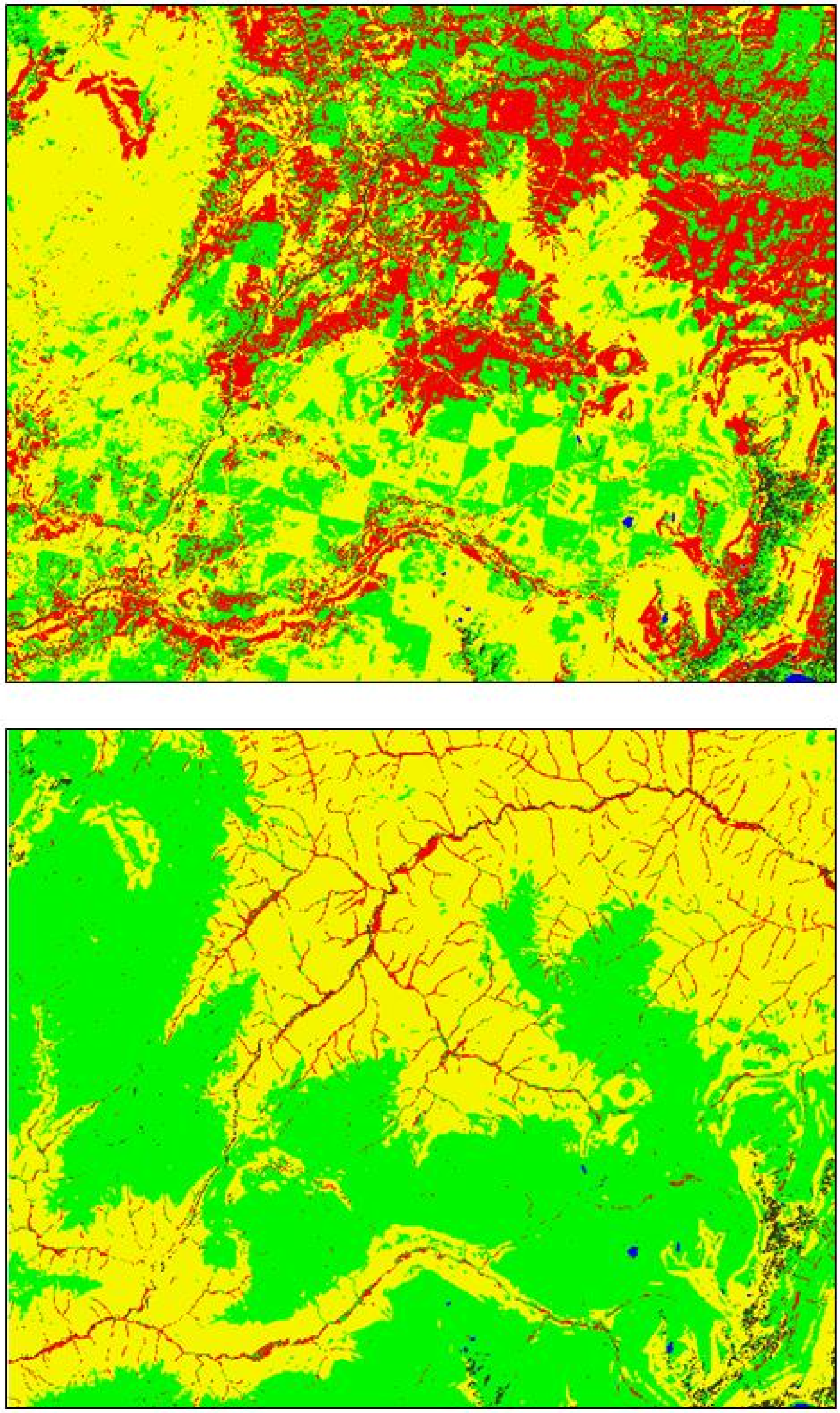


Fig. 7. GIS depiction of Stand FRCC outputs (top) versus Strata FRCC outputs (bottom) for an approximately 185,000 acre (74,870 ha.) area along the Montana/Idaho border southwest of Missoula, MT. Although pronounced geometric patterns are visible in the Stand FRCC layer,

some stands are rated as FRCC 1 because current S-Class amounts are similar to modeled reference amounts.

FRCC user resources

To date, NIFTT has developed numerous FRCC resources for user support and training. For example, the FRCC website (www.frcc.gov) serves as the official clearinghouse for a number of downloadable FRCC products and information. Users can download the latest FRCC Guidebook and associated data forms, software such as the FRCC Mapping Tool and FRCC Software Application, and various tool user guides and tutorials. The website also provides a Help Desk function, a Frequently Asked Questions page, and a Training page that links to available training opportunities. In cooperation with the University of Idaho, NIFTT offers an on-line FRCC certification course and on-line training for the FRCC Mapping Tool. In addition, NIFTT periodically presents hands-on workshops at conferences and other venues around the U.S. to help educate prospective FRCC users.

To learn more about the many varied aspects of FRCC, please visit the following websites: www.frcc.gov; www.niftt.gov; www.landfire.gov

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A comparison of fire regime condition class assessments at multiple scales in the Pacific Northwest

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Abstract
Fire Regime Condition Class (FRCC) is an interagency standard method of assessing ecological departure from the historic range of variation (HRV). The method has proven useful in identifying priorities for fuel treatments where the objective is restoring or maintaining fire as an ecological process in landscapes. Since 2003, application of the method in various landscapes across the U.S. indicates it is very sensitive to scale. To investigate this in the Pacific Northwest, we compared FRCC assessment results between watershed and ecological subsection scales. Watersheds were assessed locally and ranged from an average area of 21,000 ac to 783,000 ac; each area was matched with the appropriate fire regime. These assessments were compared with the LANDFIRE National FRCC layer, assessed at ecological subsection scale (average area 812,900 ac). Results showed the greatest differences between local and national assessments for the frequent, low-intensity fire regime. For the longest interval fire regime, both assessments showed a low amount of area within HRV (Condition Class 1), a result we question. We also found assessments of larger areas tend to show the most area in Condition Class 2. This was true of all National Forests in the Pacific Northwest. Further investigation of the preponderance of Condition Class 2 is warranted, and results should be considered preliminary.

Additional keywords: Fire Regime Condition Class (FRCC), ecological departure, landscape assessment, scale differences

Introduction

In recent years, large fires in the western U.S. have prompted concerns that ecosystems may be changing in ways making them less resilient. In some ecosystems, fire exclusion over the past century has led to unusually high fuel accumulations. Insects, disease, invasive plants, logging, severe grazing, and other ecosystem stressors have also played a role in this dysfunction.

Following the 2000 fires in Idaho and Montana, Congress and the administration wanted action on improving our management of fire as an ecological process, resulting in the Cohesive Strategy and the National Fire Plan (National Fire Plan, no date). To implement this strategy, a relatively simple, consistent metric was needed to assess, report on, and communicate a measure of departure from ecological sustainability.

To meet this need, Fire Regime Condition Class (FRCC) was developed (Hann 2004; Hann *et al*. 2004). FRCC is a measure of departure from the historic range of variation (HRV). This HRV is defined as a period prior to Euro-American settlement long enough to encompass a range of variation with relative overall stability. In the Pacific Northwest, for example, the 400 years prior to 1850 define this range.

In the FRCC method, fire regimes are defined using potential vegetation, since this is a useful index of land capability. Potential vegetation is considered to be disturbance constrained; i.e., the sere develops until a major disturbance resets it back to the earliest seral state. This disturbance-constrained view of potential vegetation is referred to as the Biophysical Setting (BpS). The BpS defines the mix of seral stages possible for an ecological type, as well as the ecological processes possible. For example, western hemlock vegetation is historically associated with infrequent but high severity fires, whereas ponderosa pine characterized frequent, low-intensity fires. The mix and abundance of seral stages varied between these two types as well.

Condition Class refers to the degree of departure from HRV within the fire regime. Simple similarity calculations are used to compare current with historic fire frequency, severity, and mix of seral stages. Departure can be reported either along a continuum of 0 to 100 or as Class 1 (within the historic range), Class 2 (moderately departed), or Class 3 (severely departed).

Early assessments of FRCC in 2000 have since been refined in stages, with the result that a national FRCC coverage is available for the entire conterminous United States. This coverage, however, was prepared for national reporting objectives and is less accurate or even inappropriate at local scales. Accordingly, local FRCC assessments have been developed. These can use the national BpS layer and seral stages provided by LANDFIRE, or local mapping efforts, provided they are crosswalked to the BpS and seral stage definitions in LANDFIRE.

As these local assessments have been implemented, it became apparent that FRCC assessments were very sensitive to scale; i.e., the size of the area assessed would change the results. For proper use of the method, it was therefore critical that assessments be done at the correct scale. Areas with historically frequent, low-intensity fires (Fire Regime I) required areas of a HUC 6 watershed (average 21,000 ac). This was also true for Fire Regime II (frequent, high severity fires, such as in grasslands). The mixed-severity fire regime III is best assessed at a HUC 5 watershed scale (average 112,000 ac), and longer-interval fire regimes IV and V require at least a HUC 4 watershed (average 783,000 ac). This approach of matching the fire regime to the appropriate HUC scale can be referred to as the ó4-5-6ô method.

Objectives

Our objective was to compare FRCC assessments done locally using the 4-5-6 method with those calculated nationally in the LANDFIRE project. That effort assessed FRCC at the ecological subsection scale. These are very broad land areas averaging 813,000 ac, and vary greatly (standard deviation 1,138,000 ac). Our goal was exploratory in nature; we sought to identify patterns in the comparison that could be further investigated to obtain specific management implications.

Methods

The FRCC Mapping Tool, an ArcMap extension developed by the LANDFIRE technology transfer team (Johnson and Tirmenstein 2007), was used to determine FRCC by the appropriate watershed (4-5-6 method) for all lands in Oregon and Washington. The same BpS layer as used in LANDFIRE National was used in the assessment. Acres in each of the FRCC 1, 2, and 3 condition classes were calculated. We then compared these with the LANDFIRE National FRCC layer, which was calculated by ecological subsection.

As part of the assessment, each National Forest within Oregon and Washington was also assessed with the 4-5-6 method.

Results

FRCC 1 of Fire Regime 1 (historically frequent low-intensity fires) showed the greatest difference between the locally-assessed and national efforts (Fig. 1), with much more indicated in the national assessment. Results in this fire regime were similar for FRCC 2 and 3. A similar pattern occurred in Fire Regime 2 (frequent high-intensity fires) (Fig. 2); as well as for Fire Regime 3 (mixed severity fires) (Fig. 3).

In Fire Regime IV (long-interval, higher severity fires) the pattern changed. Local and national assessments agreed closely on the amount of area within the historic range (Fig. 4). In Fire Regime V (very infrequent, high severity fires), the amount in the most highly departed category was the greatest (Fig 5).

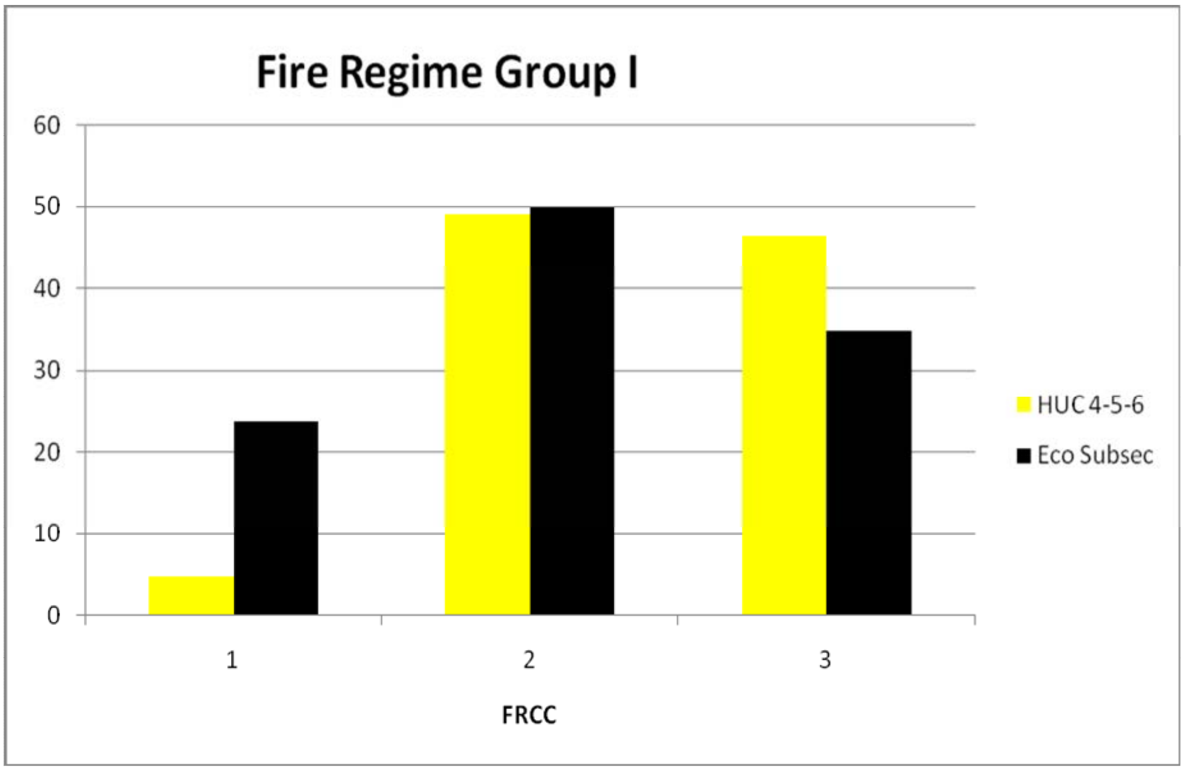

Fig. 1. Comparison of fire regime condition class between local (HUC 4-5-6) and LANDFIRE National (Eco Subsec) coverages, expressed as a percentage of all landscapes, for fire regime group I (frequent low intensity fires). Fire regime condition class (1= within historic range, 2=moderately departed from historic range, 3=severely departed) is displayed on the X-axis, and percentage of all landscapes assessed is on the Y-axis.

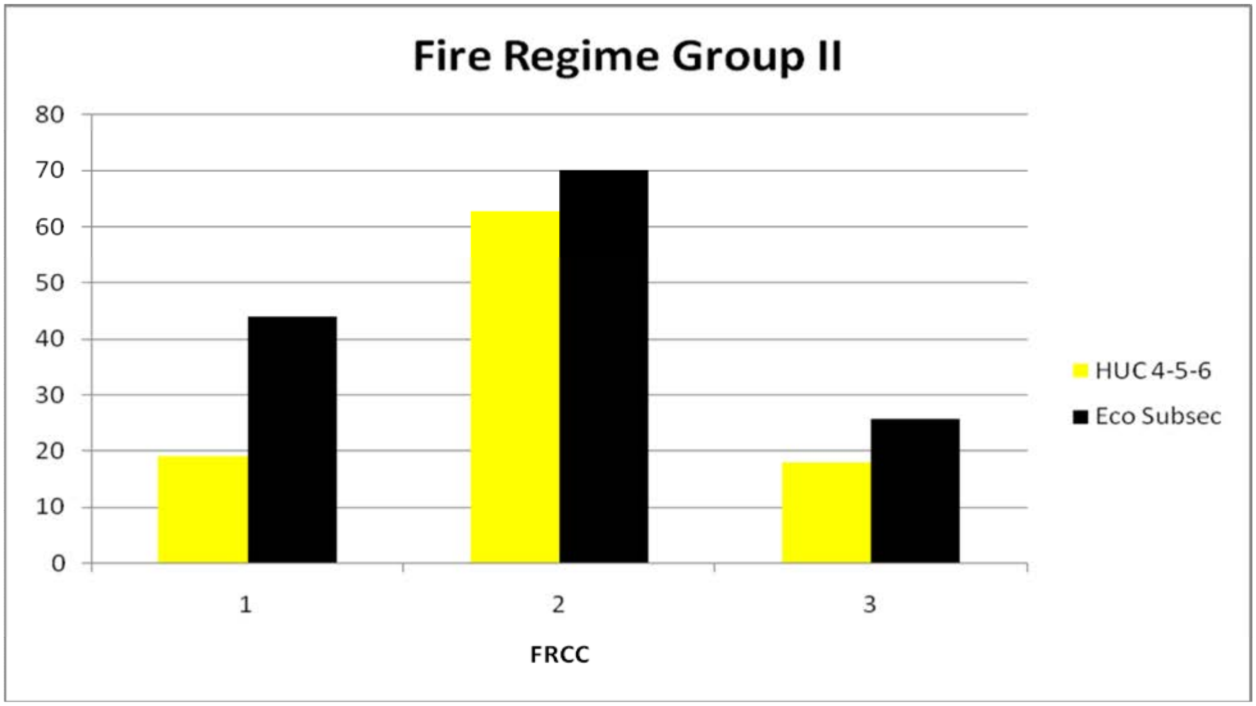

Fig. 2. Comparison of fire regime condition class between local (HUC 4-5-6) and LANDFIRE National (Eco Subsec) coverages, expressed as a percentage of all landscapes, for fire regime group II (frequent high intensity fires, typically grasslands). Fire regime condition class (1= within historic range, 2=moderately departed from historic range, 3=severely departed) is displayed on the X-axis, and percentage of all landscapes assessed is on the Y-axis**.**

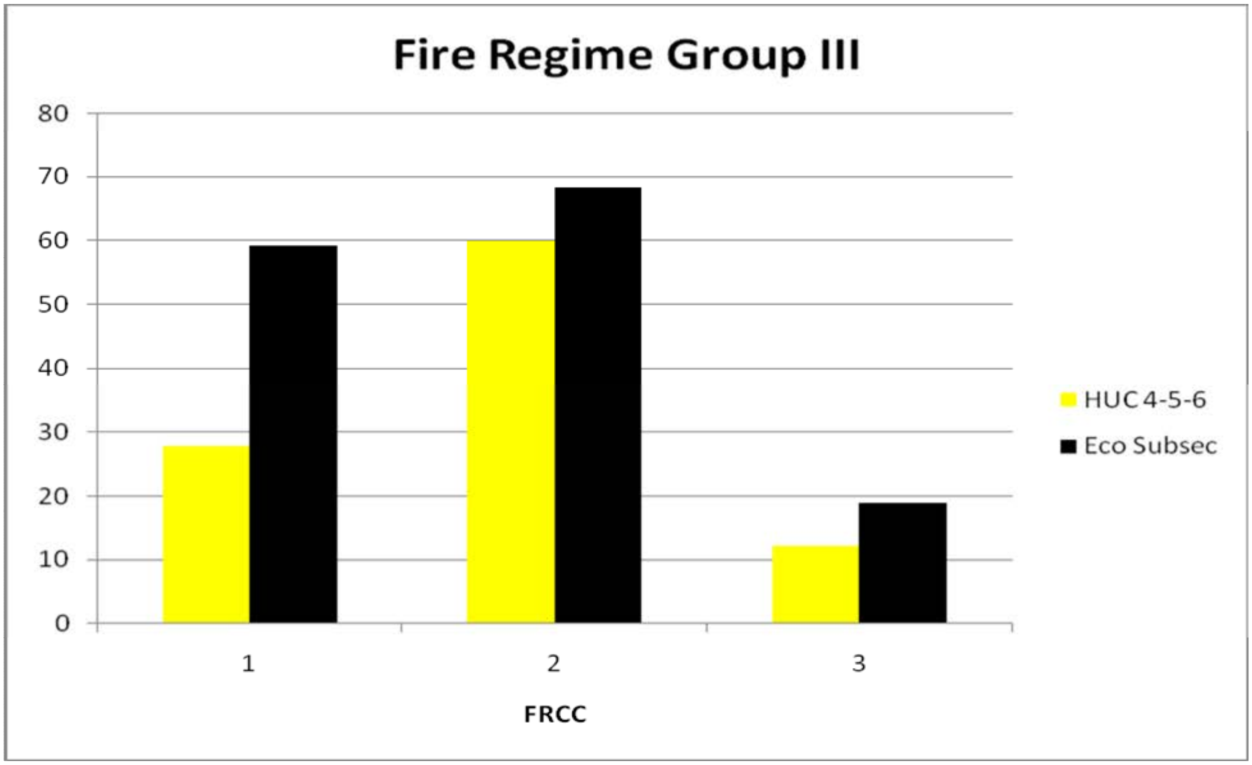

Fig. 3. Comparison of fire regime condition class between local (HUC 4-5-6) and LANDFIRE National (Eco Subsec) coverages, expressed as a percentage of all landscapes, for fire regime group III (mixed severity fires). Fire regime condition class (1= within historic range, 2=moderately departed from historic range, 3=severely departed) is displayed on the X-axis, and percentage of all landscapes assessed is on the Y-axis.

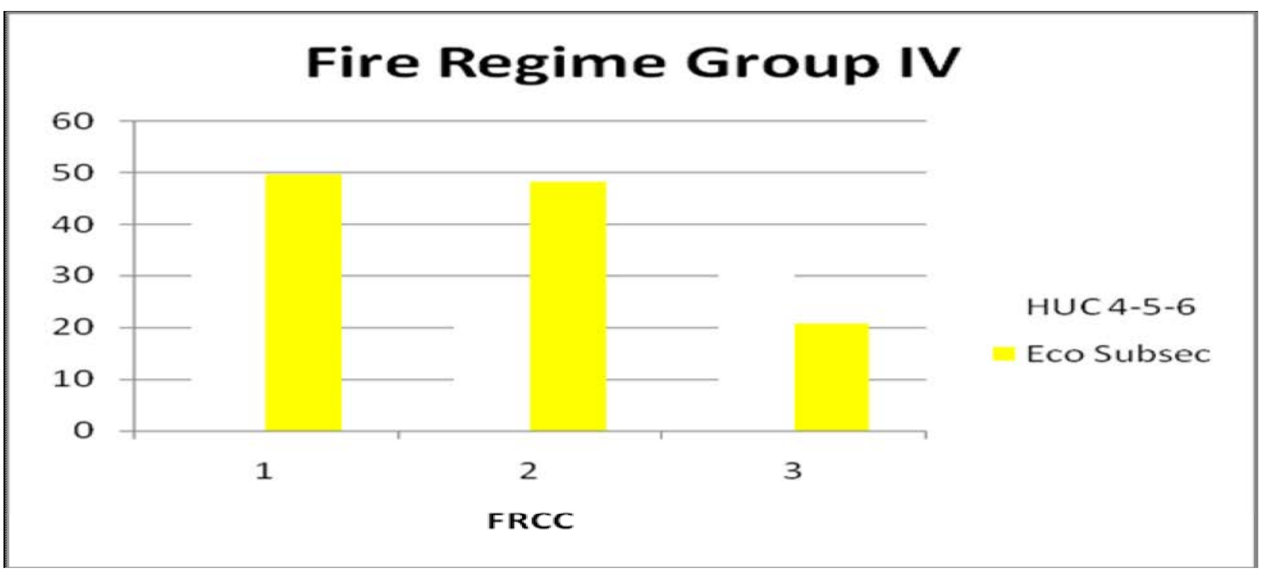

Fig. 4. Comparison of fire regime condition class between local (HUC 4-5-6) and LANDFIRE National (Eco Subsec) coverages, expressed as a percentage of all landscapes, for fire regime

group IV (infrequent high intensity fires). Fire regime condition class (1= within historic range, 2=moderately departed from historic range, 3=severely departed) is displayed on the X-axis, and percentage of all landscapes assessed is on the Y-axis.

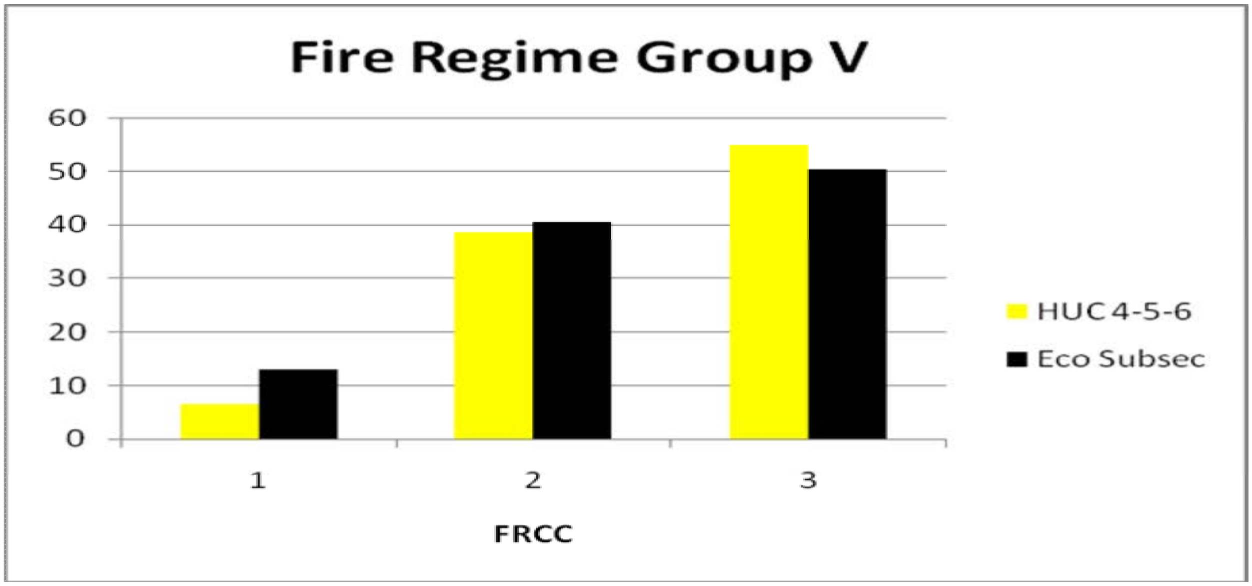

Fig. 5. Comparison of fire regime condition class between local (HUC 4-5-6) and LANDFIRE National (Eco Subsec) coverages, expressed as a percentage of all landscapes, for fire regime group I (very infrequent high intensity fires). Fire regime condition class (1= within historic range, 2=moderately departed from historic range, 3=severely departed) is displayed on the X-axis, and percentage of all landscapes assessed is on the Y-axis.

Results for the National Forests in the Region are presented in the Table 1, both by landscapes (watersheds) and by Biophysical Setting (Strata). Note that with the exception of the Columbia River Gorge (the smallest entity in the table), all the National Forests show FRCC 2 as the most abundant of the 3 condition classes

Table 1. Comparison of FRCC areas among National Forests in Oregon and Washington. Results are presented for both landscapes and by Biophysical Setting (=Strata).

National Forest or Recreation Area	GIS Acres (millions)	Acres (millions)-Landscape FRCC			Acres (millions)-Strata FRCC				
		FRCC 1	FRCC 2	FRCC 3	FRCC 0	FRCC 1	FRCC 0+1	FRCC 2	FRCC 3
Colville	1.36	0	1.36	0	0	0.026	0.026	1.24	0.096
Columbia River Gorge NSA	0.29	0	0.10	0.11	0	0.07	0.07	0.088	0.116
Deschutes	1.76	0.01	1.42	0.32	0.01	0.16	0.16	0.97	0.62
Fremont-	2.71	0	1.45	1.26	0	0.26	0.26	0.87	1.58

Winema									
Gifford Pinchot	1.46	0	1.22	0.24	0.0	0.08	0.08	0.83	0.53
Malheur	1.45	0.03	0.88	0.57	0	0.09	0.09	0.46	0.90
Mt. Baker-Snoqualmie	1.64	0.19	1.44	0.002	0.06	0.271	0.32	1.13	0.18
Mt. Hood	1.04	0	0.60	0.44	0.001	0.006	0.09	0.62	0.41
Ochoco	0.96	0	0.79	0.17	0	0.136	0.14	0.52	0.30
Okanogan-Wenatchee	4.10	0.23	3.65	0.23	0.205	0.705	0.91	1.87	1.32
Olympic	0.62	0	0.6	0.008	0.02	0.034	0.04	0.44	0.15
Rogue River-Siskiyou	1.85	0.03	1.78	0.32	0	0.29	0.29	1.31	0.25
Siuslaw	1.02	0.115	0.87	0.41	0	0.24	0.24	0.66	0.13
Umatilla	1.39	0	1.11	0.275	0	0.21	0.21	0.44	0.74
Umpqua	1.02	0	0.89	0.13	0	0.054	0.05	0.76	0.21
Wallowa-Whitman	2.41	0.13	1.78	0.50	0	0.437	0.44	0.93	1.04
Willamette	1.73	0	1.37	0.35	0	0.219	0.22	0.74	0.76

Discussion

It is not surprising that differences in FRCC 1 between local and national assessments would be most pronounced in Fire Regime 1, since this regime is normally assessed at the smallest area of any of the fire regimes. We did find surprising the low area shown in Condition Class 1 for the longest-interval Fire Regime (V; see Fig. 5), as this would be expected to have the greatest area within the historic range. This might be explained in part by the logging history in these landscapes in Oregon and Washington (Kertis, pers. comm.). In the FRCC method, clearcut logging is considered an uncharacteristic disturbance, and would tend to generate FRCC 2 (highly departed) outcomes. This outcome might also have been influenced by the reference conditions used; i.e., the values for the seral stage abundances and fire frequency/severity used to represent the historic range.

Perhaps most interesting of all the findings was the consistent pattern in landscapes showing FRCC 2 as the most abundant class (Table 1). For all National Forests in Oregon and Washington (with the exception of the Columbia River Gorge, strictly speaking not a National Forest), FRCC 2 was the most abundant. This is notable in that these Forests represent a wide range of ecosystems from dry to wet, and the full range of fire regimes.

These findings encourage further investigation. Explaining these scale differences will help us to better understand our landscapes and should lead to more accurate management implications. Revisiting reference conditions for BpSes with longer interval fire regimes is probably also warranted.

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Retrospective Fire Modeling to Quantify the Hidden Consequences of Fire Suppression

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Abstract:
Management actions to suppress lightning-ignited wildfires interfere with one of the most important natural processes of fire-dependent ecosystems. Even so, impacts of suppression are seldom evaluated and land managers do not have a consistent way to measure or monitor the effects of their suppression decisions. We developed a retrospective modeling approach using the fire growth simulation tool FARSITE to systematically evaluate the hidden consequences of suppression decisions. Environmental conditions that occurred at the time of the ignition were used in FARSITE to simulate where a fire would have spread and what effects would have resulted had it been allowed to burn. In an evaluation of cumulative suppression impacts for Yosemite and Sequoia-Kings Canyon National Parks, we used retrospective fire modeling in conjunction with Fire Return Interval Departure (FRID). FRID is a metric used by both parks to help measure progress toward restoration goals. We simulated the spread and effects of lightning ignitions that were suppressed between 1994 and 2004, used the results to estimate new FRID values, and used various fire behavior and effects metrics to evaluate other suppression impacts. Results reveal that the suppression decisions during these 11 years dramatically affected landscape conditions, and have missed opportunities to accrue managerial benefits. In another application of retrospective modeling, we are quantifying the monetary and non-monetary consequences of suppression decisions made in 2007 and 2008 and using this analysis as a learning tool for managers.

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Assessing Fire Severity among Interacting Fires in Three Western U.S. Wilderness Areas

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Abstract:
Wildfires are an important process in many ecosystems; they alter vegetation composition and density, maintain landscape heterogeneity, and consume fuel. In most areas of the U.S., however, fires are suppressed for political, economic, and/or social reasons. Recent research suggests that if fires are allowed to naturally burn, landscapes can become self-limiting or "fire resistant" over time. A few wilderness areas, because they are not actively managed and have, in recent decades, allowed natural fires to run their course, are ideal for studying the influence that prior fires can have on subsequent fires. We studied fire severity within three large wilderness areas in the western U.S. We analyzed a large number of recent (1984 – 2007) fires, examining the portion of each fire that overlapped a previous fire (i.e., it reburned) and the portion that did not overlap a previous fire. For each fire, we compared the fire severity of the reburned area to that of the area that did not reburn. Results show that in reburned areas, fire severity was generally less than areas that did not experience a reburn. While these results are not surprising, they add to the growing body of information regarding interactions among fires. Specifically, these results indicate that where a fire occurs, a subsequent fire will likely burn at a lower severity than if the initial fire had not occurred. This information provides land managers a longer timeframe at which to view the benefits and costs of an individual fire by providing quantitative information on the future reduction in fire severity. Land managers will find these results useful in assessing trade-offs in the decision of whether or not to suppress a wildfire. Future research will focus on the length of time that prior wildfires affect the severity of subsequent fires and how prior fires limit the spread/extent of subsequent fires.

Modeling Fire Behavior, Smoke Emission and Forest Succession of Insect-killed White Spruce Stands on the Kenai Peninsula, Alaska

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Abstract:
During the 1990's a significant portion of the white spruce stands on the Kenai Peninsula, Alaska, were killed by infestation from the spruce bark beetle (*Dendroctonus rufipennis*). This analysis evaluates the effectiveness of several measures to mitigate the impacts of the die-back of white spruce (*Picea glauca* [Moench] Voss). The Fire Effects Tradeoff Model (FETM) was applied to model landscape succession, wildfire behavior, and smoke emissions for several management scenarios aimed at reducing the risk of large-scale wildfires, and decreasing the anticipated increase in grasslands on the landscape. The initial vegetation distribution, totaling about 1 million acres, was classified by species, successional stage, stand density, and fuel bed characteristics. Simulations included the effects of succession, wildfire, ungulate browsing, spruce bark beetle mortality, and several fuel treatment options, including salvage logging, replanting, and prescribed fire. In simulation, grass- and hardwood dominated vegetation increased in abundance over time. Mixed hardwood-white spruce and white spruce dominated stands increased greatly if replanted following salvage logging. However, application of fuel treatments had little impact on wildfire behavior in the study area. The results suggests that while fuel treatments do help in protecting local communities, the proposed treatment levels were insufficient to greatly affect fire behavior in more remote areas.

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People and Property in High Fire-Frequency WUI Areas

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Abstract:
In 2006, municipal fire departments responded to approximately 134,587 wildfires while federal fire departments responded to another 25,867 fires, totaling 160,454 wildfires nationally. Identifying wildland-urban interface areas (WUI) that have high fire risk is necessary to mitigate against the wildfires that affect people and communities. Unplanned fires in the wildland pose a significant threat to nearby communities. Our research uses the average period between fires under a presumed historical fire regime combined with population and vegetation densities to identify high fire-frequency areas of the WUI. We then use data on structures, structure content, and population to identify the people and property at risk within these areas. These estimates provide a national scope of high fire frequency areas of the WUI.

Spatially Defining Wildland Fire Risk: A Noval Approach to WUI mapping

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Abstract:
In recent years there has been an increase in the complexity of wildland fire management due to increasing exurban development into fire prone ecosystems. Currently the wildland urban interface (WUI) is typically defined by a buffered distance from populated areas interacted with vegetation coverage. However, the approach does not take into account the risk related to this area from the event of a wildland fire actually occurring. This may lead to overestimation of the WUI around towns, even if there is little likelihood of a wildland fire occurring, and more importantly, underestimation of the WUI in rural areas where dispersed housing tends to be among areas with a higher probability of wildland fires occuring. In the following study, we produce a National WUI Fire Risk Map by interacting population and structure locations using LandSCAN data, with the probability of the proximate areas burning. This fire probability map is based on the topological fire simulation model FSIM, developed for the Fire Program Analysis, which spatially simulates the spread of fires across a landscape under various fire weather conditions. By incorporating simulated burn probabilities, with a more standard definition of WUI, land managers can better assess the effects that wildland fire will have on populations living in and around these fire adapted lands, which will aid in moving fire management decisions towards a more cohesive strategy.

From the Flames to the Frame: Communicating Messages of "Conflagration" and "Climate Change"

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Abstract:
The publicly managed practice of fire management operates in the public "marketplace of ideas." After the 1910 fires, for instance, this public debate ranged from those who sought an increased federal control of fire management to those calling for the dissolution of the fledgling Forest Service. Today, forest and fire managers are charged to respond to a more widespread though dispersed crisis -- climate change and climate variability -- and critics ask, "What climate crisis?" While managers ask, "How do we manage a variability we can't yet specifically predict?" And as in any fire season, the public asks, "How will you save my house?"

A study of historic dissemination of framing messages identifies such labels as the "conflagration" and "big burn" of 1910 and the "Let it burn" fires of 1988. Interpretations of these historic fire dialogues inform our approaches today for framing a message that will engage fire professionals and the public in a critical dialogue regarding "climate-change" fires. Specific examples of contemporary fire messaging offer a checklist of communication elements, ranging from "fire resilience" to "global wildfire," that have resonated with the media and the public.

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People, property, and preparedness: Focus on the home ignition zone

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Abstract:
From a managerial perspective, when focused on the urban interface, the question 'How do we prevent wildfires?' can be replaced by more relevant questions with direct social impact such as: 'How do we prevent wildfire property losses?' and 'How can we also sustain local ecological values?' Damage assessments after 2003 and 2007 wildfires in San Diego confirmed that most houses ignited from embers that landed on or in structures. Yet, defensible space and fuelbreaks are still given priority over policies and actions aimed at structural maintenance and retrofit, thus giving a potentially false sense of security to individuals and agencies. A 2008 pilot program with homeowners' associations in San Diego had more than 400 attendees at a series of linked events, which included an informational class that covered ignition and defensible space issues, a 'walk around' of homesites with a local fire behavior specialist and landscape architect, and a Homeowner Assessment checklist. Evaluations showed that this focus on the Home Ignition Zone increased homeowners understanding of how houses ignite and what actions they intend to take to reduce their wildfire property risk. Additional focus on sustaining local habitat values in areas with fuel/vegetation reduction treatments and the need to focus on the Home Ignition Zone to reduce future wildfire property losses is suggested.

Additional keywords: Defensible space, chaparral, wildfire education

Introduction

More than 5000 homes were lost in the 2003 and 2007 wildfires in San Diego County. Considerable local and national attention has been focused on wildfire prevention and education policies and programs to reduce losses in future wildfires. And over time the question 'How do we prevent wildfires?' is being replaced at the urban interface by the more relevant questions, 'How do we prevent wildfire property losses?' and 'How can we also sustain local ecological values?'

Research suggests that most property losses in a wildfire can be prevented by homeowners following some well-established, simple steps—yet most homeowners do not recognize or acknowledge risks on their property through typical wildfire education programming. Wildfire preparedness programs that draw attention to structures in the Home Ignition Zone (HIZ, after Cohen 2000) are generally eclipsed by those focusing on defensible space. In a 2008 pilot 'Living with Wildfire' program with homeowners' associations in San Diego, homeowners attended classes and demonstrations to help them identify and implement the steps to reduce wildfire property risks. This paper describes the evaluation conducted to assess the program's effectiveness.

Wildfire prevention programs generally emphasize defensible space that is adjacent to the structure and that is provided in fuelbreaks and 'fuel reduction zones' further from the structure. This paper reports events for homeowners that came about after recent discussions with local fire officials, open space managers, and development departments about implementing fuel/vegetation reduction treatments that retain habitat values and focus on the HIZ to reduce future wildfire property losses.

Framing the question, 'How do we prevent wildfire property losses?
Research has shown most wildfire property losses can be prevented by homeowners following some well-established, simple steps to retrofit and maintain their structures and landscaping in the HIZ (Cohen 2000). The national Firewise Communities program teaches two-day workshops on assessing wildfire hazards in the HIZ (Firewise Communities 2011).

Even when the threat of wildland fire is fully recognized, homeowner-focused wildland fire policies and communication programs have different frames of reference and causal mechanisms than fuels reduction or fire prevention efforts (Absher and Vaske 2007; Kyle *et al.* 2010; Paveglio *et al*. 2011). Unfortunately, many homeowners do not adequately recognize or understand risks on their property when informed through wildfire education programs that rely heavily on brochures, webpages, and mass media coverage. Encouraging action and monitoring pre-fire readiness is an ongoing issue that needs to be addressed, and will be most effective at a local level with strong community involvement and tailored communications (Toman *et al.* 2008; Paveglio *et al.* 2009; Brenkert-Smith 2010).

An extensive assessment of damage from the Witch Fire of 2007 was conducted by the National Institute of Standards and Technology, the International Code Council, and local wildfire and structural experts (Institute for Business and Home Safety 2008). They found that wind-blown embers, which can travel one mile or more, were the most common cause of structural ignition and that few homes burned as a result of direct contact with flames. Wildfire experts identified risks that can be modified by retrofit and/or maintenance: flammability of roof, areas where embers can make direct contact with the structure, pathways that allow burning embers to enter the structure, fuel sources near the house that embers could ignite, any wood structure connected to a house, and access to property for firefighters.

The report made a clear case for homeowners retrofitting their homes. By becoming familiar with affordable and readily available options to retrofit existing homes they can quickly and easily increase their protection against wildfire. Moreover the report emphasized that local and state government leaders should encourage this education and implementation process. A demonstration approach to homeowner education was evaluated in the program described in this paper, with the expectation that it would lead to increased knowledge about and motivation by homeowners to retrofit and maintain their homes.

Framing the question, 'How can we sustain local ecological values?'
Most wildfire prevention programs still give priority to fuelbreaks over policies and actions aimed at structural maintenance and retrofit that reduce home ignition risks. This gives a potentially false sense of security to individuals and institutions, and often results in considerable losses in habitat and property values. Using a spatial database of fuelbreaks in southern California national forests and maps of large fires, Syphard *et al*. (2010) found that fires stopped at fuelbreaks 22–47% of the time, and this was invariably related to firefighter access and

management activities. This supports the strategic location of fuelbreaks because they have been most effective where they provided access for firefighting activities.

During a wildfire, property losses are reduced when there are few places for embers to land in the HIZ. The reality is that the production of embers is only marginally reduced when fuelbreaks and fuel reduction zones are established, and that property losses are reduced only by both proper defensible space and structural preparedness. Responsible establishment of fuelbreaks and defensible space (outside the landscaped yard and within 100 feet of habitable structures) reduces fuel loads around structures, retains some habitat quality, and minimizes soil erosion. 'Irresponsible' defensible space, when trees are cut down and shrubland is 'cleared' by private contractors (or required by insurance companies), results in urban tree canopy losses, erosion, flammable weeds, loss of native habitat, and unsightly hillsides. Often these defensible space projects are adjacent to structures with such high-ignition risks as wood roofs, wood fences attached to houses, vents without screens, unpruned landscaping, and debris around the house.

Some local contractors and property owners have 'cleared' all native chaparral and coastal sage scrub vegetation and/or extended defensible space to 300 feet beyond structures—resulting in large areas of bare ground that are subject to erosion and quickly occupied by weeds and non-native grasses. These vegetation types are far more flammable than the native shrubs and must be mowed annually at substantial cost. Figs. 1 and 2 illustrate improper 'clearing' adjacent to two homes in San Diego County.

Improper establishment of defensible space increases weeds and invasive plants, with long-term local and regional implications. Research by Merriam *et al*. (2006) in California showed that fuelbreaks could provide establishment sites for nonnative plants, and that non-natives may invade surrounding areas, especially after disturbances such as fire or grazing. Fuel break construction and maintenance methods that leave some overstory native canopy and minimize exposure of bare ground are less likely to promote invasive weeds.

Fig. 1. Excessive clearance and 'scraping.'

Fig. 2 Brush management removal that exceeds recommended practices.

Methods

The Living with Wildfire program educated homeowners about wildfire property risks, helped them identify the risks of their own homesites, and outlined actions to reduce those risks (Fege 2008). The program was coordinated by RB United, a coalition of homeowners' associations; and funded by The San Diego Foundation's 'After the Fires Fund.' RB United scheduled the dates and locations for the classes; led the marketing efforts; arranged for meeting rooms and homesite locations; took reservations and assembled class participant lists; printed handouts; and answered many questions from homeowners and community members.

Each homeowner was asked to attend three learning events comprised of an informational class, a homesite demonstration and an action workshop offered about a week apart. This series was offered three distinct times to maximize participation. The combined attendance was more than 400 in aggregate over the nine classes, although some people did not attend all three events.

In general, homeowners first attended a two-hour 'Living with Wildfire' class which focused on how houses ignite, the attributes of ignition-resistant structures and 'fire wise' landscaping, low-cost maintenance and retrofits to reduce property risks and sustain natural environments, and community action. Then homeowners attended two-hour 'demonstrations' at two homesites, led by a local fire behavior specialist and landscape architect that focused on a Homeowner Assessment checklist. Attendees walked around the houses with the two experts, who inspected and assessed the structures and landscaping elements for wildfire property risks, and suggested retrofit and maintenance actions, as shown in Fig. 3 and 4. Finally, two-hour Homeowners' Action Workshops were conducted to review the Homeowner Assessment checklists completed by individual homeowners; discuss actions suitable to address structural and landscaping items that did not meet current code and/or checklist standards; discuss action plans for maintenance and retrofits; and evaluate knowledge, intent, and actions of homeowners to reduce their wildfire property risks.

Fig. 3. Applying checklist to structure maintenance and retrofit.

Fig. 4. Illustrating landscape elements in the Home Ignition Zone.

The class presentation was based on ‘Living with Wildfire: Reducing Property Risks, Habitat Losses, and Costs,’ that was first developed after the 2003 wildfires by 30 local experts. This was organized by the San Diego Natural History Museum and supported by funds from the Joint Fire Sciences program through the U.S. Fish and Wildlife Service. The presentation was updated to reflect the 2007 wildfires and recent scientific and technical information about how houses ignite and how to reduce property risks. The Homeowner Assessment checklist used in the second event is based on the latest scientific principles developed by University of California Berkeley's (UCB) Center for Fire Research and Outreach (2008) and other fire experts. The classes, demonstrations and workshops focused attention on a number of issues, especially the following:

Structural risks.
The assessments identified the most common structural conditions in these communities that increase risks of house ignition during wildfires (not listed in any particular order):

- Debris in gutters and/or roof valley
- Gaps between clay tiles and roof underlay
- Insufficient ember protection in original vents, in eaves, gables or foundations
- Single-pane windows, or lack of tempered glass panes
- Garage doors and exterior doors with inadequate seals

*Landscape risks***.**
The inspections identified the most common landscape conditions that serve as fuel to increase the probability of house ignition during wildfire (not listed in any particular order):

- Wood fences too close to eaves, between houses or attached to house
- Small-dimension (horizontal) wood patio covers and patio furniture (wood and fabric) next to the house
- Mulch or leaves or unpruned plants adjacent to the siding, windows or foundation
- Vegetation overhanging structural elements or trees overhanging roof
- Plants that are hedged and have many interior dead branches and leaves, and plants that shed leaves creating a lot of litter

Data was obtained from participants at two events: the Living with Wildfire classes and Homeowner Action Workshops. Participants were asked to complete one-page pre- and post-event surveys. These asked about basic wildland fire knowledge, awareness of fire behavior, changes in attitude towards homesite actions, and plans to reduce their wildfire risks. Some of the questions were changed slightly as the project progressed, allowing the project team to offer more relevant questions, but also complicating the data summary and analysis. Overall, the results gave insights into how well this project accomplished its goals, but was short of a full summative evaluation.

The three Living with Wildfire classes were attended by 180 residents, and a total of 74 pre-class surveys and 62 post-class surveys were completed by the attendees. Of these, 33 filled out both surveys (matched by self-reported first name), and 103 filled out at least one, for a response rate of about 60%. Participants in the Homeowner Action Workshops (attended by 101) were asked to complete an additional feedback form, and 41 were filled out, for a response rate of about 40% of attendees. (No survey was used for the 120 or so attendees at the homesite demonstration 'walk abouts'.) Generally, only one person per household completed the surveys. Although couples and other family members sometimes attended the classes and/or workshops together, for privacy reasons the exact number of individual residences represented was not recorded. Thus, the actual response rate on a residential property basis would be slightly higher.

Results

The surveys of homeowners attending the Living with Wildfire programs provided information about their awareness of wildfire property risks, actions needed to reduce those risks, and their willingness to take those actions. Homesite activity and community involvement questions were asked before the initial class. Knowledge of wildfire risk reduction and feelings of safety were asked both before and after the class in order to provide a sense of the immediate program information effectiveness. Perceptions of wildfire risk were asked only after the class.

Homesite activities.

Participants who attended the Living with Wildfire classes responded that they enjoy a variety of activities in their 'backyard' that need to be considered when landscape changes are made to reduce wildfire risks. Gardening and privacy were each identified as activities by about 70% of participants, while 'view' and 'shade' were each identified by 50 percent. Participants were asked when their houses were built; a quarter of the houses were built before 1970 and almost 90% were built before 1990.

Community involvement.

Attendees were asked about active participation in community organizations; 46% said they are active in Homeowner' Associations (HOAs), 24% in Neighborhood Watch (not given as a choice for Living with Wildfire class attendees), and 28% not active in any community group (some respondents indicated more than one group).

Knowledge of wildfire risk reduction.

Surveys from the 33 participants who completed both pre- and post-class surveys in the Living with Wildfire classes were matched by first name. Two questions were asked the same way in both surveys. These can be compared to assess changes in knowledge of wildfire risk reduction principles due to class attendance. On a 3-point scale their knowledge of how fire spreads increased 0.9 points to 2.4, and their knowledge of how houses ignite increased 0.6 point to 2.8.

Feelings of safety.

When asked 'what keeps you from feeling safe from wildland fire effects?' more than half of the homeowners responded with 'neighbor's actions' (56%) or knowing what needs to be done to reduce chances that a house will burn (50%), as shown in Table 1. These responses dropped to 25 and 32% when participants completed the survey after the classes and workshops. Home improvement skills and money were identified by about a quarter of the participants after the first class and increased to about 40% after the homesite assessments and action workshops.

Table 1. Feelings of safety, of participants in Living with Wildfire classes

Question	Category	After first class (%) n = 70	After action workshop (%) n = 34
What keeps you from **feeling safe** from wildland fire effects?	Neighbor's actions	56	32
	Knowing what to do	51	25
	Knowing how houses burn	50	26
	Landscaping skills	40	38
(check all that apply)	Home improvement skills	24	41
	Money / $	21	44
	Other	13	9

Homeowners' wildfire risk perception.
In post-surveys after the Living with Wildfire class, 57% of attendees perceived wildland fire risk to be a lot higher, 23% to be somewhat higher, and 16 % no change or lower risk, than before attending the class.

Further questions asked for a self-assessment of their motivations and barriers to retrofitting their house, with results as follows:

*Motivation to retrofit***.**
Respondents indicated they would most be motivated to make retrofits by insurance cost savings, regulations, and increased resources for doing the work (knowledge and labor), as shown in Table 2.

Table 2. Motivation for retrofit investments, of participants in Living with Wildfire classes

Question	Category	Percent
What **two factors would most motivate you** to retrofit your house to reduce wildfire risks? (check two)	Lower insurance premiums	55
	Required by code	41
	List of risks for your house	34
	Hiring someone to do it	21
n=29	Required by HOA	21
	Increased house value	17
	Low-interest loan	10

*Barriers to retrofit and maintenance***.**
When homeowners indicated their biggest barriers to doing the retrofit and maintenance work, 45% noted money, one third noted either home improvement skills or time, and the rest indicated landscaping skills, physical abilities, and other, as shown in Table 3.

Table 3. Barriers to doing retrofit and maintenance work to reduce wildfire risks

Question	Category	Percent
What is your biggest barrier to doing the retrofit and maintenance work to reduce wildfire risks? (instructed to check cone, but some checked more than one)	Money	45
	Home improvement skills	34
	Time	30
	Landscaping skills	18
	Physical abilities	23
n=60	Other	6

Because cost is an important barrier, attendees were asked to further detail their willingness to spend money on retrofitting and whether they might try to do the job themselves or hire local professionals to do it.

Likely expenditures.
After the Living with Wildfire classes, 64% of attendees indicated they were likely to spend between $101 and $10,000 and 18% were likely to spend more than $10,000, as shown in Table 4. After the final element, the Homeowner Action Workshop, 80% indicated they were likely to spend between $101 and $10,000 and 13% said they would spend more than $10,000 in the next year.

In the same post-workshop survey, slightly more than half of the homeowners indicated that they would likely hire a handyperson or contractor (76% and 31%, respectively), and about a quarter checked that they would hire someone to install a roof, windows, deck and/or fence. About 20% said they would hire an arborist, landscape contractor and/or landscape architect.

Table 4. Likely expenditures to reduce wildfire property risks

Question	**Category**	**After first class (%)** n = 51	**After action workshop (%)** n = 28
How much are you likely to **invest in property risk reduction** in the next year? (check one)	Not likely to make changes	4	3
	Labor only	2	0
	Less than $100	12	5
	$101 to $1,000	27	49
	More than $1,000	37	31
	More than $10,000	18	13
	(Total)	100	100

Discussion

How do we prevent wildfire property losses?

This program evaluation identified some specific factors that may affect homeowners' decisions about how to deal with the risks arising from wildland fires, and more broadly suggested ways to improve wildland fire preparedness in the urban interface. Overall, the classes seemed to be successful at imparting important new information and instilling a more realistic sense of wildland fire risk. Most homeowners attending the classes recognized the risks that wildfire poses to their property, and their responsibility to reduce risks of house ignition. When homeowners indicated 'what keeps them from feeling safe?' their responses suggest that the classes reduced their uncertainty about how houses burn or what to do to prevent it, and revealed concerns about their home improvement skills and the costs of firewise actions. That is, the three part program effected a transition from 'lack of knowledge' concerns to 'lack of resources' concerns. That said, the volume of information needed to better understand all aspects of wildland fire spread, home ignition, and how to assess and treat one's own house is potentially overwhelming. Programs such as the one above should incorporate good message delivery and educational processes, as these would seem to be important for topics with such implicit and complex tradeoffs and cost implications.

Since about 90% were built before 1990, older home construction techniques must also be addressed when discussing retrofitting homes, especially in light of knowledge about how houses ignite. While money is always an issue, there was some movement in the after workshop results to suggest homeowners were less likely to be complacent and do nothing or only very inexpensive actions. While many homeowners may be encouraged to spend substantial sums, the burden can be eased with individualized checklists, multiple-year planning, and the availability of skilled tradespersons to do the desired work. Respondents indicated they would be most motivated to make retrofits by insurance cost savings, regulations, and increased resources for doing the work (knowledge and labor).

Broader application of project approach

The most successful aspects of this wildfire education program will be applied with another grant from The San Diego Foundation After-the-fires Fund to RB United for 20 neighborhood-based Homeowner Wildfire Assessment classes in six communities in the northeastern part of the City of San Diego and in the city of Poway. The program will began in late 2010 with the development of training curricula and a 'train the trainer' class and emphasizes the Homeowner Assessment checklist and on-homesite demonstrations. In the 2011 classes, participating homeowners (or renters) will walk around two houses with a team of three instructors, including a fire official (perhaps retired), a local landscape professional who specializes in low-water and fire-wise landscaping, and someone experienced in home repair. Using these same checklists, homeowners are expected to identify risks at their own homesite, develop an action list, and later complete a follow-up email survey to gather feedback about expectations, knowledge, and likelihood to take various actions.

Conclusions

Because wildfire damage assessments show that most houses ignite from embers on or in structures, future property losses can be reduced in the Home Ignition Zone by retrofitting and maintaining structures and the adjacent landscaping. Homeowner education programs can be an essential part of the process that increases knowledge about the risk from wildland fires and creates a more realistic understanding of the actions homeowners can take individually and as a community to reduce this threat. Moreover, classes such as these can move them to a stronger position regarding planning and carrying out firewise actions, and perhaps motivating important investments of time and resources. Imparting important new information and working directly with residents seems to instill a more realistic sense of wildland fire risk and actions they can, or will, undertake. Our work led to a strong focus on structures because defensible space actions alone is an incomplete approach to wildfire property risk reduction and most homeowners seem able to understand the immediate gains to structural safety, and comprehend the fact that simple landscape clearance solutions may have unintended aesthetic and ecological consequences. The result from this series of events strongly suggests that it is the integrated attention to ecological, economic and social implications of fire preparedness that best informs wildfire policy and protects property and natural resource assets.

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'Lest we forget': Canada's major wildland fire disasters of the past, 1825-1938

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Abstract. This paper provides an overview and summary of nine of the most devastating wildland fire disasters to have occurred in Canada and in some cases, adjoining areas of the United States, in the distant past. The list includes the following cases: 1825 – Miramichi, New Brunswick/Maine; 1870 – Saguenay - Lac-Saint-Jean, Quebec; 1908 – Fernie, British Columbia; 1910 – Baudette, Minnesota/Rainy River, Ontario; 1911 – Porcupine, Ontario; 1916 – Matheson, Ontario; 1919 – Saskatchewan/Alberta; 1922 – Haileybury, Ontario; and 1938 – Dance Township, Ontario. The loss of life was a significant feature in all of these fires. Drawing upon written and photographic resources, the main features of each incident are highlighted. While some of the factors responsible for these past disasters have changed, there is ever reason to suspect that similar occurrences are still possible today. The first step to avoiding any further tragedies with respect to wildland fire disasters is public awareness. Hopefully the compilation of information documented in this paper will serve as a constant and endearing reminder of Canada's history of past wildland fire disasters.

Additional keywords: catastrophic fires, conflagrations, fatalities, fire environment, large fires, tragedy fires, wildfires, wildland-urban interface.

Introduction

The genesis for this paper came about as a result of a presentation I made about a year and a half ago in Moncton, New Brunswick (Alexander 2009). I was surprised to learn during my visit that one of the local fire chiefs, who had been born and raised in New Brunswick, was unaware of the Great Miramichi Fire that swept through a large region of the province and adjoining areas of Maine on October 7, 1825. This fire or series of fires still remains the largest wildland fire complex to have occurred in eastern North America. In fact, at one time a certain website (http://ca.askmen.com) ranked the 1825 Miramichi Fire as 'Number 4' on the all-time top 10 list of Canadian disasters.

Should I have been surprised at this general lack of awareness? Perhaps so. There is however a small section of the Central New Brunswick Woodmen's Museum in the town of Boiestown devoted to the 1825 Miramichi Fire and the New Brunswick Department of Natural Resources also has a summary of the incident posted on their Forest Fire Watch website. Nevertheless, this situation got me to thinking that there might very well be a general lack of awareness of Canada's past history of wildland fire disasters across the country and the lessons to be learned from these incidents. So, towards this end, I elected to examine what else has been done or is being done to memorialize the Miramichi Fire and a selection of eight other historic wildland fire disasters that have occurred across Canada and in some cases, adjacent areas of the United States (Figs. 1-10). The information on the nine wildland fire disasters presented in Table 1 has been distilled from the numerous sources referenced in this paper.

Fig. 1. Year and general location of nine of Canada's major wildland fire disasters of the past, 1825-1938. Refer to Table 1 for further details on each fire.

Fig. 2. Painting depicting the 1825 Miramichi Fires as they swept into communities in New Brunswick and Maine (Unknown source; image courtesy of Keith G. Barr, Fredericton, NB).

Fig. 3. An engraving depicting a family surviving the 1870 Saguenay - Lac-Saint-Jean Fires in Quebec by entering the river (from Blanchet 2003).

Fig. 4. The convection/smoke column associated with the major run of the 1908 Fernie Fire in southeastern British Columbia (photo from http://www.crowsnest.bc.ca/c_08276.html).

Fig. 5. Burying the dead following the 1910 Baudette, Minnesota/Rainy River, Ontario Fires (photo courtesy of Minnesota Historical Society - http://www.mnhs.org/).

Fig. 6. One of the grave sites following the 1911 Porcupine Fire in northeastern Ontario (photo from http://www.collectionscanada.gc.ca/sos/002028-4100-e.html).

Fig. 7. The immediate smouldering aftermath of the 1916 Matheson Fire in Ontario (photo from http://www.iroquoisfallschamber.com/web-content/Pages/nushka.html).

Fig. 8. Red Cross relief effort following the 1919 Saskatchewan/Alberta Fires (photo courtesy of Tom Maccagno and Lac La Biche Archives, Lac La Biche, AB).

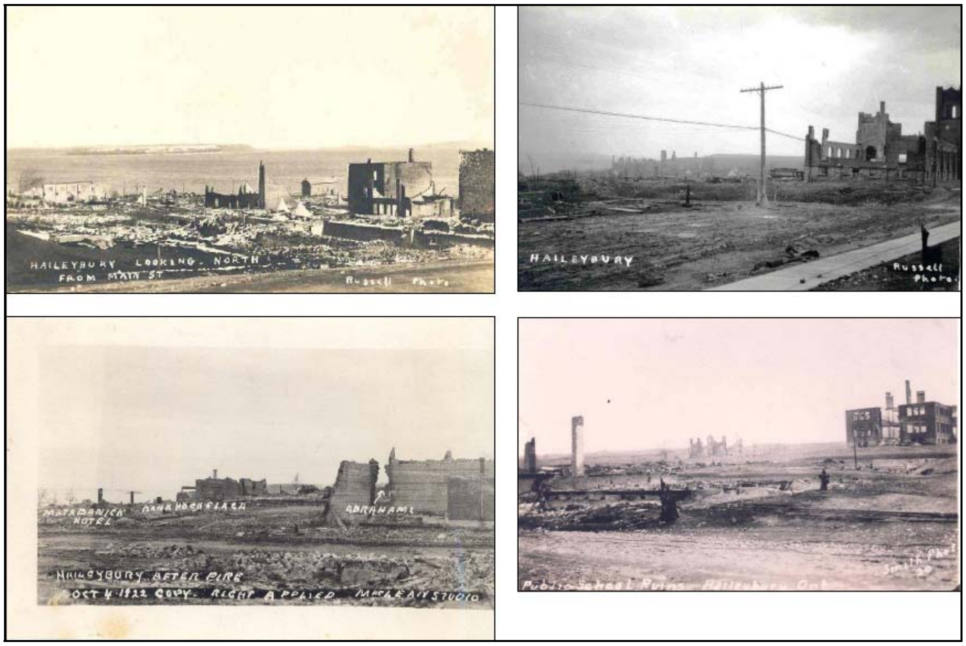

Fig. 9. Scenes of the town of Haileybury, Ontario, immediately following the 1922 fire (photos from http://www.museevirtuel.ca/pm.php?id=record_detail&fl=0&lg=English&ex=327).

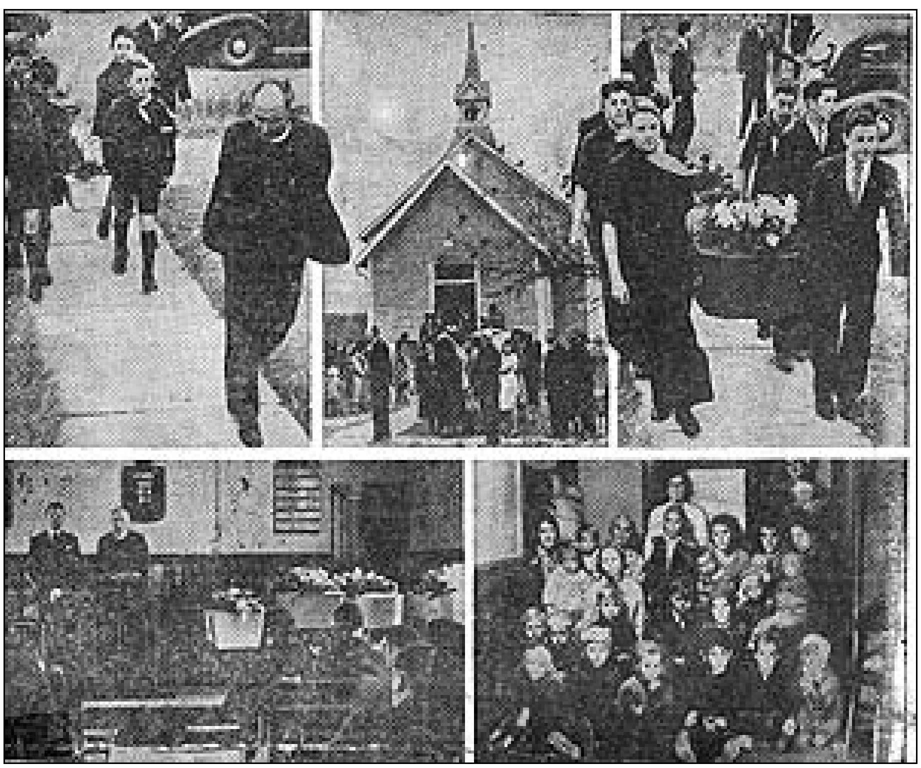

Fig. 10. Scenes associated with the memorial services for those who lost their lives in the 1938 Dance Township Fire in northwestern Ontario (collage of newspaper photos obtained from http://www.fftimes.com/100-years-100-stories/dancephoto.html).

Table 1. Summary of the associated features of nine major wildland fire disasters to have occurred in Canada and bordering regions of the United States between 1825 and 1938

Name and location	Date	Estimate of fire size	Lives lost	Notes of interest
Miramichi, New Brunswick/Maine Fires	Oct. 7, 1825	1.2 million hectares (336,000 in Maine)	At least 160 confirmed although estimates range as high as 500.	Largest fire complex of all time in eastern North America result of many small settler and logging fires. Preceded by a severe summer drought.
Saguenay - Lac-Saint-Jean, Quebec	May 19, 1870	0.4 million hectares	Only 7 but many people were reported to be seriously injured.	Settlers burning slash from land clearing operations coincided with dry conditions in the spring coupled with strong winds.
Fernie, British Columbia	Aug. 1, 1908	25,900 hectares	As many as 22 reported.	Fires burning in logging slash for a month prior to major run.
Baudette, Minnesota/ Rainy River, Ontario	Oct. 7, 1910	121,500 hectares	42 reported on the U.S. only.	Four wind-driven fires (3 caused by railroad and one by a settler).
Porcupine, Ontario	July 11, 1911	0.2 million hectares	The true toll of dead will never be known but 73 were officially reported.	Many smaller fires were burning at the time. Spring came early and the summer was a “hot, dry one”.
Matheson, Ontario	July 29, 1916	0.2 million hectares	Officially 223 although the actual number was probably much higher.	Many settler and lightning fires merged into a single, wind-driven conflagration. Area experienced very little rain that summer.
Saskatchewan/Alberta	May 19, 1919	Perhaps in excess of 2.8 million hectares	At least 13 confirmed and unknown number of burned victims. Many injured.	Undoubtedly a complex of many fires burning simultaneously over a wide area. Springtime burning conditions.
Haileybury, Ontario	Oct. 4-5, 1922	168,000 hectares	Officially 43.	Fires set by farmers and settlers outside the burning permit season. The summer had been unusually hot and dry. Exceptionally strong winds affected the fire.
Dance Township, Ontario	Oct. 10, 1938	30,355 hectares	17 plus 18 others seriously injured.	Several settler fires merged together. No rain for a month prior to fire occurrence.

Parallels with other wildland fire disasters

Upon examination of the particulars associated with these nine wildland fire disasters (Table 1), we find that there are many similarities with other wildland fire disasters in the United States and more globally (Plummer 1912; Guthrie 1936; Storey and Noel 1965; Arnold 1968; Brown and Davis 1973; Cheney 1976; Martin and Weise 1995), including the 1910 fires in the western US:

- The area burned was generally vast with homes and other building devastation high.
- The loss of life was a significant feature in all of these fires (223 fatalities officially confirmed in one fire alone)[1].
- Fuel types consisted largely of conifer-dominated forests impacted by logging and settler development (i.e. slash debris).
- Fires occurred late in the season following an extended summer drought or a rainless period in the spring prior to "green-up".
- Air temperatures and relative humidities were moderately severe but surface winds were often strong. The 1908 Fernie Fire, for example, burned a strip 4.8 km wide for a distance of about 32 km (Plummer (1912). This length-to-breadth ratio (6.7:1) suggests that the prevailing winds would have been ~50 km/h (Taylor *et al.* 1997).
- Many small to medium-sized fires burning simultaneously over a relatively large region.

Furthermore, fire protection and suppression in most of the situations given in Table 1 was either non-existent or still in its infancy. The real 'burning question' though becomes: Are the planets likely to align again? In other words, can such wildland fire disasters of the past occur again?

Comparing then and now

Presumably the public's general indifference to forest fires is no longer a factor like it was in the past (Parminter 1978; Pyne 2007). For example, in reporting on the forest fire situation for Canada in 1908, H.R. MacMillan (1909) – then the Assistant Inspector of Forest Reserves for the Department of Interior's Forestry Branch – had this to say about the Fernie Fire of 1908:

> The Fernie fire is a good illustration of what is, throughout the newer districts of Canada, a common condition. The Fernie fire was, for a month before the town was consumed, burning in the logged-over lands and waste lands of the Elk River Valley surrounding the town. Because it was not destroying timber *at that time merchantable* no one made the slightest effort to control the fire. Though for over four weeks it spread through the timberland, destroying all small growth, it was allowed to continue unchecked, and the result was that it got into the slashing near the town, a wind sprang up, and, borne upon it, the fire consumed the town and almost everything within its limits, bringing 22 persons a horrible death, and entailing on a large number the tremendous property loss of $2,000,000.

[1] I have found, as Lesile (1954) did and like many others have, that the number of fatalities associated with the wildland fire disasters given in Table 1 as reported on in various written sources varies quite widely. In many cases we will never know the true number of lives lost. Thus, except for the 1938 Dance Township Fire, the values given in Table 1 should be regarded as conservative estimates.

In order to try to answer the general questions poised above though, a number of factors need to be examined. These include assessments of the fire environment, potential causes, fire control effectiveness, and cultural changes:

- *Fuels.* – Slash fuels are not the problem they were before but other equally flammable fuel complexes have emerged (e.g. mountain pine beetle-killed forests). The fuel types around affected communities have in some cases been radically altered.
- *Weather conditions.* – Perhaps we are seeing earlier and longer fire seasons with more frequent periods of critical fire weather as a result of global climate change.
- *Ignition sources.* – Far better fire prevention programs exist (e.g. burning permits) but a multiple fire scenario is still a distinct possibility (e.g. lightning, powerline starts).
- *Fire intelligence and suppression capability.* – Obviously greatly improved as a result of modern technology (e.g. fire weather/danger forecasting, aircraft) but there are limits.
- *Values-at-risk.* – The wildland-urban interface fire problem has greatly expanded but by and large, building structures are less flammable. Advances in transportation have made successful evacuations a far more distinct option than they were in the past.
- *Understanding by the general public* – Better informed and more knowledgeable about wildland fires.

From the above summary one might tend to conclude that there is little cause for concern. Indeed, on the subject of forest fire disasters in Canada, *The Canadian Encyclopedia* website (http://www.thecanadianencyclopedia.com/) indicates that 'Great fires still ravage Canadian forests, but modern detection, firefighting techniques and air evacuations … probably mean that huge killer fires have ceased to be a threat'. Most wildland fire specialists would disagree (e.g. Haines and Sando 1969; Arnold 1971; Brown and Davis 1973; Chandler and Kiil 1977).

Admittedly it is hard to substantiate either a decrease or an increase in the chances of future disasters on the scale of the past. As Brown and Davis (1973) point out, in spite of the favorable changes in sources of fire risk and effectiveness of firefighting efforts, the 'two basic ingredients for large fires – that is suitable weather conditions and available fuels – will continue to be present'. Arnold (1971) notes that, "The fact remains … than when weather, fuel and ignition conditions peak at the same time, we can expect to continue to see comparable disasters today' and while modern communications 'should reduce loss of life from thousands to only a few – though there is the potential for large loss of life in many places'. Brown and Davis (1973) emphatically state that 'it is nonetheless both easy and dangerous to … lull one into believing that big fires cannot occur again. They can, and one should never forget it'.

Ways of helping to remember the past

The Spanish philosopher George Santayana stated that 'Those who cannot remember the past are condemned to repeat it'. So, what have we done as a society to help us remember our past wildland fire disasters and the lives lost? Several affected communities have established plaques (Figs. 11-13), monuments (Fig. 14) or memorials (Figs. 15-16). As Gulliford (1997) has noted, in this way 'The living have remembered the dead, and therefore, the dead go on living'. The memorial sculpture commemorating the 1922 Haileybury Fire located on the shore of Lake Timiskaming (Fig. 17) is especially inspirational considering that many of the town's residents were forced to take refuge in the lake's cold waters and cover themselves with wet blankets.

Fig. 11. Historical plaque established to commemorate the 1911 Porcupine Fire in northeastern Ontario (photo from http://www.ontarioplaques.com/).

Fig. 12. Historical plaque established to commemorate the 1916 Matheson Fire in northeastern Ontario (photo from http://www.ontarioplaques.com/).

Fig. 13. Historical plaque established to commemorate the 1922 Haileybury Fire in northeastern Ontario (photo from http://www.ontarioplaques.com/).

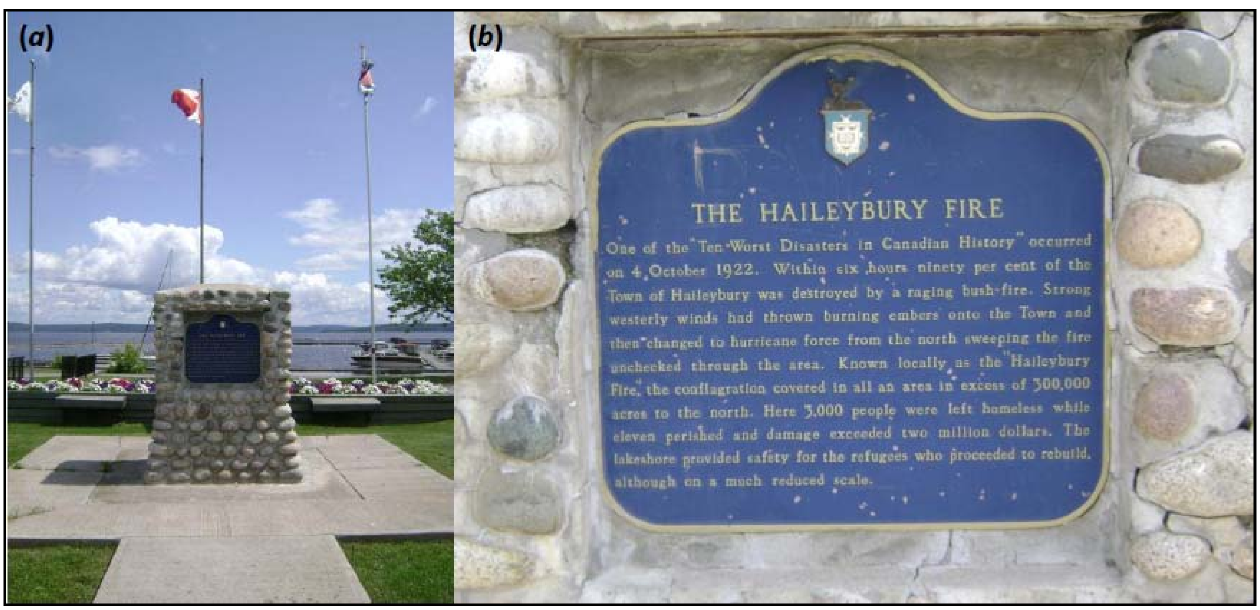

Fig. 14. Monument (*a*) with historical plaque (*b*) established to commemorate the 1922 Haileybury Fire in northeastern Ontario located on the shore of Lake Timiskaming (photos from http://www.waymarking.com/waymarks/WM7VZQ_The_Haileybury_Fire_Pioneer_spirit_Haileybury_Ontario_Canada).

Fig. 15. Monument erected in the cemetery at Val-Gagné, Ontario, in memory of Father Wilfrid Gagné and sixty-four other Nushka inhabitants who perished in the 1916 Matheson Fire (photo from http://www.iroquoisfallschamber.com/web-content/Pages/nushka2.html).

Fig. 16. Memorial established to commemorate the 1938 Dance Township Fire in northwestern Ontario (photo by Robin Payeur, Burriss, ON).

Fig. 17. Memorial sculpture by Ernie Fauvelle located on the shore of Lake Timiskaming establish to commemorate the 1922 Haileybury Fire in northeastern Ontario (upper photo from http://ih2.redbubble.net/work.310798.7.flat,550x550,075,f.great-fire-of-1922-haileybury-ontario-canada.jpg and photo insert from http://www.flickr.com/photos/franctasy/2482566381/). The following poem by Brian Beaudry appears on a granite monument associated with the memorial site (from http://outdoors.webshots.com/photo/1176337201028745782XUwABZ):

IN EACH CHILD

I HAVEN'T THE STRENGTH TO HOLD
FOR YET ONE MOMENT MORE
AN ACRID HAZE OF MOLTEN AIR
SHROUDS THE BURNING SHORE
ENTIRE TOWN ENGULFED IN FLAME
THIS LAKE OUR SOLE FLIGHT
PRAYING FOR OUR LORD'S ASSIST
TO SAVE US THROUGH THIS PLIGHT
I OFFER YOU IN FADING STRETCH
THIS PRECIOUS CHILD OF MINE
HOLD HER ABOVE THE WAVES
RESASSURE HER ALL IS FINE
ALL THAT I HAVE IS LOST TO FIRE
I COULDN'T LOSE HER TOO
PLEASE BEAR HER A LITTLE WHILE
HELP HER MAKE IT THROUGH
THIS TOWN WE CALLED OUR HOME
IS NOW ALL BUT GONE
BUT IN EACH CHILD WE WILL FIND
THE STRENGTH TO CARRY ON

Koch (1942) stated that 'If history is not written it is soon forgotten'. Weick and Sutcliffe (2001) in turn have indicated that 'If timely, candid information generated by knowledgeable people is available and disseminated, an informed culture becomes a learning culture'. In this regard, a number of books have been published to date on the nearly all nine of the wildland fire disasters focused on in this paper (Fig. 18). The latest effort appears to be a forthcoming book by on the 1825 Miramichi Fire being written by Dr. Alan MacEachern, an associate professor in the Department of History at the University of Western Ontario (MacEachern 2009). A number of smaller technical reports and popular articles have also been published over the years (e.g. Ganong 1906; Anonymous 1911*a*, 1911*b*, 1917; Leslie 1954; Haines and Sando 1969; Stocks and Walker 1973; Miramichi Literacy Writers 1985; McIntyre 2003).

Fig. 18. Covers of various books dealing in whole or in part with major wildland fire disasters in Canada written by Holbrook (1960), McClement (1969), Dion (1979), The 75th Anniversary of the Great Fire of 1922 Committee (1997), Johnson (1999), Blanchet (2003), Barnes (2004), Pyne (2007), McQuarrie (2008), and Dalstrom and Dalstrom (2009). Not included in the above collage are general disaster-related books which include chapters on wildland fires (e.g. Looker 2000).

Information on all of the wildland fire disasters discussed in this paper is available on several websites, including a number that feature films that serve to dramatize the events (e.g. http://www.onf-nfb.gc.ca/eng/collection/film/?id=53774):

1825 Miramichi, New Brunswick/Maine Fires

- http://www.gnb.ca/0079/miramichi_fire-e.asp
- http://en.wikipedia.org/wiki/Miramichi_Fire
- http://www.frenchfortcove.com/id23.html
- http://www.frederictonfirefighters.ca/museum/miramichi.htm
- http://www.woodmensmuseum.com/
- http://homepages.rootsweb.ancestry.com/~nbpast/NO/no-fire.html

1870 Saguenay - Lac-Saint-Jean Fires, Quebec

- http://www.histori.ca/minutes/minute.do?id=10172

1908 Fernie Fire, British Columbia

- http://www.crowsnest.bc.ca/ferniefirephotos.html
- http://www.crowsnest.bc.ca/fernie03.html
- http://www.passherald.ca/archives/100824/index4.htm

1910 Baudette, Minnesota/Rainy River, Ontario Fires

- http://en.wikipedia.org/wiki/Baudette_Fire_of_1910
- http://www.lakeofthewoodshistoricalsociety.com/history7.html
- http://www.baudetteregion.com/news/news/1910-forest-fire-observed-110
- http://www3.gendisasters.com/minnesota/3532/baudette-spooner,-mn-great-fire-1910
- http://www.fftimes.com/100-years-100-stories/FIRE1910.html
- http://www3.gendisasters.com/fires/17482/rainey-river-on-fire-oct-1910

1911 Porcupine Fire, Ontario

- http://en.wikipedia.org/wiki/Great_Porcupine_Fire
- http://www.collectionscanada.gc.ca/sos/002028-4100-e.html
- http://www.timminstimes.com/ArticleDisplay.aspx?archive=true&e=2037344
- http://www.timminspress.com/ArticleDisplay.aspx?archive=true&e=1112186
- http://www3.gendisasters.com/fires/8656/porcupine-district-on-forest-fires-july-1911
- http://www.thedailypress.ca/ArticleDisplay.aspx?archive=true&e=612122
- http://www.timminspress.com/ArticleDisplay.aspx?archive=true&e=2662466
- http://wapedia.mobi/en/Great_Porcupine_Fire

1919 Alberta/Saskatchewan Fires

- http://www.llbchamber.ca/index.php?option=com_content&view=article&id=5&Itemid=10

1916 – Matheson Fire, Ontario

- http://www.history.ca/ontv/titledetails.aspx?titleid=79107
- http://www.factualtv.com/documentary/Disasters-of-the-century-Matheson-Fire
- http://boards.ancestry.com/localities.northam.canada.ontario.cochrane/36/mb.ashx
- http://kinseydotca.blogspot.com/2009/03/dr-albert-lauder-kinsey-great-fire-of.html
- http://www.iroquoisfallschamber.com/web-content/Pages/nushka.html

- http://wapedia.mobi/en/Matheson_Fire

1922 – Haileybury Fire, Ontario

- http://en.wikipedia.org/wiki/Great_Fire_of_1922
- http://www.museevirtuel.ca/pm.php?id=story_line&lg=English&fl=0&ex=327&sl=8130&pos=1
- http://municipalite.notre-dame-du-nord.qc.ca/en/feu22.html
- http://www.virtualmuseum.ca/pm_v2.php?id=record_detail&fl=0&lg=English&ex=00000444&hs=0&rd=113486
- http://wapedia.mobi/en/Great_Fire_of_1922
- http://www3.gendisasters.com/fires/8381/various-towns-on-forest-fires-oct-1922

1938 – Dance Township Fire, Ontario

- http://www.fftimes.com/100-years-100-stories/thanksgivingfire.html
- http://www.fftimes.com/100-years-100-stories/patterson.html
- http://www.fftimes.com/100-years-100-stories/firerefugees.html
- http://boards.ancestry.com/localities.northam.canada.ontario.rainyriver/296/mb.ashx
- http://www.rainyriverrecord.com/node/5245

Grading our efforts to date

It would appear that we have done a lot to help us to remember our past wildland fire disasters in Canada. I would in fact give us a 'B grade' on our collective efforts to date. However, in our efforts to avoid complacency and ambivalence on the matter, those familiar with the six-stage disaster model presented in Turner's (1978) book *Man-made Disasters: The Failure of Foresight*, would point the implications of 'Stage II – The Incubation Period' of his model that centers around 'The accumulation of events that detracted from adhering to safe work practices'. So the questions now become: Is it enough to avoid relearning the mistakes of the past[2] and could we do more? The answers: No, probably not, and, yes, by all means.[3]

[2] One seldom gets second chances when high-intensity wildfires come knocking. However, fortunately this was the case in Alberta in 1968. Between May 16-31, 250 fires burned more than 385,000 ha of forest land. Most of the conflagrations occurred in a 240-km semi-circular strip across central Alberta bordering a transition zone between forest and prairie where land clearing and debris-burning is prevalent. Hundreds of settler fires were burning adjacent to this forest zone before and during the peak fire period and many of these subsequently united and spread from the agricultural zone into the forested zone. The largest conflagration burned an area of 133,565 ha, most of which occurred on May 23 when the fire advanced 64 km during a 10-h period towards the town of Slave Lake under the influence of strong southeasterly winds (Kiil and Grigel 1969). A disaster was avoided when weather conditions abated.

[3] Consider for a moment the question poised by Andrea who asked the question on an internet site (http://en.allexperts.com/q/Canadian-History-2762/Great-Fire-1916.htm) as to why did so many people die in the 1916 Matheson Fire.

Possible future initiatives

So what might possibly be done? Outside of major commemorations (e.g., 100th anniversary), I would like to suggest that we consider yearly reminders on the annual calendar dates of these wildland fire disasters. This could be in the form of articles in local newspaper and/or brief summaries on various online calendars. For example, of the nine wildland fire disasters discussed in the this paper, the 1922 Haileybury Fire is the only one included on the 'Wildland Fire Event Calendar' (http://www.iawfonline.org/calendar) located on the International Association of Wildland Fire's website. It would then be advantageous to have a website where a person could go 'for further information'. In this regard, the website devoted to 'The Great Peshtigo Fire of 1871' that occurred in Wisconsin is quite impressive (http://www.peshtigofire.info/).

I had a hand for example in compiling the list of wildland fire case studies to be included within the natural hazards section of the online *Atlas of Canada* website (http://atlas.nrcan.gc.ca/site/english/maps/environment/naturalhazards/forest_fires) developed by Natural Resources Canada. This represents a good start but I believe in addition to websites for individual wildland fire disasters that we also need a nationally dedicated website similar to that of the Canadian Fallen Firefighters Foundation (http://www.cfff.ca/en/). Such a website would also recognize lesser known, but equally important incidents[4], and other major wildland-urban interface incidents of the past such as the 1938 Bloedel Fire near Campbell River on Vancouver Island, BC (Keller 2002) and the series of wildfires that impacted communities in Newfoundland during the 1904 fire season (Wilton and Evans 1974).

Concluding remarks

While major wildland-urban interface fires have continued to occur in Canada (e.g. Pattison 1995; Qunitilio *et al.* 2001; Filmon *et al.* 2004), no members of the general public have been killed as a result of being entrapped or overrun by wildfire since the Dance Township Fire in 1938. Other regions of the globe have not been so fortunate (Alexander *et al.* 2011). Australia for example has suffered its share of wildland fire related fatalities in modern times (Cheney 1976). However, in light of the 173 deaths associated with the Black Saturday fires in Victoria, Australia on 7 February 2009 (Teague *et al.* 2010), the following passage taken from an editorial that appeared in *Australian Forestry* (Anonymous 1983) following the 1983 Ash Wednesday fires in southeastern Australia in which 75 people perished, is an especially sobering thought:

> Once again Victoria and South Australia have experienced exceptionally severe bushfires. They were not totally unexpected. Fires of similar intensity had occurred in south-eastern Australia several times in living memory – in Victoria in 1939, South Australia in 1958 and Tasmania in 1967. Long before mid-summer, drought had desiccated the fuels on forest and farm, and it needed only a day of high temperatures and very strong winds to generate perilous conditions. Ash Wednesday, 16 February 1983, was such a day.

[4] For example, in 1884 a wildfire that occurred within the Township of Morley in the Rainy River District of northwestern Ontario resulted in the deaths of a mother and her three children when their cabin was overrun (http://www.townshipofmorley.ca/fullhistory.html).

> Even if a sustained massive fire prevention program were adopted, it would be unrealistic to hope that the combination of going fire and extreme weather conditions will not occur again. It would therefore appear that holocausts can be expected somewhere or other in south-east Australia perhaps once every twenty or thirty years. This means that the people will have to learn to live with the risk of holocaust, especially people who opt for non-urban life-styles.
>
> What can be learned from the latest disasters? Progress will surely be made in various technical areas. Research and review will provide new information on such matters as fire protection and suppression, town planning strategies, refuge arrangements, the organization of relief, forest rehabilitation, and contingency approaches to the management of wood-flows, wildlife, recreation and other forest benefits. Advances in technical areas will be of great value. It would be valuable too to make comparable advances in the areas of public policy. People forget, community attitudes change and policies erode. Perhaps one of the great challenges, given the realities of south-eastern Australia, is to learn how to ensure the permanence of public interest policies where permanence is required.

Haines and Sando (1969) have stated that 'until man learns how to fireproof the forest or modify the weather, he must remain constantly alert to the threat of new fire disasters'. In this respect, a word regarding the title of this paper is in order. The words **lest we forget** form the refrain of a poem by Rudyard Kipling entitled 'Recessional' which he composed on the occasion of Queen Victoria's Diamond Jubilee in 1897. The phrase passed into common or popular usage following World War I, becoming linked with Remembrance Day observations. It has since been used in various ways in both film and song for example. It also seems a fitting means of warning or cautioning us about failing to forget the perils of wildland fire disasters.

In closing, I'd like to just say – borrowing from the title of the paper by Hartley and Langlois (1998) – 'Don't Blame the Goaltender – the Whole Team is Responsible for Wildland Fire Safety'. Everyone has a role. It is my sincerest hope that this paper will inspire others to take up the cause of instilling public awareness about Canada's past wildland fire disasters. Considerable conviction is required to try and avert such incidents from every happening again. The awareness level in communities that have been directly affected in the past is undoubtedly high. The greatest challenge will be in those areas that haven't experienced a major wildland fire disaster in the past as a result of a 'it can't possibly happen to us' type of attitude (Alexander 2004).

Epilogue

The following four line stanza or quatrain is taken from the poem 'The Miramichi Fire' by John Jardine of Black River, NB, written a few days after the 1825 disaster (Manny and Wilson 1968; Arbuckle 1978):

I heard the sighs, the cries and groaning,
Saw the falling of the tears;
By me this will not be forgotten,
Should I live a hundred years.

To view the full version of the poem visit http://www.museevirtuel-virtualmuseum.ca/edu/.

Acknowledgements
Several people have contributed to this paper in various ways. Appreciation is extended to Dr. Peter J. Murphy (University of Alberta, Edmonton, AB) for so freely providing information on his research into the 1919 Alberta/Saskatchewan fires. The kindness shown by Mrs. Karen Kellar (Devlin, ON) concerning my requests for information related to the 1938 Dance Township Fire was especially humbling. Finally, I'd like to thank Mr. Harrold Boven (Ontario Ministry of Natural Resources, Fort Frances, ON) for his efforts to address my requests and much more.

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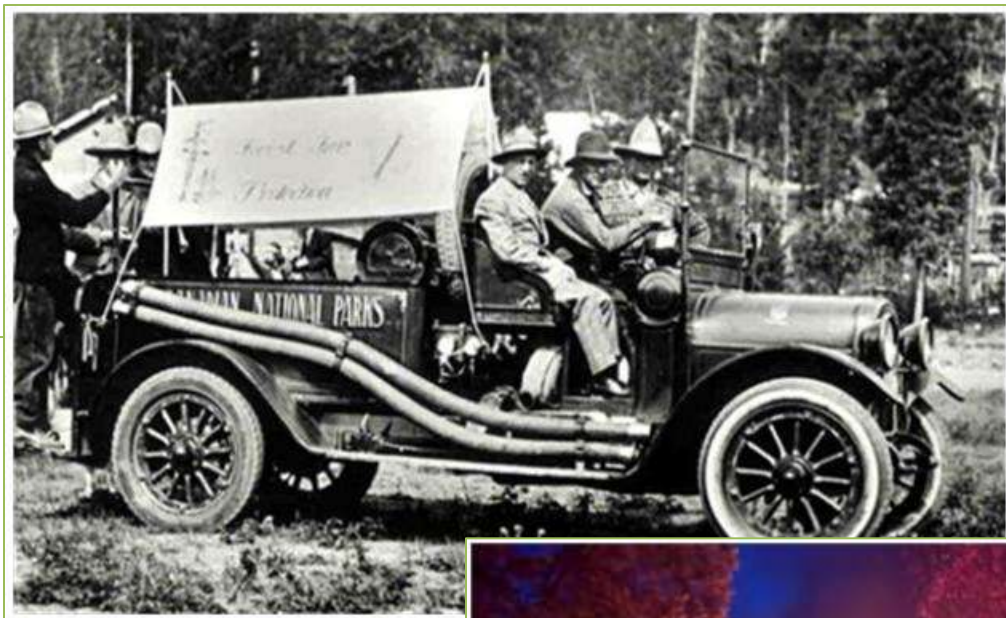

Photo Courtesy Gary Cones

Can History Help Guide Our Fire Management Futures?

Photo By Eli Lehmann

Wildland Fire Lessons Learned Center

A summary report on the special panel presentation featured at the International Association of Wildland Fire's Third Fire Behavior and Fuels Conference

Beyond Fire Behavior and Fuels: Learning from the Past to Help Guide Us in the Future

October 25-29, 2010
Spokane, Washington USA

International Association of Wildland Fire

Dr. Karen Cerulo, "Can History Help Guide Our Fire Management Futures?" panel member, was also featured as the conference's plenary keynote speaker.

Photo courtesy International Association of Wildland Fire

Contents

Paul Keller, Writer-Editor for the Wildland Fire Lessons Learned Center, prepared and designed this report.

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[Available for downloading at: http://www.wildfirelessons.net and http://www.iawfonline.org/]

Our goal with this panel is not only to have the audience listen to four excellent speakers talk about the uses of history, but to seek feedback from that audience—using techniques of large group facilitation—about what they have heard. This should make for a lively give-and-take discussion.

Most of us are familiar with the American philosopher George Santayana's quote that: *'Those who do not learn from history are doomed to repeat it.'* In the context of this panel, I believe we should consider: *'Those who cannot remember the Mann Gulch Fire, the Howling Fire, the Dome Fire, the 1910 Fires—are condemned to repeat them.'*

Dave Thomas
Panel Moderator

Panel Moderator: Dave Thomas

Over a 37-year career with the U.S. Forest Service, Dave Thomas held a variety of fire positions, including firefighter, district fire management officer, type I fire behavior analyst, and wildland fire use specialist. Thomas was one of the principal authors of an early fire plan for the Selway-Bitterroot Wilderness.

From 1999-2000, he served as the fire management analyst for President Clinton's Forest Service Roadless Area Conservation Environmental Impact Statement. In 2006, Dave retired as the regional fuels specialist for the Intermountain Region.

As a "high reliability organizing" consultant with the Wildland Fire Lessons Learned Center and a research associate with the Aldo Leopold Wilderness Research Institute, Thomas currently works with Dr. Dorothy Leonard of the Harvard Business School to capture the "deep smarts" of fire practitioners with high expertise in prescribed fire, fire behavior, and managing natural ignitions.

Panel Discussion

Can History Help Guide Our Fire Management Futures?

Panel Members

Steve Pyne is a Regents Professor in the School of Life Sciences, Arizona State University in Tempe. He is the author of more than a score of books, most of them on the history of humanity and fire; among them, *Year of the Fires: The Story of the Great Fires of 1910* (http://www.public.asu.edu/~spyne/). In a previous life he was a member of the North Rim Longshots for 15 seasons at Grand Canyon National Park. He has just published *Voyager: Seeking Newer Worlds in the Third Great Age of Discovery*. Voyager is an account of the Voyager space program—its history, scientific impact, and cultural legacy.

Karen Cerulo is Department Chair and Professor of Sociology at Rutgers University, located in Piscataway, New Jersey (http://sociology.rutgers.edu/FACULTY/cerulo.html). Her research interests address culture and cognition (with a special emphasis on conceptualization), decision-making, technology, social change, and community. Her articles appear in a wide variety of journals. Her books include *Never Saw It Coming: Cultural Challenges to Envisioning the Worst* (University of Chicago Press). Currently, she edits *Sociological Forum*, the flagship journal of the Eastern Sociological Society. She has served as the Chair of the American Sociological Association's Culture Section and the Vice President of the Eastern Sociological Society.

Jennifer Ziegler is an Associate Professor of Communication at Valparaiso University in northwest Indiana (http://blogs.valpo.edu/jziegler) where she teaches courses in organizational and corporate communication, as well as digital media and liberal arts. Her research focuses on rhetoric and culture in the management and practice of safety in dangerous occupations, with a particular emphasis on communication in wildland firefighting. Her research has appeared in journals such as *Communication Monographs, Leadership*, as well as *Management Communication Quarterly,* where she now serves on the editorial board. Committed to the cause of wildland fire safety, Professor Ziegler has helped in the planning of other IAWF conferences, including the Human Dimensions Conference and the Wildland Fire Safety Summit.

Jim Roessler is a Timber Sales Forester for the Confederated Salish and Kootenai Tribes in western Montana. Jim, raised in Enderlin, North Dakota, worked four summers as a steel gang laborer for the Soo Line (now Canadian Pacific) Railroad. Following his railroad experiences, he worked nine seasons on the Flathead, Lolo and Mission Valley Inter-Regional Fire Crews throughout the U.S. Jim retired from Federal Service in 2006 after spending 29 years in Fire Management for the U.S. Forest Service, Bureau of Indian Affairs, and BLM-Alaska Fire Service. Jim earned an A.S. Forestry, North Dakota State University-Bottineau; a B.S. Forestry, University of Montana; and an M.S. Natural Resources Management from the University of Alaska Fairbanks (UAF). His thesis at UAF is titled "Disturbance History of the Tanana River Basin in Alaska: Management Implications."

Panel Highlight 'Pull Quote' Comments

"There must begin to be some process of sifting, vetting, and judging (actual fireline experience stories). We have to have some way to evaluate and make sense out of these. Otherwise, the past just becomes a digital junkyard—filled with everything there but you can't find anything, you can't use anything, and you can't do anything with it."

"Flawed judgment is more often the source of error than faulty equipment or protocol. Humility matters as much as knowhow."

"Science helps make better pumps and pulaskis; history helps tell us what to do with them."

Steve Pyne

"Those who want to consult history and who want to learn from it and who want to apply it are fighting a difficult battle. It's not an impossible battle. But it requires us to understand the counter messages to which we're all being socialized. Messages that we're carrying around in our heads: 'Don't live in the past. Don't look back. Move forward now'. I think that recognizing those obstacles is critical to overcoming them."

Karen Cerulo

"For history to guide our fire management futures, we first need to understand the people management paradigms of the past and the present. We can then use our comparisons of different eras to escape what I call the 'tyranny of the present.' That is, we can import new management tools or rethink old ones in ways that tell a different kind of story about how people managing fire can relate to one another."

Jennifer Ziegler

"In terms of how things have changed regarding firefighter safety, my most recent bad experience was the I-90 Fire. . . It was like: 'they're doing LCES—everything is fine.' But in my book, things weren't fine.

I was also trying to get them to put in the shift plans that 'blow up' conditions are here. But I couldn't get that in there. And, as you probably know, we ended up almost having some fatalities there."

Jim Roessler

Introduction

Making Sense and Locating the 'Cash Value' of this Bewildering and Fascinating Theme:

The Uses of History

By Dave Thomas,
Panel Moderator

"If the destructible forest benefits and values are primarily sociological, what do the sociologists say? So far—almost nothing, just, nothing!"

Harry T. Gisborne

Harry T. Gisborne operating a double tripod heliograph in 1915 on Tip Top Lookout on the Wenatchee National Forest in Washington.

To meet the intent of the conference's organizing theme, the 100th anniversary of the 1910 fires, the steering committee for *Beyond Fire Behavior and Fuels: Learning from the Past to Help Guide Us in the Future* decided, early in its program planning cycle, to design a panel discussion consisting of academic experts and field practitioners. The mission of the panel presentation—entitled "Can History Help Guide Our Fire Management Futures"—was to have a robust discussion as to whether history can actually help fire managers do a better job of natural resource management, whether foresters can learn from the past to help guide their futures.

There is strong historical impetus to ask such socially oriented, historical questions, especially at a conference dedicated to fire behavior, fuels and the history of the Big Burn.

In 1943, Harry T. Gisborne, a historical figure of no small repute in fire behavior and forestry circles, founder of modern fire behavior research and the Missoula Fire Lab, in an article entitled "Sociological Shackles on Forestry," linked forestry practices with sociology. He chided sociologists for their absence from helping foresters do their work. Their motto, Gisborne wrote, seemed to say, "Let George, the forester, do it all." (Gisborne died of a heart attack while on a field trip to study the burn patterns of the Mann Gulch Fire.)

Panel members (from left to right): Jim Roessler, Jennifer Ziegler, Karen Cerulo, Steve Pyne, and moderator Dave Thomas.

Photo courtesy International Association of Wildland Fire

Panelists Prompted with Broad Questions

Our four distinguished panelists were given such broad questions as these to ponder: *Is applying history only a matter of grabbing what was available from history books and putting it to use today? Are there specific lessons to be learned from the 1910 fires that can be applied in the 21st century? Was there any truth to American philosopher George Santayana's oft-quoted statement that "Those who cannot remember the past are condemned to repeat it?" What, to piggyback on William James's phrase, is "the cash value" of history and forest management?*

The panel consisted of three academics and one practitioner chartered to discuss American fire history and its potential use in forest fire management: **Stephen Pyne**, the noted environmental historian at Arizona State University; **Karen Cerulo**, Department Chair and Professor of Sociology at Rutgers University who has studied the American version of the "optimism bias" and how this bias has created a society reluctant to fear the worst; **Jennifer Ziegler**, Professor of Communication at Valparaiso University whose research focuses on rhetoric and culture in the management and practice of safety in dangerous occupations, with a particular emphasis on communication in wildland firefighting; and **Jim Roessler**, a working—feet-still-on-the-ground—forester with numerous years of field experience, including work in fire behavior prediction and using fire history scar analysis as a management tool in such fire-evolved ecosystems as varied as those found in Alaska and Montana.

The last part of the almost two-hour panel session was designed specifically to engage the audience in one-on-one participation with the panelists, as well as with fellow audience members. At the end of the panelists' presentations, the audience was asked to pair-up with someone sitting next to them to take a few minutes to discuss what they'd just heard and digested. *Did the panelists' thoughts "make sense?" Can history actually be useful to on-the-ground, field-going fire managers? Or, were the thoughts expressed on this panel a lot of mumbo-jumbo, with history possessing little "cash value" for them?*

We would like to think that Harry Gisborne would have been delighted in our panel and in the audience's follow-up discussion on this afternoon in Spokane, Wash. A day when those specializing in history and sociology and communications and forestry joined hand-in-hand with practitioners to see if, together, they could make sense and locate the "cash value" of this often bewildering but always fascinating theme—the uses of history.

Steve Pyne Presentation Summary Highlights

Reconciling Those Who Believe in History with Those Who Don't

"I'm a historian. I've seen the past—and it works.

I believe that if you want to understand why the world looks the way it does around us—including the fire escapes that we are now dealing with—we have to understand how they were historically created.

But I'm also a member of the fire community, which shares—with Henry Ford—the dismissal of history as more or less: bunk.

What he (Ford) meant by that, was he was interested in the *future*—<u>not</u> the *past*.

My experience with the fire community is that your historical horizon is about three years.

I have spent my career trying to reconcile these two communities . . . "

Photo Courtesy National Park Service

The Fire Community Wants Data and Lessons

"I think in the fire community when we turn to history, we look to it as a depository of useful information . . . To turn history and other forms of knowledge into what William James called the 'cash value' of experience and practice.

I think what the fire community wants is data and lessons. It wants meaning.

Fire practitioners are trained that fire is an exercise in applied science that should be science-informed and not science-driven. We want to look to the past for data to expand the realm of what we can know and use.

After all, we can data mine cyber space—why not the past? . . .

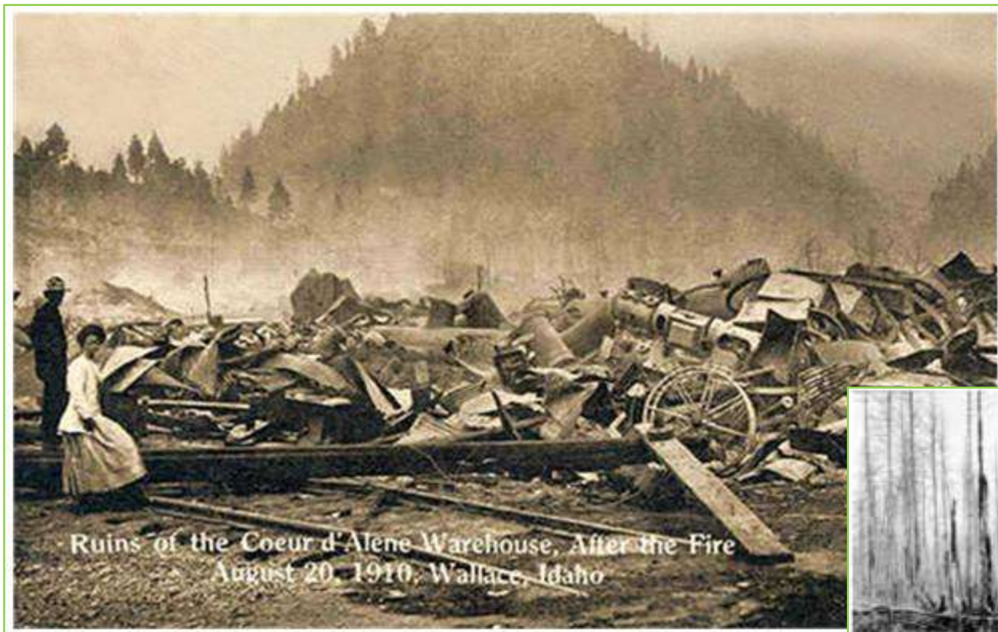
Unfortunately, it doesn't work that way. Because the past, while experimental, is not controlled, it doesn't produce information in a coded form that we can instantly slog in. It requires a lot of sorting. It requires a lot of judgment. It requires a lot of evaluation. So in that sense, you're liable to find it disappointing.

Well, if 'data' doesn't work, what about 'lessons'?

I mean, isn't history mostly 'stories'? And, aren't we suppose to learn from experience, draw lessons from the past, and code these lessons in the form of stories that we can understand and pass on?

But lessons tend to be very much a technological process. That is to say, we learn from the past to improve behavior or performance—in the same way that we could better design an automobile u-joint or perform open heart surgery. We're looking for a set of protocols, we're looking to refine and improve them. And it works very well in this form. But part of the difficulty with thinking of 'lessons' in that way is that they require a controlled environment.

I don't think 'wildland' is a dictionary definition of a 'controlled' environment. . . "



A Digital Junkyard

“ The other difficulty with ‘lessons’—as with ‘data’—is there tends to be too much or too many—particularly too many. Are there lessons and stories possible? There are showers of stories like sparks coming off a crown fire. They’re all over the place. We could assimilate thousands of fireline experiences.

But there must begin to be some process of sifting, vetting, and judging. We have to have some way to evaluate and make sense out of these.

Otherwise, the past just becomes a digital junkyard—filled with everything there but you can’t find anything, you can’t use anything, you can’t do anything with it. ”

Humility Matters as Much as Knowhow

“ We have to have some way of sorting through this—some, in effect, ‘checklist’ of stories. And we still need judgment to match stories with lessons, and lessons with probable fire line experience. They do not present themselves in an obvious way.

So I would also argue that the concept of lessons is difficult, as most of us would like to see it play out. Because the lessons of history are really about human character, not natural laws. . .

The appreciation of wisdom relies on character rather than information. Flawed judgment is more often the source of error than faulty equipment or protocol. Humility matters as much as knowhow. ”

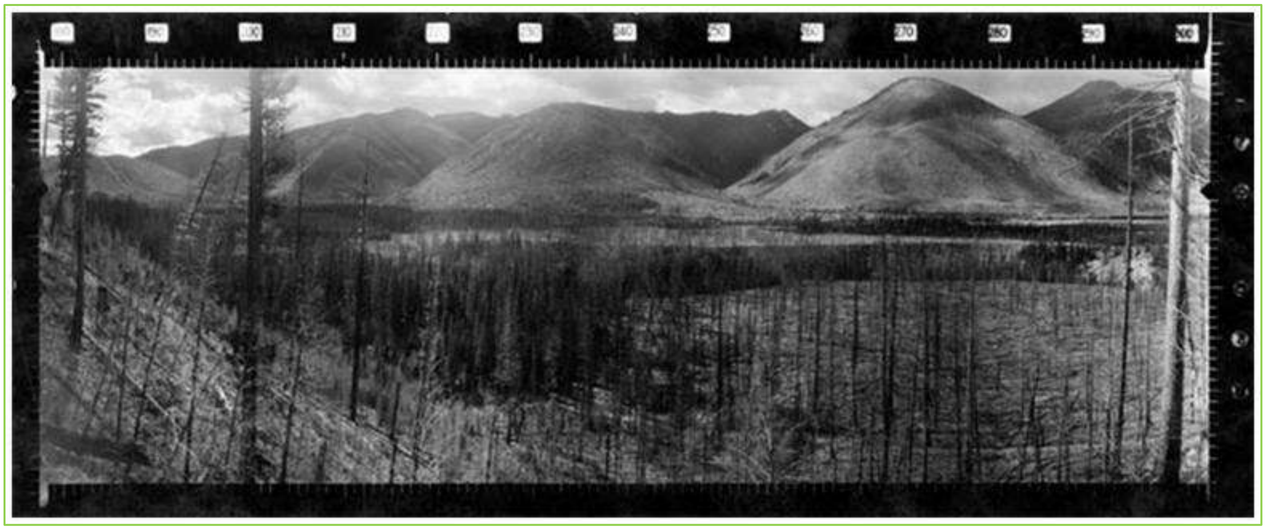


Photo Courtesy National Park Service

We Need Lots of Narratives, Just as We Need Lots of Models

"Historians preserve and celebrate the deeds of the clan. Beyond their role as chroniclers and court poets, they are critics who ponder, evaluate, and select.

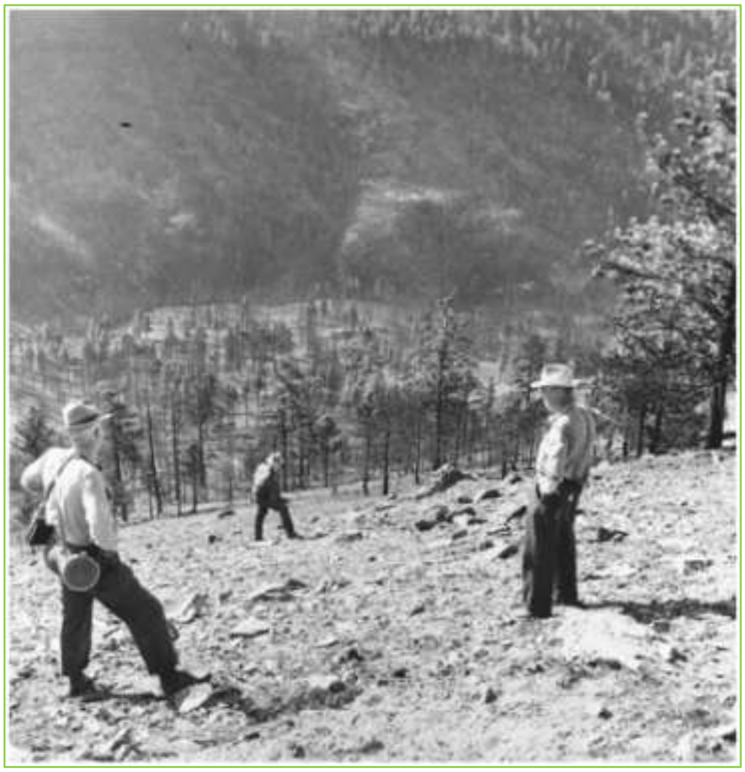
So the past then becomes usable in this way. Not just as datasets or scrolls of lessons, but because they are informed by some kind of judgment—and, for historians, this usually means recasting that judgment in the form of the narrative.

The idea of the 'usable' past is not a new one . . . It recognizes that narratives have their frames and they have their boundaries, just as scientific models have . . .

The primary exercise for historians is deciding when to begin and when to end. Because that will determine what the narrative arc is; that will determine what your theme is; that will determine what kind of meaning will be conveyed.

If you start the American fire story in 1492, you get one kind of outcome—one kind of narrative. If you begin that story in 1910, you get another outcome. And if you start that story in 1960, you're going to get still another outcome.

Is one story true and the other false? No. They're all true; they're all usable. But they all do different things; they answer different purposes. So we need lots of narratives, just as we need lots of models."



The immediate aftermath of the tragic Mann Gulch Fire.

Maclean Brought Mann Gulch to Our Cumulative Attention

"I find that very little happened as a result of the Mann Gulch (fire fatalities) in 1949 and the aftermath. It was a regional story. It was primarily a smoke jumper story—maybe a Region One story. It didn't seem to do much beyond that . . .

It's entirely possible to write a fire history of the United States without a reference to Mann Gulch. Or, it was until 1992 when Norman Maclean wrote a book about it.

Suddenly, Mann Gulch becomes an indispensable part of our contemporary history. And that is a classic exercise of how this kind of informed judgment can reflect back on the past and make impact. In a quest for cash value—Norman Maclean won the lottery."

We Need Both Science and Humanities

"I want to argue that we need both science and humanities. Science verifies data and humanities verify meaning. And, it is meaning that will ultimately guide practice because we must judge what we do by what we value and we value only what we can endow with significance.

It is through constructive meaning that we assess best practices and decide what is right and what is proper—and then determine what it is that we ought to aspire to.

Science helps make better pumps and pulaskis; history helps tell us what to do with them. And that's worth real money."

Steve Pyne

Karen Cerulo Presentation Summary Highlights

The complete text of Karen Cerulo's panel talk is available at:
Proceedings of 3rd Fire Behavior and Fuels Conference, October 25-29, 2010, Spokane, Washington USA; published by the International Association of Wildland Fire

Recognizing Key Obstacles is Critical to Overcoming Them

"The failure to use history to its utmost in planning for catastrophes is the product of three cultural patterns that firefighters, just like everybody else, have been socialized to.

What are these patterns?

The First Pattern:

Our culture is future oriented. We're taught to be planners, we're taught to set goals, we're taught to dream. Those are tasks that aren't anchored in the past. In fact, they are not even anchored in the present—they demand a future orientation.

In thinking about this idea I couldn't help but be reminded of work by social psychologist Phillip Zimbardo. You probably recognize his name. Years ago, Zimbardo did a very famous study at Stanford University called the 'Prison Experiment.' It was a study of the misuse of power. The study was referenced quite a lot during the Abu Ghraib incidents. In recent years, Zimbardo has been studying individuals, personality, and the project itself. He has been particularly interested in ways our present, past, and future selves interact with one another. Zimbardo treats those three selves as three distinct entities . . . In his many studies, the questions and answers he presents are fascinating—especially with regard to the use of the past in building "who we are."

For example, which self do people best identify with: past, present, or future? And how do these preferences influence behavior? Zimbardo and his colleagues find that those who most strongly identify with their present self often enjoy the moment, but disregard risk. Those who most strongly identify with their past self often seek the status quo; they're reluctant to deal with new and unfamiliar situations. Further, those who relate to the past are likely to suffer more emotional instability, depression, health problems, etcetera. Those who most strongly identify with their future self often engage in good goal setting and good self-control. And those who are anchored in the future are more successful at overcoming health obstacles and recovering from disease.

Zimbardo's work confirms what we have been told so many times before: 'Don't live in the past.'

The Second Pattern:

Here's the second one, on how culture discourages us from using history to avoid future catastrophes. We live in a culture that rewards ingenuity.

We value ingenuity. Our culture lauds originality; it lauds autonomy. It loves the next big thing. And often, all those characteristics require that individuals see themselves as the starting point, as the beginning of the turn, as the seed of the idea. And in that way, ingenuity is—by definition—free of history.

I did a small content analysis of essays written by people identified as innovators in their field. I wanted to see what advice such people gave to others. One recommendation kept coming up. If you want to innovate, don't look back.

Steve Jobs has been quoted repeatedly on this matter. 'Apple went rotten in the Nineties,' he argues, 'because the company became fixated with the past rather than the future.' He commands his Apple army to look forward rather than back.

In another arena, Jesse Jenkins, Director of Energy and Climate Policy at the Breakthrough Institute, has advised President Obama on economic innovation, saying: 'It's time to stop looking backwards to 2007 and instead look forward toward the new century unfolding before us.'

I think of the 'don't look back' strategy a lot in reading the papers of some of my younger colleagues. In fact, it often becomes an issue in people's tenure reviews. Many of the most innovative scholars are chided by those who evaluate them for failing to acknowledge the role of past work in their new ideas. The young, in turn, often argue that they need to break free from the past if people are to fully understand what is new and innovative about their ideas.

The Third Pattern:

And the third cultural pattern that I think is worth noting is that culture tells us that speed is good. Our culture values speed. We like fast cars, we like fast food, we like speedy service. We hate lines. We hate waiting. We're a 24/7 society. And we like quick fixes to problems . . .

Speed is something that is completely incompatible with history. History takes time. History requires us to be deliberate. In fact, good history requires us to wait and see, it requires us to step back—you have to gain perspective. Because, as the story unfolds, you may have to recode events, you have to rephrase context, you have to rethink conclusions . . . Speed is counter to productive history.

In many ways, I guess what I'm saying is that those who want to consult history and who want to learn from it and who want to apply it are fighting a difficult battle. It's not an impossible battle. But it requires us to understand the counter messages to which we're all being socialized. Messages that we're all carrying around in our heads: '*Don't live in the past. Don't look back. Move forward now'.*

I think that recognizing those obstacles is critical to overcoming them. ”

Karen Cerulo

Jennifer Ziegler Presentation Summary Highlights

The complete text of Jennifer Ziegler's panel talk is available at:
Proceedings of 3rd Fire Behavior and Fuels Conference,
October 25-29, 2010, Spokane, Washington USA; published by the International Association of Wildland Fire

Looking Outside Fire Management for Ways to Rethink Our Old Tools

"In response to the question, '*Can History Help Guide Our Fire Management Futures?*' my answer is an optimistic: Yes we can. But, specifically, I'd like us to focus on the 'management' part of that question. I think that this requires a deep understanding of the 'people' management context of whatever past that we're looking at—the people management context of the present—and then engaging the two in a productive way for the sake of the future. In some cases, this might actually mean looking outside of fire management for new tools—or, outside of fire management for ways to rethink our old tools."

Escaping the Tyranny of the Present

"My message today has three parts. First, we should cultivate the stories of the past for management lessons—but not take them too literally. Second, we should use the stories of the past to understand the management narrative or narratives in which we work today. Third, we should use the comparison between the past and present to escape what I call the 'tyranny of the present' by importing new management tools or rethinking old ones in ways that tell a different kind of story about how people managing fire can relate to one another."

The Current Management Paradigm Probably Won't Last Very Long

"I study organizational communications. My interests intersect somewhere between communications and management. So, what I'm talking about are management regimes or management paradigms as a kind of parallel as a business history approach to what Steve Pyne has done from a fire history management approach. We can think about recent history as having regimes of people management.

If you don't like the phrase 'management paradigms', you can call these management 'fads'. Because whatever the current management paradigm is, it probably won't last very long. Furthermore, the current management paradigm often becomes what I call 'the tyranny of the present.' But, thankfully, a coup will usually emerge to overthrow the current tyranny and the new paradigm will reign."

What Should Fire Managers Today Learn From the Ed Pulaski Story?

"To clarify, for history to guide our fire management futures, we need to understand the people management paradigms of the past and present. We are not to become stuck in the tyranny of the present, but to do our best to refashion the people management paradigm.

The War Eagle Mine in northern Idaho where Ed Pulaski and 42 firefighters survived the "Big Blowup" of Aug. 20-21, 1910.

First, let's see how we can cultivate the stories of the past from management lessons, but not too literally, because they're born of a different age. But also not too dismissively, because the contrast to today can help us understand both then and now.

For example, what do we do today with the story of Ed Pulaski when we think about Ed as leader on the fireline? As Steve Pyne pointed out, Ed became the cultural folk hero of the 1910 Fires and the Big Blowup. But he also continued on as a ranger. Therefore, in other ways, he was a rather mundane figure.

So what might fire managers and leaders learn today from this hero story?

. . . I think we can glean all kinds of information about the people management paradigm at the time that Pulaski did what he did. So in this pre-organized era of fire management, black-and-white thinking prevailed about firefighting goals. The stories are sprinkled with winners and losers/heroes and villains. You won if you put the fire out; you lost if you didn't. We're beyond that narrative today.

Being on the fireline then was a survive-or-die proposition. The management model then was a very simple model of command and control. In fact, I think the sociologists would call it a model of 'simple control'—literally one person controlling another. . .

It seems to me that there are lessons in the Ed Pulaski story about the value of improvisation, the importance of knowing the landscape, the importance of the ethic of caring about the safety of the others, thinking ahead, or even the terror of being entrapped by a fire when your escape route gets cut off . . .

But there's also a sense that this scene might not happen today because nowadays we might take steps farther upstream to prevent this scene from happening at all."

The Historical Meaning of the Ten Standard Firefighting Orders

“In some of my work I’ve looked at how lists like the Ten Standard Firefighting orders have been used in accident investigations. One of the things that I have seen is the tenacity of lists like the fire orders. They have been so difficult to change because they have been imbued with so much historical meaning.

One of the meanings of the fire orders is kind of like a memorial to the dead—particularly to the Mann Gulch firefighters. Therefore, if we remove or reject the fire orders, they’re sort of like a sacred cow. What happens to the promise that we made to the dead firefighters whose lives helped to bring the orders about?”

Recasting the Idea of Managing Risk

“Wouldn’t it be nice to get away from the tyranny of total quality management where we have to prove that this time we’ll now achieve perfection once and for all so that we can assure that this (a bad fireline outcome) will never happen again?

If you think about it, that promise was from a different time and place. It’s from the rhetoric of total quality management where perfection was thought to be desirable and possible.

So we might think about how we would recast the idea of managing risk—which is an emerging discourse in the fire community—in different ways.

But however the conversation does change, we need to look out for the new tyranny of the present when it does arrive. In the meantime, I think if we can change the conversation about the tools that we have and even import discourses from other cultures—who think differently about their work—there might be a benefit to this.”

Jennifer Ziegler

Jim Roessler Presentation Summary Highlights

The complete text of Jim Roessler's panel talk is available at:
Proceedings of 3rd Fire Behavior and Fuels Conference, October 25-29, 2010, Spokane, Washington USA; published by the International Association of Wildland Fire

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Three Short Decades Prove That Site Prep and Reforestation Have Been Successful

The Bureau of Indian Affairs (BIA) Flathead Agency offered me my first year-round position in December 1979 as a forester-fuels management officer responsible for planning, organizing, and managing a state-of-the-art fuels management program on the reservation.

Forestry at the time included even-aged patch harvesting of 'mixed and lethal' forest lands in 8- to 20-acre patches to treat root-rot, insect and mistletoe pockets. Uneven or all-age forest management was also the norm in non-lethal and mixed-fire regime forests. The forestry program had a backlog of prescribed broadcast burning to complete prior to hand-planting harvested stands.

The tribal forestry and BIA staff made excellent progress burning these stands from 1980 through 1985. In October 1985, I transferred to Alaska, where I worked the next 16 years for the BIA and BLM-Alaska Fire Service. In 2006, I returned to the Flathead Indian Reservation to work directly for tribal forestry as a timber sales forester. The Confederated Salish and Kootenai (CSK) Tribes 'compacted' forestry services from the BIA in 1995 through self-governance laws passed by the U.S. Congress.

These short three decades proved to me that the silviculture and subsequent site preparation and reforestation on the tribes' forest have been successful. Every day in the field I witness tribal forested landscapes that recently (within the last three to seven years) experienced large forest fires that crossed onto the reservation from adjacent U.S. Forest Service lands to the west.

I see the forest-harvested stands of 30 years ago where I worked to harvest, burn, and plant. These 30-year-old young forest stands of serial conifer species have survived the onslaught of large high-intensity and high-severity fires—such as the 2007 Chippy Creek Fire—which mostly kill the surrounding older cohort stands. . . "

A Landscape's Complete History is Missing from Our Land Management Plans

" In working in Alaska with the Indians, the State, with BLM Alaska Fire Service, the National Park Service and the U.S. Fish and Wildlife Service, we had a broad array of land management plans that were very well written. But, in a lot of cases, we were missing the big picture in terms of history.

"Jim Roessler was purposely selected for this panel. We felt it was important to have somebody here who still has one foot in the black."

Dave Thomas
Panel Moderator

For example, you can go into the archives and find information, such as a recon of Alaska in 1885. [*Editor's Note: Roessler holds up this actual reference book*]. There's a great amount of information in these books in terms of disturbance history—I'm talking landscape ecology—in terms of what shaped the landscapes and what's there today . . .

(When you do the extra archival research) it becomes obvious that there is evidence of all kinds of disturbance (to landscapes) that is not documented in current modern day management plans.

So we took this information and we approached the various land management agencies and said, hey, we can do a better job with our plans. "

On Firefighter Safety

" In terms of how things have changed regarding firefighter safety, my most recent bad experience was the I-90 Fire [2005 shelter deployment wildfire in Montana]. I was called there as a Fire Behavior Analyst. For safety purposes, every day around 2:30 p.m., I didn't want to be anywhere up those canyons *where suppression actions were occurring]. I talked to Safety, Ops, other FBANS, and a roving fire safety guy and expressed my concerns—but I couldn't get anywhere. It was like: '*they're doing LCES—everything is fine*.' But in my book, things weren't fine.

I was also trying to get them to put in the shift plans that 'blow up' conditions are here. But I couldn't get that in there. And, as you probably know, we ended up almost having some fatalities there. "

Jim Roessler

Q & A

"I can guarantee that humanity did not survive and make the world inhabitable through fire by doing prescribed burning the way that we do it now."

Steve Pyne
In response to panel Q&A question

Q

How Do We Make an Effective Narrative from a Complex Event?

"If we want to talk about the importance of history and narrative being useful, one of the limitations of that is that it needs to be a good narrative to be engaging. But a lot of the topics that we're dealing with are very complex—or they may not be optimistic. So if narrative is necessary for us to make history useful, how do we deal with the fact that maybe the stories that are the most important to learn from are not easily put into a narrative form?"

A

Steve Pyne:
"I think that's where the art and craft and history come in. That's the charge. We would ask the same thing of science. You've got a difficult phenomenon out there, how are you going to model it? How are you going to make sense out of it? If we had masterpieces coming out every time, they wouldn't be masterpieces. It's a very small fraction that actually succeeds. Think about how many books have had the impact of Maclean's *Young Men and Fire*. So I would say that that's the challenge—and there are ways to solve this.

There are literary strategies. The rules are very simple: You don't make anything up, you don't leave out anything that really needs to be there—and it needs to be there if it changes the story. Other than that, you're at liberty, I think, to shape the narrative anyway that it makes sense.

Twenty people can look at the same story and we're all going to write it differently. And they all tell us something. If you stay by the rules, you've done your job. So I think that's the challenge.

Q

What Fire Implementation Lessons Can We Learn from Native Americans?

"It occurs to me that we have a whole bunch of geographic ancestors—Native Americans—who lived with fire and intentionally set fire for thousands of years. So I'm wondering what kind of lessons we can learn from their history and the extent to which we tend not to look at that very much. How did those people live with fire, how did they use it, and what can we learn from them culturally?"

A

Jim Roessler:
"I work for tribal forestry. Indian forestry has been going on since 1855 on the Flathead Indian Reservation. They were doing forester silviculture with fire ever since then. They've been burning a long time—ten thousand years."

Steve Pyne:
"Actually, it's longer than that. In all of our existence as a species we've used fire. Increasingly, the evidence suggests that goes back to Homo erectus. We are so adapted to fire that we are physiologically unable to survive without cooked food. We cannot live on raw food alone. That's how long we have been in association with fire . . .

I think that there are a lot of things that we can learn from the past. For one thing, people succeeded in burning on landscape scales, not on set pieces as we do now—but by being, in effect, foragers over long periods of time. Starting early in the season, burning bits and pieces, following the snow up, burning around wet areas, and letting them dry, and then going back and burning these areas. It is a continuous process over a fairly long period of time. You can still see this in operation in parts of the world today.

But that is not how we do it today. The way that we do it, we're always going to lose because there's something that will cancel it and there's nothing that will put it back up and replace it. So we have a formula which is calculated to fail over the long run. We will continue to erode. We seem unable to learn from the past. How did they (the Native Americans) manage to do that? I would have crews out on some of these landscapes for two-week periods just foraging fire. Burning in bits and pieces. Following the snow up, following the weather. Adjusting it in very different ways.

That requires us to rethink how we do prescribed fire. I can guarantee that humanity did not survive and make the world inhabitable through fire by doing prescribed burning the way that we do it now."

Concluding Remarks

Can History Help Guide Our Fire Management Futures? Panel

"First, I would like to thank the panel.

Steve (Pyne), you said there's value but limitations.

Karen (Cerulo), I think you said that it takes time to filter through history.

For me, Jennifer (Ziegler), you reemphasized the importance of stories.

And, Jim (Roessler), you validated it."

Marty Alexander
Program Committee Chair
3rd IWAF Fire Behavior and Fuels Conference

Moderator Dave Thomas concluded the panel session by reading the following poem from John D. Guthrie's 1929 book *Forest Fire and Other Verse* whose 321 pages feature poems written by U.S. Forest Service employees. Will C. Barnes notes in the book's Foreword: *"A book of verses by and about the men and women of the United States Forest Service! What a fine idea to round them all up and present them for future foresters to read and wonder what manner of men and women they were—these pioneers of the early days."*

IT IS NOT EASY

To go to a fire at night.
To keep fire tools branded right.
To keep co-operators on their toes.
To listen to the permittee's woes.
To keep the tourists from leaving fires.
To keep from arousing the public's ire.
To keep timber operators up to the scratch.
To watch the smoker and the dangerous match.
To make the camper clean up his camp.
To courteously route the auto tramp.
To make a speech.
BUT IT ALWAYS PAYS.

--Paul Gilbert
1929

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Casting the stories of the past into the management narratives of the present

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Abstract
This manuscript is based on remarks presented during the panel session 'Can history help guide our fire management futures?' It focuses on the 'management' part of 'fire management' and answers the questions with a yes. Three recommendations are proposed. First, to cultivate the stories of the past for management lessons, but not too literally. Second, to use the stories of the past to understand the management narrative(s) in which we work today. Third, to use this comparison to escape 'the tyranny of the present' by importing new management tools or by rethinking old ones in ways that tell a different kind of story about how people managing fire can and should relate to one another.

Additional keywords: checklists, communication, management paradigm, paradigm shift.

Introduction

I'm the third college professor in a row to speak to you. You may or may not know that colleges and universities have to be accredited by outside agencies. What you also may not know is that the agencies that accredit us no longer require us to prove that we are actually *educating* our students. We just have to show that a) we identified a problem last year, b) we committed to do something about it, and c) we came out better this year. So, in a sense you could say they are happy if we show that we educated our students *less badly* this year than we did last year.

I'm exaggerating of course. And I can because I know that all three of us care very deeply about educating our students. But I tell this story as an illustration of what some might call a 'paradigm shift', and specifically a *management* paradigm shift.

In higher education we have apparently shifted from the paradigm of 'total quality management' to the paradigm of 'continuous improvement'. We have shifted from needing to prove that we consistently deliver the highest quality product, to needing to prove that we can self-monitor, spot trends, devise fixes, and measure our own improvement, and report it. In other words, we have shifted from the need to *speak the rhetoric of total quality* to the need to *speak the rhetoric of continuous improvement*.

Once you recognize that that's the communication game, it makes it a lot easier to play by the rules. Now, of course you might ask: Why can't we just have a conversation about good education? And the answer is that we can, but we also have to systematize and bureaucratize. Standardization not only makes it easy to measure and compare things across different organizations, but it also provides a shortcut and even a substitute for communication that might otherwise be repetitive and inefficient.

So what does moving from one management paradigm to another in higher education have to do with learning from fire management history for the sake of future fire management? Plenty, I think. In response to the question 'Can history help guide our fire management futures?' My answer is an optimistic, 'yes we can', but, specifically focusing on the 'management' part of the sentence, I think this requires a deep understanding of the *people management* context of whatever past we're talking about, the *people management* context of the present, and engaging the two in productive ways for the sake of the future. In some cases this might mean looking outside of fire management for new tools and for ways to rethink old ones.

So, my message today, like the two preceding mine, also has three parts: First, we should cultivate the stories of the past for management lessons, but not too literally. Second, we should use the stories of the past to understand the management narrative(s) in which we work today. Third, we should use this comparison to escape what I will call 'the tyranny of the present' by importing new management tools or rethinking old ones in ways that tell a different kind of story about how people managing fire can and should relate to one another.

From fire management regimes to 'people management' regimes

Steve Pyne's life's work in fire has illuminated the historic fire management regimes in the U.S. and in other places in the world. Others in business history and elsewhere have similarly told the story of 'people management' regimes that have taken hold throughout the ages. I don't mean to separate the management of fire from the management of *people* in fire too distinctly, because the closer you look, the blurrier the boundary becomes. But if we're talking about lessons for people whose job it is to manage fire now, it's also important to understand *the genealogy of management thought*, or the people management regimes that have gotten us where we are today. These originate beyond the fire community in the larger culture within corporations and organizations in general (in part aided by business schools but also by industry conferences and in everyday discourses about how best to manage people).

Now, if you don't like the phrase 'management paradigm', you could call these 'management fads' for short if you like. Because whatever the current management paradigm is, it probably won't last very long. Remember Total Quality Management (TQM)? Furthermore, the current management paradigm often becomes what I am calling the tyranny of the present. (Again, remember TQM?) But, thankfully, a coup will usually emerge to overthrow the current tyranny and a new paradigm will reign.

To clarify, for history to guide our fire management futures, we need to understand the people management paradigms of the past, the people management paradigms of the present, but not to become stuck in the tyranny of the present but to do our best to refashion a new people management paradigm when it is needed.

1. Cultivate the stories of the past

First, we should cultivate the stories of the past for management lessons, but not too literally because they were born of a different age. But also not dismissively because it is the contrast to today that can best help us understand both then and now.

For example, what do we do today with the story of Ed Pulaski? (For details, see Pyne 2008 168-169; Ribe 2010). As Steve pointed out, Ed became the cultural folk hero of the 1910 fires and the big blowup, but he also continued as a ranger in the community (of Wallace, I assume). So in other ways he was a rather mundane figure. So what might fire managers and leaders today learn from this hero story?

Obviously we can't take his leadership style literally. I mean, the new leadership curriculum emphasizes the importance of having 'command presence' (cf. Ziegler & DeGrosky 2008). But I don't think that holding people at gunpoint in a mine shaft is exactly what they are teaching lately in the L-380 course.

But we should stop ourselves if we are tempted to dismiss the story as not relevant to today. We can glean all kind of information about the people management paradigm of that time. In this pre-organized era, black and white thinking prevailed about fire fighting goals, and the stories are sprinkled with winners and losers, heroes and villains (Thackaberry 2005b). You won if you put the fire out, you lost if you didn't. And, being on the fireline was a survive or die proposition. The story that survives becomes one of the cult of the person.

The management model was a very simple version of command and control (in fact what sociologists would call simple control of one person literally standing over another). This is evident in the held-at-gunpoint moment, and at the challenge that Pulaski uttered when he apparently rose from the ashes to declare that he was not dead (when his charges were trying to leave). You can even see the understanding of management through simple control in the Miller and Cohen (1978) book: numerous artifacts show people being blamed for their own deaths because they did not listen to their supervisors.

Many of those arguments about blaming the dead wouldn't work today. We may still use these vestiges of a bygone era, but once it hits the light of day it can perish instantly, because our audiences are working within a different paradigm where different rules apply. (Consider the outcry over the original Thirtymile Fire report as one example.)

When it appears that we have reached our limits of the story's *literal* relevance, we can still look for other useful lessons from the past that now might be lost to history, for which current day examples might be difficult to find. I haven't thought too deeply about the Pulaski example but it seems to me there are still lessons in the Ed Pulaski story about the importance of improvisation, the ethic of caring for the safety of the other, the importance of knowing the landscape, thinking ahead, and jeez – even the terror of being entrapped by a fire when your assumed escape route gets cut off. I mean if this can happen to Ed Pulaski, it can happen to anyone, right? Nowadays we would talk about using the story to create some new slides for your slide tray.

What also might come to mind is the sense that this scene might not happen at all today because we would take steps further upstream to prevent it from happening in the first place. You can probably see where I'm going next.

2. Use the stories of the past to understand the management narrative(s) of the present

Second, we should use the stories of the past to understand the management narrative(s) in which we work today. Earlier this year, Larry Sutton from the Forest Service at NIFC did an interesting thought experiment in a presentation where he asked: What would happen if Ed Pulaski worked for the Forest Service today? Here are some of the ideas he came up with:

- Forest Service officials vow 'never again' as investigation begins in firefighter deaths in North Idaho firestorm
- Forest Ranger charged under workplace violence law for pulling gun on crew members
- Agency report indicates errors led to crew being placed in harm's way, resulting in 5 deaths
- Letter of reprimand given to Ranger for carrying unauthorized weapon in violation of Manual direction
- U.S. Attorney's office files negligence charges against Forest Ranger in deaths of 5 firefighters at War Eagle Mine
- Families of firefighters who perished sue Forest Service

- PETA sues Forest Service for animal cruelty in deaths of horses in wildfire (Sutton 2010)

Others I have spoken to would add that Ed Pulaski would ‘lawyer up, plead the 5th, and it would go to trial’. According to Steve Holdsambeck’s comparison between serious accident investigations and criminal investigations, ‘Even if Ed had escaped the U.S. Attorney, our own accident investigation methodology was predestined to convict him administratively and publicly’ (personal communication, October 21, 2010).

This kind of exercise reveals some of the absurdities of our present narrative precisely because it is a past hero that we are talking about.

But we should also look for things to celebrate about today that might have made Ed Pulaski’s life better today than it was back then. The story also continues that he died bitter about his medical expenses. He tried to patent the Pulaski but couldn’t spend the money to get it done. The most that could be done after his death was to put his name on the tool but no money went to his widow. So we can think about things like health benefits, worker’s comp., employee rights to physical safety, upward voice in the organizations, etc.

3. Consider picking up some new tools

Third, once we discover by contrast, the ‘the tyranny of the present’ we should think about importing new management tools or rethinking old ones in ways that tell a different kind of story about how people managing fire can and should relate to one another.

One of the tyrannies of the present is the public promise, after a tragedy fire, that ‘this will never happen again’. I’ve looked at how the Fire Orders have figured into this promise, and how sworn oaths to prevent people from having died in vain have, understandably, made it difficult to break out of the pattern (Thackaberry 2005a).

I was intrigued when physician and author Atul Gawande (2009) came out with a book called *Checklist Manifesto*. I wondered, why would someone write a ‘manifesto’ in 2009 about the importance of checklists, and particularly checklists for controlling the actions of people? And I wondered what the fire community would make of it. (To tell you the truth, I thought you all would hate it.)

It’s actually not what you would expect. That is, if you are expecting a book that rants about how the world was perfect when we organized by checklists. It’s actually, as one book review points out, a book about teamwork (Brown 2010). I also think it’s a book that can only really be understood within the paradigm of continuous improvement, which I discussed at the beginning with respect to college accreditation.

Listen to how Gawande talks about the complexity of modern day surgery. And see if any of this rings a bell with you in fire management. Hospitals now recognize that people die not only because of disease but also because of medical error, and this is happening everywhere on the globe. Gawande attributes this to the superspecialization of medical professionals. Nowadays medical professionals may have knowledge that is an inch wide but a mile deep. But this creates barriers to them working together effectively. Often people show up to the operating room at the top of their game but having never worked together before. With the aid of technology, more things can go wrong than ever before. Yet people have to work together as a team for the operation to succeed, and to prevent medical errors from killing their patients (Gawande 2009).

Medical establishments don’t even bother trying to say ‘this will never happen again’ when medical errors happen because they know they will. They measure, and try a new tool for reducing the incidence and frequency by catching the errors or complications most likely to cause harm, before they begin. So one of the functions of a list in an emergency room, according to Gawande is to generate conversation; To use a management buzzword, a list can help to create shared mind among people who don't normally work together. But it's not a property of the list itself. It's inherent in how they use it to overcome interpersonal barriers to organize themselves as a team. This is a big contrast to the historic use of lists which was to avoid or substitute for interaction.

Isn't that refreshing? Wouldn't it be nice to think about the Fire Orders, for example, in that way? Oh wait, we already have: This language crept into the management evaluation report for the Cramer Fire where the Ten Standard Fire Orders were discussed as a tool for generating conversation and coordinating interaction, even though they had never been talked about in that way prior to that (Ziegler 2007). A new management paradigm was creeping in.

Now, Gawande does not say whether after a patient death the hospital goes after the team by pointing to checklist items that went unrecognized. One would hope not. But his purposes for suggesting the list are broader than that because his aims are higher than the individual operation. He's interested in medical sustainability on a global scale. So I think we should say that he situates checklists within a rhetoric of teamwork, in service of a commitment to continuous improvement to achieve sustainability on a global scale.

I've written about a couple of different moments where the conversation could have changed about the Fire Orders in the past, but for whatever reason didn't quite reach escape velocity at the time (Thackaberry 2004, 2005a, 2006; Ziegler 2007). Despite the title of the book, *Checklist Manifesto*, I actually find some hope that Gawande's book could stand to reorient the conversation about lists because it uses the list in a very different kind of conversation about how people manage and work together. It actually focuses our attention away from the list and toward the interaction among the people doing the work, for which the list is only a tool. This turns out not to be much of a manifesto but rather a way to look at the old tools within the context of a new way of thinking about managing people.

Think about this: The promise that 'this will never happen again' was from a different time and place. It's from the rhetoric of total quality management where perfection was thought to be desirable and possible. Wouldn't it be nice to get away from the tyranny of total quality management where we have to prove that this time we will now achieve perfection once and for all by making sure this never happens again? What if we thought about it in a new way? From the point of view of continuous improvement (even global sustainability) the question can be recast as minimizing the extent and impact of inherently risky work. How would the Fire Orders be used differently in that case?

But don't get too comfortable – however the conversation does change, we should look out for the new tyranny of the present when it presents its own absurdities, like the academic assessment game that I mentioned at the top of my talk.

Concluding remarks

In conclusion, when looking to learn from history, first, cultivate the stories of the past for management lessons, but not too literally. Second, use the stories of the past to understand more clearly the management narrative(s) in which we work today, including their absurdities. Third, use this comparison to escape 'the tyranny of the present' by importing new management tools from elsewhere, or by rethinking old ones (like lists) in ways that tell a different kind of story about how people managing fire can and should relate to one another.

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Can history help us in wildland fire management?

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Abstract
Yes, history can help in fire management, as well as forest management, wildlife management, park management, and natural resources management. I will address three areas or issues where history is important: my experience in natural resources and fire management in Alaska, my current experience as a Timber Sales Forester for the Confederated Salish and Kootenai Tribes on the Flathead Indian Reservation in Montana, and my perceptions of how firefighter safety in 1910 was lacking while the same firefighter safety issues exist today.

Additional keywords: forest management, firefighter safety, 1910 fires, Alaska, Tanana Valley

History and fire and forest management in Alaska

In Alaska I realized that history—in particular, disturbance history—was missing in natural resource and land management plans in Interior Alaska. The forests of Interior Alaska have a disturbance history that has been largely ignored in the planning process, especially in public documents. Although various land management plans discussed forests, wildlife, and the landscape in detail, using terms such as *pristine* and *natural*, little or no reference was made to human-caused disturbance, such as timber harvest, deliberate or accidental fire, and fire control. Managers embraced ecosystem management, but failed to include in their planning the historical agents of change that contributed to today's forest cover mosaic. For example, in 1915, the town of Chisana was operating two sawmills; for a time, another mill was operating in Bonanza, Alaska. These upper Tanana Valley mills were in what is now the Wrangell-St. Elias National Park and Preserve (Capps 1916). How do resource managers manage such conditions for the future or account for them?

Another example is a case study of the Tolovana River area in the Tanana Valley that provides an in-depth view of timber harvest effects (Roessler 1997). This case study begins with a curious news item from the front page *Fairbanks Daily News-Miner* of 23 April 1915: 'Sawmills for the Tolovana at Mouth of Livengood Creek – This Summer for Sure – Large Timber Permits Are Taken Out by Prominent Operators.' However, neither the resource management plan for the area, detailed in the Alaska Department of Natural Resources' (1991) Tanana Basin Area Plan for State Lands, nor the Alaska Department of Environmental Quality's (ADEC) (1988) Tolovana River and Livengood Creek Basin Use Attainability Analysis make any mention of any timber harvest activities or associated disturbance. No acknowledgment or consideration was made concerning the disturbance factors that resulted in the landscape mosaic of paper birch and white spruce throughout the valley. The Use Attainability Analysis proposed that the Tolovana Basin be classified as 'high value resource management habitat' (ADEC 1988:112). For practical purposes, both documents considered the forests to be 'pristine,' suggesting an original state or only minimal impacts by humans (Roessler and Packee 2000).

The two government documents cast doubt on whether the timber harvest ever took place, yet the newspaper report from 1915 stated that a timber permit had been applied for at the U.S.

land office for two million board feet of saw timber. The timber to be cut would extend from 2 miles (3 kilometers) below the mouth of Livengood Creek for 12 miles (19 kilometers) upstream along the Tolovana River. According to the newspaper story, one sawmill—possibly two—would be erected near the mouth of Livengood Creek if the permit were granted. During a helicopter visit to the proposed timber harvest area in mid-September 1996, no obvious evidence of timber harvest was noted from the air. (In 1939, organized fire suppression in Alaska began with the creation of the Alaska Fire Control Service (Pyne 1982, Robinson 1960). From the 1950's through the early 1980's, when suppression resources were available, aggressive initial attack was taken on all fires throughout Alaska.) This area has been in 'full protection' from fire, meaning that all wildfires are aggressively suppressed. The fall color of the paper birch contrasted with the dark green of the spruce and gave the impression of a 'pristine' forest. The large patches of birch suggested disturbance as birch is an early successional species. Since there was no evidence of roads, the likely suspect was fire.

The helicopter landed on a sandbar near the mouth of Livengood Creek near one of the large, single-cohort paper birch stands. Inside the stand, there was no obvious evidence of human disturbance. The ground surface had a unique characteristic: frequent, low humps covered with vegetation and leaf litter. Further inspection revealed that these humps were remnants of white spruce stumps, and they were evident everywhere. The stump surfaces were uniformly flat, indicating that they had been cut. Thus, it was concluded that the timber sale had indeed occurred. Upon further examination of the site, charred stumps were also found. In other words, not only had the site been harvested, but it had also been burned.

The patches of birch were a second-growth forest resulting from the 1915 timber sale and subsequent harvest. Harvested stumps in the area averaged between 46 and 71 centimeters in diameter, suggesting a high-quality spruce stand. One mature white spruce approximately 28 meters tall had escaped the harvest effort and fires; it was approximately 64 centimeters in diameter at breast height and 126 years old. This tree was probably too small to be considered for harvest and was left; once its competition was removed, it grew rapidly.

Photographs located in the Archives of the Rasmussen Library, University of Alaska Fairbanks (UAF) (John Zug Collection 1908-1915), show a tent camp or logger camp near the mouth of Livengood Creek. One photograph taken in 1915 was from the same direction of another photo taken in 1996 from the helicopter. The similarity of the hill and landscape in the background of both photos is a perfect match, showing the same landscape 81 years apart. Another photo from the same photo archive collection shows a log cabin with the sign 'Lake City Road House' at the mouth of Livengood Creek. The lack of roads suggests the trees were moved to the river in late fall or winter, when the ground was frozen and covered by snow. Most likely, horse-drawn sleds were used.

Photographs taken after a fire in July 1997 about 5 kilometers south of Livengood Creek on the Tolovana revealed another possible means of transporting timber. The post fire photo demonstrated that the fire exposed a long-abandoned narrow-gauge railroad or tramway bed paralleling the Tolovana River that may have been used to transport the timber from the 1915 timber sale as well as from others. Interestingly, where the fire did not burn, there is no evidence whatsoever that any railroad or other man-made transportation system was ever built into the valley.

This case study demonstrates the need to scrutinize the past land use of an area as forests—even the reputedly slow-growing forests of the north—are resilient and can hide evidence of people's activities quite rapidly. This example also provides evidence that the harvesting of timber followed by fire is a valid prescription that works in these forest cover types of Interior Alaska.

Today much debate and conflict center on forest management policies and objectives for forested landscapes; Tanana Valley forests are no exception. Many people believe the present-day landscape of the Tanana Valley in Alaska is largely pristine and relatively untrammeled by humans. The evidence shows this is not true. Many see only a snapshot of the landscape today and believe the forest will stay that way. Yet the snapshot is only a temporary state and the result of past disturbances. The landscapes of the Tolovana and other areas throughout the Tanana River Basin and the Flathead Indian Reservation in Western Montana fit Schama's (1995: 9) conclusion that 'even landscapes that we suppose to be most free of our culture may turn out, on closer inspection, to be its product.' Schama's (1995) *Landscape and Memory* provides excellent reference material supporting this conclusion.

Findings suggest that if the diversity of landscapes today is to be continued, disturbances—whether timber harvest and/or fire—must be reintroduced into the landscape. The public and most resource managers continue to miss much; they have ignored the importance of disturbance in maintaining the supply of timber, wildlife, and recreational experiences for present and future generations. They have ignored the use of disturbance for maintaining forest health. They have ignored the essential role of past disturbance events in fuel loadings and stand structures, which affect fire risk, severity, and control. Early successional stage hardwood and coniferous forests in the subarctic and temperate forests of the Northern Rockies region are semi-barriers to wildfire and could highlight one of the most important benefits of looking at past fire use.

Historical land use information is absolutely necessary to develop cost-effective fire and forest management plans. By including historical evidence of disturbance, fire, forest, and natural resource management plans can be refined and justified. Timber and wildlife managers must work with fire management specialists in order to better emulate ecosystem processes. Forest managers who attempt to harvest white spruce in Alaska or non-lethal, mixed, and lethal forests of the Northern Rockies to mimic ecosystem processes without using fire are missing an important ecosystem component.

Without considering and documenting historical disturbance in disturbance-driven ecosystems, resource plans are flawed. The public and Tribal membership must be fully informed of historical disturbance and the implications of such disturbance, particularly when addressing such debates as harvest versus no harvest in perpetuity, areas that are provided full fire protection, or areas that are the result of past logging, even when not apparent.

I believe that 'nature' will be what we humans make it to be. Botkin (1990:193) insightfully addresses this prediction: 'The question is the degree to which this molding of the future will be intentional or unintentional, desirable or undesirable.' In terms of natural resource management, the public and resource managers need to look to the past for answers for today and the future.

Experiences with history related to forest and fire management on the Flathead Indian Reservation

The Bureau of Indian Affairs (BIA) Flathead Agency offered me my first year-round position in December 1979 as a Forester-Fuels Management Officer responsible for planning, organizing, and managing a state-of-the-art fuels management program on the reservation. Forestry at the time included even-aged patch harvesting of mixed and lethal forest lands in 8- to 20-acre patches to treat root-rot, insect and mistletoe pockets. Uneven or all-age forest management was also the norm in non-lethal and mixed fire regime forests. The Forestry

Program had a backlog of prescribed broadcast burning to complete prior to hand planting harvested stands.

The Tribal Forestry and BIA staff made excellent progress burning these stands from 1980 through 1985. In October 1985, I transferred to Alaska, where I worked the next 16 years for the BIA and BLM-Alaska Fire Service. In 2006, I returned to the Flathead Indian Reservation to work directly for Tribal Forestry as a Timber Sales Forester. The Confederated Salish and Kootenai (CSK) Tribes ‘compacted’ forestry services from the BIA in 1995 through self-governance laws passed by the U.S. Congress.

These short three decades proved to me that the silviculture and subsequent site preparation and reforestation on the Tribes’ forest have been successful. Every day in the field I witness Tribal forested landscapes that recently (within the last three to seven years) experienced large forest fires that crossed onto the Reservation from adjacent U.S. Forest lands to the west. I see the forest harvested stands of 30 years ago, where I worked to harvest, burn, and plant. These 30-year-old young forest stands of serial conifer species have survived the onslaught of large high intensity and high severity fires, such as the Chippy Creek Fire of 2007, which mostly kill the surrounding older cohort stands. The patch dynamics of even aged, all aged, or uneven aged forest silviculture harvest work, if followed by prescribed fire, were much more successful than the adjacent forest stands I worked on the Flathead, Lolo and Kootenai National Forests as a forest technician with the U.S. Forest Service (USFS) from 1975 through 1979. Let me clarify that my observations are by no means a slam against the people of the USFS of the past or present. In my view, the enactment of the National Environmental Policy Act (NEPA) and other legislation in the past, albeit based on good intentions, has created an infinite array of legal conflicts that allow litigation to enjoin and ensnare almost any management decision on USFS lands. Government funding of non-government entities has contributed to thousands of lawsuits against proactive USFS forest management, each of which creates conflicts in terms of meeting the original goal of the sustained yield of forest products for the nation and the communities that depend on them.

Many people do not realize that the CSK Tribes are also required by law to comply with NEPA through the statute of Code of Federal Regulations (CFR) 25, just like the adjacent USFS Lolo, Flathead and Kootenai National Forests in Western Montana. People ask how can the Tribes sustainably harvest 18 to 58 million board feet of mixed conifers species annually, under the same NEPA laws as the USFS, especially as the three adjacent USFS Forests can barely get any timber harvesting conducted. I tend to agree with Bill Hagenstein (2010:114) that it may be time to have Congress restate what our national forests are for. The Act for the Administration of Forest Reserves of June 4, 1897 (known as the Organic Act), states that, ‘No forest reservation [which is what national forests were called then] shall be established except to improve and protect the forest, or to secure the favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of the citizens of the United States’ (US Government 1897). To date, there have been no changes to the original intent of this act.

Why the difference? How can the CSK Tribes actively manage and sustainably harvest millions of board feet of their forests annually under the same NEPA laws as the USFS while the USFS is stymied to harvest? In my view, the special interest non-government entities use NEPA law as a ‘club’ over the USFS to prevent any active forest management of public lands. These groups do not, for the most part, interfere with Tribal management of their ‘Trust’ reservation lands. This is likely due to the fact that their arguments would not hold up in a court of law and their organizations would probably have to pay for court costs and costs associated with the delay of actively harvesting and managing Tribal forests.

I agree with Michael Newton's commentary *Using Goals, Not Courts to Manage Federal Forests* (2010:11): ideally, 'a rollback of conflicting rules, regulations, and laws would pave the way for a return to a focus on accomplishing forest management goals on U.S. Forest Service Lands.' However, this will take time and a change in leadership. Within the last year, I listened to presentations at an annual Society of American Foresters Conference in Missoula, Montana. There was discussion among the states of Montana and Idaho questioning the federal government's (U.S. Forest Service) ability to manage the public lands. The talk resembled what I recently read in Henry Clepper's (1971:44) book, *Professional Forestry in the United States* when Governor Frank F. Gooding of Idaho claimed that 'the interests of the whole country would be best served if Congress would turn over to the States all of the public domain, under proper laws looking to the protection of the forest and the range, to be administered and developed by the citizens of those States.' And I was proud when Clepper (1971:44) noted that 'fortunately, not all the governors were so self-seeking as these honorable delegates.' Governor John Burke of North Dakota pointed out that there are some delegates who want to give the States the control of the National Forests. Affirming the constitutional right of the federal government to establish national forest reserves, this enlightened governor urged the federal government 'to retain absolute control over such territory… and to conserve the whole interests of those who are to come after us as well as those who are now enjoying its benefits' (Clepper (1971:44). Being that I am originally from North Dakota, it makes me proud to see 'common sense' coming from your home state in the past. I agree with Mr. Burke's ideas at the 1908 conference in Washington, D.C. And rightly so, Governor Burke was elected honorary secretary of the conference for his foresight and judgment.

Why is the management of USFS forests important to the CSK Tribes? If current management trends or lack of management of USFS lands adjacent to the Reservation continue, there will be a continued lack of 'continuous supply of timber for the use and necessities of the citizens of the United States.' Since my more recent employment with the Tribes on the Flathead Reservation, numerous forest product industry saw and paper product mills have closed down in the area and region not only due to a lack of non-guaranteed 'continuous supply of timber,' but also due to a future that shows a bleak opportunity to ensure a supply of timber. The Tribes' forest raw materials provided to local and regional mills are not enough to maintain an economic business. These mills require more forests to acquire the volume of timber they need to meet their business models and payrolls. This was the reason behind the Organic Act of 1897: 'to improve and protect the forest, or to secure the favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of the citizens of the United States.' Yet this is not entirely fitting to Pyne's (2008: 34) interpretation or description of the intention of the Organic Act of 1897 in his recent book entitled *Year of the Fires – The Story of the Great Fires of 1910*. Could it be that the early Foresters and public servants of the Forest Reserves (today's national forests) were just trying to do their jobs in the best way that they could by attempting to 'improve and protect the forest' and 'furnish a continuous supply of timber for the use and necessities of the citizens of the United States,' including 'securing favorable conditions of water flows'? Could it be that these early public servants were trying to do their job under difficult—to say the least—conditions, complying with the additional direction of the Organic Act of 1897 when the statute directed that, 'for the purpose of preserving the living and growing timber and promoting the younger growth on national forests, the Secretary of Agriculture, under such rules and regulations as he shall prescribe, may cause to be designated and appraised so much of the dead, matured, or large growth of trees found upon such national forests as may be compatible with the utilization of the forests thereon, and may sell the same…, but not for export there-from.' The idea of 'not to export there-from' makes sense. We should not be exporting USFS lumber to other countries. In October 2010, representatives from China approached the CSK Tribal Forestry Department to enquire about possibly purchasing Tribal forest logs. Not that the Tribes were interested, but what would future generations think about all the timber and paper mills in Western Montana and the surrounding region being closed due to a lack of continuous supply of timber from USFS lands while the Tribes of the Flathead Indian Reservation sell their harvested forest logs to countries like China? China could then, in turn, mill the logs and sell them back to the United States to build homes, furniture, railroads, and infrastructure. That would truly be a sad story.

The Organic Act also directed that 'such timber, before being sold, shall be marked and designated, and shall be cut and removed under the supervision of some person appointed…and not interested in the purchase or removal of such timber nor in the employment of the purchaser thereof.' This occurs each and every work day on the Flathead Indian Reservation commercial forests by Indian and non-Indian foresters and forest technicians. This could also occur on adjacent USFS lands if special interest groups would quit using NEPA as a club over USFS employees.

This leads me to the conclusions that the CSK Tribes do not fall under the law(s) of the Organic Act of 1897. Indian Reservation lands are not Federal reserves or national forests. Indian Reservation forest lands are held in 'trust' by the United States for the benefit of the Indian people who reside within the reservation. However, it is my belief that present and future public and USFS employees need only drive through and look at the actively managed commercial forests and non-commercial wilderness forested landscapes of the Flathead Indian Reservation to see what the national forests landscapes could look like while still providing a continuous supply of timber for citizens' use and necessities. The people driving and/or walking through Tribal-managed forest lands will see healthy diverse forests of a wide variety of conifer and deciduous forests all aged classes and structure—forests that today more closely resemble the forested landscapes that existed prior to European influences. The Tribes on the Flathead Indian Reservation have been managing and harvesting their Reservation forests sustainably since 1855, when the Hellgate Treaty was signed.

What has helped me in my professional forester responsibilities on the Flathead Indian Reservation, as compared to other Federal public lands I have worked on, is a broad foundation of factual forest history. The book the Tribal Foresters call the 'Red Book'—officially titled *Timber, Tribes and Trust: A History of Forest Management on the Flathead Indian Reservation, Montana 1855 through 1975* (Historical Research Associates, 1977)—is an example of this foundation of facts regarding the Tribes' forests. Regardless of whether we work for a National Forest, National Park, U. S. Fish and Wildlife Refuge, Bureau of Land Management lands, The Nature Conservancy Lands (TNC), state forests, Indian Reservations, or Alaska Village or Alaska Native Claims Settlement Act (ANCSA) lands, a thorough history of the disturbance of landscapes—especially forested landscapes—is necessary for effective resource planning and fire management.

The recent article 'Two Forests Under the Big Sky: Tribal v. Federal Management' (Berry, 2009) provides a good example of how the Salish, Pend d'Oreille, and Kootenai Tribes manage their lands more efficiently for timber production and ecological values than the adjacent Lolo

National Forest. It is not because the Tribes are born to appreciate the environment more than people who work for the USFS. As Berry (2009:11) explains in her article, 'the Tribes need forest productivity to support their livelihood.' From my experience, the active forest management activities include timber harvesting, forest seedling planting, forest thinning from below and above, forest fire protection and fire use through prescriptions, and—most importantly—ecosystem management.

Every day I work with five different Indian-owned logging companies that employ not only Tribal members from the Flathead Reservation, but also non-tribal members from surrounding communities both on and off the reservation. The raw forest products are produced from their ground and line-based logging systems, which require hard and skillful work and—yes—a silvicultural understanding and respect for future forest growth and health that are ever-present with the men and women who work for these companies. To see their work go into the planned scheduled commercial forest stands and harvest according to well-planned and thought-out silvicultural prescriptions that produce a 'net profit' after logging and reforestation, including timber stand improvement costs, makes me proud to be part of the planning and implementation effort. Moreover, all this work is in compliance with NEPA. What makes me most proud is to see the designated commercial forests of the Tribes furnish a continuous supply of timber for use and necessities of Tribal membership and self-governance in addition to securing favorable conditions of water flow, all while improving and protecting the forests within the boundaries of the Flathead Indian Reservation. Such efforts provide immediate and long-term value to the local and regional economies by providing meaningful jobs in the woods, in the lumber and paper mills, and in businesses providing services to logging companies and loggers, thereby providing income for families to purchase homes, feed themselves, and send their children to college. As Stephen J. Pyne stated in his article entitled 'The Cash-Value of Environmental History' (2010:2), the forestry and natural resources management of the Tribes on the Flathead Indian Reservation seem comparable to Norman Maclean's *Young Men and Fire* (1991). Pyne stated (2010:2) Maclean's book 'helped connect wildland fire to the larger culture and forces the guild of practitioners to confront how they should deal with it.' Maclean's examples and story inspired those in the culture of and workforce of fire to 'do their work better.' Maybe the American public(s), Congress, and special interest environmental groups can learn and be inspired by the CSK Tribes' management of their forests. As Tribal Forest Department Manager James Durglo wrote in his letter to the readers of *Ecosystem Management on the Flathead Indian Reservation* (2005), 'our forest is a vital part of everyday Tribal life. Timber production, non-timber forest products, and grazing provide jobs and income for Tribal members and enhance the economic life of surrounding communities. Forest protection and use remain core values on our lands.' Perhaps Pyne's closing statement—'now that's cash-value for scholarship' and for the wise use of forested landscapes—can be applied here.

According to the Wildland Fire Decision Support System (WFDSS 2010) for the Flathead Indian Reservation, fire and forest management activities 'will not impede the opportunity to provide income to the Tribal government from an estimated annual harvest of 700 thousand board feet of ponderosa pine and 17.4 million board feet of other species for the first thirty-year period of the 2000 Forest Management Plan. And all this while providing employment to about 200 other wood products workers based on an annual harvest of 18.1 million board feet generating about $ 6.3 million in wages annually.' This is today's history of the Flathead Indian Reservation Forests.

Firefighter safety in 1910 compared to firefighter safety in 2010

Firefighters today face serious problems that could be better managed and mitigated to improve firefighter safety. These include ordering, directing, or sending firefighters into wildland areas in extreme fire danger and fire behavior potential to fight fires that are near or at the size and intensity of exceeding almost any chance of success. Why even be there or send people to these areas when the fuels, weather, and topography are all lined up for extreme fire behavior? In 1910, firefighters were also directed into remote or near-remote areas to suppress fires during extreme fuel and weather conditions by mid and upper management—a problem that continues in 2010. Indeed, my most recent experience related to this issue occurred on the I-90 Tarkio Complex in Western Montana in 2005.

I recently read ‘Managing the Unexpected 3: A Workshop on High Reliability Organizing’ (Ziegler and Fay 2006), which was based on the I-90 Tarkio Fire. The authors ask ‘was it worth it to put the division, or multiple divisions, in harm’s way to save this resource?’ My answer would be a resounding no. For the I-90 Tarkio Complex, I absolutely know it wasn’t worth it. I was there. My view would be the same for the circumstances facing fire management or control of the 1910 firefighters.

My concerns with the I-90 Tarkio Complex relate to firefighter safety. I was assigned as a second Fire Behavior Analyst (FBAN) to the Type I Incident Management Team (IMT). When I arrived at the incident, I learned there were three FBANs assigned. I was briefed, and it was determined that the FBAN from California would focus on the major power line corridor and I would work with the primary FBAN permanently assigned to the T-1 IMT. I agreed. However, I still have problems with firefighting tactics and strategy today in the Northern Rockies. (I don’t know what is going on with tactics in other areas of the West. I haven’t been on fires in other regions of the West much since the 1970s and early 1980s.) My primary problem is the end or lack of aggressive night-shift operations—namely, the decision to change the way we used to use night’s higher relative humidity and calmer winds to get a handle on the fire. My experiences on inter-regional fire suppression crews from 1975 through 1985 proved to me that the night shift was when the major work and containment occurred, primarily through the efforts of hand crews and some mechanical equipment if terrain allowed. In 1985, I transferred to Alaska. When I returned to the lower 48 Northern Rockies in 2000, I discovered that night shift operations were gone for the most part, other than the patrol and placement of engines. I believe that such a move meant that upper and middle management, not IC teams, were placing more firefighters in harm’s way with day operations than necessary. We need more night shifts, mitigating safety concerns the best we can. Meanwhile, during the day, when dealing with fires with similar conditions to the I-90 Tarkio Complex that require containment and suppression, we can keep people out of harm’s way and use air support where applicable. We need to get after the fire at night by bringing back the night shift.

In preparation for this Conference, I wondered if I was the only ‘nut’ who thinks this way. I googled the words *night shift*; lucky for me, I discovered I was only half nuts. I found the article ‘Night Shift’ (Mangan 2002) by Dick Mangan, a retired USFS employee, who turned out to be the other half nut. Suffice it to say, I recommend ‘Night Shift’ as Mangan’s thoughts and views mostly fit mine, concluding that we need to ‘take back the night’ (Mangan 2002:6).

Getting back to the I-90 Tarkio Complex, my first three to four shifts I had serious issues with what day shift plans were calling for from hand crews and equipment operators. Every day, the primary FBAN and I (I was driving so I had control of the wheel and gas pedal) left the fire area from mid and upper slopes and canyons by 2:30 pm. I wanted to be back down in the valley floor near Interstate 90 for my safety and the safety of the person with me in the vehicle.

Now I struggled with this, day after day, discussing it with the primary FBAN on the T-1 Team and, sometimes heatedly, with a safety representative from a Federal Fire Aviation Safety Team (FFAST) from Missoula visiting fires in Region I of the USFS. I also discussed my concerns with the safety officer on the team and with operations. The night prior to the day of the burn over and shelter deployment, while the primary FBAN and I were writing the dayshift forecast for the next day, I wanted to put in bold lettering at the top of the forecast 'BLOW UP CONDITIONS EXIST!!!' in an effort to bring attention or force a change of aggressive day shift tactics. The primary FBAN did not agree, probably for various reasons. We discussed it, there was no red flag forecasted for the next day, although the day we just finished had a red flag. My major concern was the day after day record-breaking temperatures and single-digit relative humidity in the late afternoon. Cumulatively, BLOW UP CONDITIONS EXISTED, even for the day we just completed. Too much crew burn out was occurring too late in the morning, and extreme fire behavior conditions and drainages aligned with prevailing winds were imminent. I struggled with the thought that I didn't want to be anywhere up those canyons after 2:00 or 3:00 pm. Yet we, as a Type I team directed by middle and upper Federal management, had crews and human resources spread out all over and up these various canyons. I really had a hard time with this. If I wouldn't or didn't want to be there for safety concerns, why should I or the team ask the crews and equipment operators to work in those canyons and steep slopes? To this day I still can't believe that the crews, especially the T-1 crews, didn't raise issues. I asked a couple of R-5 Hotshot crew superintendents if they had concerns, questioning them about what had happened to night shifts the way we used to get the work done 70-90 percent of the time. I asked if they had complained about the lack of night shifts. The reply was, 'we did in the past, not on this fire, but other fires. And nobody listened. Besides, we get more overtime with all this dayshift activity; as the fires get a lot bigger and last a lot longer, more money in the bank.'

Over the past few years, since about 2000, I've talked with a number of Type I and II Overhead Team Plan Chiefs, Safety Chiefs, Logistics Chiefs and assorted firefighters. There is talk that teams prefer only day shifts. They're using firefighter safety as the reason, claiming that night shifts are too dangerous. Indeed, it is much easier for teams to have to prepare only one major shift plan and for logistics to plan for only one major crew and equipment deployment; all other team members have an easier time of it as well. Firefighter and crew time (hour) work limitations and work–rest ratios would be possibly violated with night shifts. In my experience, we did not exceed 16-hour work shifts with night shifts. Shifts were more like 12 to 14 hours working at night. As long as good day sleeping arrangements are planned, away from loud camp noise and heliports, night crews can get better rest and get the job done at night, when upper and middle Federal management need to contain and control fires in the heat of the summer.

I attended the Unexpected 3 Workshop in Missoula in the spring of 2006—a good workshop, in my mind—and went on the field tour or staff ride. I still wonder why Bonneville Power Association (BPA), Plum Creek, or any of the Type I general staff team, were not involved in the initial workshop or staff ride? And I was never contacted or asked questions about being an FBAN assigned to the I-90 Tarkio Complex. When I heard there was going to be an accident investigation report, I wondered if I was going to be called. I was somewhat surprised I wasn't; but maybe I wasn't all that surprised. My gut feeling is that the primary FBAN would have been okay with my involvement in the investigation of the burn-over; however, some people assigned to a FFAST team, with whom I discussed my concerns with firefighter safety at length for days before the burn-over, were probably not okay with my involvement. I was finally able to get for a response from a fire team safety representative, who informed me that the team and divisions were adhering to lookouts, communications, escape routes and safety zones (LCES). I again told the safety representative that I was leaving the hills and divisions where the crews and resources were assigned to get to the valley floor every day by 2:30 pm, for the safety of me and my passenger. It did not matter; the LCES was occurring—without secure anchor points, in my view, while escape routes switched back time and again, taking us toward the fire and falling trees and rocks that were blocking roads.

I remember at the close-out of the Unexpected 3 Workshop. The Incident Commander (IC) of the T-1 Team assigned to the I-90 Tarkio Complex gave a talk. In fact, he spoke his mind, and I take my hat off to him. I was impressed by and appreciative of his thoughts. What really surprised me was his comment—and I am grossly paraphrasing now as it has been a few years—that 'nobody was telling or informing me that there were concerns out there and no one was asking for a time out from the team on tactics or a change of tactics.' When I heard this from the IC's presentation, I felt I hadn't done a good enough job of getting the word out about my concerns. I had tried through channels, but it hadn't worked. Next time I'll go straight to the top. It is at times difficult to be assigned to a team as an FBAN when they do not know you or have not had the chance to work with you. It's hard to get people to listen. Next time I'll pound my fist on the table.

The book *Never Saw It Coming* (Cerulo 2006) is an excellent read, particularly in regard to how it relates to fire management—both the control and use of fire—and how the costliness of failing to anticipate worst-case scenarios can have lifelong impacts on fire managers. Many of us in the fire business probably know a co-worker, a friend, or an acquaintance who has had their lives changed by the unpredictability of fire. The art and science of fire management will never be exact—or even close. There are far too many variables in the fuels, weather, and topography.

My evaluation of 'Managing the Unexpected 3: A Workshop on High Reliability Organizing Workshop' (Ziegler and Fay 2006) and 'Night Shift' (Mangan 2002) summarize my thoughts on the history of firefighter safety, comparing 1910 to the 21st century firefighter safety. Personnel Protective Equipment (PPE) is much better today; indeed, it didn't exist in 1910. However, we're still losing people—needlessly so—to burn-overs and facing near fatalities with shelter deployments. Firefighters should not be directed to the lines during the heat of the day in the dog days of summer. Bringing back the night shift will provide, in many ways, a safer work environment. When mid and upper management direct that certain fires need to be contained and suppressed at the smallest acreage possible, the Indian crews, Hotshot crews. and type II hand crews will work more happily and produce results when given the cool of the night in which to work. As Mangan (2002:6) states in his article, it is time to 'take back the night.'

Conclusion

'That the history of the past can be commemorated while that of the present placed on record forms a dual duty to the people of the pasts and their events connected to the people of the present' (Leeson 1885:3). The power to accomplish this is found in local and regional history. 'Steel may wear away, rust efface the inscription on iron, wood decay, and even the marble rock break to pieces, but the page of history, once printed, is carried down the river of time unchanging and unchangeable' (Leeson 1885:3).

I connect with history, being drawn to people and laborers similar to my father, grandfather, and two brothers: railroad track laborers, conductors, brakeman, and engineers. I enjoyed my years working on railroad steel gangs in much the same way as the Navajo rail track laborers and the Mohawk iron workers in the east continue to enjoy their labors. There is pride in working the iron and wood, whether on a railroad bed or a skyscraper in New York City. There is a similar pride among wildland firefighters, the Indian crews, the Hotshot crews, the smokejumpers, the multi-ethnic firefighters of the U.S., and—yes—loggers and the logging industry.

I hope I've made my point that history, local, regional and global, can help us in fire and natural resources management. I will close this article by providing a couple more thoughts on my historical experience in fire management and control. In the 1970s I had the fortunate opportunity to work with the USFS. I experienced 'cash value' work on the forest service lands following the harvesting of timber with prescribed fire and then tree planting. Since 2000, I have observed how millions of (tax) dollars have been spent on hazardous fuels reduction projects on USFS, BLM, USFWS, BIA and NPS lands through the National Fire Plan. On USFS lands prior to the 1990s, forest stands and landscapes were managed by timber harvests followed by prescribed fire and reforestation. Most—if not all—of the follow-up work on these forest stands didn't come from federal taxes or funds from the National Treasury. The dollars came from return on timber stumpage. Today, forest stands and hazardous reduction projects are funded from the National Treasury, costing huge amounts of tax dollars with little or no 'wise use' of the wood fiber resource.

This is not the case on the Flathead Indian Reservation, where the forests are managed by the Confederated Salish, Pend d'Oreille and Kootenai Tribes by ensuring conservation first, and afterward the wise use of those resources. My perception of CSKT forest and natural resources management fit Nancy Langston's (1995:306) thoughts in that the Tribes of the Flathead are not being driven or forced to 'maximum efficiency and commodity production but upon allowing other ideals which allow some production and efficiency while allowing for complexity, diversity, and uncertainty' in forest management and harvesting. The connection between the Tribes and their lands is evident, they know the places they harvest timber, they know the place they work, and they are very responsive to what the land is telling them by acting upon that knowledge. They 'read the land' very well. I feel very fortunate to work with a progressive forest management program that actively manages and harvests its commercial forest lands. I hope to last physically for a few more years, walking, working, managing, and tending the forests held and owned in common by the Tribal members of the Flathead Indian Reservation.

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Fire in the Southland: The Natural and Cultural Heritage of Prescribed Burning in the Southeastern United States

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Abstract:

Fire has been a key natural and cultural process shaping the Southeastern United States for millennia. Fires ignited by lightning – and those set first by Native Americans and later by African and European settlers – have uniquely sculpted the Southland – its soils and waters, plants and animals, and people – in an elegant yet intricate cycle, the study of which has had a profound effect on fire ecology and fire management worldwide. I will discuss the singular aspects of the region's fire ecology (e.g., longleaf pine and other grassland biomes); the "mining" of the South's forests in the early days; the South's pioneer fire managers and researchers (e.g. Herbert L. Stoddard et al. scientists at Tall Timbers Research Station); misguided fire suppression programs such as the "Dixie Crusaders;" and how these matters play into today's situation. I will discuss present conditions and challenges, including the region's swelling population, loss of rural values, and increasingly fragmented landscape, as well as positive developments I hope to see continue and grow.

Snag Fall, Coarse Wood Decomposition, and Fine Fuel Succession Following High-Severity Fire in Dry-mixed Conifer Forests of Oregon's Cascades

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Abstract:
Reducing future fire severity is a proposed objective of salvage and reforestation operations following wildfire disturbance. Considerable debate continues over the ability of such management practices to achieve this objective given limited understanding of coarse woody detritus (CWD) dynamics, fuel bed alterations, and post-fire vegetative growth. The objective of this study was to estimate future fire severity by understanding the dynamics of CWD and fine surface fuel succession. A total of 6,275 snags in thirty 0.25-ha plots were sampled at seven different fire sites, covering a 24 year chronosequence following high-severity fire. Three cross-sections from sixty fire-killed *Pinus ponderosa* snags, sixty *Abies sp*. snags, and forty *Pinus ponderosa* logs were sampled to estimate decay rate constants for standing and downed CWD. A snag and CWD dynamics model was created to track the accumulation of surface CWD and its decay state across time. Custom fuel models were developed at points across time, incorporating CWD and post-fire vegetative fuels.

Legacy CWD was responsible for the largest total accumulation of surface fuel as snags break and fall, but primarily in 100- and 1000-hr fuel classes. Decomposition rates more than double as CWD transfers from standing to downed material reducing total CWD biomass by 30-40% in 24 years. Fine fuels are primarily derived from post-fire vegetation and steadily increase over the 24 year period. Herbaceous fuel loads peak within 2-4 years but decrease rapidly as *Ceonothus velutinus* and *Arctostaphylos patula* shrub cover exceeds 65% by year 5, steadily increasing in total biomass over 24 years. Spread rates and flame lengths in post-fire environments are primarily driven by fuels generated from new growth. In addition to the size of CWD, the dynamic processes of snag fall, breakage, and decomposition limit its influence on fire spread and flame length when reburning occurs. Soil heating and total heat release is exacerbated by combustion of CWD, but the severity of this effect is dependent on its decay state and combustion efficiency. Results of this study therefore suggest post-fire management decisions consider vegetation dynamics as well as dead wood dynamics to meet objectives.

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Spatial Variation in Fuel Moisture and Bulk Density within *Pinus jeffreyi* and *Abies concolor* Forest Floors in the Lake Tahoe Basin, California

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Abstract:
Recent research in temperate coniferous forests has linked variation in forest floor fuels to several post-fire effects, including fuel consumption, mineral soil heating, and tree mortality. Forest floor duff (fermentation and humus horizons) moisture is a primary predictor of fire effects, and varies depending on spatial position. Forest floor bulk density influences heat transfer between organic particles, and the rate at which the duff dries. We collected forest floor fuels from each forest floor horizon (litter, fermentation, and humus) from large (>50cm DBH) white fir (*Abies concolor*) and Jeffrey pine (*Pinus jeffreyi*) in the Lake Tahoe Basin of California. To isolate the effects of spatial position, fuels, depths, and bulk density were collected at the base of each tree, at the crown drip line, and beyond the crown in open "gaps". A total of 180 bulk density samples were collected and 360 forest floor depth measurements were made. To track seasonal moisture dynamics, collections were spaced ca. 20 days apart from July through October 2009. Fuel samples were oven-dried for 48 hours at 60 degrees celcius to obtain dry weights to estimate fuel moisture and horizon bulk density. In July, results between species revealed a reversed fuel moisture spatial pattern; fuels near the bases of *P. jeffreyi* were drier than gaps, while in *A. concolor*, canopy openings were significantly drier than near tree bases or beneath crowns. A reverse bulk density spatial pattern was also found between species; higher overall forest floor bulk density was found in canopy openings than beneath crowns and near tree bases for *P. jeffreyi*, whereas *A. concolor* had higher forest floor bulk density near tree bases than under crown drip lines and in canopy openings. Future work will focus on linking these patterns to resulting fire behavior in prescribed fires and under laboratory conditions. Linking spatial patterns in moisture content and bulk density to post-fire forest floor consumption patterns will allow for greater predictability and understanding of post-fire effects.

A Conceptual Model of the Interactions among Introduced Pathogens, Fuels, and Fires

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Abstract:
Forest diseases have been increasing for the last century, with far-reaching effects on fire regimes. Emergent diseases have begun to alter fuels and are raising alarm for potential interactions with subsequent fires. Here, two diseases are reviewed with contrasting spatial and temporal effects on fuels and corresponding fire hazard. We pair these syntheses with a conceptual model of pathogen-fire interaction pathways that is applicable to emergent diseases elsewhere. Chestnut blight, caused by the pathogen *Cryphonectria parasitica*, led to the decline of American chestnut (*Castanea dentata*) throughout the eastern US beginning ca. 1920. The short-term effects of chestnut blight were altered microclimate, increased surface litter fuels, with subsequent increases in surface woody fuels. The legacy of chestnut extirpation was a change in surface fuel flammability, perhaps facilitating the mesophication of many eastern forests. Although discovered very recently in California (ca. 1995), sudden oak death (SOD), caused by the pathogen *Phytopthora ramorum*, has already caused widespread mortality of several native tree species, most notably tanoak (*Lithocarpus densiflorus*). In the short term, SOD leads to steep declines in foliar moisture content (mean fire season= 7 %) that elevate the potential for individual tree torching and may exacerbate canopy ignition. In subsequent years, tanoak branches and stems are recruited to the surface fuelbeds, but their patchiness may ameliorate elevation of surface fire hazard over large areas. As with chestnut, the extirpation of flammable tanoak litter over the long-term may dampen surface fire flammability and alter the region's fire regimes. Using evidence from these diseases and others, we provide a model with multiple pathways for predicting changes in fire regimes wrought by emergent diseases elsewhere, including laurel wilt (caused by *Raffaelea lauricola*) in the southeastern US and hemlock wooly adelgid (*Adelges tsugae*) in New England and the mid-Atlantic region. Utilizing knowledge of past and present disease "syndromes" will assist managers in prioritizing where and when to focus scarce resources to mitigate changes in fire regimes linked to non-native pathogens.

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Deriving Conifer Needle and Branch Mass for Crown Fuel Modeling Using Terrestrial Laser Scanning

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Abstract:
Requirements for characterizing coniferous forests in the U.S. are changing in response to wildfire concerns, bio-energy needs, and climate change interests. At the same time, technology advancements are transforming how we measure forest properties. For example, Terrestrial Laser Scanning (TLS) is yielding promising results for measuring fundamental tree crown biomass parameters that historically have required costly destructive sampling and correspondingly small sample sizes. In this study, we use a near-infrared TLS to examine the effects of range and scan density on quantification of needle and branch mass. We systematically image conifer specimens at multiple ranges and point densities, then dry and weigh needles and branches of each. Comparisons of biomass with laser-derived reflection intensity and density suggest that the TLS can represent results obtained by destructive sampling. However, there are range dependencies that appear to be caused by variable target geometry, influencing the partitioning of crown fuels by size class. By understanding these range dependencies, we anticipate increasing the efficiency of biomass sampling for derivation of accurate crown fuel models using relatively large samples of trees.

The effect of decay on course woody debris consumption

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Extended abstract
Coarse woody debris (CWD) in various states of decay is found in abundance in numerous forested ecosystems, serves a variety of ecosystem functions, and impacts air quality as it combusts. However, our understanding of the quantities of this debris consumed in forest fires is poor, especially when addressing debris in various states of decomposition. In this study we examine the impact of decay on consumption and characterize these fuels based upon wood properties and three numeric decay classification systems. Logs in this study were from a mixed conifer forest and between 7 and 23 cm in diameter with moisture contents between 6 and 13%. Two ignition methods were used, one exposing samples to surface temperatures of approximately 800°C for two minutes, and the other exposing logs to 300°C - 500°C for three to five hours. Results for both ignition methods indicate that coarse woody debris in class four, the most advanced decay class, are likely to consume to a greater degree than logs in classes one through three. This supports the current convention of grouping all CWD into two broad categories, sound and rotten, in consumption models such as Consume and the First Order Fire Effects Model. Intermediate classes showed high variation in consumption; this was in part due to surface properties which impact the decay classification and do not reflect the condition of the entire log. For this reason we suggest the use of physical properties to predict consumption of these fuels. In examining CWD properties, wood density, lignin content, and volumetric heat content, were the most highly correlated with consumption. This study should be repeated in areas with different decomposition and combustion dynamics, such as that found in the southeastern United States.

Mean consumption values for all classification and ignition methods. Standard deviations are shown in parenthesis.

Average consumption by class and ignition method						
	High temperature low duration		Low temperature high duration			
	Fogel method		Maser method		Extended method	
Class	Hi temp.	Low. Temp	Hi temp.	Low temp.	Hi temp.	Low temp.
1	8.6 (21.2)	3.7 (6.4)	10.9 (27.4)	8.0 (11.9)	9.2 (25.3)	5.9 (8.3)
2	3.6 (3.1)	51.1 (46.7)	6.5 (10.3)	34.0 (45.6)	6.6 (9.6)	33.0 (41.9)
3	33.1(39.2)	54.8 (44.8)	14.8 (27.6)	53.4 (44.7)	42.4 (44.3)	58.9 (45.5)
4	88.2(26.4)	96.1 (1.4)	95.7 (2.9)	98.5 (1.3)	96.3 (2.7)	99.0(1.2)

Additional keywords: CWD, decay, fuel properties, ground fuels

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The Influence of an Incomplete Fuels Treatment on Fire Behavior and Effects in the 2007 Tin Cup Fire, Bitterroot National Forest, Montana

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Abstract

Extensive forested areas have received fuels treatments in recent decades and significant funding is available for additional treatments in an attempt to mitigate undesirable high wildfire intensities and impacts. Fuel treatment successes and failures in moderating fire behavior and effects can be found in quantified and anecdotal reports. Questions remain about the efficacy of biomass removal projects for modifying wildfire characteristics such as; (1) Do wildfires respond to fuel treatments differently under different fire weather? (2) Are fire behavior changes within fuel treatments frequently due to suppression activity? (3) Are conflicting reports of treatment effectiveness often due to contrasting types of treatments?

To address some of these questions, we retrospectively examined several data sources from the 2007 Tin Cup wildfire which burned through a partially completed fuels treatment. We collected stand and fuels data including measurable fire effects in treated and untreated units, interviewed fire fighters, reviewed the incident commander's report, utilized local weather data, and examined photographs and GIS data. We concluded that the variation in fire behavior and fire effects throughout treated and adjacent untreated areas could be explained only by a comprehensive examination of this diverse quantitative and qualitative data set. In addition, similar crown burn severity between paired units, suggests that similar fire behavior and effects can be expected between partially treated units with slash piles and untreated units with ladder fuels.

Additional keywords: Crown scorch, crown burn, flame lengths, fire spread rate, ponderosa pine, lodgepole pine, Douglas-fir

Empirical Tests of Fuel Management Effectiveness in Jack Pine

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Abstract:
Forest managers have little empirical evidence to support investment in forest fuel management for the purpose of community protection. Documented case studies would help managers decide what treatments to do, and also provide tools to educate public on the benefits of fuel management. Two test burns to evaluate the effectiveness of vegetative fuel management in Jack Pine stands were carried out near Fort Providence, Northwest Territories, Canada. A square 1 ha stand was thinned to 3 m inter-crown spacing (500 stems/ha) following FireSmart (Partners in Protection) recommendations. Large down woody debris and ladder fuels were also removed. Adjacent stands were left untreated with no break between the thinned stand. The site was typical of boreal Jack Pine dominated stands that are subject to high intensity stand replacing crown fires, as was highlighted by the nearby International Crown Fire Modelling Experiment.
For these tests, a crown fire was ignited in an up wind of the stand and allowed to burn into the thinned stand from two directions (2005 and again in 2007). Two structures were placed in the thinned stand at 10m and 30m down-wind of the border with the natural forest without any suppression (2007 only). In both cases the fire changed from a crowning to surface fire with intermittent candling. The structure 10m from the natural stand experienced direct flame contact and was destroyed. The other cabin survived, although surface fire (head fire and flying embers) occurred throughout the thinned stand in both tests. Surface fire was limited immediately around the 30m structure because of compaction and raking. Results indicate that fuel management can be effective at altering fire behaviour at small a spatial scale, but on its own may not be enough. Vegetation management coupled with other techniques (building materials, sprinkler systems) does have great potential to prevent loss due to wildfire. Two videos produced from the test burns have proven to be valuable public education tools. The presentation will include fire behaviour documentation and video highlights of the burns.

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Assessing Efficacy of Landscape Restoration in Juniper Savannas in Southern Arizona

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Abstract:
The Clifton Ranger District on the Apache-Sitgreaves National Forest is restoring large tracts of juniper savanna and grassland in southern Arizona using prescribed fire, mechanical thinning, and livestock grazing manipulations. Their use of fire is innovative both in efficiency and application. Treatment blocks are large, ranging in size from 3-10 thousand hectares and fire is allowed to burn freely within natural barriers during hot, dry, windy summer conditions. Fire is applied by small teams of practitioners funded mostly by consortia of state and private wildlife organizations, and is used to reduce tree canopy densities and tree encroachment, increase forage production, and maintain hiding cover for wildlife. This study examines the cumulative effectiveness of treatments at reducing canopy cover. Canopy cover change is quantified systematically using a dot-grid approach on conventional 1:15,840 aerial photography acquired in 2000 and 2008. Preliminary results from the Mesa Treatment Area (totaling 3890 ha) indicate that canopy cover was reduced by 26% ($n = 3465$, $p < 0.001$) in units that received fire and 42% ($n = 3080$, $p < 0.001$) in units receiving mechanical thinning and fire. Adjacent control units saw an increase in canopy cover of 8% ($n = 2310$, $p < 0.001$). Results also suggest that certain soil associations with deeper soil beds, greater water retention, and reduced erosion may support more positive fire effects. If the latter results hold up to scrutiny, it is thought that significant efficiencies can be gained in restoration by identifying areas where fire alone will meet resource objectives and more precisely targeting mechanical treatments to landscapes where fire will not have the desired effect.

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Using wildfire risk analyses for restoration objectives in dry forests

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Abstract.
Fuel management programs in dry forest areas often emphasize restoration of natural managed fire on a systematic basis rather than protection from uncharacteristic wildfire. The restoration process can involve active or passive management to restore forest structure and create fuel profiles that burn under the desired characteristic fire regime. From a landscape management perspective, the overall objective of restoration projects is to create large contiguous area(s) within which natural ignitions can be managed rather than suppressed. Thus the restoration strategy is one of aggregation rather than breaking large contiguous fuels to facilitate suppression and impede large-scale fire spread.

One approach to developing a treatment optimization system for restoration activities is to use fuel treatments to create the largest possible area within which fire behavior thresholds that trigger suppression are not exceeded. In this way, the use of natural and prescribed fire can be optimized over time. Further benefits are achieved if these core areas have the largest possible concentration of stands that are targeted for restoration and need fuel treatments to preserve large trees. We developed such a treatment optimization process within ArcFuels and are testing it on the Fort Rock Ranger District on the Deschutes National Forest. The process is being used to reduce the conditional loss of old growth ponderosa pine by creating the largest area within which stand fire behavior does not exceed a flame length threshold, while treating a minimum of acres.

For more information about the ñTreatment Minimizerò tool within ArcFuels please visit the ArcFuels webpage http://www.fs.fed.us/wwetac/arcfuels/index.html and download the program manual.

Additional keywords: wildfire risk, simulation modeling, restoration, ponderosa pine

Evaluating fuel treatment alternatives for fire hazard reduction in the Southeastern United States

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Abstract
Quantifying the degree of effectiveness of hazardous fuel treatment options is important for fuel planning and efficient use of resources. This abstract describes a proof of concept effort that used the Fuel Characteristic Classification System (FCCS) to evaluate the potential fire hazard reduction of commonly used fuel treatment alternatives in the southeastern United States.

Additional keywords: Fuel treatment, fire hazard reduction, Fuel Characteristic Classification

System, Savannah River Site

Introduction

Fuels are often treated to reduce fire hazard in the southeastern United States. Although its effectiveness is consistently demonstrated in reduced wildfire acreage and damage, quantification and degree of effectiveness is not known which is critical for fuel planning and efficient use of resources. This abstract describes a proof of concept effort that used the Fuel Characteristic Classification System (FCCS) to evaluate the potential fire hazard reduction of commonly used fuel treatments options in the southeastern United States. Results will help managers determine which fuel treatments are most effective and how best to allocate resources for wildfire hazard reduction.

Thirteen forested units on the Savannah River Site located in South Carolina were selected for this study and included unthinned and thinned forested sites with one or more of the following treatments: (1) no treatment, (2) prescribed fire, (3) herbicide, (4) chip and shred, and (5) raking. Fuels were characterized in each unit using common and accepted field measurement techniques. These data were input into FCCS to build fuelbeds and calculate fire potentials and surface fire behavior for comparing fuel treatment options.

Total above-ground loading for the litter, fine woody (0-7.6 cm diameter), shrub, and grass fuelbed strata was highest at 32 Mg ha^{-1} for the thinned, untreated unit and lowest at 3 Mg ha^{-1} for the unit unthinned and treated with herbicides, prescribed burned, and raked. Results indicate fuel treatments that target the litter, shrub, grass, and fine woody material reduce surface fire behavior potential, reaction intensity, flame length, and rate of spread by up to 90% as compared to a unit untreated. Months since treatment, site productivity and treatment specifications accounted for variations in average length of treatment effectiveness. Monitoring several replicate units throughout the treatment cycle using permanent inventory plots would provide increased scientific rigor.

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Significant Wildland Fire Potential in the Pacific Northwest of the US

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Abstract:
Significant wildland fire potential as defined by the National Wildfire Coordinating Group Glossary is the likelihood that a wildland fire event will require mobilization of firefighting resources from outside the area in which the fire originates. Costs associated with mobilization of firefighting resources to suppress significant wildfire outbreaks are high and fire managers are under pressure reduce expenses as much as possible. To aid prediction of significant fire outbreaks, Predictive Services at Northwest Coordination Center has developed a methodology for evaluating factors known to contribute to the ignition and growth potential of wildfires: weather patterns, background fire danger, and ignition sources. Analysis of the historical influence of all of these factors has revealed patterns that can be separately evaluated and objectively predicted.

The presenter will summarize the development and application of this applied research into daily significant fire potential products in the Pacific Northwest region on the national scale.

The tale of Tumblebug and the thermal trough: A case study of critical fire weather patterns of the Pacific Northwest

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Abstract

Sharp upper level ridges and the east winds they can bring in the late summer and early fall have long been known to be a critical fire weather pattern for the west slopes of the Cascade Mountains. One such ridge built along the coast and gradually shifted inland from September 21st to 23rd of 2009 illustrating the potential for these features to bring together several different extreme weather conditions for the Oregon Cascades. Multiple days of large fire growth on 3 different fires occurred on the south Willamette and north Umpqua National Forests. This case study will focus primarily on the sequence of weather events that allowed one of the small lightning fires in the Tumblebug Complex to grow over 9000 acres in a 3 day time period.

As the ridge aloft strengthened and sharpened just offshore, an extremely dry air mass aloft settled over the Pacific Northwest and sunk toward the surface in the form of a subsidence inversion. Offshore surface flow also strengthened rapidly as the pressure difference between the east and west side of the Cascades intensified. Relative humidities in the mountains plummeted as easterly downslope winds further warmed and dried the already parched air mass. Minimum relative humidities hit lows of 2% and 3% at Remote Automated Weather Stations (RAWS) near the fires while nighttime humidity recoveries struggled to reach the lower teens. Warm temperatures and these very low relative humidities preconditioned fuels and allowed the existing fires to become better established. Meanwhile, as the ridge aloft shifted east so that its axis was aligned with the coast, a surface based thermal trough developed near the coast further tightening the offshore pressure gradient and increasing easterly winds. On ridges near the Tumblebug fire, air operations reported gusts of 40 mph. As both the upper level ridge and thermal trough shifted slowly inland over western Oregon and Washington and finally into the Cascades over the fires, east winds gradually relaxed. Enhanced low level instability from the thermal trough passage shifted to the primary concern. The fire growth pattern switched from the narrow elliptical signature of a wind driven fire to a rounder perimeter indicating instability enhanced growth on all sides.

Additional keywords: extreme fire weather, blow-up conditions

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Breakdown of the Upper Ridge - A Critical Fire Weather Pattern

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Abstract:
The Davis Fire began June 28, 2003 in a pre-frontal airmass over Central Oregon in the lee of the Cascades. The fire quickly became plume-dominated within 12 hours under a surface thermal trough associated with the breakdown of an upper level ridge of high pressure. A wind speed max at mountain top level aided the spread of the fire with winds advecting very dry air from the south. The end result was 21,000 acres of burned lodgepole pine and conifer at an expense of $4 million.

The purpose of this presentation is to examine the impact of high fire danger and critical weather patterns that contributed to this large and costly wildfire, whose size exceeded the 99th percentile in its rating area. The central feature of the critical weather pattern is the breakdown of the upper ridge and the role of the thermally induced surface pressure trough.

By systematically examining forecast weather parameters leading up to the breakdown of the upper level high pressure ridge, this presentation will reinforce the importance of identifying critical fire weather patterns that can create explosive fire growth and intensity. This will be done in case study/analysis format through oral and power point presentation.

The key implication of this examination is two-fold. First and most importantly, to stress the predictability in recognizing this critical fire weather pattern to students of fire. On the contrary, critical fire weather support decisions such as Red Flag Warning issuances are not always "cut and dry" as criteria might suggest. Often data can present conflicting cases for and against Red Flag Warnings, which ultimately are more subjective decisions.

Although the Davis Fire was relatively unknown to many in the wildland fire community, analysis of the fire weather elements reinforces the patterns that should be identified in preparing forecasts. Live fuels on the Davis Fire were considered too moist for large fire growth on this timbered North aspect in June. This case study illustrates our heavy reliance on assumptions rooted in seasonality and slope. It also encourages further study into the interdependent nature of fuels, weather, and topography.

In conclusion, an examination of the Davis Fire will provide a case study analysis to reinforce recognition of the breakdown of the upper ridge as a critical fire weather pattern.

Climatic variability of a fire-weather index based on turbulent kinetic energy and the Haines Index

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Abstract
Combining the Haines Index (HI) with near-surface turbulent kinetic energy (TKE_s) through a product of the two values ($HITKE_s$) has shown promise as an indicator of the atmospheric potential for extreme and erratic fire behavior in the U.S. Numerical simulations of fire-weather evolution during past wildland fire episodes in the U.S. indicate that large wildfires and periods of rapid fire growth are often associated with and accompanied by periods of significant near-surface atmospheric turbulence. These findings provide new insight into the variability of ambient atmospheric turbulence during wildfire events over relatively short time periods. However, the ultimate application of a fire-weather index based on the product of the HI and TKE_s in fire-weather forecasts requires an understanding of where and when high values of the index typically occur. This study examines the spatial and temporal variability of TKE_s and $HITKE_s$ values over the U.S. using North American Regional Reanalysis (NARR) data. Study results indicate that there are preferred locations and periods for large TKE_s and $HITKE_s$ values, the temporal variability of TKE_s and $HITKE_s$ is regionally dependent, and there has been a general increase in TKE_s and $HITKE_s$ values over much of the U.S. over the last 30 years.

Additional keywords: turbulence, wildfire

Introduction

Recent modeling studies (Heilman and Bian 2007, 2010) have examined the feasibility of using atmospheric mesoscale model predictions of near-surface TKE (TKE_s) (Mellor and Yamada 1974, 1982; Janjić 1994) in combination with predictions of the well-known Haines Index (HI) (Haines 1988) as an atmospheric indicator of the potential for erratic wildfire behavior. The results from their studies suggest that periods of rapid wildfire growth are often associated with episodes when TKE_s exceeds 3 m^2s^{-2} at the same time the HI is equal to 5 or 6. These conditions are indicative of a highly turbulent boundary layer sitting beneath unstable and dry atmospheric layers aloft.

While these studies have provided a first step in determining the association of significant atmospheric boundary layer turbulence with extreme and erratic fire behavior, additional analyses are needed to determine how often high turbulence episodes occur and where they typically occur. Determining the climatic variability of TKE_s and the product of the HI and TKE_s ($HITKE_s$), including spatial and temporal patterns over the U.S., will provide critical baseline climatologies for comparisons with predicted and observed ambient TKE_s variability during actual wildfire events. It is through these comparisons that the efficacy of TKE_s as a potential operational fire-weather index can be assessed. This study provides a climatic assessment of the spatial variability of and temporal trends in TKE_s and $HITKE_s$ across the U.S. based on 30 years of 3-hourly TKE_s, temperature profile, and wind speed data obtained from the North American Regional Reanalysis (NARR) dataset (Mesinger *et al.* 2006).

Methods

The climatological analyses carried out in this study utilized data obtained from the National Centers for Environmental Prediction (NCEP) NARR dataset (Mesinger *et al.* 2006), a gridded and dynamically consistent atmospheric and land-surface hydrology dataset that covers the 1979-present period. Data are available every three hours on a 32-km horizontal grid spacing domain covering North America at 45 vertical levels.

For this study, TKE data at the NARR hybrid grid level 1 (12.0 m – 21.7 m above the surface) were used to quantify near-surface turbulent energy (i.e. TKE_S). Thirty years of TKE data at the hybrid grid level 1 were extracted from the NARR data set at each 3-hourly interval (0000, 0300, 0600, … 2100 UTC) from 0000 UTC on 1 January 1979 through 2100 UTC on 31 December 2008. These data provided the basis for developing a climatology of TKE_s and for examining its temporal variability over a sub-region of North America that includes the conterminous U.S. (25°N to 50°N, -65°W to -125°W). Three-hourly temperature, dew-point temperature, wind speed, sensible heat flux, and friction velocity data for the same 30-year period were also extracted from the NARR data set in order to compute values of $HITKE_s$ and the flux Richardson number (Ri). These additional data were analyzed to compare the spatial and temporal variability of TKE_s over the U.S. with the corresponding variability of $HITKE_s$, a potential fire-weather index (Heilman and Bian 2010), and to determine the relative contributions of wind shear and buoyancy in the production of near-surface turbulence over different regions of the U.S.

Key Results

Average daily maximum TKE_s and $HITKE_s$

There are regional differences in the average daily maximum TKE_s values that occur across the U.S. (Fig. 1) The highest average daily maximum TKE_s values occur over the high elevation areas in the Rocky Mountain and Appalachian Mountain regions, with the largest values (> 5 m^2s^{-2}) occurring during the months of April, May, and June. Values of TKE_s greater than 3 m^2s^{-2} indicate a highly turbulent environment. Over the Rocky Mountain and Great Plains regions, the highest daily maximum TKE_s values tend to occur from March through June. The Midwest and Southeast tend to have very low TKE_s values (< 1.5 m^2s^{-2}) during the months of June, July, and August. In the Northeast, the highest TKE_s values tend to occur during the months of October through April. The Autumn and Spring periods coincide with the primary wildfire periods in the Northeast.

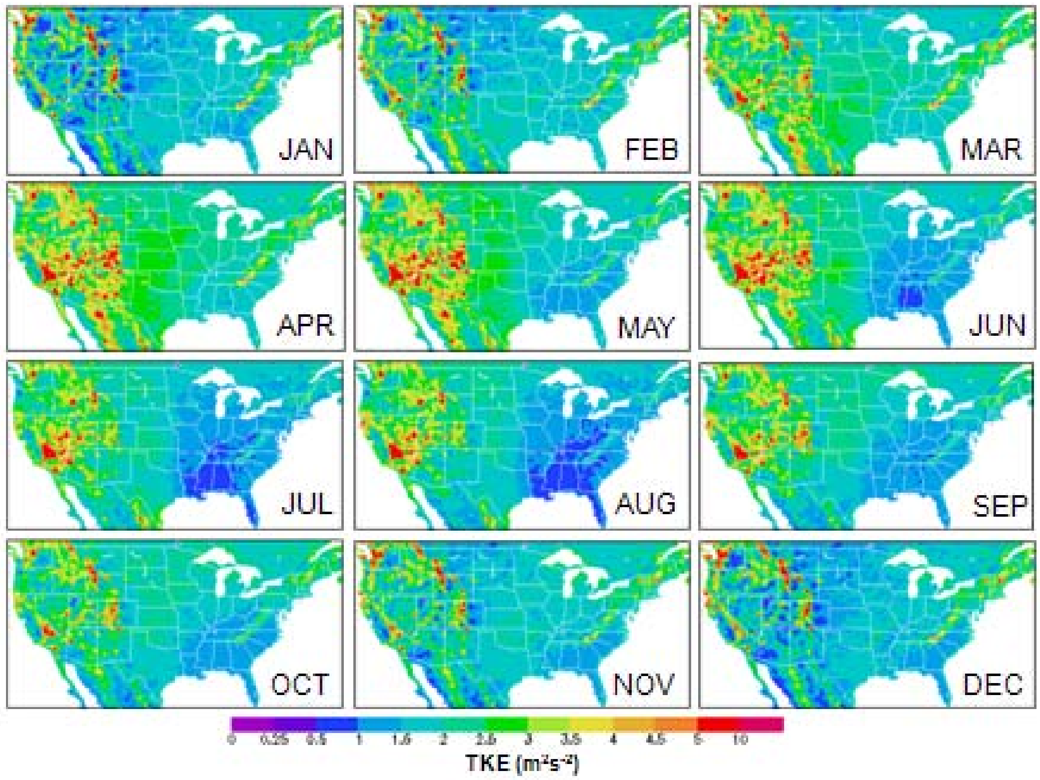

Fig. 1. Average daily maximum near-surface turbulent kinetic energy (TKE_s) over the U.S. for each month based on 3-hourly NARR data for the 1979-2008 period.

The average daily maximum $HITKE_s$ values across the U.S. also exhibit regional differences (Fig. 2). High daily maximum $HITKE_s$ values initially appear over northern Mexico and the Southwest in March and then spread northward through the Rocky Mountain region from April to August. Maximum values routinely exceed 15 m^2s^{-2} over many areas in the Rocky Mountain region. Over the eastern half of the U.S., average maximum $HITKE_s$ values are usually less than 10 m^2s^{-2} throughout the year, except for parts of the Appalachian and the northeastern U.S. regions where average maximum values reach 12-14 m^2s^{-2} from December through April. These results suggest that the use of the 15 m^2s^{-2} threshold value (Heilman and Bian 2010) as an indicator of the atmospheric potential for extreme or erratic fire behavior because of anomalous atmospheric turbulence conditions with high HI values is probably more applicable for the eastern half of the U.S., and that a higher threshold on the order of 20-25 m^2s^{-2} may be needed for the western U.S.

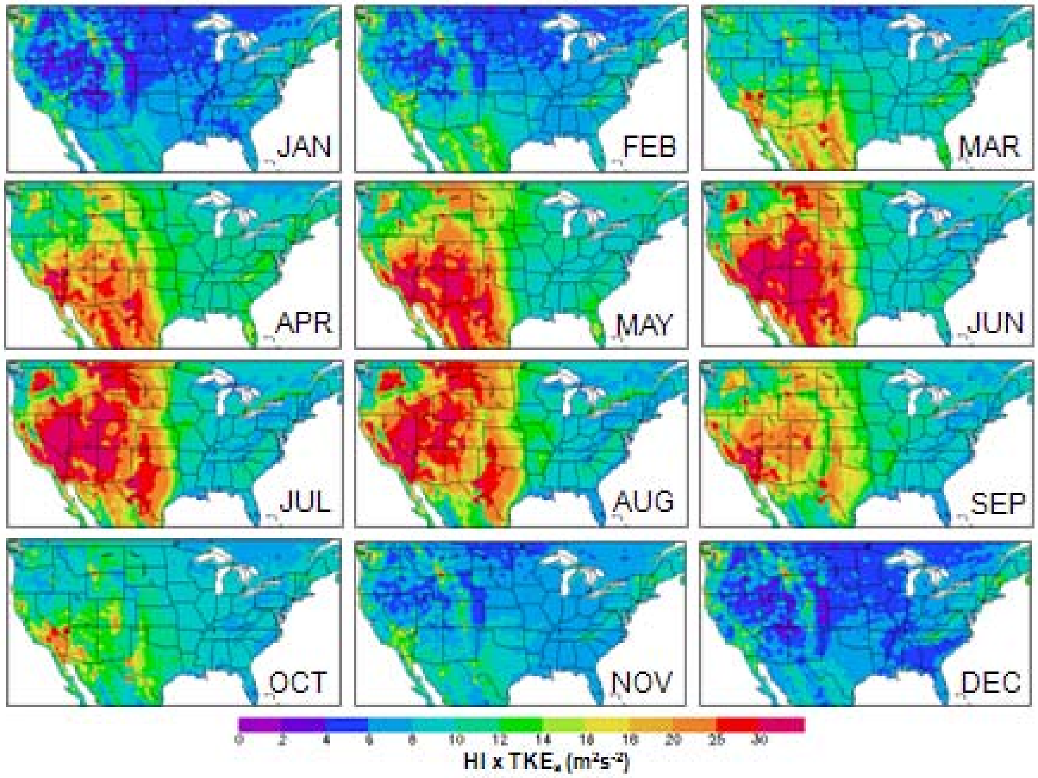

Fig. 2. Average daily maximum values of the product of the Haines Index and near-surface turbulent kinetic energy ($HITKE_s$) over the U.S. for each month based on 3-hourly NARR data for the 1979-2008 period.

Frequency of occurrence of high TKE_s and $HITKE_s$

The frequency of occurrence of daily maximum TKE_s values greater than 3 m^2s^{-2} and daily maximum $HITKE_s$ values greater than 15 m^2s^{-2} varies substantially from east to west across the U.S. For daily maximum TKE_s exceeding 3 m^2s^{-2}, the highest frequencies of occurrence are found over the western U.S.; many locations there typically have more than 60% of the days in any given month with maximum TKE_s exceeding the 3 m^2s^{-2} threshold. For most of the eastern U.S., the occurrence of daily maximum TKE_s values greater than 3 m^2s^{-2} is fairly rare (< 10% of the days each month). The exception is over the Appalachian Mountain and northeastern U.S. regions, where frequencies range from 30-60% during the November-May period. Over the Great Plains where grass fires are common, occurrences of maximum TKE_s values exceeding 3 m^2s^{-2} are most likely during the March–June period (30-50% of the days during those months).

The frequency of occurrence of daily maximum $HITKE_s$ values exceeding 15 m^2s^{-2}, a threshold indicative of a turbulent boundary layer sitting beneath dry and unstable atmospheric layers aloft, has a similar spatial pattern to the high TKE_s frequency pattern across the U.S. The highest frequencies of occurrence are found over the western half of the U.S., with frequencies in the 15-30% range (i.e. 15-30% of the days in a month have maximum $HITKE_s$ values that exceed the 15 m^2s^{-2} threshold). The eastern half of the U.S, with the exception of the Appalachian Mountain region, typically has frequencies of occurrence of 2% or less. Over the

Appalachian Mountains, high $HITKE_s$ values typically occur from November through April, with ~10-25% of the days in those months having $HITKE_s$ values that exceed 15 m^2s^{-2}.

Buoyancy and wind shear contributions
To assess the relative significance of wind shears and buoyancy in generating the observed TKE_s and $HITKE_s$ patterns across the U.S., a flux Richardson number (Ri) analysis was carried out. The frequencies of occurrence of Ri < -0.03, a threshold indicative of a buoyancy dominated turbulence regime, were mapped across the U.S. for each month. During the spring, summer, and early autumn seasons, buoyancy tends to be the dominant factor in generating high near-surface turbulence over the western half of the U.S. Wind shears are the dominant factor in generating high near-surface turbulence over the northern U.S. during the months of November through February. Over the Gulf Coast states of Mississippi and Alabama during the months of July and August, high turbulence events tend to be associated with wind shears under stable conditions. Both buoyancy and wind shear effects play a role in generating high turbulence events over many areas in the Midwest, Northeast, and Southeast during the spring and autumn wildfire seasons.

Temporal variability of TKE_s and $HITKE_s$
In order to identify possible differences in the prominent periods or frequencies of variability in the 3-hourly NARR TKE_s and computed $HITKE_s$ time series that may exist in different regions of the U.S., a continuous wavelet transform spectral analysis (Graps 1995, Torrence and Compo 1998) was performed on regionally averaged TKE_s and $HITKE_s$ time series for defined northwest (37.5°N-50°N, 95°W-125°W), southwest (25°N-37.5°N, 95°W-125°W), northeast (37.5°N-50°N, 65°W-95°W), and southeast (25°N-37.5°N, 65°W-95°W) domains covering the conterminous U.S. For both the northwest and northeast domains, the most prominent cycles or periods of variability in the 3-hourly TKE_s time series over the 1979-2008 period were annual, 6 months, and daily. Three-day to 4-month cycles were also common throughout the 1979-2008 period. This is in contrast to the southwest and southeast domains, where only daily and annual cycles in the TKE_s time series were prevalent.

The temporal variability in the $HITKE_s$ time series for the northwest, northeast, southwest, and southeast regions over the 1979-2008 period differs from the observed TKE_s variability. For the northwest and southwest regions, the most prominent cycles or periods of variability in the 3-hourly $HITKE_s$ were annual and daily, while the northeast and southeast regions were characterized by annual, 6-month, and daily cycles. Three-day to 4-month cycles in $HITKE_s$ variability were also prominent in the northeast and southeast regions. The east-west contrast in $HITKE_s$ temporal variability across the U.S. compared to the north-south contrast in TKE_s temporal variability is a key difference in the two turbulence-based indices.

In addition to the continuous wavelet transform spectral analysis of the 3-hourly NARR turbulence data, a 30-year trend analyses of the annual means of region-averaged TKE_s and $HITKE_s$ were performed to determine whether there have been any substantial long-term trends in these indices. The time series shown in Figs. 3 and 4 suggest there has been a general increase in TKE_s and $HITKE_s$ values over the 1979-2008 period for all regions of the U.S. For TKE_s, overall increases during the 1979-2008 period ranged from 4.12% in the northwest region to 12.92% in the southeast region. The largest increases in TKE_s occurred over the last 13 years (1995-2008) in all regions except the southwest, with the northeast and southeast regions showing 13.39% and 13.65% increases, respectively. Overall increases in $HITKE_s$ values over the 1979-2008 period ranged from 3.24% in the northwest region to 14.25% in the southeast region. Similar to the recent trends in TKE_s values, the largest increases in $HITKE_s$ values occurred over the 1995-2008 period in all regions except the southwest. Increases in the northeast and southeast regions were 15.46% and 16.54%, respectively.

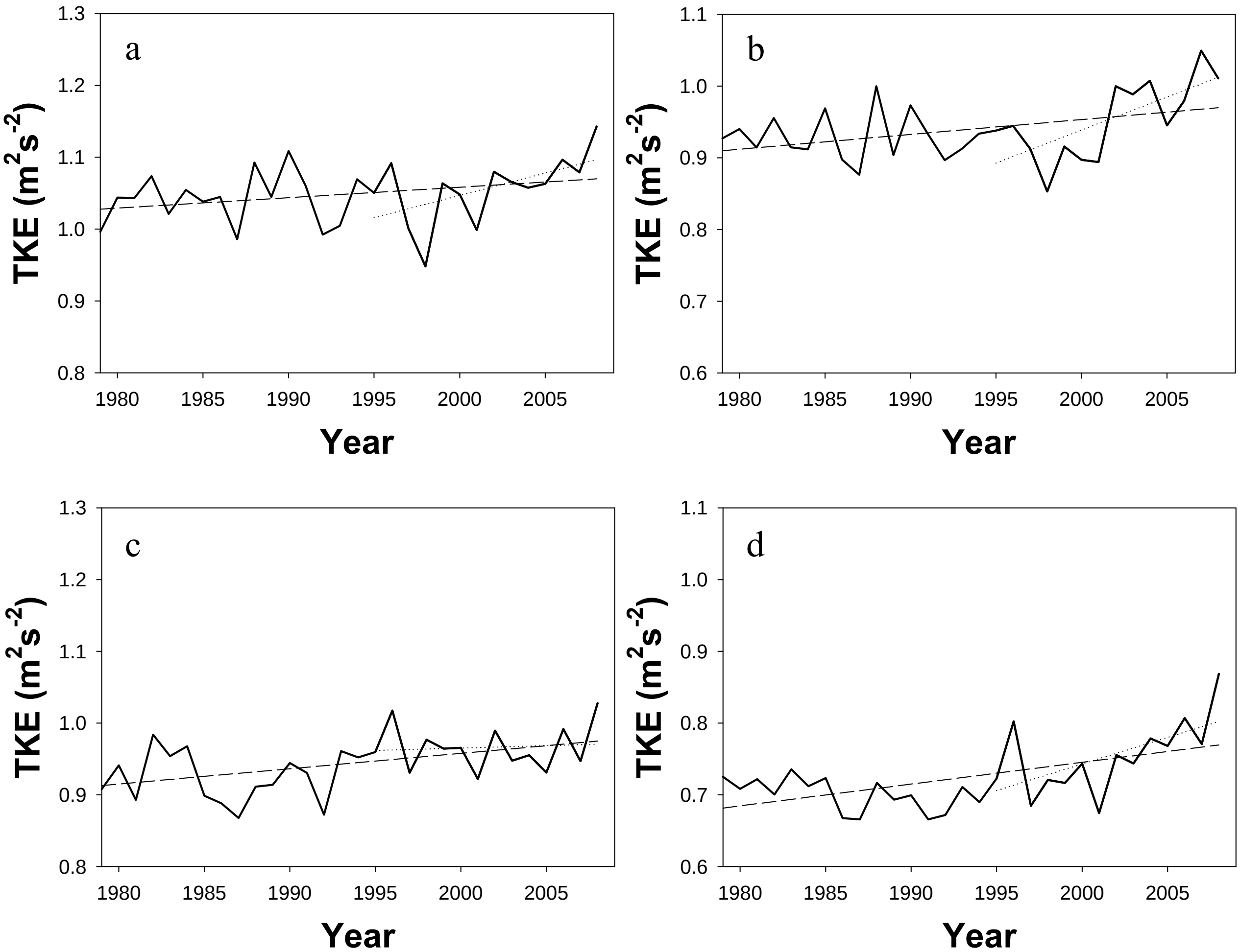

Fig. 3. Thirty-year (1979-2008) trends (solid) in the annual means of region-averaged near-surface turbulent kinetic energy (TKE_s) for the (a) northwest, (b) northeast, (c) southwest, and (d) southeast regions of the U.S. Linear regression lines represent the overall 1979-2008 (medium dashed) and 1995-2008 (dotted) recent trends.

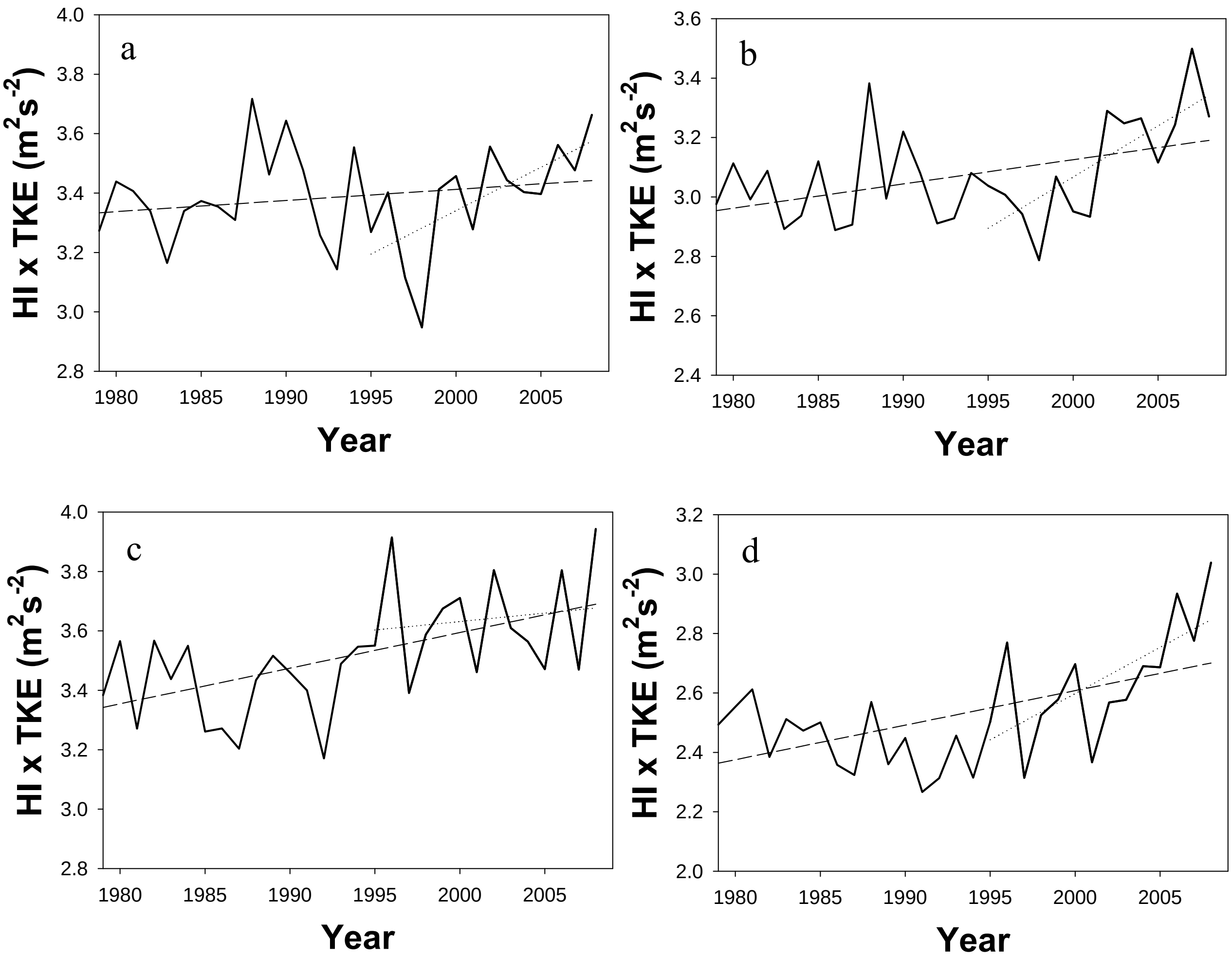

Fig. 4. Thirty-year (1979-2008) trends (solid) in the annual means of region-averaged $HITKE_s$ values for the (a) northwest, (b) northeast, (c) southwest, and (d) southeast regions of the U.S. Linear regression lines represent the overall 1979-2008 (medium dashed) and 1995-2008 (dotted) recent trends.

Conclusions

The analyses of the spatial and temporal patterns of TKE_s and $HITKE_s$ based on the 1979-2008 NARR data suggest that there are substantial regional differences in these indices across the U.S. Average daily maximum TKE_s and $HITKE_s$ values are highest over the high-elevation Rocky Mountain and Appalachian Mountain regions. Over the western half of the U.S., occurrences of daily maximum TKE_s and $HITKE_s$ values exceeding 3 m^2s^{-2} and 15 m^2s^{-2}, respectively, are relatively common from April through September. These thresholds are indicative of a highly turbulent atmospheric boundary layer sitting beneath dry and unstable atmospheric layers aloft, an atmospheric condition conducive to erratic or extreme fire behavior. Over the eastern half of the U.S., exceedances of these thresholds are less common. Because the 3 m^2s^{-2} and 15 m^2s^{-2} thresholds for TKE_s and $HITKE_s$ are frequently exceeded over the western U.S., adopting higher thresholds for these indices for operational fire-weather forecasts in the western half of the U.S. may be needed such that when threshold exceedances occur, it's truly an indication of an anomalous fire-weather event. More research is needed to identify appropriate region- or area-specific threshold values to enhance the efficacy of TKE_s and $HITKE_s$ as operational fire-weather indices.

The observed 30-year (1979-2008) trends in TKE_s and $HITKE_s$ indicate that, at least on a regional average basis, values of these indices have generally increased in every region of the U.S. The most significant increases in these indices have occurred during the 1995-2008 period in the northwest, northeast, and southeast regions of the U.S. An analysis of the long-term trends in near-surface wind shears and near-surface buoyancy, the primary mechanisms for generating atmospheric turbulence, is currently underway to determine their role in producing the observed long-term TKE_s and $HITKE_s$ trends.

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Season Ending Events, A Matter of Perspective

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Abstract:
Agency managers are often faced with making difficult wildland fire management decisions based on collating a significant amount of information regarding a fire. Supporting the decisions is understanding how long an incident may persist, especially if the fire has potential for resource benefits. Analysis of historical season ending events has occurred since the mid-1990's and was initially incorporated into the Rare Event Risk Assessment Process (RERAP) computer program. Definition of the season ending event has always been subjective and typically included a substantial rain event across a two or three-day period. For instance, ½ inch of rain over three days is commonly used in the northern Rocky Mountains. Data from Remote Automated Weather Stations (RAWS) are frequently used to determine the dates these events occurred each year in the past. Then a Weibull distribution ('term distribution') is developed from which to predict the probability of an event occurring by a particular date. A review of several term distributions developed by different analysts for the northern Rocky Mountains during the 2007 fire season was completed to compare season ending criteria and date selection in a relatively small geographic area. These distributions had a vast spread in season ending dates that caused the Weibull distribution to shift as much as three months. This paper highlights the differences among several term distributions, demonstrates the need for consistent definitions and determinations of season ending events within a small geographic area, and proposes a potential solution for greater consistency and thus higher reliability in season ending event distributions.

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A cultural history of fire across the wild, wild West

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Abstract
Humans have had a long and fruitful relationship with fire. At the time of Euroamerican settlement, fires of natural and anthropogenic origin were the primary managers of western wildlands. The establishment of forest reserves beginning in 1891, and creation of the U.S. Forest Service in 1905, provided both a land base and an institutional framework for large-scale management of fire across the West. The great fires of 1910 argued for a óone size fits allô fire exclusion policy across the West. Prescribed burning in dry forests was derided as óPaiute forestryô, but slash burning after clearcutting in wetter, cooler forests was institutionalized. Major policy shifts began in the 1960ôs and in 1968 prescribed and natural fire were allowed on Department of the Interior lands. The Forest Service followed suit, until in the aftermath of the Yellowstone fires all fire use programs were suspended pending a review of each individual plan. As natural fire programs recovered in the 1990ôs, urban interface fires exploded, resulting in a National Fire Plan and the Healthy Forests Restoration Act. In 2009, national fire policy was clarified so that all strategic and tactical options are both available and considered in the response to every wildland fire.

Introduction

Humans are relative newcomers to the fire environment we call earth. Yet we have an exceptionally long cultural history with fire; it is both friend and foe, sometimes in the same event (Pyne 1995). In the western United States (hereafter called the óWestô), lightning fires have occurred for thousands of millennia, and Native Americans have used fire here for tens of millennia (Agee 1993). These fires created the landscape patterns and biodiversity that the early Euroamericans encountered. But until the late 19th century, when settlement began in earnest across the West, there was little need for a wildland fire policy. Even the large wildland fire disasters in the Midwest were overlooked or overshadowed by other events (Brown and Davis 1973). The 1871 Peshtigo and Michigan fires covered over 1.5 million ha and killed at least 1,500 people, but somehow Mrs. OôLearyôs cow kicking a lantern into the hay in Chicago (óThe Great Chicago Fireô) received most of the press coverage on fire that week. In 1884 the Hinckley fire devastated cutover Minnesota and killed 418 people, who were trapped within coalescing escaped slash burns. But the control of fire on a national scale seemed impossible in those times, both technically and economically, and would have been resisted by many residents who started many of the fires to scrape out a meager living on the land. Large fires were occurring in the West, too: fires in the 1840ôs drove Native American of the Oregon Coast into the sea (Morris 1934), and in 1868, much of the central Coast Range of Oregon burned in a large event. In

Washington, the 1902 Yacolt fires (175,000 ha) in southwest Washington, together with other regional fires, began to stimulate private organizations to focus on fire problems (Davis 1959, Cowan 1961). But a comprehensive wildland fire policy demanded both large events and large institutions capable of responding to those events. The intersection of events and institutions have defined the evolution of major wildland fire policy in the western United States.

The beginnings of wildland fire policy

The beginnings of institutionalized forest fire policy began around the turn of the 20th century, and were largely driven by problems occurring on forest reserves, those massive federal land withdrawals that were later to become the national forest system (Dana and Fairfax 1980). In 1891 President Cleveland established the first portion of the system of forest reserves from the public domain that would later become the national forests, but fire control on these lands would remain elusive into the 20th century. By 1897, 16 million ha had been reserved, mostly in the West, but fire was still free on those landscapes.

In the first decade of the 20th century, the seeds of a national forest fire policy were sown. Forest reserves were located within the Department of the Interior, but a growing professional forestry cadre, led by charismatic Gifford Pinchot, was located in the Department of Agriculture as the Bureau of Forestry. In 1905, Pinchotõs close relationship with President Teddy Roosevelt helped to move the forest reserves to Agriculture into a newly named Forest Service. In 1907, forest reserves were renamed ónational forestsô, and the act of 1908 institutionalized deficit spending for forest fire control, but without any standards for an economically sound fire policy. This lack of standards has persisted to the present. Nonfederal landowners, meanwhile, were working on their own to control and use fire. By 1910 a number of organized forest landowner associations had sprung up in the West, primarily for the purpose of forest fire prevention and control. Meanwhile, the timber industry in California was practicing underburning on its ponderosa pine lands.

The big fires of 1910 were to change these practices (Pyne 2001). Millions of acres of land, much of it national forest in Idaho and Montana, burned that summer, and 78 firefighters died (see S.J. Pyne paper in this volume). Considered a disaster at the local level, the óbig blowupô galvanized political strength in Washington, D.C. New political lobbyist Gifford Pinchot, recently fired by President Taft as chief of the Forest Service, helped the Weeks Act pass Congress in 1911, enabling the federal government to buy land for watershed protection and help states with fire protection.

Although the wildlands of the West had a continuum of fire regimes, including low severity (frequent but low intensity fires) and high severity (infrequent but stand-replacing), the lack of understanding of these differences resulted in a óone-size-fits-allô fire policy: complete fire suppression. Ironically, the use of prescribed fire in dry forests, where the historical fire regime was of low severity, was banned, but in wet forests where high severity burns were the norm, burning after clearcut logging, especially in the Pacific Northwest, was institutionalized (Agee 1993).

Dry forests and wet forests: the odd couple

The use of prescribed fire in dry forests, then called ólight burningô, was promoted by industrial forestry companies such as Southern Pacific and the Red River Lumber Company, not for altruistic goals but to save the old growth pine for later logging. The debate began as early as

1910 (Hoxie 1910, Pratt 1911), and the opponents of burning focused their arguments on how light burns killed tree regeneration, and therefore destroyed the forests of the future. California was the scene of a large public debate in *Sunset Magazine* in 1920 (Graves 1920, White 1920, Redington 1920) on the practice of ólight burningô, but the California Forestry Commission, established to resolve the debate, concluded that fire exclusion appeared more practical than light burning (Agee 1993). In fact, fire suppression was relatively simple in these open forests with little fuel buildup. Munger (1917) wrote of rangers riding up to fires in pine forests and suppressing the fire by walking the horse, with a pine bough tied to its tail, along the edge of the fire. On what was to become the Trinity National Forest in northwestern California, Wilson (1904) described fires as óé ground fires, and easily controlled. A trail will sometimes stop them.ô Some research by the Forest Service smacked of bias similar to that described by Schiff (1962) for the southern United States. Haefner (1917) claimed that southern Oregon forests never experienced fires before Euroamerican settlement. Hoffman (1917) and Show and Kotok (1924) worked the ódamage to reproductionô angle. This óresearchô along with the results of the California Forestry Commission, resulted in full fire exclusion being applied across the West, aided by cooperative funding to the states for fire control authorized by the 1924 Clarke-McNary Act. Some southern states had their funding contingent on eliminating traditional underburning of pine forests, but that need was less in evidence across the West, which had much less of a cultural tradition of burning the woods. Funding from the Clarke-McNary and associated acts became the cornerstone of cooperative fire programs at the state level.

Ironically, in wet forests where clearcutting was the norm, slash burning was defended as the antithesis of ópromiscuousô light burning. Slash burning was ónever allowed to run at random; it is systematically set out, and controlled absolutelyô (Boerker 1912). In fact, slashing fires were still the major cause of area burned in the Pacific Northwest (Elliott 1911). In 1921, a severe windstorm caused major windthrow on the Olympic peninsula of Washington. Subsequent burning of 28,000 ha of slash from old timber operations in the next year resulted in no large wildfires within the blowdown, somehow convincing foresters that slash burning was therefore effective at preventing wildfires (Cowan 1961). In 1922, several slash fires ignited in the spring escaped and burned 40,000 ha of cutover and virgin timber. The discussion came to a head at the 1925 Pacific Logging Congress. George Joy, the Washington State Forester, argued for mandatory slash burning in autumn. E.T. Allen, an industry spokesman, took a middle road but generally supported Joy. Frank Lamb, president of a coastal timber company, argued against mandatory burning, as it destroyed any advance regeneration, often escaped, and was treating a fire hazard that lasted only 5 years or so. He concluded his talk with a classic takeoff of Hamlet: óTo Burn, or Not to Burnö. Eloquent though it was, Lambös talk did not sway the political process, and subsequent liability laws forced landowners to burn all slash, or be deemed liable for fires of any origin that started on their land and moved elsewhere. These laws persisted into the 1960ös in Oregon and Washington.

10 A.M. and the beginning of a problem

In 1935, the ó10 A.M. policyô was adopted as standard fire suppression policy on all Federal lands (Pyne *et al.* 1996). This policy stipulated that the control goal for every wildland fire would be to achieve control by 10 A.M. the next morning, and if unsuccessful, by 10 A.M. the following morning, until the fire was controlled. The midmorning period was chosen as the period, after humidity recovery at night, when control might be most successful. This policy was to remain federal policy, applied to low-value lands as much as to high-value lands, for almost 40 years. In the early 1940s, the wildland fire problem in the South became serious enough, together with manpower shortages associated with World War II, that the Forest Service formally recognized the use of prescribed fire. However, underburning did not escape from the South for use on federal lands in other regions until the late 1960s.

Ecological change, meanwhile, was occurring in dry forests. The tree regeneration that had historically been removed by frequent fires was wildly successful in dry forests where fire had been removed. But the blanket rule against burning had contributed to increased insect problems, fuel hazards, and undesirable changes in species composition (Weaver 1943). Weaverøs ideas were so controversial at the time he was forced by his superiors at the Bureau of Indian Affairs to place a disclaimer as a footnote to his 1943 Journal of Forestry article: óThis article represents the authorøs views and is not to be regarded as an official expression of the attitude of the Bureau of Indian Affairs on the subject discussed.ô

The 'glory days' of fire control

The end of World War II ushered in the óglory daysô of fire control. Surplus military equipment and the specter of the Cold War kept resources devoted to fire control, and fire prevention became a high priority with the advent of Smokey Bear and a number of óKeep Greenô organizations in western states. Fire statistics (Fig. 1) showed declines in burned area, and the institutions were successfully achieving their goal of fire exclusion. Coincidentally, the application of wartime technology to wildland firefighting occurred as a long-term, persistent, and recurring pattern of atmospheric pressure and circulation anomaly switched phases. The

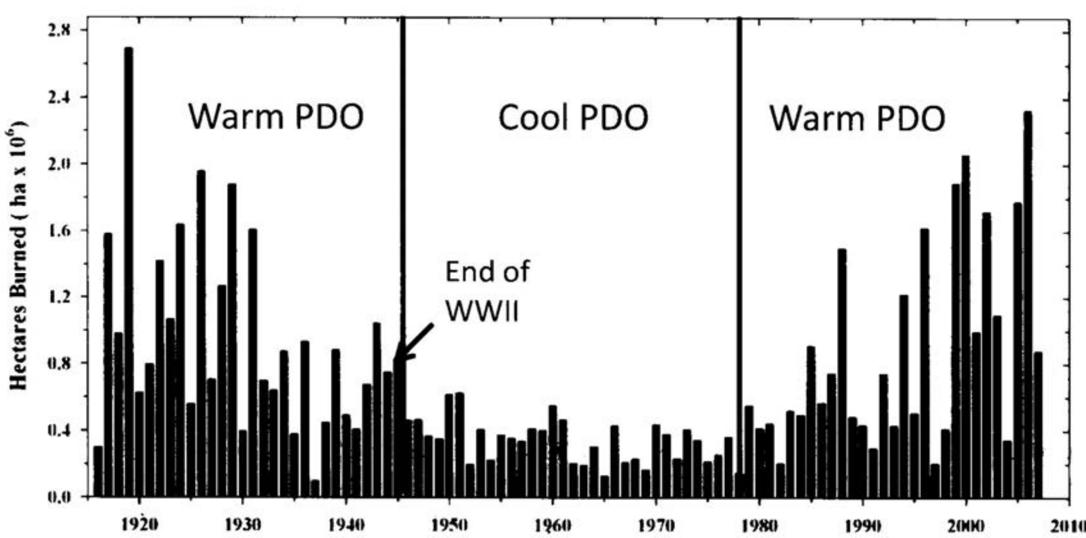

Fig. 1. Wildfire statistics from the 11 Western states (AZ, CA, NV, NM, CO, WY, OR, WA, ID, MT, UT) (Littell *et al*. 2009) overlain over phases of the Pacific Decadal Oscillation (Mantua *et al.* 1997).

Pacific Decadal Oscillation (PDO) moved from a warm, dry phase, to a cool, wet phase (Fig. 1; Mantua *et al*. 1997). While the efficacy of firefighting surely increased, success in wildfire suppression was aided by climate teleconnections, at least into the 1970s.

In the 1950ôs, Harold Weaver was joined by Harold Biswell of the University of California, Berkeley, in promoting the use of prescribed fire in western pine forests. Both were shunned and attempts were made to fire Professor Biswell (Biswell 1989). But their arguments made sense, and they both doggedly but separately continued to show through demonstrations, workshops, and research that fire could be used as a forest management tool.

Policy re-evaluations

In the early 1960s two events helped to shape a fire policy re-evaluation in the West. The first was the advent of the Tall Timbers Research Station fire ecology conferences, which gave a platform for westerners like Weaver and Biswell to argue for a more intelligent fire policy. The second was the formation of a wildlife committee by Secretary of the Interior Stewart Udall to investigate wildlife policy in national parks, triggered by elk population controversies at Yellowstone National Park. Led by Biswellôs colleague A. Starker Leopold, they produced a radical report that argued that primitive America was a mosaic of landscapes molded by disturbance, including fire, and that many undesirable effects had been caused by the exclusion of fire. They asked if it was possible, at least at a local scale, to recreate this óvignette of primitive Americaô (Leopold *et al*. 1963). Secretary Udall, realizing he had a real hot potato on his hands, vetted the report to national conservation groups, who concurred with Leopold and his colleagues, and the report was accepted by the Secretary. In 1968, the use of prescribed fire and natural fire became official fire policy of the Department of the Interior.

Wilderness fire

That same year, the first large scale western prescribed fire was set at Sequoia and King Canyon National Parks (Kilgore and Briggs 1972). The first natural fire allowed to burn in the national forests of the West occurred in 1973 in the Selway-Bitterroot Wilderness (Mutch 1974). In 1974, the Forest Service broadened its 10 A.M. policy, and this evolved to a policy of óappropriate responseô by the 1980s (Pyne *et al*. 1996). The use of fire, either prescribed or naturally ignited, and the ability to use flexible suppression responses (e.g., lower-priority response for backcountry fires where life and property threats are low), initiated a trend at the federal level of óintegrated fire management,ô where the mix of control and use of fire could be applied in a site-specific manner, on the same fire.

The 1960ôs also saw the end of mandatory slash burning (Agee 1989), primarily due to urban population demands for less smoke. Once the liability laws were overturned, the annual area of slash burned dropped by a third. Oregon (1969) and Washington (1970) both implemented smoke management plans which attempted to keep smoke away from fire-sensitive corridors (especially the Interstate 5 corridor), and later in the decade, the Clean Air Act Amendments of 1977 gave the states regulatory power over slash burning on federal forest lands.

Wilderness fire continued to grow through the 1970s and into the 1980s, as more national parks and Forest Service wilderness areas allowed fire to play a more natural ecosystem role. Yellowstone, which was to be the controversial focus of the natural fire policy in the late 1980ôs, began a natural fire program in 1972, and between 1972-1987, 235 fires burned over 15,000 ha in the park. And then came 1988, "the summer we let wildfire loose" (Pyne 1989). It was a big wildfire year anyway (Fig. 1), but when 400,000 ha of Yellowstone burned (about half from human-caused fires on which full suppression was immediately attempted), the controversy threatened the very existence of the natural fire program. The fires of 1988 initiated a review of the natural fire policy. An interagency team responded that the policy was sound but its implementation had been flawed, and all natural fire plans were suspended pending incorporation of new management guidelines (Wakimoto 1990). Programs began slowly coming back on line in 1989 with more conservative criteria. Sequoia-Kings Canyon and Yosemite National Parks were the first two programs to be revived, as they had from the beginning used these management guidelines. Since then, the use of natural fire, which has undergone myriad name changes (let-burn, prescribed natural fire, wildland fire managed for resource benefit, wildland fire use, and now simply wildfire [of natural origin]), has been ranging from 50,000 to 150,000 ha per year.

Escapes, safety, and increasing costs

Prescribed fire escapes and safety concerns were major policy issues in the 1990's. The 1999 Lowden Ranch fire in northern California escaped and burned 25 homes and 1,000 ha, while the Cerro Grande fire (2000) in New Mexico burned 10,000 ha and 235 homes. Like the natural fire program, it was not policy but implementation that went wrong in these fires. Safety concerns were highlighted by the deaths of firefighters at South Canyon (1994) in Colorado (USDA-USDI 1994) and 30 Mile in Washington State (2001).

Many of these fires demonstrated the paradox of successful fire exclusion. The more successful that the fire suppression policy was in reducing wildland fire area burned, the more fuel accumulated on these lands that once burned frequently, and subsequent wildland fires became more intense and uncontrollable. Climate has also played a significant role as the PDO (Fig. 1) moved into a warm/dry phase (Mantua *et al*. 1997). Fire statistics on western lands show a clear U-shaped trend, illustrating the initial effectiveness of fire exclusion through the 1950s and the difficulty of fire control over the last three decades. The Forest Service budget directed to fire has risen from 13% in 1991 to 45% in 2008. In 2007, 27 large fires cost $547 million in suppression costs alone (WFLC 2009). Direct suppression costs are a small fraction of the total costs (limited to market valued items). The WFLC (2009) evaluated six case studies of large wildfires in the 2000-2003 period and found suppression costs to range from 3 to 53% of total costs. These additional costs included private property losses, damage to utility lines, damage to recreational facilities, loss of timber, and aid to evacuated residents. Loss of ecosystem services such as water quality, wildlife habitat, carbon sequestration, and cultural/spiritual values were not included in the analysis.

Recent policy affirmations

Beginning in 1995 fire policy has been re-evaluated several times. The Federal Wildland Fire Management Policy of 1995 reaffirmed fire as a critical natural process and it "… will be integrated into land and resources management plans and activities on a landscape scale" (NWCG 2009). The policy was again reviewed in 2001 and the conclusion was that it "remains sound". But the continued high losses of area burned and lives, culminating in the southern California fires of 2003 (Mutch 2007), generated almost unanimous passage through Congress of the Healthy Forests Restoration Act of 2003. It directed Federal agencies to focus efforts in the wildland urban interface, lands experiencing uncharacteristic fire effects (such as dry pine forests), catastrophically disturbed lands, and threatened and endangered species habitat. Treatments were directed to small diameter trees, fuelbreaks, and prescribed fire. An upper limit of 8 million ha of treated land was imposed.

In 2009, Guidance for Implementation of Federal Wildland Fire Management Policy was issued by the National Wildfire Coordinating Group (five members including the Forest Service from USDA and 4 USDI agencies) (NWCG 2009). It reaffirmed the 1995 and 2001 policy documents as ósoundô, but the most significant change in policy was that óa wildland fire may be concurrently managed for one or more objectives and objectives can change as the fire spreads across the landscape.ô Previously, only one objective was allowable on a single event. A large fire can, at least for the moment, be managed with a monitoring tactic at one point and aggressive suppression elsewhere on the perimeter (Fig. 2).

Because the direct suppression costs of multiple large fires are not budgeted, agencies have been forced to borrow funds from other agency functions, disrupting the ability of the agencies to function normally. In 2009, the Federal Land Assistance, Management, and Enhancement Act (FLAME Act ï P.L. 111-88, Division A, Title V) was signed into law. It establishes a dedicated fund for catastrophic emergency wildland fire suppression activities, separate from appropriated firefighting funding. The dollars are available when appropriated funds are exhausted, once a declaration of need is made by the Secretaries of Agriculture and/or Interior. It directs the agencies to produce a ócohesive strategyô aimed at restoring healthy landscapes, creating fire-adapted communities, and allowing a flexible fire response. State, tribal, and local partners are promised a voice in evaluating policy. Tension is clearly likely, as the Federal agencies are moving towards a looser fire strategy (e.g., Fig. 2) while state and local partners are more likely to be focused on accelerated initial attack.

Conclusion

Frank Lambôs 1925 takeoff of Hamlet is still with us: óto burn, or not to burnô. As land managers see a need to use fire to restore ecosystems, there are multiplying constraints against its use: smoke, endangered species, fire escapes, and safety. While Shakespeare almost had it right, the question is not such a binary choice. It depends on wildland vegetation and how close to historic condition it is; on land objectives, which very widely from wilderness to the wildland

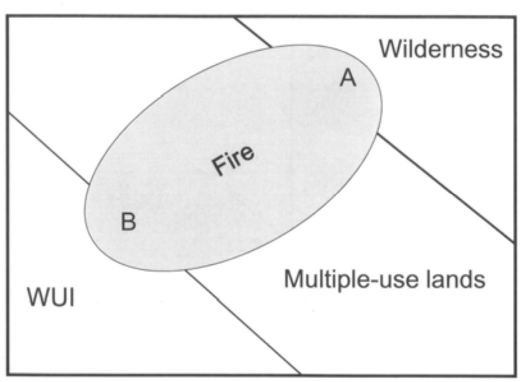

Fig. 2. The 2009 ôGuidanceö allows a monitoring strategy at point ôAö in wilderness and an aggressive suppression strategy near the wildland urban interface (WUI) at point ôBö.

urban interface; and to social and economic objectives, in a nature-deficit-disorder society (Louv 2005) that seems less capable each year of understanding the choices in ecosystem management. There are also major unknowns, such as climate change (McKenzie *et al*. 2004) and carbon sequestration policy (Hurteau *et al*. 2008) which are likely to affect fire policy in future decades. This suggests that the history of wildland fire policy in the wild, wild West is a living history, and will likely see future significant changes as events and attitudes continue to evolve.

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Producing a Canadian Forest Fire Danger Rating System (CFFDRS) Fuel Map Using the Vegetation Resource Inventory (VRI) for Kootenay and Yoho National Parks

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Abstract
Parks Canada is developing a new fuel type map with higher accuracy. The fuel map currently in use is outdated and often misrepresents fuel types on the ground. In 2000, Parks Canada in conjunction with the Province of British Columbia undertook a project to map all vegetation resources within British Columbia, including federal lands in Yoho, Kootenay and Mount Revelstoke National Parks. Vegetation Resource Inventory (VRI) mapping consists of landcover polygons mapped at a 1:20,000 scale with information including species, crown cover, stand age, tree height, timber volume, and understory vegetation. Known fuel type classification criteria were used to define SQL (structured query language) queries performed within ArcGIS to categorize the landscape into fuel types by dominant species, crown closure, and other data fields within the VRI data set. Since there are areas within most landscapes that fall outside the 16 main FBP fuel types, additional data was used to define an additional seven non-standard fuel types commonly found in the Canadian Rocky Mountains. Although fire behaviour in these fuel types has not been defined, caveats to predict fire behaviour in adjacent areas can be made when managing fire in these areas.

Additional keywords: Fuel mapping, GIS, prescribed fire planning, fire behaviour, vegetation resource inventory, fuel types

Introduction

Fire and vegetation management in Canada's national parks is becoming increasingly more complex due to a range of prescribed fire, suppression and wildland urban interface issues. In the mountain national parks (MNPs), which include Banff, Jasper, Kootenay and Yoho National Parks, the fire and vegetation management program is based on the objective of restoring fire to the landscape. While the overall aim is to restore a vital disturbance agent back onto the landscape, each prescribed fire is planned with multiple objectives in mind. Some such objectives are wildlife habitat improvement, ecosystem restoration, preservation of rare or uncommon vegetation types and increasing overall forest resistance to insects and disease.

One of the primary tools used in fire management in Canada, is the Canadian Forest Fire Danger Rating System (CFFDRS), which is used to determine forest fire danger (Stocks *et al*. 1989). The Fire Behaviour Prediction system (FBP) is a subsystem of the CFFDRS which uses a variety of inputs to determine a suite of primary and secondary fire behaviour outputs (Forestry Canada Fire Danger Group 1992). Characterized into 16 key types, fuel type is one of the main inputs into the FBP system. While the CFFDRS and the FBP systems are widely used in Canada and abroad, there are several caveats to the system that should be mentioned,particularly within the context of other tools used in North America.

First, the FBP fuel typing system is based on qualitative descriptions of fuel arrangements rather than quantitative assessments such as fuel beds used in the Fuel Characterization and Classification System (FCCS) used in the United States (Ottmar *et al*. 2007). Furthermore, the FBP system is relatively limited in the number of available fuel types and some fuel complexes are not accurately described by one of the FBP fuel types. In these situations, forest managers must choose the appropriate fuel type based on local knowledge of vegetation cover, and predicted fire behaviour.

Current FBP fuel maps for the MNPs have been based on the Ecological Land Classification database (ELC) (Achuff, *et al*. 1984; Coen and Kuchar 1982; Holland 1982; Holland and Coen 1982). This database represents the basic resource inventory method for landforms, soils, vegetation and wildlife in the MNPs. Completed through a co-operative agreement between the Canadian Wildlife Service and Parks Canada, the ELC for Kootenay National Park (KNP) and Yoho National Park (YNP) was completed in 1984 and 1972 respectively. While the ELC proved to be a highly useful tool prior to the dawn of GIS systems, it has lagged behind as remote sensing and GIS technology has evolved, and newer, more accurate datasets have been developed.

The original ELC was developed using 1:60 000 air photos which were then classified by hand resulting in significant generalization of information. Map units were then developed using landforms and soils to which vegetation themes were applied afterwards, resulting in a loss of accuracy in the vegetation theme. Hand digitization of the original dataset coupled with the continuing dynamic change in vegetation over time has resulted in a further degradation of precision in the dataset. The ELC also represents a static data source with no process in place for regular updates. Lastly, due to the nature of the ELC, it is not compatible with either the Alberta Vegetation Inventory (AVI) or the Vegetation Resource Inventory (VRI) in British Columbia, the neighbouring jurisdictions to the MNPs.

Armed with the need for updated vegetation data, Parks Canada entered an agreement with the province of British Columbia to complete a vegetation resource inventory for the Federal Lands within Kootenay and Yoho National Parks. Between 2003 and 2007, a vegetation resource inventory was completed for both KNP and YNP. The VRI database was developed using the most current mid-scale aerial photograpy; photo interpretation and mapping of vegetation landcover units; and field plot development with rotary wing air calls to ground truth the mapping. While the data collection was completed by early 2007, the complete database was only accessible to Parks Canada managers in fall 2009.

The VRI represents a vast improvement in both the precision and accuracy of vegetation mapping in the MNPs (Fig. 1). Landcover polygons in the VRI are mapped at a 1:20 000 scale with over 200 attributes including information on vegetation species, crown cover, tree height, and a host of other information. Despite the vast number of attributes included in the VRI, there is no direct attribute linking each VRI polygon with a corresponding FBP fuel type.

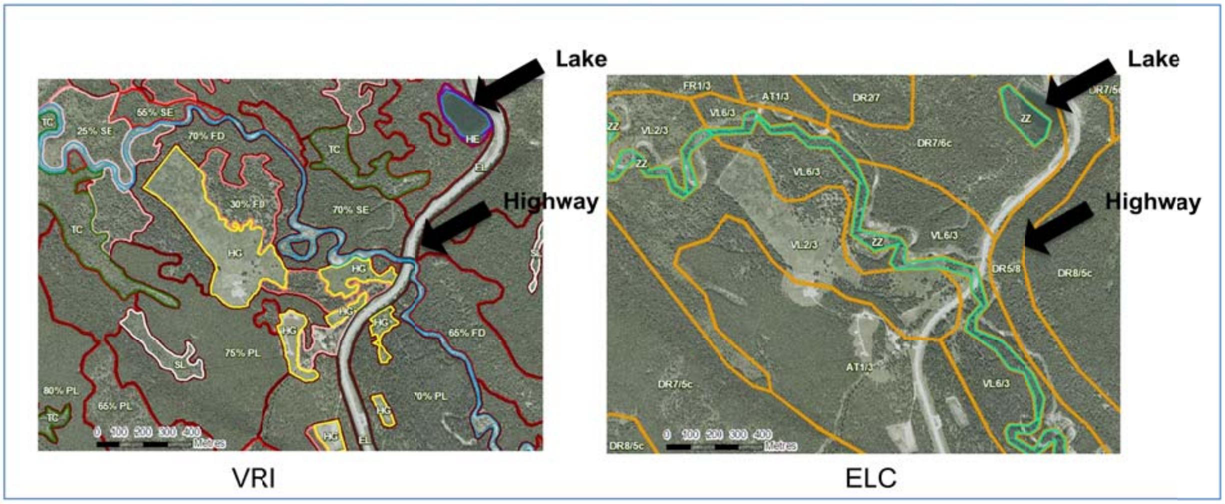

Fig. 1. Comparison of vegetation polygon precision in VRI dataset versus existing ELC dataset. Arrows indicate key features on the landscape and errors in location. Labels within VRI polygons indicate some of the key attributes that are available in the VRI dataset. For example the polygon labeled VL2/3 represents a Vermillion Lakes ecosection with a combination of ecosite 2 and 3.

Previous attempts to map forest fuels in Canada have relied on satellite imagery (Hawkes *et al*. 1995; Nadeau *et al*. 2005). However maps created often lacked detailed vegetation information such as species, crown closure and stand height. Furthermore, certain satellite imagery had the inability to distinguish between different conifer species resulting in highly generalized fuel maps (Nadeau and Englefield 2006).

In this study, we aim to develop a FBP fuel map based on detailed vegetation information from the VRI database for Kootenay and Yoho National Park. By directly relating vegetation attributes for each polygon to descriptions of FBP fuel types, we seek to develop an accurate fuel map that will assist in the planning of fire and vegetation management across the landscape.

Methods

Data

The November 2009 version of the VRI dataset was used in the analysis and creation of the fuel map. VRI data was downloaded from the www.GeoBC.gov.bc.ca website. A digital elevation model (DEM) with a 30mx30m grid resolution and a 1m vertical resolution was used to overlay elevation values and to derive slope values. The official Parks Canada boundary file (2005/2006 version) was used for the cadastral boundaries of Kootenay and Yoho National Parks.

Determining Fuel type classification Criteria and Thresholds

Using FBP Fuel type descriptions from the CFFDRS (Van Wagner *et al*. 1992) key fuel type classification criteria were defined. These included dominant tree species, stand structure (crown closure), surface and ladder fuel characteristics (amount/type of surface fuel, depth of organic layer, height to live crown etc.), and stand density.

Once characteristics and thresholds were determined for the FBP fuel type descriptions, equivalent terms and thresholds within the VRI dataset were chosen. However, once the process of developing SQL queries from the VRI dataset commenced, it was evident that there was an insufficient number of equivalent fields within the VRI data to provide discrete fuel types with no overlapping polygons.

Therefore, we used the BC forest inventory based fuel map develop by Hawkes *et al*. (1995) to extract further fuel type descriptors to link to the VRI dataset. Specific criteria that were used in the 1995 paper were:

- Height Class (i.e. Stand Height)
    - Tall - >28.4m
    - Short - ≤28.4m
- Crown Closure
    - Open - ≤49% crown closure
    - Closed - >49% crown closure
- Crown type
    - Conifer
    - Broadleaf

Other criteria used were directly related to predefined inventory type groups within the Forest Inventory system and therefore did not maximize the newly acquired data containing the VRI.

We used forest criteria that Hawkes *et al*. used to define fuel types in their fuel map as a basis from which to define our own criteria in the VRI. Leading tree species, crown closure and stand height were the three main determinants of forested fuel types that could be used from the VRI data. By reducing the number of descriptors used to develop our fuel map and classifying all non vegetated polygons, we ensured that each polygon only represented one fuel type, and that most polygons would be classified.

The main criteria that were used to determine fuel type were height class, crown closure and crown type (i.e. conifer vs broadleaf, mixed, graminoid etc.) (Table 1).

Table 1. Main Hawkes criteria , associated VRI field and attribute names as well as thresholds assigned.

Hawkes *et al*. (1995) Criteria	VRI Attribute name	VRI Field	VRI Thresholds
Height Class	Projected_height	Projected_height	Tall >20m Short ≤20m
Crown Closure	Crown_Closure	Crown_Closure	Open <35% Closed ≥36%
Crown Type	Species_cd_1	Leading Species	All leading species

When creating the BC forest inventory based fuel map, forests across the entire province of British Columbia were considered. Given the wide distribution of stand heights across such a large geographic region and given that the mean stand height is likely higher across areas which include tall coastal forests, we chose to reduce the stand height criteria to a value more representative of our study area. We examined the histogram of stand heights within polygons in our study area, used local knowledge and consulted with a local vegetation expert (Kubian, pers. comm.), and determined that 20m was a more accurate depiction of the cut off between immature (short) and mature (tall) stands in our study area. Using the Projected height field of the VRI data accounts for the average height, weighted by the basal area, of the dominant, co-dominant and intermediate trees for the leading and second species.

Furthermore, Since we did not use the forest inventory group types to differentiate between different stand species compositions, we used the leading species as a way to help further classify polygons into the appropriate fuel type. To ensure full coverage of all polygons, we made sure that all leading species represented by all polygons were classified into a distinct fuel type.

In addition to the main fuel type descripters, we also used the VRI field, BC Land Cover Classification Scheme 4 (BCLCS_4), describing vegetated cover types. Using this field, we were able to ensure complete coverage of the map and develop a simple process to draw out mixedwood and grass fuel types given that polygons with those types of vegetation complexes were classified outright in VRI verification. Table 2shows the additional VRI thresholds for BCLCS_4 and their associated fuel types.

Table 2. BCLCS_4 categories, their descriptions and the types of fuels that they encompass.

BCLCS_4 Category	Description	Fuel Types Included
TC	Treed Coniferous	Coniferous fuel types
TB	Treed Broadleaf	Deciduous fuel types
TM	Treed Mixed	Mixed fuel types - Defined as polygons where neither coniferous nor broadleaf trees account for more than 75% of polygon tree basal area
HG	Herb-Graminoid	Grass fuel types
ST/SL	Shrubs Low and Tall	Alpine and shrub fuel modifiers
BY/BM/BL	Bryoids/Moss/Lichen	NA
HE/HF	Herbs/Herbs-Forbs	NA
SI/RO	Ice/Rock	Non-fuel

Once all appropriate thresholds were developed for the VRI dataset, individual queries were formulated for each stand type (Table 3). ESRI ArcMap version 9.3.1 (ESRI, 2009) with an ArcInfo license was used to generate the database queries, maps and all geoprocessing. The resulting map formed the basis by which field verification of fuel classes was planned (Fig. 2).

Table 3. Database queries used to classify each polygon into FBP fuel types.

Fuel Type	*ArcMap Query (March 18 2010)*
C-1	*‘BCLCS_LV_4 ‘ = 'TC' AND (‘PROJ_HT_1 ‘ <= 20 AND ‘CR_CLOSURE ‘ <= 49 AND (‘SPEC_CD_1 ‘ = 'BA' OR ‘SPEC_CD_1 ‘ = 'BL' OR ‘SPEC_CD_1 ‘ = 'L' OR ‘SPEC_CD_1 ‘ = 'LA' OR ‘SPEC_CD_1 ‘ = 'LW' OR ‘SPEC_CD_1 ‘ = 'PA' OR ‘SPEC_CD_1 ‘ = 'S' OR ‘SPEC_CD_1 ‘ = 'SE' OR ‘SPEC_CD_1 ‘ = 'SS' OR ‘SPEC_CD_1 ‘ = 'SW' OR ‘SPEC_CD_1 ‘ = 'SX')) OR (‘PROJ_HT_1 ‘ > 20 AND ‘CR_CLOSURE ‘ <= 49 AND (‘SPEC_CD_1 ‘ = 'BL' OR ‘SPEC_CD_1 ‘ = 'L' OR ‘SPEC_CD_1 ‘ = 'LA' OR ‘SPEC_CD_1 ‘ = 'LW' OR ‘SPEC_CD_1 ‘ = 'PA') AND ‘ELEVATION ‘ > 2100)*
C-2 spruce	*(‘PROJ_HT_1 ‘ <= 20 AND ‘CR_CLOSURE ‘ > 49 AND ‘BCLCS_LV_4 ‘ = 'TC' AND (‘SPEC_CD_1 ‘ = 'BA' OR ‘SPEC_CD_1 ‘ = 'BL' OR ‘SPEC_CD_1 ‘ = 'FD' OR ‘SPEC_CD_1 ‘ = 'FDI' OR ‘SPEC_CD_1 ‘ = 'L' OR ‘SPEC_CD_1 ‘ = 'LA' OR ‘SPEC_CD_1 ‘ = 'LW' OR ‘SPEC_CD_1 ‘ = 'PA' OR ‘SPEC_CD_1 ‘ = 'S' OR ‘SPEC_CD_1 ‘ = 'SE' OR ‘SPEC_CD_1 ‘ = 'SS' OR ‘SPEC_CD_1 ‘ = 'SW')) OR (‘PROJ_HT_1 ‘ > 20 AND ‘CR_CLOSURE ‘ > 49 AND ‘BCLCS_LV_4 ‘ = 'TC' AND (‘SPEC_CD_1 ‘ = 'BL' OR ‘SPEC_CD_1 ‘ = 'PA' OR ‘SPEC_CD_1 ‘ = 'S' OR ‘SPEC_CD_1 ‘ = 'SE' OR ‘SPEC_CD_1 ‘ = 'SS' OR ‘SPEC_CD_1 ‘ = 'SW')) OR (‘PROJ_HT_1 ‘ > 20 AND ‘CR_CLOSURE ‘ <= 49 AND ‘BCLCS_LV_4 ‘ = 'TC' AND (‘SPEC_CD_1 ‘ = 'S' OR ‘SPEC_CD_1 ‘ = 'SE' OR ‘SPEC_CD_1 ‘ = 'SS' OR ‘SPEC_CD_1 ‘ = 'SW' OR (‘ELEVATION ‘ <= 2100 AND (‘SPEC_CD_1 ‘ = 'BL' OR ‘SPEC_CD_1 ‘ = 'L' OR ‘SPEC_CD_1 ‘ = 'LA' OR ‘SPEC_CD_1 ‘ = 'LW'))))*
C-3	*‘PROJ_HT_1 ‘ > 20 AND ‘CR_CLOSURE ‘ > 49 AND ‘BCLCS_LV_4 ‘ = 'TC' AND (‘SPEC_CD_1 ‘ = 'L' OR ‘SPEC_CD_1 ‘ = 'LA' OR ‘SPEC_CD_1 ‘ = 'LW' OR ‘SPEC_CD_1 ‘ = 'PL' OR ‘SPEC_CD_1 ‘ = 'PLI') OR (‘PROJ_HT_1 ‘ > 20 AND ‘CR_CLOSURE ‘ <= 49 AND ‘BCLCS_LV_4 ‘ = 'TC' AND (‘SPEC_CD_1 ‘ = 'PA' AND ‘ELEVATION ‘ <= 2100))*
C-4 pine	*‘BCLCS_LV_4 ‘ = 'TC' AND ‘PROJ_HT_1 ‘ <= 20 AND (‘SPEC_CD_1 ‘ = 'PL' OR ‘SPEC_CD_1 ‘ = 'PLI')*
C-7 fir	*‘BCLCS_LV_4 ‘ = 'TC' AND ((‘PROJ_HT_1 ‘ <= 20 AND ‘CR_CLOSURE ‘ <= 49 AND (‘SPEC_CD_1 ‘ = 'FD' OR ‘SPEC_CD_1 ‘ = 'FDI')) OR (‘PROJ_HT_1 ‘ > 20 AND (‘CR_CLOSURE ‘ <= 49 AND (‘SPEC_CD_1 ‘ = 'PL' OR ‘SPEC_CD_1 ‘ = 'PLI' OR ‘SPEC_CD_1 ‘ = 'FD' OR ‘SPEC_CD_1 ‘ = 'FDI') OR ‘CR_CLOSURE ‘ > 49 AND (‘SPEC_CD_1 ‘ = 'FD' OR ‘SPEC_CD_1 ‘ = 'FDI'))))*
D-1 tall and short	*‘BCLCS_LV_4 ‘ = 'TB'*
M-1 and M-2	*‘BCLCS_LV_4 ‘ = 'TM'*
O-1 alpine	*‘BCLCS_LV_4 ‘ = 'HE' OR ‘BCLCS_LV_4 ‘ = 'HF'*
O-1 steep shrub	*(‘BCLCS_LV_4 ‘ = 'ST' OR ‘BCLCS_LV_4 ‘ = 'SL') AND ‘SLOPE_MEAN ‘ >= 30*
O-1 flat shrub	*(‘BCLCS_LV_4 ‘ = 'ST' OR ‘BCLCS_LV_4 ‘ = 'SL') AND ‘SLOPE_MEAN ‘ < 30*
O-1a and O-1b	*‘BCLCS_LV_4 ‘ = 'HG'*
Bryoids and Lichens	*‘BCLCS_LV_4 ‘ = 'BY' OR ‘BCLCS_LV_4 ‘ = 'BL'*
Water	*‘BCLCS_LV_2 ‘ = 'W'*
Non-Vegetated Land	*‘BCLCS_LV_2 ‘ = 'L'*

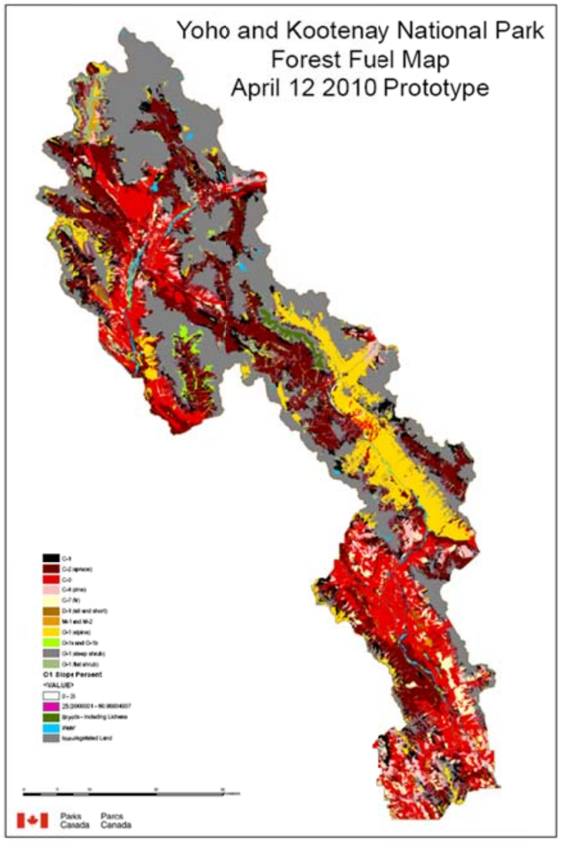

Fig. 2. Complete fuel map prototype following VRI database query to classify fuel types

Map Verification

In June 2010 work began to verify the most complex queries by collecting a range of stand attributes for randomly selected plots. Plots were chosen from classified polygons but stratified by leading species which is one of the most diverse query values. By doing so, we sought to determine whether inaccuracies stem from incorrect assumptions of leading species.

At each plot, we measured: tree species, tree height, stand density, stand composition, height to live crown, crown base height, coarse woody debris (qualitative), litter and duff depth, and crown closure. Plot photos from each cardinal direction were also taken. We hope to have data collection of the most complex queries complete by 2011.

Once these data have been summarized for each plot, a package containing plot information and photos will be provided to several fire experts who will classify each plot according to their expertise. Congruence between expert opinion and the fuel map will indicate the accuracy of fuel type classification by our VRI query method.

If consistent inaccuracies are determined, we will further refine the data queries so predictions from the fuel map better match expert opinion.

Discussion

The completion of an accurate, up to date fuel map for Yoho and Kootenay National Parks will greatly improve the ability of Park managers to manage fire and vegetation on the landscape. This map represents a coarse scale tool with which land managers will make landscape level decisions. Within the context of planning prescribed fires, it will be useful in determining appropriate containment areas for burn units, areas of non-fuels for anchors and changes in fuel types for fire guards. Accurate mapping of fuel will also assist in the determination of the boundaries of wildfire suppression zoning, locating community fire guards in the wildland urban interface, and research plots for fire and vegetation projects.

While this map will assist park managers at the landscape scale, we acknowledge that certain circumstances warrant more detailed fuel bed analyses. In these situations, we will conduct ground level fuel bed surveys to meet specific research objectives or to obtain additional information for fire behaviour predictions or for the measurement of fire effects.

Once the basic FBP fuel types have been verified, we will seek to further develop a dynamic fuel map that also includes rapidly changing vegetation types such as insect affected fuels, recent burn areas and non-FBP standard fuel types such as avalanche paths, shrub meadows and alpine vegetation. By doing so, we hope to further extend the shelf life of the vegetation resource inventory and the associated fuel map.

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Simulating Fire Hazard Across Landscapes Over Time Through Integration of the Vegetation Dynamics Development Tool (VDDT) and the Fuel Characteristic Classification System (FCCS)

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Abstract:
The Vegetation Disturbance Dynamics Tool (VDDT) and the Fuel Characteristic Classification System (FCCS) are two valuable products used by many land managers throughout the United States. VDDT is a state and transition model that simulates changes in vegetative composition and structure across a landscape under different disturbance regimes and management scenarios. The FCCS is a software application that allows users to record fuel characteristics as fuelbeds and analyze fire potential of wildland and managed fuels. Although the utilities of VDDT are many, VDDT does not directly assess fire hazard for different vegetation states.? We are integrating VDDT and FCCS to enhance the utility of VDDT and enable simulation of vegetation composition, structure and related fire potential across a landscape over time. Multiple FCCS fuelbeds will be created, based on plot data, for every VDDT state class (vegetation structure and cover combination) in mid-scale (5th field watershed) models covering the states of Oregon, Washington, Arizona and New Mexico. Fire potential, including fire behavior potential, crown fire potential, and available fuel potential, will be calculated for each fuelbed in FCCS, and mean fire potential will be calculated for each VDDT state class. The resulting link between VDDT state classes and fuelbed fire potential will allow users to assess the effects of disturbance regimes and management activities, such as fuel treatments, on vegetation communities and related fire hazard across a landscape over time.

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The Path Framework for simulating landscape level vegetation dynamics under alternative management scenarios

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Abstract
The Path Framework (Path) is a newly developed decision support tool for simulating landscape level vegetation dynamics and testing alternative strategic fuel management and restoration actions. Path is based on the state and transition modeling approach originally developed in the Vegetation Dynamics Development Tool (VDDT) but includes enhancements designed to overcome challenges observed in the application of VDDT over large landscapes. In particular, Path is designed as a framework within which multiple ecological and management strata can be simulated simultaneously with results being summarized or aggregated at multiple levels. Furthermore, Path allows for the automated calculation of ecological departure and fire regime condition class (FRCC) across a landscape. Path includes a Treatment Analyzer feature that heuristically explores tradeoffs between allocating budgets towards alternative management actions and landscape strata. We applied Path to explore alternative management scenarios for restoration of a landscape in southwestern Idaho. Results suggest that the most effective use of ecological restoration resources is to apply treatments to the depleted sagebrush state classes on the landscape. These state classes are the most vulnerable to both tree encroachment and invasion by annual grasses. Path is versatile enough to be applied to a diversity of other strategic planning efforts. Ongoing applications include an analysis of alternative forest management strategies in Oregon, Washington, Arizona and New Mexico, and an assessment of climate change impacts on landscapes in Nevada.

Additional keywords: decision support, simulation modeling, states and transitions, VDDT, landscape, ecological departure, fire regime condition class

Bridging the scales and approaches of simulation models: the case for planning with FVS and VDDT

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Abstract

Land managers use simulation models to help them analyze and understand how different management scenarios could affect future landscape conditions. Two commonly used tools are the Forest Vegetation Simulator (FVS) and the Vegetation Dynamics Development Tool (VDDT). Depending on circumstances that can include data availability, fire and disturbance dynamics, non-forested conditions, and the scale and type of issues that are being addressed, analysts may decide to use either or both of these tools. Although they are complementary, the models differ in their approach to projection, in the spatial and temporal resolution of projections, in the fundamental simulation units and in the required input data. When both are used there is a need to harmonize the parameters and dynamics of the two models for purposes of comparison, inter-model calibration and consistency.

To produce a tractable comparison we made side-by-side simulations using FVS and VDDT to project 250 stands from mixed conifer dry sites located in the East Cascades of Washington, USA. The stands are principally made up of Douglas-fir and ponderosa pine and are accompanied by a corresponding set of VDDT models. The study includes detailed analyses of FVS run behavior, the consequences of post-processing FVS outputs to make them consistent with VDDT (using the USFS Preside software) and a comparison of the long term transition dynamics of the two models.

Our model comparison shows that each modelôs ñblind spotsò can be illuminated by the other model. In our analysis of an unmanaged scenario, we found that regeneration was weakly modelled by VDDT and that periodic under-burning disturbance was weakly modelled by FVS. Recognizing these gaps makes it possible to iteratively correct them, improving both the models and the decisions they are intended to support. The ongoing study will next repeat the analyses with the addition of some simple management scenarios.

Additional keywords: Forest Vegetation Simulator, Vegetation Dynamics Display Tool, scale, simulation

Long-term Simulated Wildfire Behavior and C Emissions Following Fuel Treatments in the Klamath Mountains, USA

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Abstract:
We modeled stand-level wildfire behavior, above- and below-ground carbon storage, and fire-induced carbon emissions for 100 years following common fuel treatments (prescribed broadcast fire, mechanical thin-from-below, thin + prescribed fire, and thin + pile & burn) in montane mixed-conifer forest stands in the Klamath Mountains of northern California, USA. Stands were dominated by *Pinus ponderosa*, *Pinus lambertiana, Abies concolor*, and *Pseudotsuga menziesii*. We utilized the Fire and Fuels Extension of the Forest Vegetation Simulator to simulate changes to forest structure, fire behavior, and C dynamics through time. Model inputs included field measurements of surface and canopy fuels in treated stands and untreated control stands and estimates of tree regeneration through time following treatment.

Results showed that total C storage did not significantly vary (α=0.10) between the treated stands and untreated control stands at any point through time, which was apparently due to minimal vegetation removed in the treatments. However, treatments increased stand-level canopy base height and reduced surface loads of fine fuels, which subsequently led to significantly lower modeled flame length than untreated controls even under severe weather conditions. After ~20 years, simulated fires in treated stands began to transition from surface fires to crown fires. C emissions during simulated wildfires were also significantly lower for in treated stands and strongly interacted with on-site C storage and simulated flame length. A combination of mechanical treatment (which impacted canopy base height) followed by a secondary treatment (which impacted surface fuel loading) seemed to have the greatest impact on long-term potential C loss from wildfires. The modeled results demonstrate that fuel treatments can significantly impact wildfire behavior and subsequent C emissions for extended time periods in these stands even with minimal impacts on total C storage.

Canopy differences of southwestern ponderosa pine following rotational prescribed fire treatments

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Abstract
Two burn rotation study areas were established on the Coconino National Forest in Northern Arizona, one in 1976 (Chimney Spring) and one in 1977 (Limestone Flats). The primary objective of this research was to evaluate the effectiveness of prescribed fire rotational burning on fuel reduction in southwestern ponderosa pine (*Pinus* ponderosa Law.) stands that had not received any disturbance within the previous 75-100 years. Burn interval treatments tested were 1-, 2-, 4-, 6-, 8-, and 10-years along with an unburned control treatment. Each treatment was replicated 3 times. This paper reports base of live crown height responses after 30 years of treatment application. Diameter, tree height and crown base height were recorded for each tree found in five permanent subsample 0.1 acre circular plots established at the inception of each study area. At Chimney Spring, estimates of mean crown height on the control and 2-year burn treatment were significantly less than the remaining burn treatments. The estimates of mean crown height of the control, 1-, 6-, and 10-year burn rotations at Limestone Flats were significantly lower than the 2-, 4-, and 8-year burn rotations. But if both sites are combined, the mean crown height on the control treatment was significantly less than all burn treatments. Crown height ratio analysis showed significant differences between burn treatments but not with the control treatment. When sites were combined, the 8-year burn rotation crown height ratio was significantly smaller than the control, 2-, and 6-year bun treatments.

Additional keywords: Southwestern ponderosa pine, prescribed fire, crown height, crown ratio

Introduction
Prescribed fire has been recognized by forest managers as a tool for reducing hazardous fuels, improving wildlife habitat, and preparing areas for natural regeneration. Two long-term research areas were established in northern Arizona on the Coconino National Forest, one in 1976 (Chimney Spring – CHS) and the other in 1977 (Limestone Flats – LMF). Chimney Spring was established on basalt soils common in northern Arizona and Limestone Flats is located on limestone/sandstone soils common along the Mogollon Rim. Sites are located on the Fort Valley Experimental Forest (CHS) and Long Valley Experimental Forest (LMF). Various fire affects have been studied on these two sites over the past 30+ years which can impact fire behavior. Crown height and ground fuels play critical roles in modifying fire behavior. A common management goal is to raise the base of live tree crowns to reduce crown ignition potential from below thereby reducing the risk of crown fire. Previous work has shown that prescribed burns reduce the ground/surface fuels necessary to sustain crown fire and we wondered whether our fixed interval moderate intensity underburns might also have raised the height to the base of the live tree crowns.. These preliminary results suggest that moderate intensity prescribed fires do

affect crown height, but whether these changes are significant or not has yet to be tested through simulation using fire behavior prediction models.

Methods

Seven treatments were randomly applied to twenty-one 2.5 acre (1ha) plots. Treatments consisted of 1-, 2-, 4-, 6-, 8-, and 10-year autumn burn rotations and a no burn control. Each plot had five circular 0.1 acre subplots established and arranged in an 'X' pattern. Tree diameter, total height and live crown height were measured for each tree located in the subplot resulting in a database of 5,563 trees at CHS and 5,861 at LMF.

Results

Findings summarized in Tables 1 and 2 show that repeat moderate intensity prescribed fires affect tree crown height and crown ratio. At Chimney Spring study site, estimated mean crown height of trees found on the 1-, 4-, 6-, 8-, and 10-year burn rotation treatment plots were significantly higher than the control. The estimated mean crown height on the 2-year burn rotation, although not statistically significant, was 7 feet higher than the mean height on the controls. The 10-year burn treatment had the highest estimated mean crown height, but was not significantly different from the 1-year and 4-year treatments. At the Limestone Flats site only the 2-, 4-, and 8-year burn rotations were significantly different from the control treatment. When both sites are combined, mean crown height on all burn treatments was significantly higher than the control mean crown height.

Table 1. Estimates of mean crown height and standard errors. Treatments in the same columns with like letters are not significantly different at the 5% level using Tukey's HSD test.

Treatment	Chimney Spring		Limestone Flats		Both sites	
	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.
Control	12.2a	1.2	13.3a	1.3	12.8a	0.9
1 year	27.3bc	1.9	19.6ab	1.6	23.3bc	1.2
2 years	17.4ad	1.5	20.9b	1.6	19.1b	1.1
4 years	24.3bcd	1.8	21.4b	1.6	22.8bc	1.2
6 years	21.7bd	1.7	19.4ab	1.6	20.5bc	1.1
8 years	21.3bd	1.6	22.7b	1.7	22.0bc	1.2
10 years	33.2c	2.1	19.7ab	1.6	26.0c	1.3

Crown ratio is the length of live crown in relation to the overall height of the tree and is a measure of the bulk density of the tree crown. The smaller the crown ratio, the less likely the crown will be ignited by a surface fire assuming the lower the crown ratio, the higher the base of the live crown for a given total tree height. Forest managers thus often desire a small crown ratio to reduce the risk of crown fire. The control's mean crown ratio at the Chimney Spring site was not significantly different from the burn treatments. At the Limestone Flats site, the 8-year burn treatment was significantly smaller than the control treatment. The same result holds true when both sites are combined, the 8-year burn treatment is the only treatment significantly smaller than the control.

Table 2. Significance of crown height ratio between treatments for each site and combined. Treatments in the same columns with like letters are not significantly different at the 5% level using Tukey's HSD test.

Treatment	Chimney Spring		Limestone Flats		Both sites	
	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.
Control	0.42ab	0.017	0.42ab	0.017	0.42a	0.012
1 year	0.36b	0.017	0.45a	0.018	0.40ab	0.012
2 years	0.46a	0.017	0.41ab	0.017	0.43a	0.012
4 years	0.44ab	0.018	0.37ab	0.017	0.41ab	0.012
6 years	0.39ab	0.017	0.45a	0.018	0.42a	0.012
8 years	0.38ab	0.017	0.35b	0.017	0.37b	0.012
10 years	0.35b	0.018	0.41ab	0.017	0.38ab	0.012

Conclusion

Few studies are able to evaluate the affect of repeated prescribed burns treatments on crown characteristics. At the time the data was collected, the annual plots had been burned 30 times and the 10-year burn plots were going to be burned that fall for the fourth time. The size and close proximity of the plots to each other makes it difficult for observational conclusions to be made. The collection and analysis of this data supports visual differences between initial photos and current photos at permanent photo points. These data along with fuel load changes still need to be used as inputs in fire behavior models to simulate the effectiveness of the burn rotation treatments on the probability of crown fire initiation. But these preliminary findings are encouraging in supporting the continuing use of prescribed fire to protect stands of southwestern ponderosa pine and a viable tool for forest managers.

Snag Retention, Wildlife Usage, and Surface Fuel Deposition Following Large, Stand-replacing Wildfires in Dry Coniferous Forests

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Abstract:
Fire-killed trees provide critical habitat for wildlife, but also add to surface fuel loads as they decay and fall. We studied patterns of snag decay and fall, surface fuel accumulation, and snag usage by cavity-nesting birds following stand-replacing wildfires in dry western coniferous forests to better understand trade-offs between managing fire hazard and wildlife habitat. We sampled fire-killed trees and surface fuels on 126 plots within a chronosequence of 49 wildfires that burned dry coniferous forests of eastern Washington and Oregon during 1970-2007. Surface accumulations of small diameter fuels (up to 7.6 cm) and larger diameter (> 7.6 cm) sound fuels increased to a maximum 10-20 years following fire and then declined, with large diameter fuels peaking later than small diameter fuels. Rotten large diameter fuels increased monotonically with time since fire up to 37 years. Pre-fire stand basal area was positively correlated with amounts of large diameter fuels. The probability of a standing snag containing a wildlife cavity increased over time, but probabilities varied among snag diameter size classes and species. Snags with broken tops were more likely to have cavities than whole snags, and ponderosa pine snags were somewhat more likely to have cavities than Douglas-fir snags. Habitat usage of medium diameter snags (30 to 60 cm diameter) increased at a faster rate than that of small or large diameter snags with time since fire up to 30 years. Small diameter snags generally fell without being used by cavity-nesting species, while wildlife usage of large diameter snags was low for the first 20-30 years after wildfire. Removing smaller trees after fire, especially in dense stands, may help reduce fuels with little impact on cavity nesters, but retaining some medium-sized snags could help provide continuity in habitat availability for cavity-nesting wildlife species during the first few decades following wildfire.

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Fuel Buildup and Potential Fire Behavior after Stand-replacing Fires, Logging Fire-killed Trees and Herbicide Shrub Removal in Sierra Nevada Forests

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Abstract:
Typically, after large stand-replacing fires in forests in the Sierra Nevada, dense shrub fields occupy sites formerly occupied by mature conifers, until eventually conifers overtop and shade out shrubs. Attempting to reduce fuel loads and expedite forest regeneration in these areas, the USDA Forest Service often disrupts this cycle by the logging of fire-killed trees, replanting of conifers and killing of shrubs. We measured the effects of these treatments on live and dead fuel loads and alien species and modeled potential fire behavior and fire effects on regenerating forests. Sampling occurred in untreated, logged and herbicide-treated stands throughout the Sierra Nevada in four large fire areas 4-21 years after stand-replacing fires. Logging fire-killed trees significantly increased total available dead fuel loads in the short term but did not affect shrub cover, grass and forb cover, alien species cover or alien species richness. Despite the greater available dead fuel loads, fire behavior was not modeled to be different between logged and untreated stands, due to abundant shrub fuels in both logged and untreated stands. In contrast, the herbicide treatment directed at shrubs resulted in extremely low shrub cover, significantly greater alien species richness and significantly greater alien grass and forb cover. Grass and forb cover was strongly correlated with solar radiation on the ground, which may be the primary reason that grass and forb cover was higher in herbicide-treated stands with low shrub and tree cover. Repeat burning exacerbated the alien grass problem in these stands. Although modeled surface fire flame lengths and rates of spread were found to be greater in stands dominated by shrubs, compared to low shrub cover conifer plantations, surface fire would still be intense enough to kill most trees, given their small size and low crown heights in the first two decades after planting.

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A Simulation Study of Fuel Treatment Effects in Dry Forests of the Western United States: Testing the Principles of a Fire-safe Forest

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Abstract:
Forest and fire managers need guidelines to develop effective fuel treatment options for reducing potential fire behavior in dry forest ecosystems. We evaluated treatment effects on 45,162 stands in low -to mid-elevation dry forests in the western United States. We simulated and quantified the effects of thinning and surface fuel treatments on fire hazard and fire behavior using the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) at the project scale (tens of hectares). Thinning and surface fuel treatments consistently reduced crown fire behavior (fire type) and fire hazard (increased torching index). Thinning treatments that resulted in low stand densities (125 and 250 trees ha^{-1}) were more effective than were lighter thinning treatments (500 and 750 trees ha^{-1}) for changing active crown fire hazard proportions across FFE-FVS variants. Prescribed fire was the most effective surface fuel treatment. This study is the first to statistically test treatment effects with FFE-FVS. Despite potential shortcomings of using this modeling approach, the results support inferences from recent empirical studies about stand density and fuel structures on crown fire hazard. The concurrence of results from modeling and empirical studies provides quantitative support for "fire-safe" principles of forest fuel reduction (*sensu* Agee and Skinner 2005).

Remote sensing of WUI fuel treatment effectiveness following the 2007 wildfires in central Idaho

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Abstract
The 2007 East Zone and Cascade wildfires in central Idaho burned through fuel treatments in the wildland-urban interface (WUI) surrounding two local communities: Secesh Meadows and Warm Lake. The WUI fuel treatments funded by the National Fire Plan were designed to increase fire fighter safety, protect people and property, and mitigate severe fire effects on natural resources. It has been shown previously via two independent on-the-ground assessments that these WUI treatments were generally effective by these criteria. In this study, we demonstrate that fuel treatment effectiveness also can be assessed remotely, using data from Burned Area Reflectance Classification (BARC) maps that are customarily produced by the USFS Remote Sensing Applications Center (RSAC) in response to major wildfires. A simple GIS analysis was used to calculate and compare the proportion of hectares burned at high severity between treatment units and untreated lands in the two study landscapes. In both landscapes, a higher proportion of untreated lands burned at high severity than treated lands. Furthermore, this result was consistent whether using an immediate post-fire BARC map indicative of *fire severity* or a one-year post-fire BARC map indicative of *burn severity*. The method can be used to assess treatment effectiveness on other large wildfires.

Additional keywords: burn severity, fire severity, National Fire Plan, wildland-urban interface

Introduction

The 2007 wildfires burned more forest in Idaho than in any year since 1910. On the Payette and Boise National Forests (NF) in central Idaho, new annual records were set with an estimated 190,577 ha and 98,467 ha burned, respectively. Several large wildfires caused by multiple lightning strikes in July grew and converged to form the East Zone and Cascade complexes, that eventually merged and burned >240,000 ha by the end of September at a cost to suppress of >$70M (Independent Large Wildfire Cost Panel 2008). The huge size and extreme fire behavior of these wildfires, rugged terrain, and paucity of available firefighting resources caused fire crews to use an Appropriate Management Response strategy (AMR) of wildland-urban interface (WUI) and point protection (McCarthy *et al.* 2008; Graham *et al.* 2009).

The cost to suppress wildfires nationally has doubled in the past decade and many expect this trend to continue due to increased residential development in the WUI, hazardous fuel build-up, and probably climate change (National Wildfire Coordinating Group 2009). One strategy to try to mitigate these escalating costs is to remove or reduce hazardous fuels in advance of wildfire occurrence. Fuel treatments are implemented with the simple goal to reduce the surface, ladder, and canopy fuels available to burn in the event of a wildfire (USDA Forest Service 2005). Treatments are designed to moderate fire behavior to reduce fire intensity and fire severity (Graham *et al.* 1999, 2004).

Fuel treatments are widely believed to decrease wildfire risk to communities and increase ecosystem resiliency to wildfire effects (USDA USDOI WGA 2002, 2006). Since 2000, the National Fire Plan (NFP) has annually provided millions of dollars to treat millions of acres, with the twin goals of reducing hazardous fuel loads and restoring healthy ecosystems. The NFP mandates that half of treated lands be strategically placed in the WUI.

Given that the NFP has invested so much into fuel treatments, a fair and obvious question to ask is: Have NFP-funded fuel treatments been effective? Treatment effectiveness can be assessed by three criteria: (1) evidence of a beneficial change in fire behavior (from a crown fire to a surface fire), (2) evidence of improved protection of people and property, and (3) evidence of diminished negative impacts on vegetation and soil resources. The emphasis of this study is on the third criterion.

The East Zone and Cascade wildfires burned through WUI treatment units designed to help protect homes in the local communities of Secesh Meadows and Warm Lake in Idaho. Graham *et al.* (2009) found that the WUI fuel treatments at Warm Lake were highly effective at slowing the momentum of the advancing crown fire, allowing firefighters to safely and effectively protect several dozen homes at Warm Lake. Hudak *et al.* (2011) reached a similar conclusion at Secesh Meadows and Warm Lake, using a simple statistical comparison of paired field sites to show that the fuel treatments did effectively mitigate adverse fire effects on vegetation and soils. Furthermore, Hudak *et al*. (2011) showed that a satellite-image derived indicator of fire-induced change between pre- and post-fire environments, the differenced Normalized Burn Ratio (dNBR), calculated by differencing NBR indices calculated from pre- and post-fire Landsat Thematic Mapper (TM) images respectively (Key and Benson 2005), significantly differed between treated and untreated sites at both Secesh Meadows and Warm Lake. Therefore, it appears feasible to assess fuel treatment effectiveness remotely (Wimberly *et al*. 2009), and not just on the ground.

The USFS Remote Sensing Applications Center (RSAC) produces Burned Area Reflectance Classification (BARC) maps from continuous dNBR values. The maps are delivered to incident management teams on important wildfires and are used as preliminary inferences of four burn severity classes (high, moderate, low, and unburned) as defined by Key and Benson (2005). These maps are used by Burned Area Emergency Rehabilitation (BAER) teams that rapidly respond to major wildfire events, where they plan and implement emergency rehabilitation treatments (e.g., hydromulch, straw mulch, aerial seeding) to mitigate post-fire erosion (Robichaud *et al.* 2009). Harbert *et al*. (2007) demonstrated that the number and proportion of hectares burned at high or moderate severity as indicated by four-class BARC maps provide a useful measure of fuel treatment effectiveness.

In this paper we report the utility of two post-fire BARC maps for assessing fuel treatment effectiveness. The first BARC map was produced operationally by RSAC immediately post-fire and indicates immediate fire effects that are considered measures of *fire severity* (Lentile *et al*. 2007). Examples of immediate fire effects include fuel consumption, ash deposition, and soil charring. The second BARC map was produced for this research study one-year post-fire and indicates extended fire effects that are considered measures of *burn severity* (Lentile *et al*. 2007). Examples of extended fire effects include delayed tree mortality and vegetation regrowth. Hudak *et al*. (2011) reviewed previous quantitative studies of fuel treatment effectiveness, nearly all of which were based entirely on ground assessments. Our objective in this study is to determine if it is feasible--either immediately or one-year post-fire--to use BARC maps and GIS tools to remotely assess fuel treatment effectiveness more quickly, cheaply, and broadly than is practical using only expensive ground assessments.

Methods

Study landscapes

The community of Secesh Meadows (45.245°; -115.822°) is located ~50 km north-northeast of McCall in central Idaho. The community occupies the Secesh River valley with steep, forested terrain on both sides (Fig. 1). The subalpine forest type is dominated by lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*). Several homeowners implemented Firewise fuel treatments around their homes circa 2005. Thirteen pile and burn fuel treatments totaling 220 ha were funded by the NFP and implemented in 2006 on surrounding Payette NF lands. The fuel piles had been burned in only eight of the units when the Loon Fire (part of the East Zone Complex) burned through them in 2007 (Hudak *et al*. 2011).

The Warm Lake community (44.645°; -115.688°) is built around Warm Lake located ~45 km east-northeast of Cascade in central Idaho. The Warm Lake Basin is relatively flat but is surrounded by steep, heavily timbered slopes (Fig. 2). The mixed conifer forest type is dominated by lodgepole pine, Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*). A popular resort destination, Warm Lake is surrounded by approximately 70 structures including two lodges, three public campgrounds, a youth camp, a church camp, and a USFS project camp. Most of the residents are part-time lessees of Forest Service administered land; therefore, treatments were implemented within 15 m of each residence (Graham et al. 2009). The ten treatments include 1215 ha in three units northeast of Warm Lake that were treated with prescribed burns in 1996, 1997 or 1998, and 412 ha in seven units funded by the NFP. The NFP-funded treatments include: one 2004 mastication unit; five 2000-2005 pile and burn units, two of which were further treated with prescribed surface fire; and one 2006 prescribed burn unit on Kline Mountain immediately west of Warm Lake.

Remote sensing and GIS data analysis

To produce BARC maps for Type I and BAER teams working at the East Zone and Cascade Complexes, RSAC followed normal operational procedures to geometrically and radiometrically correct Landsat imagery (http://landcover.usgs.gov/pdf/image_preprocessing.pdf) and then calculated NBR as the difference between Landsat TM bands 4 and 7 divided by their sum (Key and Benson 2005). The dNBR subsequently was calculated as pre-fire NBR minus post-fire NBR. Because the East Zone and Cascade complexes were such high priority fires, RSAC produced three BARC maps using dNBR values derived from an 11 October 2004 Landsat 5 Thematic Mapper pre-fire image and either Landsat 5 TM or Landsat 7 Enhanced Thematic Mapper Plus (ETM+) post-fire images that were acquired 25 August (ETM+), 2 September (TM) and 26 September 2007 (ETM+) in the case of the East Zone Complex and on 25 August (ETM+), 10 September (ETM+), and 26 September 2007 (ETM+) in the case of the Cascade

Complex. For this analysis, the 26 September ETM+ image was selected because the firelines did not fully progress through Secesh Meadows and Warm Lake until 17 September 2007.

The 31 May 2003 failure of the scan line corrector mechanism on board Landsat 7 causes data voids in the image parallel to the scan direction (perpendicular to the satellite path) that widen toward the edges of the scene. A majority filter is employed to fill the categorical data gaps in the classified BARC map and produce a more visually satisfying result but can produce local inaccuracies. To overcome this difficulty in preparing a one-year post-fire BARC map for this study, two successive ETM+ images that were collected on 10 July 2008 and 26 July 2008 were merged. The data gaps in the two scenes fortunately offset just enough to produce a composite one year post-fire image with continuous coverage across the entirety of both study landscapes. A 13 July 2006 TM image from Landsat 5 provided the pre-fire NBR values needed to calculate dNBR.

The Quickbird satellite was tasked to collect high resolution (0.6 m panchromatic and 2.4 m 4-band multispectral) imagery over the two study landscapes. The scene in a standard order has a spatial extent of 64 km^2, so we used the boundaries of the two Quickbird scenes to define the boundaries of the two study landscapes. A simple rectangle fully encompassed the treatment units surrounding the Secesh Meadows landscape (Fig. 1), but in the case of the Warm Lake landscape, some reshaping of a simple rectangle was required to encompass all of the fuel treatment units and adjacent areas of relevance (Fig. 2). The multispectral-panchromatic fused image product was ordered to provide 0.6-m resolution in color for maximum visual benefit. While Quickbird imagery is obviously superior to Landsat for visual interpretation, we did not use the Quickbird imagery analytically for three reasons: 1) Quickbird lacks the spectral equivalent of 30-m Landsat band 7 needed to calculate NBR, 2) pre-fire Quickbird imagery was not available for calculating an alternative indicator of fire-induced change (i.e., differenced Normalized Difference Vegetation Index, or dNDVI), and 3) Landsat images are freely available and are the customary choice by RSAC to produce BARC maps, making Landsat more relevant for evaluating BARC maps as a tool to assess fuel treatment effectiveness.

The simple GIS procedure applied for this analysis was to calculate the areal percentage of hectares that burned in each severity class within each treatment unit, and on untreated lands, within the two 64 km^2 study landscapes. These percentages were then compared with the assumption that, had the units not been treated, they would exhibit the same percent area burned in each severity class as observed on untreated lands. At Secesh Meadows, 277 ha of private lands containing some unknown number and extent of Firewise treatments were considered separately, while in the Warm Lake landscape a 201-ha area including the lake plus a 50-m riparian buffer zone was excluded from consideration. Also excluded from consideration were 130-ha and 69-ha buffer zones within 50 m of the Secesh and South Fork Salmon Rivers that cross the Secesh Meadows and Warm Lake landscapes, respectively (Figs. 1 and 2). This left 5,774 ha and 4,506 ha that were considered untreated in the Secesh Meadows and Warm Lake landscapes, respectively.

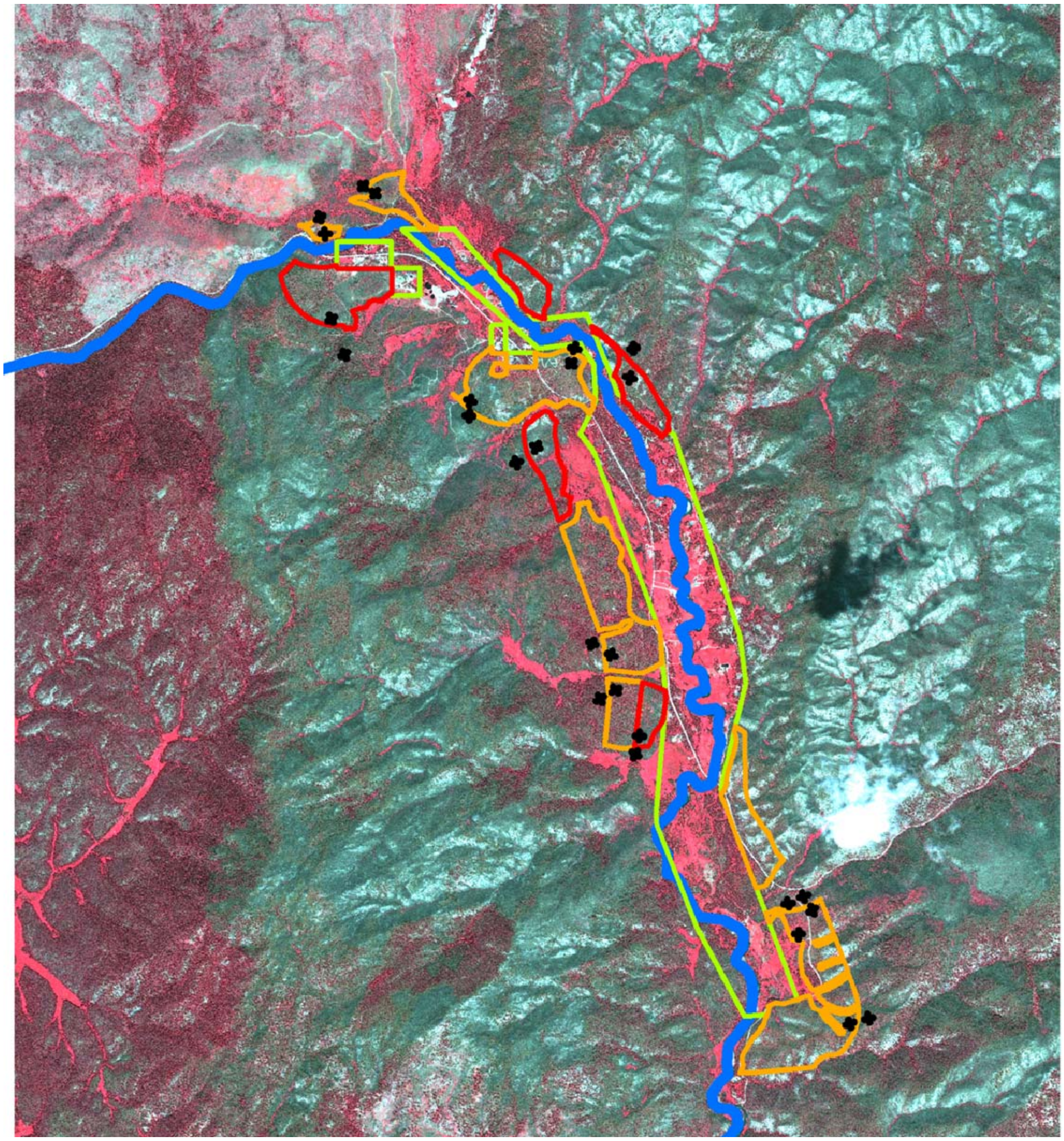

Fig. 1. Quickbird satellite image (collected 16 July 2009) of the 64 km^2 Secesh Meadows area burned by the 2007 Loon Fire in central Idaho. Pile and burn treatment units (2006) where the fuel piles were burned as prescribed prior to the wildfire are indicated in orange. Pile and burn treatment units (2006) where the fuel piles burned in the wildfire are indicated in red. Firewise treatments (2005) on private lands are located within the polygons indicated in green. The Secesh River is indicated by the blue line. The black dots indicate the location of paired field sites installed by Hudak *et al.* (2011) to assess treatment and fire effects. This is a color infrared composite display that highlights unburned forested areas in dark red, unburned grassy meadows in bright pink, and burned areas in bluish-green. The pale pink area in the upper left is from the 2000 Burgdorf Fire and served as an effective firebreak to the northward advance of the 2007 Loon Fire. A white cloud is visible in the lower right, and its black shadow to the north.

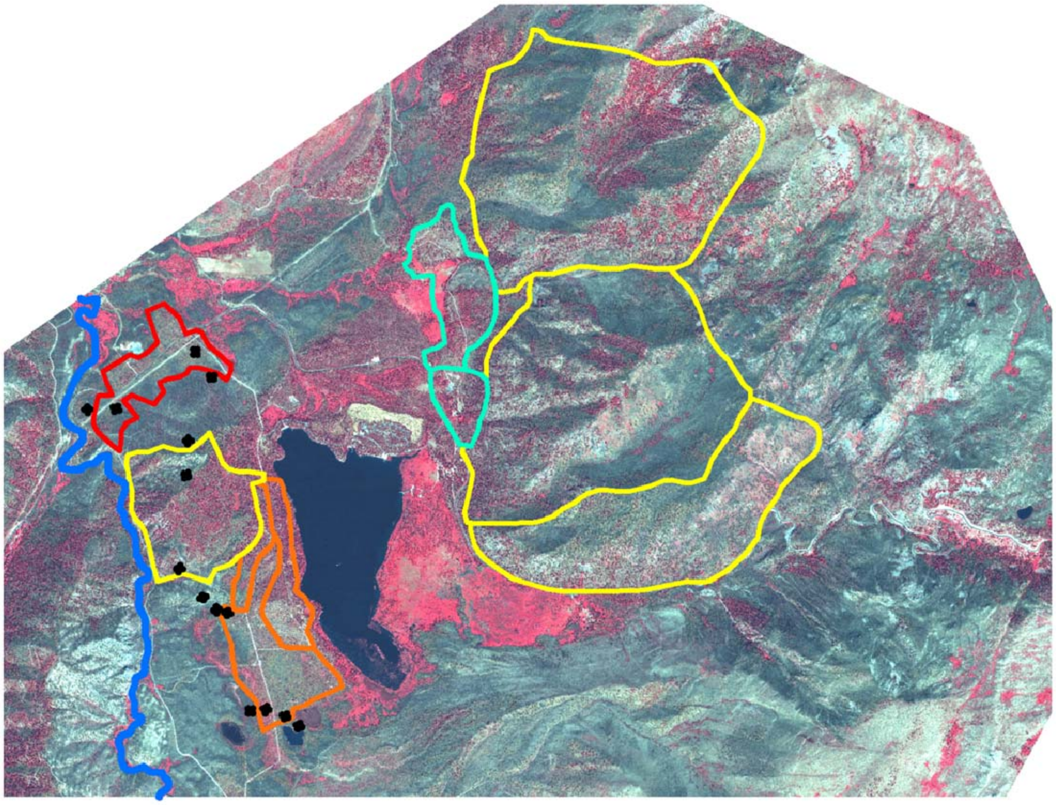

Fig. 2. **Quickbird satellite image (collected 18 August 2008) of the 64 km^2 Warm Lake area burned by the 2007 Monument and North Fork Fires in central Idaho. A mastication treatment unit (2004) straddling the Warm Lake Highway is indicated in red. Pile and burn treatment units (2000-2005) are indicated in orange. Pile and burn treatment units that were subsequently burned by prescribed surface fire (2004-2005) are indicated in cyan. Underburn treatment units west (2006) and east (1996-1998) of Warm Lake are indicated in yellow. The South Fork Salmon River is indicated by the blue line. The black dots indicate the location of paired field sites installed by Hudak *et al.* (2011) to assess treatment and fire effects. This is a color infrared composite display where unburned forested areas are dark red, unburned grassy meadows are bright pink, and burned areas are bluish-green. The 2007 Monument Fire burned through the southern portion of the scene from SW to NE, while the 2007 North Fork simultaneously burned through the northern portion of the scene from W to E, so it was the treatment units west of Warm Lake that proved critical for slowing the momentum of these advancing crown fires.**

Results and discussion

The areal extent of the Secesh Meadows and Warm Lake study landscapes was delimited at 6400 ha (64 km^2) to include not just the treatment units but also adjacent untreated lands that burned at the same time and under the same weather conditions, to provide context and allow quantitative comparison of BARC severity classes between treated and untreated lands. The proportion classified as high severity decreased in both landscapes after one year. This result was not surprising, as some areas can be mapped as high severity in immediate post-fire BARC maps due to the lack of any residual green vegetation immediately post-fire (Hudak *et al.* 2007), but subsequently vigorous vegetation regeneration suggest only minor effects on soils and available seed sources. The one-year post-fire dNBR is thus considered a more accurate indicator of ecological impact than the immediate post-fire dNBR (Key and Benson 2005).

At Secesh Meadows, Firewise treatments on private lands appeared most effective for reducing high severity fire, according to either BARC map. Both BARC maps also indicated that a lower areal percentage within pile and burn treatment units burned at high severity in the wildfire, provided the piles were burned as prescribed ('Rx Piles', see Fig. 3), compared to untreated lands. In the pile and burn treatment units where the piles burned in the wildfire ('WF Piles', see Fig. 3), the areal percentage burned at high severity was similar to that observed on untreated lands according to the immediate post-fire BARC map. However, the one-year post-fire BARC map showed a marked decrease in the high severity class within the WF Pile units, suggesting that fire effects were not as severe as indicated by the immediate post-fire BARC map. Vegetation recovery in these units was similar to the other, Rx Pile units, which corroborates what was observed by Hudak *et al.* (2011) at paired field sites (Figs. 1, 3). They found that field sites located in the five treatment units where the fuel piles burned in the wildfire exhibited more severe fire effects than their paired sites situated on adjacent untreated land; conversely, sites located in the eight treatment units where the fuel piles had been burned as prescribed exhibited less severe fire effects than their paired sites situated on adjacent untreated land.

At Warm Lake, pile and burn treatments were most effective at mitigating high severity fire, especially if followed by prescribed surface fire treatments. The mastication treatment was less effective, although it is important to consider that this treatment unit bore the brunt of the North Fork crown fire coming from the west. The prescribed underburn treatments were least effective at reducing high severity fire relative to untreated sites (Fig. 4). As reported by Graham *et al*. (2009), the weather and fuel moisture conditions during prescribe burn implementation were highly variable with some areas experiencing low fire intensities and less fuel consumption. In places where prescribed fires were applied, the wildfire effects were more heterogeneous (some crown fire and crown scorch did occur) compared to the more homogeneous wildfire effects in mechanical treatments which were not affected by weather conditions during implementation (Graham *et al.* 1999, 2004). However, there is evidence that the prescribed burn treatments did have a beneficial influence on subsequent wildfire behavior and effects (Graham *et al*. 2009). In addition, Hudak *et al.* (in press) found significantly less severe wildfire effects at treated sites than at their paired sites situated on adjacent untreated land (Figs. 2, 4).

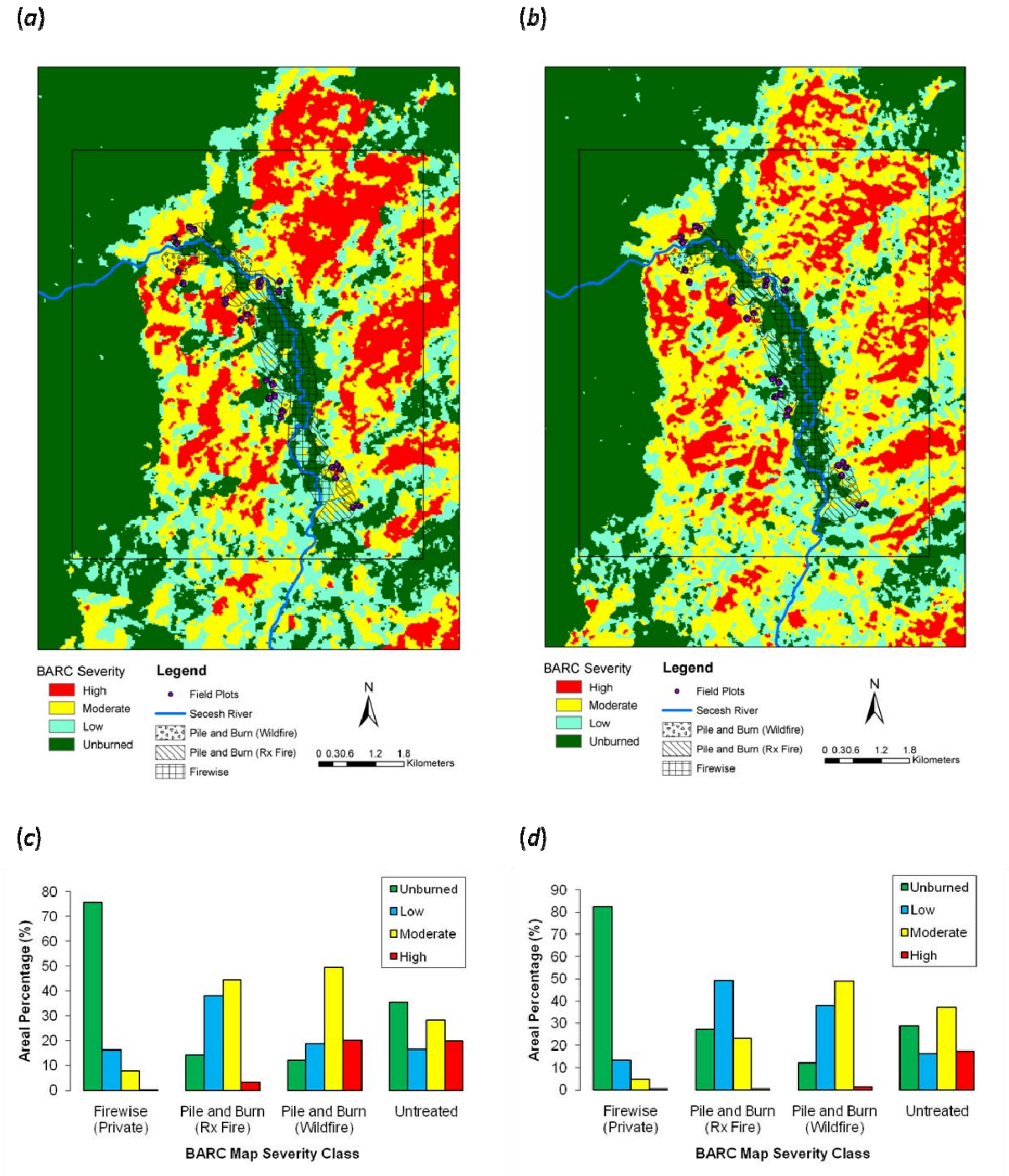

Fig. 3a-d. BARC maps produced from Landsat satellite imagery collected at Secesh Meadows (a) immediately post-fire and (b) one-year post-fire. The areal percentages of each burn severity class within the different types of treatments were calculated from these BARC maps and are shown in (c) and (d), respectively. The large black rectangle indicates the extent of the Quickbird satellite image displayed in Fig. 1.

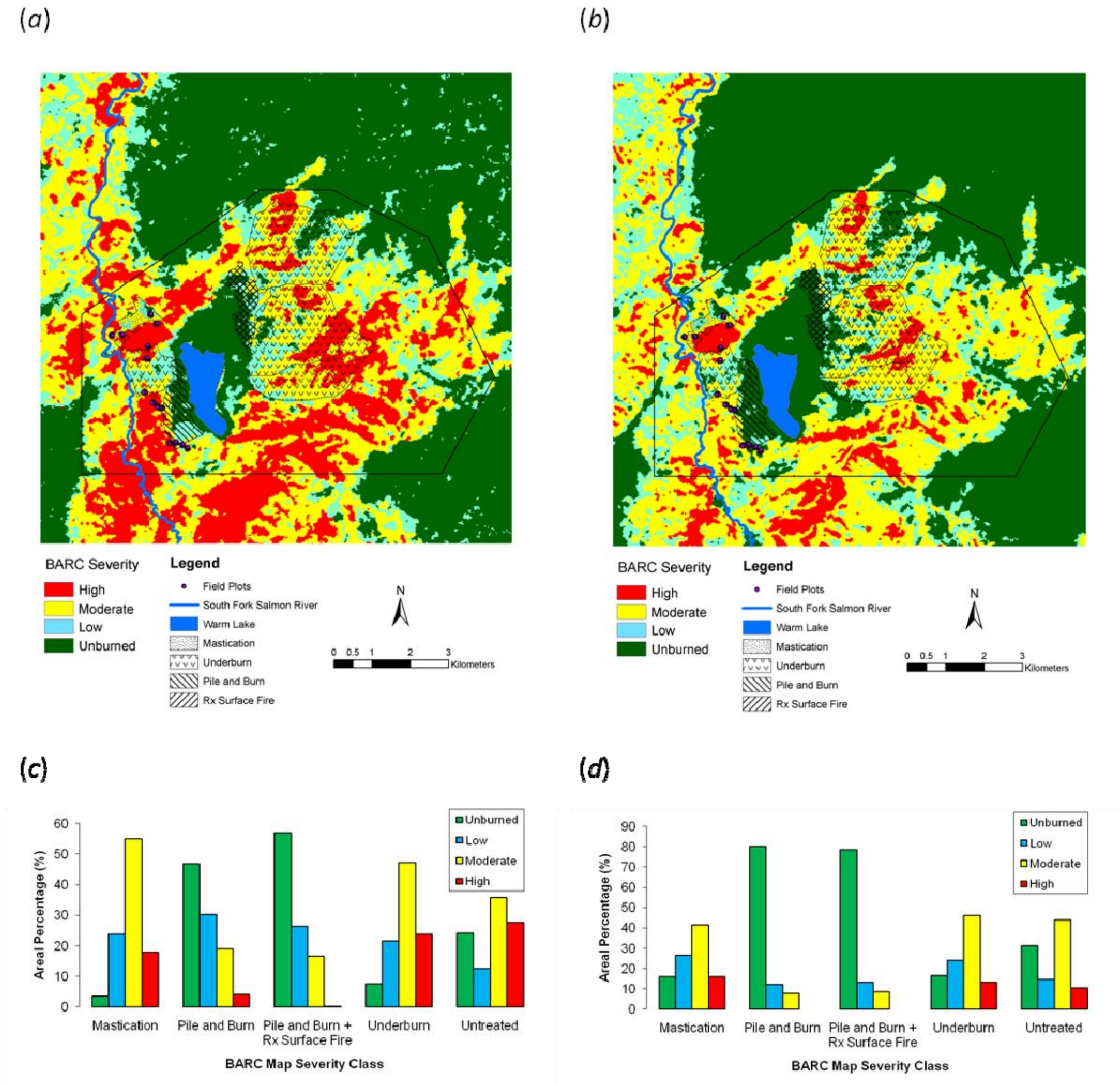

Fig. 4a-d. BARC maps produced from Landsat satellite imagery collected at Warm Lake (a) immediately post-fire and (b) one-year post-fire. The areal percentages of each burn severity class within the different types of treatments were calculated from these BARC maps and are shown in (c) and (d), respectively. The large black polygon indicates the extent of the Quickbird satellite image displayed in Fig. 2.

Concluding remarks

The BARC maps customarily produced by RSAC in response to major wildfires have utility for remote assessment of the effectiveness of fuel treatments for mitigating severe fire (Harbert *et al*. 2007), as do the dNBR values from which classified BARC maps are derived (Wimberly *et al*. 2009). The dNBR is sensitive to post-fire vegetation condition whether collected immediately post-fire or one-year post-fire (Key and Benson 2005; Hudak *et al.* 2007; Lentile *et al*. 2007). The results of this remote assessment of fuel treatment effectiveness corroborate on-the-ground assessments by Graham *et al.* (2009) and Hudak *et al.* (2011) in these local communities. They also support the consensus widely held by managers that fuel treatments generally are effective for mitigating severe fire effects.

Acknowledgments
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Do you BEHAVE? – Application of the BehavePlus fire modeling system

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Abstract
The BehavePlus fire modeling system is the successor to BEHAVE, which was first used in the field in 1984. It is public domain software, available for free use on personal computers. Information on user communities and fire management applications can be useful in designing next generation systems. Several sources of information about BehavePlus are summarized to indicate the number of users, level of use relative to other systems, and fire and fuel management applications that BehavePlus supports.

Additional keywords: Fire behavior, decision support, fire suppression, prescribed fire

Introduction

The BehavePlus fire modeling system is a desktop application that produces tables, graphs, and simple diagrams of modeled fire behavior, fire effects, and fire environment. BehavePlus is used to model surface and crown fire spread rate and intensity, transition from surface to crown fire, fire size and effect of containment efforts, tree scorch height and mortality, fuel moisture, wind adjustment factor, spotting distance, and more. BehavePlus is not limited to a specific application, but is designed to be used for any fire management application for which fire model results are useful. BehavePlus is used for a range of applications including wildfire prediction, prescribed fire planning, and fuel hazard assessment, as well as communication, education, and training.

BehavePlus has been available since 2001. It is the successor to the BEHAVE fire behavior prediction and fuel modeling system, which was first available at Rocky Mountain Research Station's Missoula Fire Sciences Laboratory in 1977 and was offered for field application in 1984. The update from BEHAVE to BehavePlus version 1.0 was funded by the Joint Fire Science Program (JFSP). Updates through version 5.0 have been supported by the U.S. Forest Service Fire and Aviation Management (sponsor) and the Rocky Mountain Research Station (developer). Background of BehavePlus including its relationship to the spatial systems FARSITE, FlamMap, and FSPro is provided by Andrews (2007).

This paper was written for a conference with the theme 'Beyond Fire Behavior and Fuels: Learning from the Past to Help Guide Us in the Future.' Examination of application of a system that has been in place from the early years of the use of computers in fire management to the present can contribute to a discussion of future systems.

Several sources of information on application of BehavePlus are summarized in this paper. As an indication of how many people use the system, we report on responses to the license agreement and visits to BehavePlus web pages. The use of BehavePlus in comparison to other systems is shown in the results of four separate surveys. User responses to inquiries about application of BehavePlus are summarized, and examples of formal use of BehavePlus by U.S. Agencies are described.

While summaries about application of BehavePlus are given here without interpretation, the information can be used in formulating an analysis of user communities and their fire modeling needs. While BehavePlus is a relatively simple system with broad application and many users, other systems are necessarily more complex with a specific application and a limited user group. Relationships among systems, modeling capabilities, and applications can indicate areas for potential consolidation in the development of the next generation of systems that support fire and fuel management.

How many people use BehavePlus

There is no way to determine exactly how many people use BehavePlus. A program that is available for unrestricted distribution is not designed to be tracked. We summarize responses we have received from the ‘postcardware’ license agreement and visits to the BehavePlus web pages as an indication that there are a large number of users.

Postcardware license agreement

BehavePlus is public domain software and available for free download from www.firemodels.org. It was developed by the Rocky Mountain Research Station on contract with Systems for Environmental Management (SEM). The installation window describes the license agreement (Fig. 1): ‘By installing and using BehavePlus5 you agree to mail a picture postcard depicting your local area…’

According to Wikipedia, ‘Postcardware, also called cardware, is a style of software distribution similar to shareware, distributed by the author on the condition that users send the author a postcard. … Postcardware, like other ‘novelty’ software terms, is often not strictly enforced.’

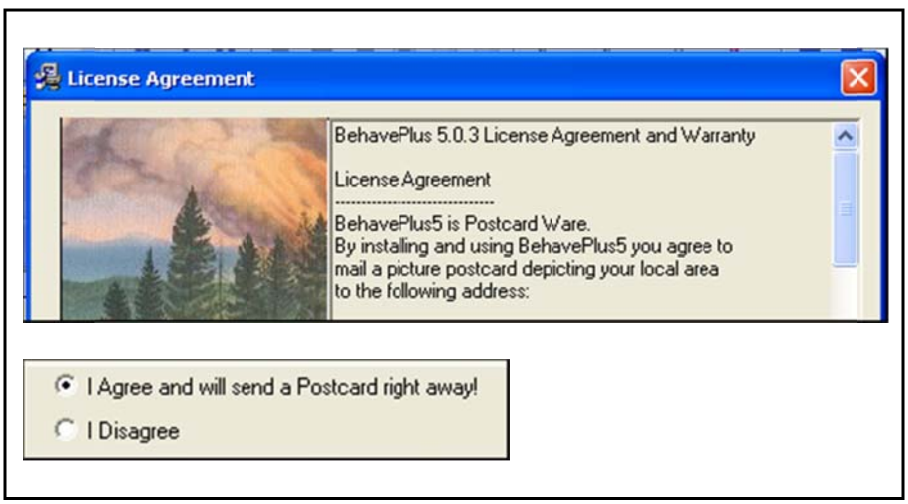

Fig. 1. Installation of BehavePlus program displays a license agreement, by which a person has to agree to send a post card depicting his or her local area.

We have received 571 postcards, cards, and letters, which we greatly appreciate. Responses came from 46 U.S. States and 16 other countries: Australia, Botswana, Brazil, Canada, Finland, France, Gabon, Germany, Italy, Mexico, New Zealand, Philippines, South Africa, Spain, Sweden, and Uruguay. We also received a cap from Saskatchewan, Canada, and a fire prevention air fresher from Valencia, Spain.

We did get some excellent photos of local fuel and fire. Other postcards were vacation spots or jokes. We received formal letters apologizing for not having a postcard to send and asking if the letter would suffice. Several admitted they had downloaded several versions and hadn't sent a card, but were finally sending one. The Stewardship Coordinator for the Aldo Leopold Foundation in Wisconsin sent a CD of their fuel types. Participants in a Prescribed Fire Planning and Implementation course in Tallahassee, Florida, sent a package of postcards representing their home bases. The University of North Texas Wildland Fire Ecology and Management Class sent class photos labeled 'Behaving Ourselves.'

Others (don't worry…we don't know who you are) didn't send a card, which is fine, even if you checked 'I agree…' As noted in Wikipedia, the agreement is not strictly enforced. We do know that far more people have downloaded BehavePlus than have sent a postcard.

While the 'postcard' information isn't in a form suited for generating a summary of application of BehavePlus, we did learn that many people are using it for a range of applications. The postcards provide an interesting personal perspective.

Webpage visits and download count

The BehavePlus program and supporting material is on www.firemodels.org. Google Analytics showed that for the year prior to October 1, 2010, there were 163,313 pageviews on FireModels.org by 21,340 absolute unique visitors. The BehavePlus Introduction page was viewed 12,833 times (9,833 unique page views) (Fig. 2). The BehavePlus Downloads page was viewed 8,205 times (6,191 unique views) in that year.

Because of changes in the server and software support for www.firemodels.org in the last year, we have not been able to specifically count downloads of the BehavePlus version 5.0. There were, however, 4,586 downloads of BehavePlus version 4.0 from September 2008 through June 2009.

Fig. 2. The BehavePlus Introduction page was viewed 12,833 times (9,833 unique page views) in the year prior to Oct. 1, 2010.

Use of BehavePlus Relative to Other Systems

Results of four surveys indicate that BehavePlus is the most widely used computerized fire system in the U.S. Two surveys gave responders a list of systems from which to select. The other two asked open-ended questions. The following discussions of survey results are restricted to BehavePlus.

Exploring Information Needs for Wildland Fire and Fuels Management, 2004

Miller and Landres (2004) reported the results of a questionnaire and workshop that sought to gain a better and deeper understanding of the information needs of wildland fire and fuel managers. They listed 50 types of information and tools in nine categories and asked respondents to indicate which ones were used to support fire and fuel management decisions in their management areas. Fig. 3 shows the percentage of users that selected each of the 27 computerized tools in three categories: fire spread/behavior models, fire danger/fire weather models, and fire effects models. BEHAVE was used by 95% of the 143 responders.

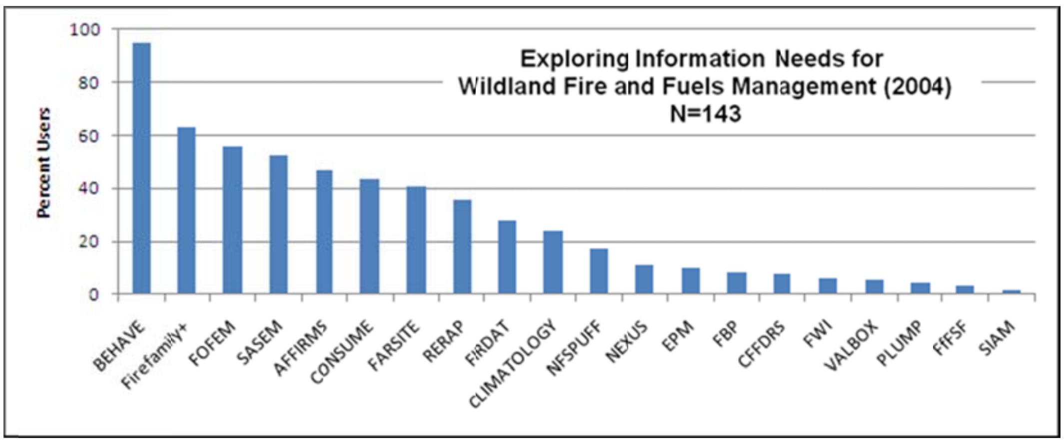

Fig. 3. BEHAVE was used by 95% of responders to a survey by Miller and Landers (2004). The plot shows the results for 27 computerized tools in the categories of fire spread/behavior, fire danger/fire weather, and fire effects models.

NAFRI RX-510 and FML course survey, 2006

In gathering information about which fire and fuel analysis tools are used, Tim Swedberg, JFSP Communications Director, conducted surveys during two courses (RX-510 and FML) at the National Advanced Fire & Resource Institute (NAFRI) in Tucson, Arizona, in 2006. The survey form was titled 'Which Models Do You Use?' and asked each person to 'Please make a checkmark next to the programs you now use!' A table of 40 applications was taken from a review draft of Peterson *et al*. (2007). (FEIS was only on the RX-510 list and FIREMON was only on the FML list.)

The target group of the RX-510 course, Applied Fire Effects, was 'natural resource managers involved in planning and implementing the use of wildland fire from the project level to the landscape scale.' The Fire Management Leadership course (FML) was directed to Forest Service Forest Supervisors/Deputy Forest Supervisor levels and their equivalent in other agencies. The course was 'a comprehensive look at the Agency Administrator's leadership role within the Fire Management Program….'

The trainees in the two courses were quite different (operations and management), but the responses were surprisingly similar. The percentage of trainees who use the top 16 systems is shown in Fig. 4. The other 24 systems were used by fewer than 6% of the responders. Fourteen systems had either one or no checkmarks indicating use. All but one person in each of the courses indicated that they use BehavePlus: 51 of 52 FML trainees and 24 of 25 RX-510 trainees.

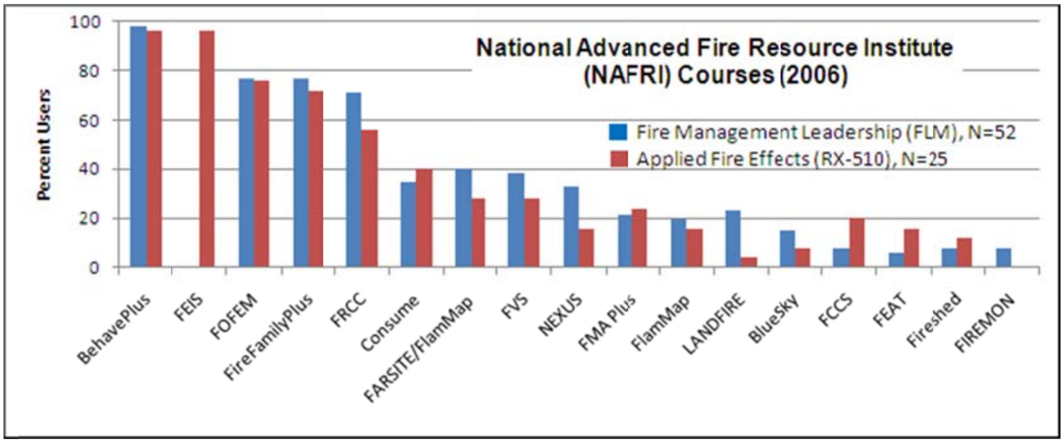

Fig. 4. BehavePlus was used by 76 of 78 trainees (97%) in the 2006 NAFRI courses, FML and RX-510. The top 16 of 40 listed systems are shown on the plot. Twenty-four other systems were selected by fewer than 6% of responders.

Fire and Fuels Specialists Software Tools Survey, 2008

A summary of Fire and Fuels Specialists Software Tools Survey conducted by the Joint Fire Science Program and National Interagency Fuels Working Group was reported by H. Michael Rauscher (2009). 'As part of a comprehensive study of the issues related to software systems in the fire and fuels subject area, it was desirable to understand what software tools were actually in use nationwide for fuels treatment analysis and planning. The survey asked each respondent the following questions: What software program(s) are you using to perform fuels treatment planning work? ... the point of the survey was not to produce a statistically valid result but rather to obtain an impression of what software tools fuels specialists used most frequently and conversely, which ones they did not use.'

Forty-six software tools were listed in the 44 responses. Thirty-nine (89%) listed BehavePlus (or BEHAVE) (Fig. 5). The next highest was listed by 19 (43%). Six of the 46 tools were listed by more than 25 percent of the responders, and twenty-five tools were listed only once.

The report stated: 'Behave, with all its variants, is one software tool that is almost universally used (89% of respondents) on a routine basis. It is by far the single most widely used software tool.'

Technical and Social Influences on the Success of Fire Science Delivery, 2007-2008

Data for a study titled 'Technical and Social Influences on the Success of Fire Science Delivery' were collected in 2007 and 2008 during fire and fuels preseason meetings, workshops, and training courses (Wright 2010). While an assessment of software tools was not a primary purpose of the study, the following survey question was included: 'In your current job, how often do you run fire behavior or vegetation prediction models? Please list which ones?'

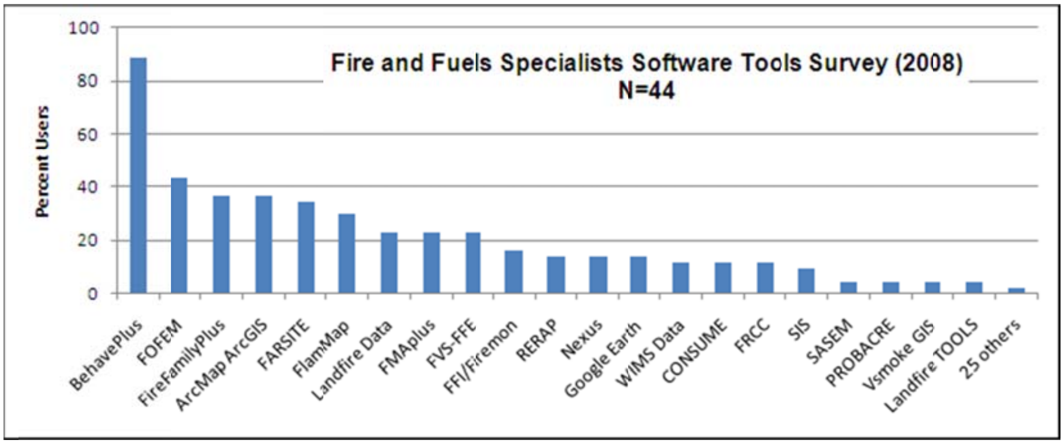

Fig. 5. BehavePlus was listed by 89% (39 of 44) responders to the question 'What software program(s) are you using to perform fuels treatment planning work?' (In addition to the tools on the plot, 25 others were listed once.)

Fig. 6 shows the seventeen systems that were listed by more than 1% of respondents. Of the 385 respondents who listed specific tools, 331 (86%) listed BehavePlus; the next highest listed system was 26%. Thirty-four tools were listed by three or fewer respondents. Thirty percent (116 of 385) listed only BehavePlus.

Results were also categorized by Agency, region, position, and fire assignment (Table 1; unpublished data). BehavePlus had the highest use in all subcategories; the next highest is listed for reference. It is not surprising that BehavePlus is used by a large percentage of people in the Fire Assignment categories or by those with the positions of Fire Management Officer; Fuels, Fire Use, Prescribed Fire Specialist; and Fire Planner. It is more notable that Fire Ecologists also listed BehavePlus more than any other system. BehavePlus, however, includes fire effects models, and fire behavior is important in the study of fire ecology.

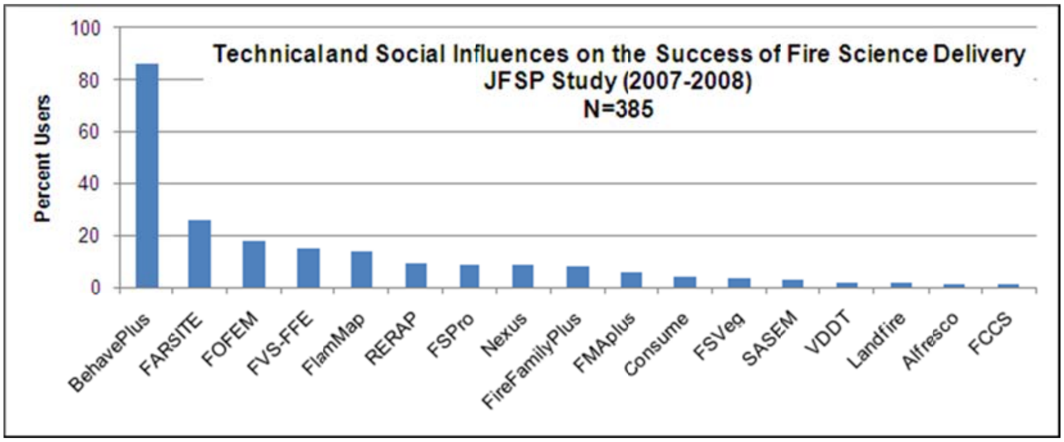

Fig. 6. Results of a survey conducted as part of a JFSP study. In addition to the 17 systems shown, 34 others were listed by three or fewer respondents.

Table 1. Number and percentage of responders in each category that use BehavePlus, compared to the percentage of the next highest listed system. (unpublished data)

Category		Number in category	Percentage that use BehavePlus	Percentage of next highest listed system
Agency	USFS	216	85%	29%
	NPS	83	82%	31%
	BLM	59	93%	14%
	USFWS	13	93%	31%
	BIA (6), States (7), TNC (1)	14	86%	29%
Position	Fire Management Officer or AFMO	111	88%	21%
	Fuels, Fire Use, Prescribed Fire Spec., Fire Planner	109	93%	31%
	Fire Ecologist	24	58%	42%
	Line Officer, Deputy LO, Staff Officer	30	60%	23%
Fire assignment	Long Term Fire Analyst (LTAN)	41	83%	63%
	Fire Behavior Analyst (FBAN)	28	86%	43%
	Prescribed Fire Burn Boss	152	90%	22%
	Prescribed Fire Manager	30	93%	23%
	Fire Use Manager	63	94%	19%
	Incident Commander	23	100%	22%

How is BehavePlus used

BehavePlus is not designed for a specific fire management application. It is suited to any application that uses fire behavior or fire effects models. Following are summaries of two informal questions on application of BehavePlus (and BEHAVE), from 1983 and from 2009, providing some documentation on how BehavePlus is used.

BEHAVE pilot test, 1983

While the fire behavior prediction portion of the BEHAVE system was available at the Missoula Fire Sciences Lab in 1977, it was not immediately available for field application because of computer limitations (Andrews 2007). BEHAVE was used for fire management applications as soon as it was available.

The initial development test was conducted in 1982. Testers used the program via telephone lines to the Missoula Fire Lab computer. One line was available during working hours, and people had to sign up for time. Six lines were available without reservation at other times. The initial letter to testers included a list of evaluation questions. The thank you letter included the following: 'When we designed the review form, we didn't anticipate that some users would incorporate BEHAVE into their regular fire management duties during the test period.' Following is from the pilot test report, December 1983.

For what fire management activities did you actually use BEHAVE during the pilot test?

- Slash burns
- Writing and analyzing fire prescriptions
- Estimating behavior of escaped fires
- Fuel treatment evaluation
- Wilderness fire planning
- Comparison with observed fire behavior
- Building site-specific fuel models
- Gaming of various fire situations
- Timber sale fuel assessments
- Define economic parameters for the activity fuel appraisal process
- Prescribed underburning project
- Developing burning windows for burn bosses
- Preattack planning
- Teaching fire behavior
- Designing a system to classify fire hazard
- Contingency planning
- Dispatching
- Assess wildlife proposal to leave small mammal habitat. Determined what effect that would have on spotting potential.

'Do You BEHAVE?' e-mail question, 2009

Under the subject line 'Do You BEHAVE?' an informal request for feedback was sent by the author in January 2009 to people who were registered for News on BehavePlus on FireModels.org. The e-mail was also forwarded to those on the International Association of Wildland Fire (IAWF) FireNet e-mail list, and it was posted to www.MyFireCommunity.net.

'I'm doing an informal canvas to find out how people are using the BehavePlus fire modeling system (or the old BEHAVE). Please tell me by e-mail …. Do you use it for fire prescriptions, wildfire, research, training, fuel hazard analysis, etc.? …'

We received 54 replies:

- 25 U.S. Federal agencies (19 FS, 4 BLM, 1 FWS, 1 BIA)
- 9 U.S. State agencies (2 CA, CO, KS, MN, MT, OH, WA, WI)
- 7 Private, contractors, consultants
- 2 Universities
- 1 TNC (The Nature Conservancy)
- 2 Research
- 2 City of Santa Barbara
- 2 Canadian provinces (NB, ON)
- 4 Other international (New Zealand, Scotland, South Africa, Spain)

Following are selected excerpts from the replies without reference to an individual, position, location, or employer.

While most responses provided more detailed description of their use of BehavePlus, one gave the brief answer:

> *'I use it for fire behavior predictions, just as intended.'*

Many use it for a range of applications:

> *'I use BehavePlus for prescribed fire prescriptions, research, fuels hazard analysis and training.'*

> *'I use BEHAVE for Rx fire planning and review, training, wildfire behavior prediction.'*

> *'I use both BehavePlus and the old BEHAVE for fire prescriptions when developing prescribed burn plans, fire behavior forecasts when working as an FBAN on wildfire assignments, development of pre-suppression fire behavior forecasts on days of high fire potential, fuel hazard analysis, and during large fire reviews.'*

Twenty-three of the responses specifically mentioned use for wildfire prediction, many in their role as a Fire Behavior Analyst (FBAN). Thirty-three cited use for prescribed fire. Following are quotes related to those categories and others.

Wildfire.

> *'… for writing firing plans to evaluate firing methods.'*

> *'As an FBAN trainee I have used BehavePlus to predict and verify the fire behavior while on an incident.'*

> *'When we are under severity conditions I use it to model potential fire behavior and then discuss suppression options with my crew.'*

'In any fire situation from prognostications at the regional level to those for specific slopes on specific fires I will use what I call benchmark BEHAVE runs. These are generally runs that are already completed, many of which I store on my own website, and I only use them for documentation and reference purposes.'

'Actually as an FBAN I only use BEHAVE to get the down and dirty worst case scenario and then do field verification and modification of my predictions (many times I've only done one run per fire, unless there's a significant wx [weather] or fuel type change), …'

'Use BehavePlus mostly on wildfire as a FBAN. . . .mostly as a CYA because the limitations of the model prevent any real representational forecasting of the extreme fire behavior I'm observing.'

'I generally use BehavePlus for the electronic files for fire records and I still use the BEHAVE Appendix B for general initial attack on fires and when working on fires as an FBAN since I can have the line personnel refer to the Appendix B while out on the fire line.'

Prescribed fire.

'For us with the Fire Crew at the university any potential prescribed burn must be scouted and modeled in BehavePlus before we can commit to or initiate a prescribed burn.'

'I also use Behave to illustrate adequacy of holding or contingency resources on burns, but I have zero faith in the outputs…. But it's about all you have to come up with some rationale for the number and kind of resources needed for a particular burn.'

'For RX prescriptions I can see how it does help; since one had a much wider span of fuel loadings to choose from – it eliminates some of the old 'professional' judgment and is much cleaner in the burn plan.'

'I utilize BehavePlus to model fire behavior for fire prescriptions and to justify contingency resources.'

'We include Behave modeling in every one of our Prescribed Burn Plans to develop and support the burn prescription.'

'BehavePlus is the primary modeling tool the Forest uses for Burn Plan development, to identify resources needed to manage the fire at the highest potential of the burn window. Tables are printed and included in the Burn Plan appendix.'

Training.

'Students use the software to learn how fuels, weather, and topography affect fire spread and intensity, and they also use it to compose a burn prescription/burn plan for a real site as their final project.'

'I also give my students Behave to 'fool around with' – most of them have no idea of fire, being Easterners, and behave allows them to investigate the various aspects of weather, fuels and topography without leaving the lab…'

'As a training tool for my fire fighters, expanding their knowledge.'

Analysis.

'…sensitivity analysis.'

'I used, in part, models including CONTAIN in BehavePlus to demonstrate that the guideline is false. No publications or reports, but this will change our training materials and heuristic thinking a bit.'

Communication.

' … we used behave effectively in community based fire education programs designed to promote coordinated, community-wide hazard mitigation on private lands … the results and maps were used in meetings with community leaders and later at community meetings to show the wildfire threat to neighborhoods. … we were able to demonstrate the benefits of doing coordinated fuel modifications…'

'Using in conjunction with FlamMap/FARSITE to illustrate the changes in fuel hazard. … show this to local fire cooperators and occasional public meetings.'

Planning.

'Enclosed is a link to a wildland fire plan that I used behave on for the initial hazard assessment.'

'Pre fire planning, gaming fires for community wildfire protective planning'

'As a matter of fact, I am using it today on a project for a major land owner who needs to know fire ROS for a proposed subdivision. It works well for this application.'

'I have used behave to look at ROS, FL, and intensities during the NEPA process to identify areas to create or extend fuel breaks. Working with the silviculturist on proposed treatments to verify the effectiveness of the treatment.'

Hazard analysis and fuel treatment.

'I periodically use BehavePlus in my consulting work to demonstrate the potential of wildfires in treated and untreated fuel profiles.'

'…for supporting recommendations for post-harvest fuels reduction treatments in commercial and pre-commercial timber sales and projects. I often would print the output tables as appendices to the planning document.'

'I do use it somewhat for hazard analysis, (Is the area in question flammable? And if so what would a fire there look like?)'

'We use BehavePlus in fuel hazard analysis. We use it in the drafting of fuelbreaks networks…'

'I still use Behave infrequently for fuel management project evaluations.'

Post-fire analysis.

> *'I helped with the fire behavior calculations for the NFPA publication to help verify the actual values observed that day …'*

> *'I use it to estimate initial spread of a fire I am investigating and prove/disprove my theory on that fire start. It becomes part of my fire investigation report.'*

Relationship to other systems.

> *'Even though we use the Canadian System, I have found it useful for comparative purposes and also some of the other features and capabilities …'*

> *'While not as temporal or reflective of terrain variability like FARSITE it gives a good quick indication of conditions for initial discussions with my colleagues.'*

> *'I use Behave … to get a feel for the difference between what models using the same algorithms as Behave are going to say a fire is going to do. I think it helps to get more complex models fine tuned quicker to fiddle with changes in Behave, then take what you learn and apply it to other models.'*

> *'As I don't know how to use Farsite or the other geospatial fire behavior prediction tools, due to my lack of GIS skills and access to GIS software, I use BehavePlus or the old BEHAVE for all of my fire behavior modeling work. Behave is a very important program to me. I hope that it continues to be supported.'*

> *'I tend to distrust the products that do fire progressions on a landscape basis. There are just too many variables that change too fast, but they make really nice maps that people just love to look at and so request the products without having a clue on the model limitations.'*

> *'Now that there are dozens of complex fire behavior modeling programs out there of different sorts with different end products, I am ever more appreciative that your program has withstood the test of time. When I am out on a fire many of the inputs for these other models are often unavailable, or there is a long delay in obtaining them, and it takes several days to calibrate the models to current fire behavior. But with BehavePlus, some field observations and a weather forecast, I am always able to produce a satisfactory product in a timely manner to respond to the many and varied questions of fie managers. I am so thankful to have Behave as the 'old reliable' in my hip pocket, and that it is still the basis of all the other fire models out there.'*

U.S. interagency applications

BehavePlus is formally mentioned in various U.S. Interagency documents including training, guides, and ICS task books. BEHAVE was originally developed to automate fire behavior modeling taught in the 1976 S-590 course. Courses and application of BehavePlus have changed and expanded since then.

NWCG training courses
BehavePlus is a prerequisite for, is used in, or results are shown in at least the following courses (NWCG 2010):

- S-390, Introduction to Wildland Fire Behavior Calculations
- S-490, Advanced Fire Behavior Calculations
- S-495, Geospatial Fire Analysis, Interpretation, and Application
- S-590, Advanced Fire Behavior Interpretation
- RX-301, Prescribed Fire Implementation
- RX-341, Prescribed Fire Plan Preparation

ICS positions
The National Interagency Incident Management System Wildland Fire Qualification System Guide, PMS 310-1, establishes 'minimum requirements for training, experience, physical fitness level, and currency standards for wildland fire positions which all participating agencies have agreed to meet *for national mobilization*' (NWCG 2009).

The Task Book for Fire Behavior Analyst (FBAN) and Long Term Fire Analyst (LTAN) describes position performance. Use of BehavePlus (and other systems) is specifically mentioned in several evaluation tasks. There is also a position designated as Behave Technical Specialist (BHAV) with S-490 as the required training (NWCG Chair 2005). Prescribed Fire Burn Boss Type 1 (RXB1) and Prescribed Fire Manager Type 1 (RXM1) require S-490.

The S-590 course is a requirement for FBAN/LTAN qualification. In order to assure an adequate supply of highly qualified FBAN and LTAN candidates for future incident management teams, a mentoring program for S-590 candidates was established. While an S-590 candidate cannot serve as an FBAN or LTAN trainee, they can be assigned to an incident as a Behave Technical Specialist (BHAV). This provides experience in the use of the fire behavior tools prior to attending the S-590 course.

Prescribed Fire Guide
The Interagency Prescribed Fire Planning and Implementation Procedures Guide (USDA/USDOI 2008) describes the required elements of a Prescribed Fire Plan (a legal document). The prescription includes a range of fire behavior (flame length, rate of spread, spotting distance, etc.) required to meet the burn objectives while meeting control objectives. 'These predictions must be modeled using fire behavior model runs or empirical evidence …' 'When used, fire behavior calculations must be developed using an appropriate fire behavior modeling program.' BEHAVE is specifically mentioned as an option in determining minimum holding resources.

Appropriate application

Models should be used in conjunction with human judgment based on experience and education. There has always been an appropriate concern about people putting too much faith in models. Consider the following two quotes, the first from the 1983 BEHAVE Pilot Test and the second from the 2009 'Do You BEHAVE?' e-mail question. The young people referred to in the first quote are probably now the experienced people who are worried about young people.

> *'We are starting to get people who are taking the outputs generated by many of our computer programs and fire management as pure fact—especially our young people who are less trained and experienced.' (1983)*

> *'What is more important in any prognostication of fire behavior is what is between the ears. I have seen too many young folks taken down the wrong road of believing that what comes out of BEHAVE and other modeling tools is what the fire is going to do.' (2009)*

The proper use of models can, however, play an important role in wildland fire management. It is not possible to have the full range of experience as noted by Gisborne (1948).

> *'If you have fought forest fires in every different fuel type, under all possible different kinds of weather, and if you have remembered exactly what happened in each of these combinations your experienced judgment is probably pretty good. But if you have not fought all sizes of fires in all kinds of fuel types under all kinds of weather then your experience does not include knowledge of all the conditions.'*

Wildland fire personnel should seek a balance in using models while developing experience, always keeping in mind the limitations of both models and experience. Use of BehavePlus and other modeling systems for predicting wildfire behavior is suited to judgment and adjustment of model results. On the other hand, fire modeling is applied differently in planning applications. A relative change (e.g., higher or lower intensity) might be a useful result, without as much concern for specific values. And planners might not have and might not be gaining on-the-ground fire experience. Care should always be taken in interpreting model results in the context of the fire and fuel management decision they support.

When the BEHAVE pilot test was conducted, computers were a new tool for fire managers. One of the evaluation questions was 'Do you want to get anything off of your chest concerning use of computers in fire management?' The 1983 Evaluation report stated 'Very few answered 'NO' in response to this question. … Responses indicate that BEHAVE pilot test participants feel that computers have a definite place in fire management activities.' Following is an insightful comment by one of the pilot test users (Dr. Stew Pickford, professor, University of Washington):

> *'Computers and fire management—they are unavoidable. As such, they will be used as crutches, excuses, and scapegoats. They will be misused, overused, and unused. They will bemuse, confuse, diffuse, intimidate and irritate, but Management must realize that computers are not the problem—only a tool of the problem.'*

It seems that in 2010, computers do in fact have an established place in fire management activities. The rate of change in computer technology is overwhelming, and the workload of fire and land managers is expanding. Fire models will always have limitations, and it will continue to take time for users to feel comfortable with a computer software tool. Fire modeling systems, however, can and do effectively support wildland fire management.

Summary

It is apparent from the summaries of various sources of information on application of the BehavePlus fire modeling system (and its predecessor) that people do in fact 'BEHAVE.' The user community includes fire behavior analysts, prescribed fire planners, students, professors, researchers, fire ecologists, line managers, and incident commanders. They work for U.S. government agencies at all levels: federal, state, county, city. Contractors, consultants, and private organizations use BehavePlus. And there are a significant number of users outside of the U.S.

A reason that BehavePlus is used by so many is that it is not designed for a specific application such as wildfire prediction or fuels management. It is used for those applications and also to give people a basic understanding of wildland fire, to communicate fire management alternatives to the public, to gain an understanding of the mathematical fire models, to develop fire prescriptions, to support research analyses, to do post-fire investigations, and more.

The broad, diverse base of users with various backgrounds as well as the wide range of applications indicates that there is a need to assess available and needed training for BehavePlus (and its successor). BehavePlus has an extensive context-sensitive help system that includes description of variables and relationships; and a series of self-study lessons are available for download from www.firemodels.org. Some aspects of BehavePlus are incorporated into established NWCG courses or pre-work; and various groups have developed training as needed. A comprehensive training package would include not only program operation, but model understanding and application. It should address basic model limitations, assumptions, and sensitivity of results to input values. Additional instruction is needed for specific applications such as prescribed fire planning. A consideration in developing training material is the audience. Some users might not have the background to be able to recognize problems in input or output values that require additional examination and analysis. A Fire Behavior Analyst (FBAN) will have both background training and extensive fire experience. But many BehavePlus users have neither the fire experience nor access to the S-courses. Although we might like to do so, it is not possible to say that people should not use BehavePlus unless they've had a specified level of coursework and fire experience.

Another reason that BehavePlus is widely applied is that it is relatively simple to use and freely available to run on a personal computer. The user enters input values without the need to develop or access data files. This allows incorporation of user experience, judgment, and adjustment of values. The user has significant control over the form of the output and also has the option of exporting results for further analysis using other software.

Many fire management applications do not require the detailed information provided by spatial systems, but are in fact better satisfied by simple tables and graphs. When the products generated by spatial systems are needed, BehavePlus can serve a supporting role. While the spatial systems FARSITE (Finney 1998) and FlamMap (Finney 2006) are based on essentially the same mathematical models as is BehavePlus, there remains a need for a point-based system. It is difficult to see specific cause and effect relationships in a landscape of thousands of model calculations. BehavePlus overcomes the necessary black-box aspects of spatial systems. A user can and should use BehavePlus to examine, for example, the effect of fuel model, live fuel moisture, or canopy cover on modeled fire behavior.

Similarly BehavePlus can support the fire behavior modeling that is being incorporated into Internet-based systems including the Wildland Fire Decision Support System (WFDSS) (Seli *et al.* 2010) and the Interagency Fuel Treatment Decision Support System (IFT-DSS) (JFSP 2009). Those systems are designed for specific applications and user groups and will not include all of the modeling capabilities and features of BehavePlus.

While it is not possible to know exactly why responders to the four surveys use BehavePlus (or BEHAVE) more than other systems, there are likely reasons in addition to those described above. BEHAVE was one of the first systems available to fire managers and became an established tool. It has had the continued support of the developers and sponsor, and design and fire modeling capabilities have been updated and expanded over time.

It is hard to draw general conclusions from these surveys. Some widely used systems didn't show up because of the way that the question was asked. And the reason that only a few users selected or listed a system might be a function of the group that was surveyed or of a narrow focus of the system application. While these surveys give some guidance on development of next generation systems, another approach might be to examine details of applications and the information needed to support decisions. An assessment of which systems provide that information can identify gaps and overlaps in the large selection of systems available for fire and fuel management (Andrews 2006).

Although BehavePlus is an established tool for many fire and fuels management applications, it is in need of update. Much of the BehavePlus design was determined in 1998 (Andrews and Bevins 1998). While the program has many good features, there are recognized weaknesses (Heinsch and Andrews 2010). Similar to the major update from BEHAVE to BehavePlus, it is time for another major update (BehavePlusPlus?). The approach, however, should not be merely an update to the BehavePlus program, but rather a broader update that facilitates integration of fire behavior, fire effects, and fire danger rating systems and of point and spatial systems. A step in moving forward is to start with a sound foundation of the basic building blocks in the form of a library of mathematical fire model code. This will facilitate resolving internal differences among existing systems, will provide an improved means of incorporating new research results, and will aid development of both web and desktop applications.

Fire and fuels managers would undoubtedly welcome systems that are developed to meet their needs in the form of complementary components with a consistent modeling foundation, user interface, look and feel, and graph and report generators. This examination of application of BehavePlus can be taken into consideration in the planning of the next generation of systems.

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The Art and Science of Incorporating a Canopy Inventory into Florida's Wildland Fire Risk Assessment

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Abstract:
Purpose: Creating and incorporating canopy inventory and surface fuels into Florida's Wildland Fire Risk Assessment.

Statement of Approach: Seventeen separate vegetation types with different tree canopy characteristics were mapped using remote sensing and GIS technologies. These vegetation types were stratified by height and canopy closure. Height, canopy bulk density, and canopy base height factors that will impact crown fire of these canopied areas were estimated for each class using plot data. These data were matched against a matrix developed by Florida fire behavior experts that specifies under what physical and climatalogical conditions fire will passively or actively crown in these vegetation types. This information is combined with the surface fuels data to produce an all-inclusive Wildland Fire Risk Assessment.

Summary: An interagency group of Florida experts determined vegetation types that characterize canopy wildfire activity in Florida. Remote sensing tools including Radar, LiDAR and LANDSAT imagery were used to create these layers. Information from previous surface fuel inventories, along with additional data collections were used to validate the remotely sensed data and provide plot information for the modeling of canopy wildfire behavior. Florida fire behavior experts developed matrices that indicated types of crown fires expected at different vegetation classes and climatological conditions. This was done to mitigate some of the problems with the current fire behavior prediction models. In this way we have incorporated the science with Florida's fire behavior expert experience in making the determination when to expect passive and active crown fires.

Conclusions: Bringing the canopy data into a wildland fire risk assessment is critical when attempting to display the total potential risk from wildfire. Most wildland fire risk assessments done to date only includes the surface fuels data. However, including the canopy and allowing the current models to make the determination as to when an area will crown or not, will result in erroneous outputs. By adjusting the model to crown either passively or actively under a given set of conditions we are utilizing the calibration technique taught in S-493 for FARSITE.

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Extreme Fire Behavior - Is It Really?

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Abstract:
Extreme Fire Behavior. It's one of the most common terms used to describe fire behavior in so-called "banner years." It's also a term that has come to be despised by many, including many fire behavior and long-term analysts, for a variety of reasons.

According to the NWCG definition, "'Extreme' implies a level of fire behavior characteristics that ordinarily precludes methods of direct control action." By this definition, "extreme" is purely in relation to our ability as humans to control fire, and does not convey any further information about the actual fire behavior in question.

Moreover, while the term "extreme fire behavior" has been applied to conditions underlying most fire shelter deployments, this term is not mentioned in any of the common denominators of fire behavior on tragedy fires: relatively small fires or quiet sectors of large fires; relatively light fuels, such as grass and light brush; unexpected wind shifts or increase in windspeed; fire responded to terrain and ran uphill.

What is frequently deemed as "extreme" is a realm of fire behavior that, while more intense and less predictable than other types of fire behavior, is entirely natural and within the wide spectrum of fire behavior that has been witnessed regularly since humans got involved with fire. This fire behavior occurs whether people are around or not; it seems to be considered "extreme" only when it threatens to elude our most determined control efforts.

So what does the term "extreme fire behavior" actually mean, what information does it convey, why is it so widely used - and also despised - and just how useful or valid a term is it? This presentation will explore the various facets of the "extreme fire behavior" issue, and discuss the present state of the ongoing debate.

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Wildfire Analyst: Enhancements in Fire Behavior Simulation for Operational Use

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Abstract

The use of wildfire simulation tools is growing with the evolution of the well-known Farsite and Flammap software tools. Nevertheless, due to technical requirements there has been minimal use of these simulation tools in operational scenarios for areas with high wildland fire risk and extreme fire conditions, such as California and the Mediterranean area.

An approach to provide real time evaluations of fire behavior focused on operational user needs is presented in the form of the software Wildfire Analyst (WFA), an ArcGISÊ based extension developed by the Spanish firm Tecnosylva (Tecnosylva 2010). Main enhancements include real time processing performance, automatic rate of spread (ROS) adjustments based on observations, and the calculation of evacuation time zones (or ófireshedsô), and integration of simulation results for asset impact analysis.

The tool was developed during the EC VI R+D Framework Program PREVIEW between 2005-2008 (PREVIEW Consortium). It was implemented by the Spanish Military Emergency Unit (UME) and is the analysis module of fiRESPONSE, the wildfire incident management system of several Spanish regions (Andalucia, Aragon, Murcia and Extremadura), and the Wildfire COP developed by DTS (Orlando, FL), who will offer it to the US wildfire community in early 2011.

In October 2010, WFA won the prize for the best technological innovation in the 3rd Spanish National Symposium on Forest Fires (Simposio Nacional de Incendios Forestales 2010) and the Best Collaborative Enterprise-Public Services prize, given by the Spanish newspaper óEl Mundoô (Mundo 2010).

Introduction

Situational awareness on incidents is enhanced by the increasing power of combining GIS and spatial databases, GPS and AVL systems, remote sensing and weather predictions services. These together with desktop and mobile computers adapted to real time operations, are becoming a critical tool to support Incident Actions Plans (Teie *et al.* 2010). The weakest point continues to be data integration and communications, although promising technologies such as BGAN and X-Band satellite based modems are beginning to provide data transfer capabilities wherever the incident is. This is especially important for wildland fires that tend to originate in remote locations.

As use of this technology becomes commonplace (Lunder and Fire Geek 2009), with users trained in geospatial technologies, standards on GIS use have been created (National Wildfire Coordinating Group 2006). However, there is a gap in the use of the simulation tools to support the decisions based on quantitative evaluations of fire behavior (Xanthopoulos 2005), although the main emphasis is not about fire modeling. There is a wide scientific basis that began with wildland fire behavior modeling in the 1920ǒs. Work at the Fire Lab in Missoula, MT by Rothermel (1972) and Albini (1976) created the basis for operational approaches to the problem. The emergence of Farsite (Finney 1998) has showed that the use of these tools is a great improvement in the scientific explanation of fire behavior. And from this point, Sullivan (2009) reviews work completed from 1990 to 2007 with the efforts completed and applied in the development of new models: 12 Physical, seven quasi-physical, 15 empirical, five quasi-empirical, 11 simulation and 22 mathematical analogous models are described.

Our diagnosis is that there is a substantial need for simulations to be provided in real time, so any incident alarm could have a quantitative evaluation or any incident action plan can be supported in the field, with no web connectivity and no time for data manipulation available.

Operational use of fire behavior simulations

The concept *operational use* we are focusing on has a different spatial modeling context and applicability than the one used for Boreal Forests described for Canada in Anderson *et al.* (2009). These scenarios the initial attack times, values at risk and wildland urban interface (WUI) issues are not as critical as in Mediterranean areas, like California, Australia, Chile and Southern Europe. In these more temperate conditions first response and initial attack is critical, and real time simulations provide important information to guide incident response staff in making decisions. This is especially important in areas with predominant shrub and grass fuel models that typically result in high rates of spread for most weather conditions.

The use of fire behavior simulation tools can be described in terms of the roles and response scenarios that occur during a wildland fire. Table 1 presents a brief summary of the requirements of the different roles and response scenarios we may find for decision making. This includes consideration of time frames during a typical incident in these temperate weather zones.

Table 1 Typical scenarios for operational use of fire simulation tools

			
	Dispatch Centers	**Incident Command Posts**	**Incident Field Team**
Architecture used	Web & desktop	Desktop	Desktop and Mobile
Main use	Evaluation of incident alarms	Support to IAP, ICS, and safety and evacuation issues	Evaluation of a determined front fire behavior
Horizon expected	Below 6 hours	Between 3 to 12 hours	Below 6 hours
Time requests	Immediate, below 2 min	Medium, below 10 min	Immediate, below 2 min
Fuel Data Inputs	Based on existing databases, i.e. LANDFIRE	Real time actualization of existing fuel layers based on direct observations	
Terrain	Existing terrain elevation models, 100 ft resolution or better		
Weather predictions	Web based: NWS, Predictive services or similar	Via connections to command centers (phone or web)	Via connections to ICP (voice)
Weather observations	RAWS stations or similar fixed networks	Mobile or Personal weather stations on the incident	
Availability of internet	Yes	Not at the beginning of the incident, increasing use of satellite based modems as incident progresses	No

From these needs, an operational fire spread simulation tool, Wildfire Analyst, has been developed to fulfill these requirements. The most important characteristic is the ability to derive simulation results quickly to support real time decision-making. The ability to revise conditions based on local observations and re-run simulations is a mandatory component for operational use. Wildfire Analyst has been successfully field tested in operations during the summer 2010 campaign by the Spanish Military Emergency Unit and the Wildfire regional Service of Extremadura (Spain).

Architecture Requirements for an Operational Simulation Tool
The software tool has been designed to provide maximum flexibility for data integration, model implementation and viewing of results (Fig. 1). A key component in providing

flexibility for operational use involves seamless input data preparation and integration. Minimizing the requirements of the user for technical data *mechanics* is fundamental for facilitating wide spread utility for the tool ï especially for the incident command center and the field. The use of predefined weather and fuel scenarios is an important aspect of this use making it easy for incident staff to simulate fire behavior and spread, and interpret the results to support decision making. To date, the need for technical knowledge to accommodate data mechanics (i.e. getting data in and out of the tool), has been a limiting factor among existing software tools.

In addition, to provide maximum GIS capabilities, the core platform is based on ArcGISÊ ArcEngine 9.3. This provides a GIS data and modeling platform as the underlying architecture for WFA without the complex and often expensive licensing requirements of commercial desktop ArcGIS software. For existing ArcGIS users WFA can be used as an extension of ArcMap, or as a separate standalone software application not requiring any ArcGIS installation of licensing prerequisites.

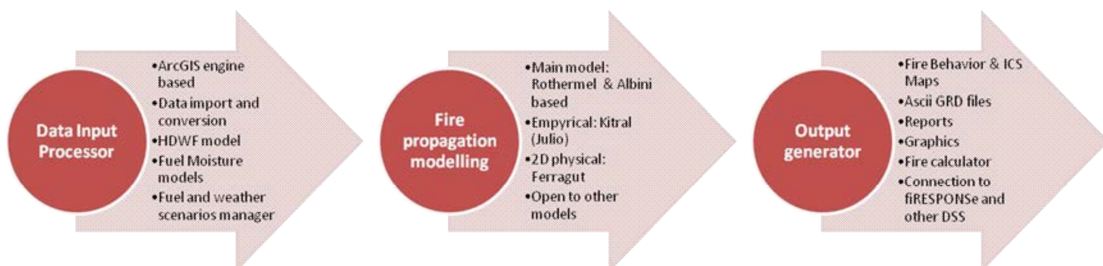


Fig. 1 Wildfire Analyst: basic architecture

Analysis and Modeling Requirements

The first propagation model implemented in the WFA tool is the Rothermel (1972) model and the modifications proposed by Albini (1976). It accepts Scott and Burgan (2005) fuel models, as well as custom fuel models. The two dimensional evolution of the fire is computed as a discrete process of ignitions across a regularly spaced landscape grid through a óminimum arrival timeô function (Finney 2002). This time evolution function has some relevant improvements like accepting non-constant wind profiles as an input and minimizing the small inherent fire shape distortion caused by this standard approach without increasing computational time. Other models implemented models are Kitral (Julio *et al* 1998)

The tool includes two main ways to tune the final fire ROS: 1) firebreaks and 2) adjusting ROS factors. Firebreaks are treated in an innovative way in which their effect does not depend on the cell size of the underlying grid data but on the actual width of the firebreak. In this regard firebreaks are not considered absolute barriers. Modeled ROS can also be adjusted to incorporate observed rates of spread, thus accommodating continual adjustment to the algorithms as more observed field data is gathered. The ability to perform simulations very quickly (below two minutes) provides the basis for this ROS adjustment capability. To date, few tools have been able to incorporate this due to computational and performance issues, restricting any possible consideration of operational utility.

Wildfire Analyst standard fire behavior outputs include:

- Static and dynamic ROS, flame length and fire intensity
- Static and dynamic out of suppression control analysis
- Campbell Prediction System (Campbell 2005) alignment of forces analysis
- Minimum Travel Time fire paths (Finney 2006)
- Crown fire (Van Wagner 1977; Rothermel 1991)
- High Definition Wind field (Ferragut *et al.* 2010; *Monedero* 2006)
- Moisture content

In the output, *static* means those layers considering the direction of maximum spread given by the Rothermel´s model while dynamic means those that are based on the actual fire spread of a given simulation. In this regard outputs are similar to those created by programs like Flammap and FARSITE. Operational maps are automatically created, stored and presented in a mapping interface for the user. Outputs are generated in standard ArcGIS format complete with ICS symbology that are usable in the WFA interface and also in standalone ArcMap (Fig. 2). Additional outputs include options for PDF files and KML Google Earth display. To facilitate potential integration with other software all outputs are also created in ASCII grid format, consistent with other software, such as FARSITE.

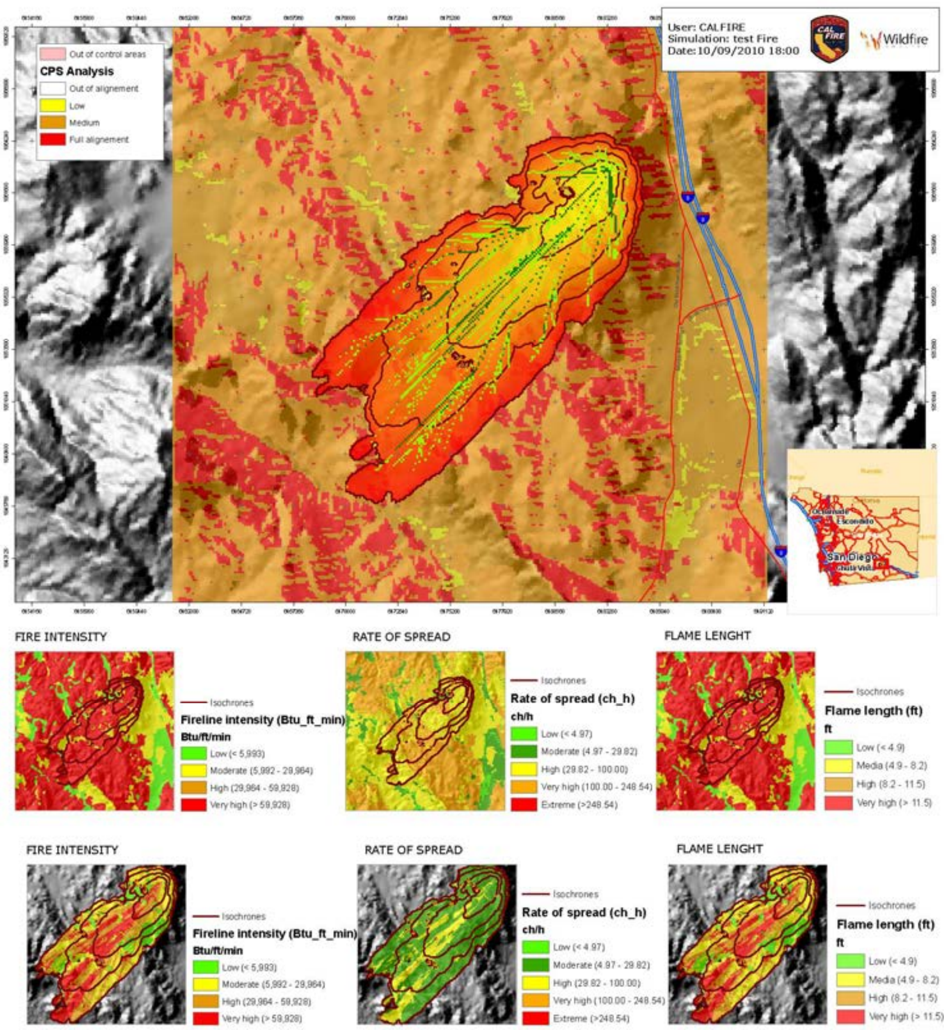


Fig. 2 WFA output example

Simulating Fire Propagation

An advanced feature of the Wildfire Analyst software is that it includes several different propagation modes and features, which offers new uses for the simulation results. In addition to the conventional fire spread propagation other modes are available to support simulations for prescribed fire scenarios, evacuation time (referred to as *firesheds*), and ROS adjustment.

Reverse time mode

Given the burned extent and perimeter of a fire, this mode computes the evolution backwards in time assuming Rothermelǒs model. This mode may be used to find fire ignition sources as well as possible spotting sites. The idea of the method was proposed in (Cova 2005) in the context of finding trigger points for fire evacuation but may be easily generalized to finding ignition points of a fire. The implementation is based on modifying the Minimum Travel Time algorithm in such a way that instead of computing the minimum time for a source cell A to reach a neighboring cell, we compute the minimum time it would take for cell A to be reached by a neighboring cell. This capability is ideal to evaluate possible ignition sources for a prescribed burn, assuming a known desired extent for the fire (i.e. are fuel treatment area). Run with current weather data this mode will identify the best possible ignition location for the fire.

Evacuation time mode
Computes for each cell, the minimum time required for a fire to reach the defined evacuation points (or ó*fireshed*ô). The evacuation time mode is based on (Finney 2002). It takes a source layer defining the evacuation points as an input. All standard outputs including the useful MTT fire paths are also generated. This provides a perfect framework for analyzing defense actions to increase evacuation times of vulnerable assets. By identifying structures or wildland communities this mode will determine the time of arrival for each location identified providing a baseline for evacuation planning.

Adjustment mode
Given a fire simulation and a set of points where the arrival time of the fire being simulated is known, Wildfire Analyst seeks the best ROS adjustment factors defined over a fuel layer such that the final simulation result best fits a given real fire dataset in a least square sense. The main achievement of the method is that is not based on trial and error algorithms. In addition it is solved almost instantly. This capability allows the real time correction of simulations based on observations in the field. Control points may come from AVL ground and air resources, water drops, field observers, etc. New adjusted results are available in seconds. Additionally, after the incident is over, a database of observed ROS adjustments can be used with the Fire calculator capabilities described below. This provides a historical database of observed rate of spread that can be applied to develop adjustment factors to be used for future incident simulations.

Probabilistic mode
The probabilistic mode is inspired by FSpro (WFDSS nd), but at present lacks the ability to automatically create weather scenarios. It allows the user to run a set of *n* simulations with varying weather conditions in order to obtain a fire presence probabilistic analysis. Different simulations are automatically carried out and WFA then analyzes how many times each cell has óburnedô in the simulations in order to give the probabilistic output. There is work in progress to use portable supercomputing capabilities offered by CUDA capabilities (NVIDIA 2010) in desktop workstations.

Fire calculator
Together with the standard 2D simulation outputs, Wildfire Analyst also incorporates a simplified fire calculator inspired by BehavePlus (Andrews 2007), but with dynamic calculation. This tool is also used to analyze relationships between the different ROS factors, found for every fuel in real fires calculated in the Adjustment mode, and weather parameters. It will help the fire behavior analyst to create a óROS adjustments scenarioô or modified fuel models after the analysis of a number of wildfires so they can be applied for future incidents.

High Definition Wind Field Modeling
Wind is considered to be the most important factor in fire spread. The importance of the wind effects over the fire, combined with the impossibility of a direct numerical approach to the

three dimensional Navier-Stokes equations modeling fluid's dynamics, forces the development of reduced simplified models to predict wind speed at the scale of the fire.

The core approach of the high definition model has been developed in (Ferragut, 2010). The initial equations of the model are the Navier-Stokes equations coupled to the temperature of the surface through the energy equation. These initial 3D equations are simplified, among others, by the following considerations:

1. Moderate wind profiles
2. Incompressibility of the air, div U =0
3. Linear dependency of the temperature with the height
4. Domain height small with respect to horizontal dimensions

These assumptions lead to the following system of coupled differential equations inside of a 3D approach that can be solved involving only 2D equations.

$$-\partial_{zz}^{2} V + \nabla_x P = 0$$

$$\partial_z P = \lambda Q$$

$$\nabla_x \cdot V + \partial_z W = 0$$

Where the boundary conditions are given by:

Ö$_z$**V**= ɜ **V**, (**V**, W)·**N**=0 On the surface S,

Ö$_z$**V**=0 W=0 On the upper boundary A,

V*·**n**=(ŭ-h) v$_m$·**n** On the lateral boundary Öd

Where ɚ=űRe and models the influence of the temperature gradients on the surface of the terrain over the wind, V is the horizontal wind speed, W the vertical wind speed, Q the temperature, P the potential, ŭ the height of the domain, h the surface function, V^* the horizontal flux (the integral of V around the boundary), V_m the meteorological wind which is supposed to be known, , ɜ the inverse of the friction forces over the terrain, and the couple **n** and **N** are the unit normals with respect to the domain and the surface respectively. The numerical resolution of these equations is based on the Finite Element Method (FEM) with, and without, mesh refinement.

Numerical Example of Propagation Modes

To properly describe the capabilities an example is provided. The following example uses a 3-fire source 4-hour simulation fire defined over a 200x200 cell domain with a 25 meter cell size. The simulation input is taken from a set of GIS datasets developed for San Diego County, CA. We consider as a reference the standard simulation of the fire shown in Fig. 3a. We then use the outer perimeter of the fire and use the reverse time mode in order to obtain the initial sources of the fire. This is given in Fig. 3b. As can be seen the results are very similar. The difference between both figures is not due to the algorithm itself, which is expected to give identical results in this case, but to the fact that the WFA implementation of the algorithm uses a 12 direction minimum travel time algorithm in which 4 of those directions are chosen based on a different criteria in each simulation. Using the same conditions, the source points may be considered as evacuation points instead of fire sources and then be used in the evacuation time mode. The obtained 4-hour evacuation time is given in Fig. 3c.

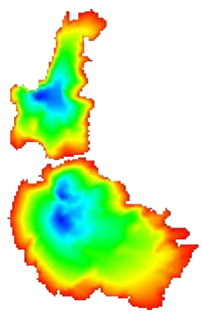


Fig. 3a (left) = standard

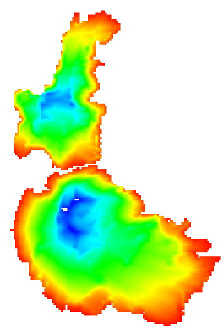


Fig. 3b (middle) = reverse time mode

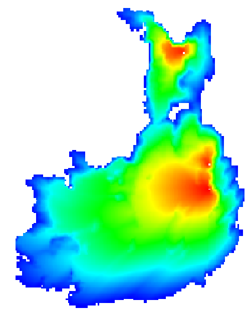
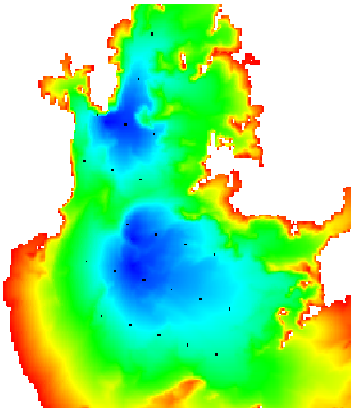


Fig. 3c (right) = evacuation mode

In order to use the adjustment mode, a set of known arrival times on the terrain is required. In this example the set of control points will be obtained from the standard simulation in Fig. 3a and are represented as black dots in Fig. 4a. Initial weather conditions of the simulation are then changed in order to obtain a simulated fire (Fig. 4a) that differs enough from the óreal fireô data. The algorithm provides the following adjustment factors:

- ROS factor 0.227155 for Rothermel fuel type 1,
- ROS factor 0.606604 for Rothermel fuel type 3,
- ROS factor 0.777106 for Rothermel fuel type 4,
- ROS factor 0.479729 for Rothermel fuel type 6.

The mean error in time between the control points and the simulated fire is 0.2454 hours and the variance is 0.0629. A new simulation is done based on these ROS adjusting parameters obtaining the final adjusted fire shape (fig. 4b).



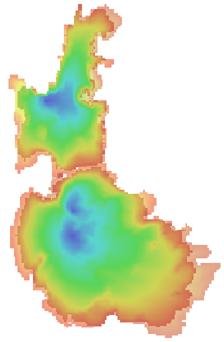


Fig. 4a Simulated fire	**Fig.4b** Superposition of adjusted fire and initial fire

Conclusions

WFA has been designed to meet users requirements in operational wildland fire incidents that need fire behavior outputs in a usable form within minutes. Computational speed and performance is critical for meeting initial attack requirements. In addition, operational demands dictate that the mechanics of data conversion and integration are minimized and seamless, allowing the analyst to focus on selecting appropriate scenarios and interpreting results.

WFA can be used in the three operational scenarios: evaluation of incident alarm and related initial attack, support to the FBAN in Incident Command Posts, and in the direct analysis of a fire front progression. These uses require the generation of simulation results quickly to meet real time decision making. The capabilities developed within WFA have been field tested and scientifically validated in numerous incident scenarios by military and government fire fighting agencies in Spain. Projects are underway to evaluate WFA for similar utility in the United States.

The automatic adjustment of fire simulations based on observed fire behavior and conditions, high resolution wind fields calculation, and the new propagations modes introduces new grounds for the use of simulation tools by first responders and incident commanders. Further analysis in real incident scenarios will lead to continued enhancements to capabilities and the refinement of scientific algorithms. However, this development must continue to focus on computational performance and seamless data integration to meet operational decision-making needs.

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Improving Capacity to Apply Fire / Fuels Research to Management

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Abstract:
Using social science theory and methods, I investigated potential fire / fuels research user beliefs about research usefulness, ease of use, and scientist traits; attitudes toward using research; organizational learning culture and processes of work units; supervisor support for innovation; and agency support of science. Surveys were completed by 495 fire / fuels specialists and line / staff officers in the United States Forest Service, National Park Service, and Bureau of Land Management.

Survey results indicated the fire management community is comprised of subgroups with varying levels of receptivity to research. Fire ecologists, long-term fire analysts, higher grade levels, centralized positions, National Park Service employees, and those with graduate degrees were more likely to be innovative, have positive beliefs and attitudes about research, and use research than respondents in other categories. Respondents cited fire ecologists and fuels specialists as responsible for locating scientific information and tools, yet fuels specialists demonstrated lower innovativeness and beliefs about research usefulness than fire ecologists. In addition to improving beliefs about research usefulness, managers may want to formally recognize, train for, and reward fire ecologists and fuels specialists for science application responsibilities. Fire Behavior Analysts represent another opportunity to build capacity, as they demonstrated similar innovativeness but lower beliefs about research usefulness than Long-term Fire Analysts.
Of 9 organizational learning measures, time for reflection and experimentation showed the greatest opportunities for improvement. Additionally, respondents slightly agreed they felt psychologically safe to introduce new ideas; however, they were neutral about whether different ideas were appreciated or likely to be analyzed. Research will most likely be used in work units that foster time for reflection, experimentation, information transfer, appreciation of differences, and productive debate at all pay grade levels.

Communication effectiveness is influenced by perceptions of speaker expertness and trustworthiness. Respondents agreed scientists knew what they were doing; however, they were neutral about whether research was run by scientists working the benefit of managers. Scientists will be more credible when communicating they can be trusted to study topics important to managers. Boundary spanners can also improve effectiveness by sharing culture and language with both researchers and managers.

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Historical Overview of Fire in Southern California

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Abstract:

Fire has been an integral portion of the history, culture, and politics of Southern California for hundreds of years. It has been debated, deliberated, suppressed, and encouraged by a wide variety of scholars, managers, practitioners, and elected officials. Despite all the rhetoric and deep root calls for change, for as long has fire been a part of the culture, there has been very little change. This paper will focus on events within the last five years and relate them to the historical attempts to change them.

First, the definition of Southern California is that area from Mexico to Arizona/Nevada, then generally west across the San Joaquin Valley to Santa Barbara, and then South along the ocean back to Mexico. In the last 12 years, some of the largest, most costly, and deadly fires have occurred. How could this happen, given the numbers of dollars spent to prepare for these common events?

Air pollution from the LA Basin has been linked to the over stocking densification of the San Bernardino and San Gabriel Mountains. Extended drought has modified fuel beds with an increase of fine dead fuels, which the classic Fuel and Fire Behavior Models under predict.

Technology gains, many of which began as part of the California Fire Solution, have been effective but often overwhelmed in both wind-driven and fuel-driven fires.

Southern Californian is the moniker of the Wildland Urban Interface. Yet, the definition eludes the most scholarly debates and results in confusion and discourse to the firefighters on the ground – those whose commanders are left to figure it out on the ground.

The Fire Service in Southern California (although the wildland agencies debate they are only resource technicians) touts itself as the model of interagency coordination. Yet recent events suggest that there is less now than pre-Fire Scope.

Cost-Sharing through Cost Apportionment has been also viewed as the fairest method to align costs based on jurisdiction and responsibility. The term *cost shifting* has taken its place.

Last, arson, the scourge of humanity and domestic terrorism, is still alive and well, even after taking eleven lives since 2003.

The present is rooted in the base purpose for which the wildlands and forests were created. Water and its insatiable demand will likely remain the only constant in the shape of fire in Southern California.

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Identifying Trends in Climate and Fire Severity: Implications for Fire Management

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Abstract:
Wildfire burn severity is a key indicator of climate impacts on fire regimes. An analysis of Alaskan trends in burn severity over the last quarter-century revealed that cooler, wetter conditions were more conducive to smaller, but more severe fires, while larger fires burning under warmer and drier conditions had lower overall severity. This counterintuitive relationship is attributed to the types of vegetation burning (i.e., shrub versus conifer) and interannual climate variability. It may also indicate that deciduous shrubs and more early successional ecotypes in Alaska constitute a distinct fire regime separate from the dominant spruce regime in the interior region. For Alaska fire managers, an apparent increase in the availability of these early succession ecotypes to burn is highly problematic. Anecdotal evidence indicates that Alaska fire managers have historically used earlier succession stands of deciduous shrubs and trees as natural fire barriers: places where they strategically direct wildfires since fire activity decreases significantly or ceases altogether. The observed increase in fire activity across these ecotypes has and will continue to reduce their ability to act as fire barriers, resulting in wide-ranging implications for human infrastructure, wildlife habitat, and other resources-at-risk. This paper reviews the methods by which we can utilize multi-temporal landscape-scale burn severity data to assess changing fire regimes, and contextualizes the Alaska trends in terms of impacts on fire suppression strategies and land management practices. It also underscores the role of climate change in driving these changes and their subsequent repercussions for natural resources.

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Plant Community Responses to the East Amarillo Complex Wildfires in Texas

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Abstract:
Over a 4-day period in March 2006, two wildfires occurred in the Panhandle of Texas. These wildfires, known collectively as the East Amarillo Complex (EAC), were the largest in the contiguous U.S. since the Yellowstone fires of 1988. They affected over 360,000 ha of native shortgrass plains and mixed grass prairie rangeland. We have conducted an intensive study of the effects of these fires on vegetation resources. We established permanent sampling plots in August and September 2006 in burned and adjacent non-burned areas. We have monitored net annual primary production, ground cover, species composition and perennial grass mortality for 3 years following the fires.

We are studying plant community responses with multivariate analyses of species composition. Species composition data were collected at two spatial scales using two metrics. On a small scale, composition was determined from aboveground biomass data harvested from 0.25-m^2 quadrats located inside exclosures established after the fire to exclude livestock. On a large scale, we collected percent frequency along three 50-m transects established in burned and non-burned areas. Changes in species composition 1, 2, and 3 years after the wildfires were analyzed with correspondence analysis.

At both scales of analysis, there was more variability among sites than between burned and non-burned areas. In addition, there was little evidence of coordinated changes over time; i.e., time-trajectories were not apparent either in burned sites or in non-burned sites. In the small-scale analysis, variation in vegetation over time was generally similar in burned and in non-burned sites. At the large scale, however, results were more variable. In some sites, non-burned vegetation was more stable over time whereas in other sites the reverse was true; this supports the general pattern of more site-to-site variability than burn-to-nonburn variability or year-to-year variability. Similar results are found when data were analyzed on a landscape level (including all study sites) or on an individual study site basis. We have found little evidence that wildfire has caused directional changes in this vegetation over a 3-year period.

10 Years Post-wildfire: Fire Behavior Indications on Varying Levels of Tree Mortality

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Abstract:
Severe wildfires across the West in ponderosa pine (Pinus ponderosa) forests have led to concerns about heavy fuel loading and the resulting potential for high intensity reburning. We sampled fuel loadings in 2009 and 2010 across a range of tree mortality on two high severity wildfires that occurred in 2000: the Pumpkin Fire on the Kaibab National Forest in Arizona, and the Jasper Fire on the Black Hills National Forest in South Dakota. We classified plots into five post-fire mortality classes: 0-20%, 21-40%, 41-60, 61-80, and 81-100% mortality, plus unburned controls. We sampled 10 plots within each class to characterize stand structure and fuel loadings. We measured height, diameter, status (alive or dead) and crown base height of each tree, plus woody fuels by size class, litter and duff depth, and fine herbaceous biomass in each plot. Our preliminary analyses indicate that there is an inverse relationship between basal area and fuel loadings. On the Pumpkin fire we see a significant increase in woody fuels at mortality levels of >40% and an increase in fine herbaceous fuels at >60% mortality. On the Jasper fire, significant changes did not occur until higher mortality levels; >60% mortality for woody fuels and >80% for fine herbaceous fuels. Our next step is to examine the implications of these differences by modeling predicted fire behavior attributes. Our goal is to provide post fire management guidelines for different ranges of ponderosa pine forests and to account for varying levels of tree mortality. This information may be particularly relevant in the future, in light of projected climate changes and associated increases in stand-replacing fires.

Overstory Structure Effects on Fuelbed Components in a Frequently Burned Oak Woodland

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Abstract:
Fire is widely recognized as a disturbance agent influencing the structure and composition of woodland and savanna ecosystems worldwide. Importantly, frequent fire limits the encroachment of woody forest species in these ecosystems, thereby promoting herbaceous species richness. Fire exclusion in these communities results in a suite of structural and compositional changes affecting fuelbed properties, flammability, and ultimately their fire regimes. This study examined fuelbed heterogeneity across a wide range of stand structures in Oregon white oak (*Quercus garryana*) woodlands in the Bald Hills of Redwood National Park, California USA. Woodlands were stratified into 5 structural communities including prairies, isolated single-stemmed oaks, isolated oak clusters, oak forest, and oak forest invaded by Douglas-fir (*Pseudotsuga menziesii)*. Live and dead fuel moisture and fuel mass (Mg ha^{-1}) in three strata (herbaceous, litter, woody) were sampled in mid-late summer, 2008 and 2009. Fuelbed components were compared across structural types with ANOVA while regression analysis was employed to quantify relationships between overstory and understory components. Pyrometers (temperature-sensitive paints applied to copper tags) were utilized to estimate fire temperature maxima across structural types during prescribed burns. Results reveal herbaceous mass decreases from prairie (3.37+-0.18 Mg ha^{-1}), to the understory of single stemmed oaks (2.63+-0.19 Mg ha^{-1}), oak clusters (2.13+-0.18 Mg ha^{-1}), oak forest (1.80+-0.12 Mg ha^{-1}), and Douglas-fir invaded oak forest (0.03+-0.03 Mg ha^{-1}), while litter and woody mass increase in the opposite direction along this same gradient ($p < 0.001$). Mean fire temperatures ranged from 75 degrees (C) in Douglas-fir invaded oak forests to 208 degrees (C) in grasslands and was somewhat correlated with herbaceous mass ($R = 0.49$). Areas heavily invaded by Douglas-fir tended to have lower maximum air temperature, higher relative humidity, and lower wind speeds compared to prairies and woodlands. This study links fuelbed components with overstory structure and importantly illustrates mechanisms driving differences in fire behavior among highly flammable (e.g., savannas and grasslands) and relatively less flammable (e.g., Douglas-fir forest) vegetation types.

Effectiveness of post-fire mulches in the Santa Barbara front country

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Abstract
Use of aerially-applied hydromulch for erosion control after wildland fire has increased in areas where high winds are expected to make straw mulch ineffective. Hydromulch consists or wood or paper fiber held together with a tackifer that also binds it to the soil. Several recent large wildland-urban interface fires in southern California were treated with aerial hydromulch due to postfire erosion threats to highways, other critical infrastructure, and homes. Past studies have shown mixed effectiveness for this expensive (about $4000/ac) treatment, and public concern is high over hydromulch effects on native plant recovery, especially in chaparral where a rich native herbaceous flora takes advantage of the light and nutrients available after fire. We examined the erosion-control effectiveness and vegetation impacts of postfire hydromulch on two urban-interface burns near Santa Barbara, California, and we took advantage of the burned areas to test two other mulch materials ï wood shreds and woodstraw ï as alternative treatments. Erosion was measured with silt fences, and we estimated vegetation cover and species composition in 1-m^2 plots.

On the 2008 Gap fire, hydromulch reduced hillslope sediment movement by over 60% compared to untreated control plots the first year after fire. Wood shreds were only slightly less effective. Rainfall was under 60% of the long-term average during the first postfire year, and intensity was moderate. During the wetter second year hydromulch was still effective, even though it is generally expected to break down after 6 to 12 months; wood shreds also remained effective despite some loss of cover. Vegetation recovery ï in terms of total plant cover, shrub seedling density, and species richness ï was unaffected by hydromulch or wood shreds. Rainfall was greater after the 2009 Jesusita fire, resulting in more first-year hillslope sediment movement. Hydromulch reduced sediment movement by 84% overall compared to control plots, while woodstraw effectiveness varied with application density (60% and 30% initial ground cover reduced erosion by 54% and 24%, respectively). Effectiveness of hydromulch varied with slope aspect, as it did with woodstraw, which largely blew away on west-facing slopes. Vegetation regrowth was abundant in 2009-2010 on the Jesusita fire site, amounting to virtually 100% cover on many plots, with no negative effects of hydromulch or woodstraw observed. In general for the windy Santa Barbara front country, woodstraw was less effective than hydromulch or wood shreds.

Additional keywords: chaparral, erosion reduction, hillslope sediment movement, hydromulch, postfire recovery, vegetation recovery, wood shreds, woodstraw.

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A laboratory-scale comparison of rate of spread model predictions using chaparral fuel beds – preliminary results

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Abstract
Observed fire spread rates from 240 laboratory fires in horizontally-oriented single-species live fuel beds were compared to predictions from various implementations and modifications of the Rothermel rate of spread model and a physical fire spread model developed by Pagni and Koo. Packing ratio of the laboratory fuel beds was generally greater than that observed in natural stands of chaparral. Fuel bed moisture content was greater than that in Rothermel's or in Wilson's data. Correlation between observed and predicted spread rate was 0 for Rothermel's original model and ranged from 0.07 to 0.49 for the other implementations and modifications of the Rothermel model. Correlation between observed and predicted rate of spread for the Pagni/Koo model was 0.74 and 0.89 in chamise and broadleaf chaparral fuel beds, respectively. Additional comparisons with vertically-oriented live fuel beds and with additional models are planned.

Additional keywords: [Adenostoma fasciculatum, Arctostaphylos, Ceanothus, Quercus]

Introduction

Fire burns in living fuels such as chaparral in California, sagebrush and pinyon-juniper woodlands in the interior West, palmetto-gallberry in the southeastern coastal plain, and coniferous forests in the U.S. annually. While these fires can be significant events, our ability to predict when fire will spread in these fuels is limited by two factors: 1) current fire spread models were not designed primarily for live fuels and 2) a limited set of experimental data to develop and test models exists. This problem has been recognized for over 60 years (Buck *et al*. 1941). In the U.S., limited modeling of fire spread in live fuels has occurred (Albini 1967; Rothermel and Philpot 1973; Albini and Anderson 1982; Cohen 1986; Albini and Stocks 1986; Butler *et al*. 2004; Zhou *et al*. 2005, 2007).

The basic formulation of the Rothermel model (eq. 1) assumed that a fire would spread in the absence of wind and slope (Rothermel 1972). Wind and slope terms function as multipliers of rate of spread where φ_w and φ_s are wind and slope multipliers, respectively. If wind or slope is a requirement for spread, the Rothermel model formulation fails (Weise and Biging 1997). This requirement indicates the need for a different formulation for the effects of wind and slope on rate of spread. The Rothermel model was derived based on several simplifying assumptions. Fuels were assumed to be uniform, dominated by dead material, and in close proximity to the ground. Environmental conditions were assumed constant. The various heat transfer mechanisms of radiation, convection, and conduction were not explicitly described. Several sensitivity analyses have been performed to determine the important input variables for the Rothermel model (Sanderlin and Sunderson 1975; Salvador *et al*. 2001; Clark *et al*. 2008; Jimenez *et al*. 2008) and the responsiveness of the model to fluctuating wind velocity was reported (Albini 1982). Jolly (2007) recently evaluated the sensitivity of spread model predictions to live fuel moisture using the thirteen original fuel models (Rothermel 1972) and the recently developed 42 additional fuel models (Scott and Burgan 2005). Recognizing the limitations of the original thirteen fuel models, Hough and Albini (1979) previously formulated a fuel model for the palmetto-gallberry fuel complex of the U.S. southeastern coastal plain.

$$R = \frac{\xi h w_n \Gamma' \eta_M \eta_s \left(1+\varphi_w+\varphi_s\right)}{\rho_b \varepsilon Q_{ig}} \quad (1)$$

where ɜ˜ is the propagating flux ratio, h is the fuel heat content (kj kg^{-1}), w_n is the wet fuel loading (kg m^{-2}), ũ ôis the reaction velocity (min^{-1}), η_m is the moisture damping coefficient, η_s is the mineral damping coefficient, ρ_b is the fuel bed bulk density (kg m^{-3}), ε is the effective heating number, and Q_{ig} is the heat of preignition (kj kg^{-1}). The moisture damping coefficient is a cubic polynomial function of the ratio of the moisture content m_f to a moisture of extinction m_x. Rothermel (1972, modified in Albini 1976a), implemented a live fuel moisture of extinction based on work of Fosberg and Schroeder (1971) which uses the ratio of the dead to live fine fuel mass (W) as follows: $\left(m_x\right)_{Live} = 2.9W\left(1-m_{f,Dead}/\left(m_x\right)_{Dead}\right)-0.226$. Using this equation, a fuel bed with dead and live fuel moisture of extinction = 0.2, and dead fine fuel moisture content of 0, requires a dead to live ratio of 0.28. In other words, by setting the minimum live fuel moisture of extinction to 0.2, a mixed fuel bed needs to have at least 28% dead fine fuel that is absolutely dry in order to spread. If the calculated $(m_x)_{live} < (m_x)_{dead}$, then $(m_x)_{live} = (m_x)_{dead}$.

Wilson (1982, 1985, 1990) examined fire spread in moist fuel and proposed changes to the moisture content term in the Rothermel model (eq. 2). The original moisture damping coefficient η_M , , was replaced by a new moisture damping coefficient $\langle \eta_m \rangle$, a function of $\exp(-m_f/m_c)$.where m_c is a characteristic moisture content. An extinction index $P_f(n_x) = \ln\left(\sigma\beta\delta h_v/Q_w\right)/\left(m_f + Q_f/Q_w\right)$ was derived and incorporated into a revised reaction velocity $\langle \Gamma \rangle = 0.34\left(\sigma\beta\delta\right)^{-0.5}\exp\left(-\sigma\beta/3\right)P_f\left(n_x\right)$ and a new propagating flux ratio was developed $\langle \xi \rangle = 1-\exp\left(-0.17\sigma\beta\right)$. σ, β, and δ are the fuel particle surface area to volume ratio (cm^{-1}), fuel bed packing ratio, and fuel bed depth (m^{-1}), h_v is the heat of combustion of pyrolyzate gases, Q_f and Q_w are the heat of pyrolysis and heat of desiccation, respectively.

$$R = \frac{\langle \xi \rangle h_v w_o \langle \Gamma \rangle \langle \eta_m \rangle \left(1+\varphi_w+\varphi_s\right)}{\rho_b \varepsilon \left(Q_f + m_f Q_w\right)} \quad (2)$$

Cohen (1986) incorporated the dynamic fuel model for chaparral proposed by Rothermel and Philpot (1973) into FIRECAST providing 2 basic fuel models for chamise (*Adenostoma fasciculatum*) and broadleaf chaparral such as manzanita (*Arctostaphylos* spp.), ceanothus (*Ceanothus* spp.), and scrub oak (*Quercus berberidifolia*). Fuel loading, depth, and fraction of dead material were modeled as a function of age. The heat content of the fuel changed over the year as a function of time between May 1 and November 30. Fire behavior prediction for the 20 National Fire Danger Rating System fuel models was also implemented. The FIRECAST implementation of Rothermel (1972) did not change the fire model formulation; it only provided additional fuel models for use.

In FIRECAST, σ for both chamise and mixed brush foliage was assumed to be 72 cm^{-1}. We used 58 cm^{-1} for the broadleaf chaparral species by averaging the values for *Arctostaphylos patula*, *Ceanothus velutinous*, and *Castanopsis sempervirens* (Countryman 1982). Countryman and Philpot (1970) reported packing ratios ranging from 0.00068 to 0.00374 for 16 chamise plants sampled near the location fuels were collected for the current study. Others have reported remarkably similar packing ratios for the fine fuels (leaves and stems < 0.64 cm diameter) in various chaparral stands (Table 1). Reported fine fuel loading in various chaparral species mixes ranged from 0.71 to 3.33 kg m^{-2} (Countryman 1964; Ottmar *et al*. 2000).

Catchpole *et al.* (1998) burned 357 fires in a variety of dead fuel beds composed of excelsior and sticks in a wind tunnel. Using these data and building on the work of Frandsen (1971), Wilson (1990), and others, they developed a predictive model similar in formulation to the original Rothermel model (eq. 3). They estimated the three parameters associated with the wind term (*U*) using weighted least squares. Note that this related model does not currently include a slope term as none of the experimental data included slope.

Table 1. Packing ratio estimated in natural chaparral fuel beds.

Source	Species	Sample Location	Sample Size	Packing ratio
Countryman and Philpot (1970)	*Adenostoma fasciculatum*	North Mountain Experimental Area, Riverside, California (NMEA)	16 shrubs	0.0007-0.0040
Unpublished data (Weise)	*Adenostoma fasciculatum*	NMEA	20 1m^2 quadrats	0.0007-0.0013
Rundel and Parsons (1979) [1]	*Adenostoma fasciculatum*	Sequoia National Park, California	3-5 shrubs	0.0005
Countryman (1982) [2]	*Arctostaphylos patula*	Shasta Experimental Forest, Mt. Shasta, California (SEF)	3 4m^2 quadrats	0.0005-0.0014
	Ceanothus velutinus	SEF	3 4m^2 quadrats	0.0007-0.0013
	Ceanothus cordulatus	SEF	2 4m^2 quadrats	0.0009-0.0010
FIRESTOP (1955)	*Adenostoma fasciculatum, Ceanothus cuneatus*[3]		12 4m^2 quadrats	0.0006
	Quercus berberidifolia		12 4m^2 quadrats	0.0008

1. Used foliage and < 0.5 cm branch mass for 37 year old stand (Rundel and Parsons, Table 4). Assumed depth of 1.2 m and 737 kg m^{-3} for fuel density.
2. Estimated foliage and < 0.63 cm branch mass by assuming 65% of foliage and 24% of branch mass in upper half of shrub (0.91 m). Multiplied these percentages by percent of total mass of quadrat that was foliage and branches (Countryman, Table 6).
3. Assumed same vertical distribution as in 2 and depth = 1.2 m. Use values for typical plot.

$$R = \frac{(495.5 + 1934U^{0.91})e^{-347/\sigma}\beta^{-0.499}e^{-km_f}}{\rho_p\left(Q_f + MQ_w\right)} \quad (3)$$

where k is a fuel bed dependent constant, and ρ_p is the fuel particle density (kg m^{-3}), respectively.

Recognizing that the fuel models presented in Albini (1976b) and Scott and Burgan (2005) are idealized simplifications of natural fuel beds that contain the necessary information to predict a fireǿs rate of spread, Sandberg *et al.* (2007) reformulated Rothermel (1972) to allow the direct use of inventoried fuel properties in place of the stylized fuel models. This reformulation, which preserved the basic form of the Rothermel model, is part of the Fuel Characteristic Classification System (Ottmar *et al.* 2007) and contains data for several hundred different ñnaturalò fuel beds. The ñheat sinkò term of Rothermelôs model (the denominator) was decomposed into four components of a ñnaturalò fuel bedð shrub, woody, non-woody, and litter-lichen-moss strata.

At approximately the same time as the Rothermel parameterization of Frandsenôs (1971) rate of spread model formulation was presented, Pagni and Peterson (1973) presented a rate of spread model for litter-like fuel beds based on solution of the conservation of energy, mass and momentum equations. The model explicitly contained terms for radiative, convective, and conductive heat transfer. The model requires flame length as an input in addition to the usual fuel and environmental variables. This is noticeably different from the Rothermel-type models which require only fuel and environmental variables for input. The Pagni model predicted rate of spread reasonably well in litter-like fuel beds (Rothermel and Anderson 1966) and grass and chaparral stands in northern California (Pagni *et al.* 1971; Peterson 1972). Koo *et al.* (2005) modified the original formulation in light of additional sets of data for litter-like fuels. This modified model is referred to as the Pagni/Koo model in this paper.

There are several different models and modeling systems which can be used to predict fire behavior in wildland fuels. Several reviews of existing models have been performed over the past 20 years (Pastor *et al.* 2003; Sullivan 2009a, 2009b, 2009c; Weber 1991) focusing on different aspects of the models. While some of these models could also be used in the present study, we chose to focus on Rothermel-type models and a simple physical model. In future work, we plan to include the Sandberg variant and the Albini (1967) physical model.

Methods

The effects of wind, fuel moisture content, fuel bed height and slope on flame propagation in live fuels were investigated in a series of 240 experimental fires. Fuel beds (2 m long x 1.0 m wide x various depths) were constructed of live branch and foliage material collected from chaparral growing at an elevation of 1160 m in the North Mountain Experimental Area 50 km east of Riverside, California. Branches < 0.64 cm diameter from manzanita (*Arctostaphylos glauca*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), and scrub oak (*Quercus berberidifolia*) plants comprised the fuels. The fuel beds were elevated above the surface of a tilting platform by 40 cm to simulate an aerial fuel. Air could be entrained from the ends of fuel bed; metal sheeting prevented air entrainment from the sides to reduce the curvature of the flame front and simulate a line fire. Plant material was generally collected in the morning and burned in the afternoon of the same day to minimize moisture loss. Dead fuel was removed to the extent possible; for all practical purposes, no dead fuel was present in the fuel bed. The fuels were bagged and transported to the burn facility at the USDA Forest Service PSW Research Stationôs Forest Fire Laboratory in Riverside, CA. Moisture content of a 5-10 g sample was determined using a Computrac[1] moisture analyzer immediately prior to ignition. Fuel temperature was assumed in equilibrium with air temperature since air temperature at the collection site was generally only a few degrees different from the laboratory temperature. Five fuel beds constructed 24 hours after collection using refrigerated fuels were allowed a few hours to come to equilibrium with ambient air temperature prior to ignition. Fires were ignited along the 1 m side with a flame zone depth of 50 cm section along the length of the live fuel bed. Between 300 and 400 g of excelsior and a small amount of isopropyl alcohol were added uniformly in the ignition zone to initiate and sustain the ignition. Further details are available in Weise *et al.* (2005).

[1] Tradenames are provided for informational purposes only and do not constitute endorsement by the U.S. Department of Agriculture.

Three 50.8 cm rotary box fans (Air King Model 9700) induced airflow to simulate wind. No attempt was made to ñsmoothò out the vorticity in the flow. The fans produced an average velocity of 2 m s-1 above the fuel bed. The slope effect was generated by raising the down-wind end of the tilting platform. Ambient air temperature and relative humidity in the burn facility were measured at the beginning of each experiment using a Kestrel 3000 Pocket Weather Meter. If the fire propagated the entire length of the fuel bed, a rate of spread was calculated using data from 0.51 mm diameter type K thermocouples buried in the fuel bed and/or direct video image analysis from digital imagery collected at 30 hz (Canon ZR10).

Fire spread predictions by our implementations of the Rothermel-type models (Original, Cohen, Wilson, Catchpole), and the Pagni/Koo model were made using data from the chaparral fuel beds. Parameters describing two fuel bed types were used ï the original static chaparral fuel model 4 (Albini 1976) adjusted for depth and loading and the dynamic models developed by Philpot and Rothermel (1973) for chamise and broad-leaved chaparral (Table 2). The original Rothermel and FIRECAST calculations produce slightly different fuel bed packing ratios. The percentage difference between the two calculations was 4.4% and 11.8% for chamise and broadleaved species, respectively. These did not have an appreciable effect on the rate of spread calculation.

Rothermelõs weighting of fuel bed properties requires a moisture of extinction for both live and dead fuels. The minimum moisture of extinction for the live fuel components of a fuel bed in FIRECAST was 0.3 which we used for the static chaparral fuel model instead of the original 0.2. For this experiment, we chose to estimate the extinction moisture from our data for the dynamic chaparral fuel models. The maximum moisture content at which a fire spread successfully under no-wind and no-slope conditions was determined from the 16 chamise, 3 ceanothus, and 1 manzanita fuel beds with successful fire spread. The maximum moisture contents for these three species were 0.65, 0.66, and 0.74, respectively. Live moisture of extinction was set at 0.65 and 0.74 for chamise and broad-leaved chaparral, respectively. Calculation of moisture of extinction for live fuels in Rothermelõs original formulation was unchanged (Table 3).

As described previously, the fuel beds consisted of green foliage and branches < 0.625 cm diameter. In order to partition the fuel bed loading between foliage and branches, a small sample of branches with foliage was selected to determine the proportional mass within these two categories. As a result, we used the following proportions for foliage and branches, respectively: chamise ï 0.10 and 0.90, broad-leaved chaparral ï 0.27 and 0.73.

Table 2. Physical and chemical constants for chaparral fuel beds by fuel particle size class.

Species	Size class (cm)	Surface area to volume ratio (ů, cm^{-1})	Silica-free mineral content (η_s)	Particle density (ρ_p)
Chamise	Foliage	72.0	0.035	513
	Live < 0.63	21.0	0.015	737
	Live 0.64-1.26	4.2	0.015	737
	Live 1.27-2.54	2.1	0.015	737
	Live 2.54-7.64	0.9	0.015	737
Broadleaf	Foliage	58.0	0.035	513
	Live < 0.63	10.5	0.015	737
	Live 0.64-1.26	4.4	0.015	737
	Live 1.27-2.54	2.3	0.015	737
	Live 2.54-7.64	1.2	0.015	737

Table 3. Fuel bed bulk properties.

Species	Surface area to volume ratio (ů, cm^{-1})		Mass fraction		Heat of combustion of volatiles (kJ kg^{-1})	Moisture of extinction	
	Rothermel	Others	Foliage	Woody		Rothermel (dead)	FIRECAST (live)
Chamise	35	21	0.10	0.90	12960	0.30	0.65
Broadleaf	43	12	0.27	0.73	11790	0.30	0.74

The amount of energy in the fuel beds was modelled differently by the various implementations of the Rothermel model. The low heat of combustion was used in the Rothermel and FIRECAST variants; the Wilson and Catchpole variants use the heat of combustion of the pyrolyzed gases. For the static fuel model, low heat of combustion of the fuel bed (h) was 18608 kj kg^{-1} and the low heat of combustion of the pyrolyzed gases was 12960 and 11790 kj kg^{-1} for chamise and broad-leaved chaparral, respectively (Susott 1982). The low heat of combustion for the dynamic fuel model (Rothermel and Philpot 1973) was calculated originally using the number of days (D) from May 1 for the time period May 1 to October 30. Cohen (1986) modified the calculation to cover the entire year.

$$h = 2.326\left(9613 - D + 0.1369D^2 - 0.000365D^3\right) \qquad \text{foliage}$$

$$h = 2.326\left(9509 - 10.74D + 0.1359D^2 - 0.0004055D^3\right) \qquad \text{branches}$$

In the Catchpole formulation, fuel bed values and moisture terms from Wilsonǿs formulation were used. Based on the ů for the fuel beds, a *k* value of 2 was used in eq. 3 (Catchpole *et al.* 1998). Wilson (1990) recommended that the relationship between response times for fine fuels (Anderson 1988) and the characteristic moisture be examined as well as how characteristic moisture is related to moisture diffusion and other physical characteristics. The applicability of this to live fuels is unknown since moisture movement in live fuels is a more complex process than in dead fuels (Nelson 2001) and this type of work has not been carried out for live fuels to our knowledge.

As mentioned above, the Pagni/Koo model requires an independent measure of flame length in order to calculate rate of spread. Currently, flame length data are not available for these experimental fires. For those fires with measured spread rates, we calculated flame length using the average of three different flame length (m) mass loss rate (lb min^{-1}) correlations using Albiniǿs formulations (1981). Mass loss rate was estimated by multiplying the rate of spread by the oven-dry fuel loading and dividing by the length of the fuel bed exclusive of the ignition zone (1.5 m).

$L_f = 0.981\dot{m}''^{0.46}$ Byram 1959

$L_f = 0.954\dot{m}''^{2/3}$ Fons et al 1963

$L_f = 1.201\dot{m}''^{2/3}$ Thomas 1963

where $\dot{m}'' = w_0 R/l = 0.67\, w_0 R$

Spread rate success ($R > 0$) was summarized by species in contingency tables for actual and predicted spread rates with the exception of the Pagni/Koo model. Correlation coefficients between actual and predicted spread rates were calculated and scatter plots were made to determine if there were any trends.

Preliminary Results and Discussion

Because a variety of factors influencing rate of spread were examined in an exploratory fashion, the combined data set of 240 fires is not well-balanced experimentally (Table 4). Of the 240 fires (113 chamise, 127 broadleaf), 123 (70 chamise, 53 broadleaf) successfully spread the length of the fuel bed producing a measurable spread rate (Table 4). Fuel from seven of the chamise fuel beds was allowed to dry which resulted in moisture contents of 0.09 ï 0.30. Generally moisture content of the fuel beds ranged from 0.54 to 1.06. This range of moisture content resulted in oven-dry fuel loadings of 1.1 ï 4.9 kg m^{-2}. The original, Wilson, and Catchpole variants of the Rothermel model use dead fuel particle density while the FIRECAST variant uses both live and dead fuel particle density to calculate packing ratio (fuel bed bulk density/fuel particle density) resulting in slightly higher values; these slight differences are of no practical importance (8-14%). When compared with packing ratios observed in chaparral stands, the chamise fuel beds were generally less porous than naturally occurring chamise shrubs while the packing ratio of the broadleaf fuel beds was of the same order of magnitude as those reported for northern California brush fields (Table 1).

Table 4. Summary of laboratory experimental fires.

Type[1]	Wind ($m\ s^{-1}$)	Slope (%)	n	Fuel mass ($kg\ m^{-2}$)	Moisture content	Success[3]	Spread rate ($m\ min^{-1}$)
Broadleaf	0	< 0	13	1.74-3.89	0.58-0.74	0.31	0.100-0.154
	0	0	26	1.09-4.86	0.54-1.06	0.15	0.079-0.171
	0	<30	17	1.89-3.78	0.54-0.74	0.35	0.136-0.600
	0	>30	49	1.63-4.90	0.54-1.04	0.47	0.099-1.364
	2	0	23	1.09-4.86	0.66-1.06	0.70	0.056-0.368
Chamise	0	< 0	19	1.74-3.53	0.49-0.60	0.79	0.080-0.207
	0	0	37	1.41-3.19	0.30-0.91	0.43	0.078-0.380
	0	<30	11	1.25-3.16	0.09-0.66	0.18	0.474-0.639
	0	>30	23	1.42-3.19	0.55-0.80	0.65	0.130-1.769
	2	0	18	1.41-3.37	0.26-0.91	0.94	0.184-0.940
	2	<30	4	1.25-3.37	0.26-0.64	1.00	0.547-0.883
	2	>30	1	1.42	0.80	1.00	1.451

1. Broadleaf ï *Ceanothus crassifolius, Quercus berberidfolia,* or *Arctostaphylos glauca*; chamise ï *Adenostoma fasciculatum*
2. Rothermel (1972), Cohen (1986)
3. Proportion of fires that spread entire length of fuel bed.

Observed rate of spread ranged over two orders of magnitude (0.05-1.77 m min^{-1}). These rates of spread are slow compared to head fire spread rates compiled for chaparral from large fires (Abell 1940 and Chandler *et al.* 1963 reported average fire spread rates of 3.5 m min^{-1}). In general, the predicted spread rates from the various models also ranged over a few orders of magnitude with the exception of Rothermelôs original version (Table 5). With the exception of the fuel bed with moisture content of 0.09 (Fig. 1), the original version predicted spread rate = 0 for all other fuel beds. This is due to the moisture of extinction being set at 0.30. All other variants of Rothermel predicted non-zero spread rates because of the higher moisture of extinction assigned (Table 2). Because of the requirement of the Pagni/Koo model to have a flame length used in prediction, the number of fires available to compare spread rates for this model was smaller than for the other models. Predictions from the Pagni/Koo model were of the same magnitude as the Rothermel variants.

There was a wide range of agreement between actual and predicted values for the five models tested (Fig. 1.). In general, the original version of the Rothermel model with moisture of extinction of 0.20 did not predict a non-zero spread rate so the correlation, as measured by the Pearson product-moment correlation *r*, was 0 for broadleaf chaparral fuel beds and low for the chamise chaparral fuel bed (Table 6). The predicted spread rate (0.69 m min^{-1}) for the fuel bed with moisture content of 0.09 was very close to the observed spread rate (0.64 m min^{-1}) which reflects the original data used to parameterize the model very well. In most cases, all other variants of Rothermel exhibited some level of correlation with actual spread rates for the fuel beds with moisture content > 0.30. For the broadleaf fuel beds, the correlation values for the Wilson and Catchpole variants were significantly different from 0 even though very low. For the chamise fuel beds, all three variants of the Rothermel model exhibited correlation coefficients significantly different from 0 and the values of the correlation coefficient were higher than for the broadleaf fuels. Correlations of the Pagni/Koo model for both fuel bed types were significantly different from 0 and the values were the highest of the five models considered.

Table 5. Summary of actual and predicted fire spread rates (m min^{-1}) in chaparral fuel beds in a laboratory.

Type[1]	Wind	Slope	Actual	Rothermel-based[2]				Pagni/Koo
				Original	FIRECAST	Wilson	Catchpole	
Broadleaf	0	< 0	0.00-0.18	0.00	0.005-0.365	0.018-0.115	0.043-0.322	0.120-0.202
	0	0	0.00-0.17	0.00	0.000-0.068	0.001-0.020	0.008-0.040	0.138-0.219
	0	<30	0.00-0.60	0.00	0.000-0.143	0.009-0.043	0.041-0.108	0.178-0.468
	0	>30	0.00-1.36	0.00	0.000-0.761	0.004-0.213	0.032-0.814	0.109-0.951
	2	0	0.00-0.37	0.00	0.000-0.527	0.017-0.215	0.067-0.255	0.132-0.545
Chamise	0	< 0	0.00-0.21	0.00	0.096-0.957	0.072-0.516	0.052-0.454	0.111-0.244
	0	0	0.00-0.38	0.00	0.000-0.382	0.006-0.180	0.019-0.129	0.101-0.635
	0	<30	0.00-0.64	0.00[3]	0.000-1.054	0.057-0.831	0.092-0.711	0.837-1.902
	0	>30	0.00-1.77	0.00	0.000-0.470	0.098-0.271	0.117-0.306	0.199-0.944
	2	0	0.00-0.94	0.00	0.000-5.545	0.089-2.889	0.156-1.203	0.354-1.665
	2	<30	0.55-0.88	0.00	0.181-6.147	0.384-3.200	0.967-2.945	0.918-1.728
	2	>30	1.45	0.00	0.000	0.189	0.930	1.442

1. Broadleaf ï *Ceanothus crassifolius, Quercus berberidfolia,* or *Arctostaphylos glauca*; chamise ï *Adenostoma fasciculatum*
2. Original ï Rothermel 1972, FIRECAST ï Cohen 1986, Wilson 1990, Catchpole *et al.* 1998
3. 1 fire with moisture content = 0.09 had predicted spread rate of 0.691 m min^{-1}. All others were 0.00.

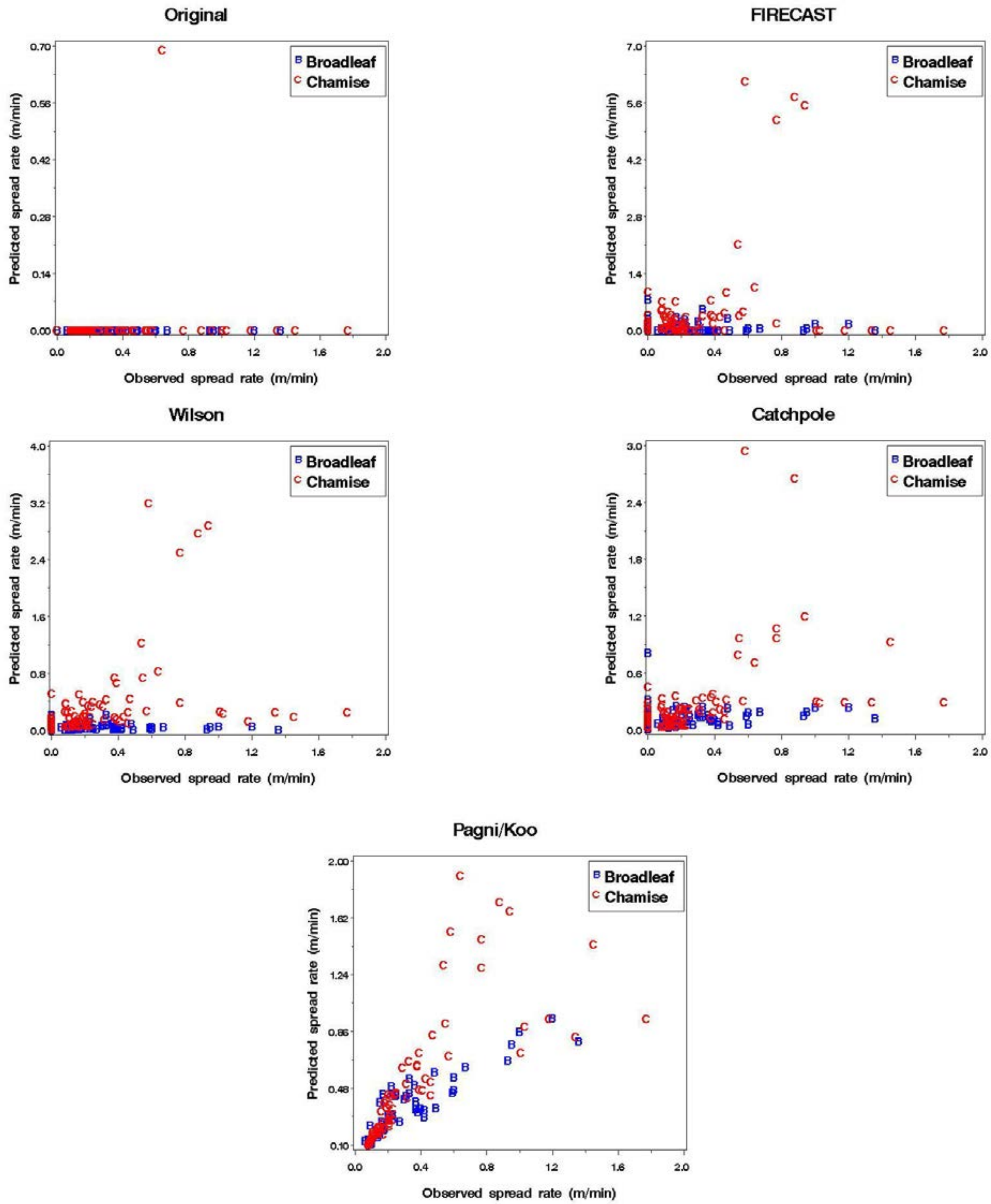

Fig. 1. Comparison of actual fire spread rates with predicted fire spread rates for four variants of the Rothermel model and the Pagni/Koo model in fuel beds of live chamise and broadleaf chaparral fuels.

Table 6. Correlation between actual and predicted fire spread rates in chaparral fuel beds in a laboratory.

Type[1]	Model[2]	r[3]	$Pr > \|r\|$[4]	n
Broadleaf	Original	0.0		127
	FIRECAST	0.07	0.451	ñ
	Wilson	0.17	0.053	ñ
	Catchpole	0.24	0.006	ñ
	Pagni/Koo	0.89	0.0001	51
Chamise	Original	0.12	0.213	113
	FIRECAST	0.34	0.0002	ñ
	Wilson	0.42	0.0001	ñ
	Catchpole	0.49	0.0001	ñ
	Pagni/Koo	0.74	0.0001	69

1. Broadleaf ï *Ceanothus crassifolius, Quercus berberidfolia,* or *Arctostaphylos glauca*; chamise ï *Adenostoma fasciculatum*
2. Original ï Rothermel 1972, FIRECAST ï Cohen 1986, Wilson 1990, Catchpole *et al.* 1998
3. Pearson product-moment correlation.
4. Two-tailed probability associated with test that r=0.

While moisture of extinction is a ñuser-selectableò variable that can be associated with a fuel model (Burgan 1987), increasing the moisture of extinction only changes the range of the effect of the moisture dampening coefficient. This type of tuning to the fuel model parameters is an example of the ñartò of fuel modeling to attempt to improve the agreement between model predictions and observations. It is not something that is readily available to users with the current implementation of the Rothermel model (BEHAVEPlus) unless a user has access to the computer code. Even though the Wilson and Catchpole variants used a different formulation for the effect of moisture on fire spread, predictive capability was improved slightly over the original model. The basic assumption that energy is required to vaporize all of the water in fine fuels prior to ignition may not be appropriate for fine live fuels as has been demonstrated by Pickett and coworkers (2010). As others have demonstrated (Finney *et al.* 2010), flame bathing of fuels may be required for successful ignition and radiant heating may not be sufficient for successful flame propagation through live fuels. Flame bathing is heat transfer by convection. Weise *et al.* (2005) demonstrated that wind velocity (which affects flame angle and flame contact with fuels) is an important (and perhaps required) environmental variable in these laboratory fuel beds.

The relatively good predictions from the Pagni/Koo physical model which explicitly contains heat transfer terms for flame radiation, ember radiation, and convective heating are promising. This simple physical model appears to capture the important mechanisms of heat transfer in live fuel beds; however, the comparison presented here is not completely ñfairò. Recall that the observed spread rate in fuel beds was used to estimate a flame length which was then used to predict rate of spread. This is not a completely independent test. For fair comparison to be made, we need to derive flame lengths from video of the experiments and then predict spread rate. To be a useful predictive tool, either a correlation that can predict flame length from the environmental and fuel variables which is then used in the spread calculations is needed or a quick iterative solution method to solve for flame length and rate of spread is required to enable the use of this model for fire spread prediction.

Additional comparison of the models is planned using results from over 100 laboratory fires in vertically-oriented live fuels to determine performance. Even though the present comparison is limited in nature, it does indicate that additional work and modeling is needed to improve our ability to predict fire spread in live fuels. A physics-based fire spread model that eliminates some of the art based on improved science is needed.

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Impact of the live fuel structure on fire behavior in limestone Provence (SE France).

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Abstract
Live fuels were described in limestone Provence and fire behavior simulated to assess the impact of fuel characteristics on rate of spread (ROS). Vegetation structure was described at particle and stand levels. The horizontal and vertical continuities of the vegetation were assessed taking into account overstory and understory cover and height, and biomass. Simulations of fire behavior were performed using the FIRETEC fire simulation code. Multivariate analysis showed that, in each type of vegetation, ROS could be explained by vegetation structure. The simulations highlighted three different types of ROS: low ROS in vegetation types characterized by a heterogeneous horizontal continuity with a low/medium tree density, intermediate ROS in shrublands, and high ROS in types characterized by either high tree cover and high biomass or high tree cover and high understory cover (3-6m stratum). If vertical discontinuity, the ROS was heterogeneous according to the vegetation stratum, higher in the overstory than in the understory where the biomass was lower. If vertical continuity, the ROS was the fastest and homogeneous regardless of the stratum.

The 8 vegetation types described in this typology could then be merged into 3 fuel types according to the ROS and fire risk assessed through fire behavior in the different fuel types.

Additional keywords: Rate of spread, Mediterranean fuels, vegetation typology

Introduction

Assessing fuel combustibility is a crucial point in fire risk management. The characterization of fuel types can be made at different levels from the particle to the stand. Fuel typologies have been carried out in different countries (Trabaud 1977; Albini 1976, Rothermel 1983; Marchetti and Lozupone 1985; Salas *et al*. 1994 and Giakoumakis *et al*. 2002).

One of the methods used to characterize fuel particles was the 'Cube method' (Cohen *et al*. 2003; Vigy 2006) allowing the determination of the volume fraction for many species in different Mediterranean countries. This method was designed for modeling the spatial distribution of fuel particles within individual shrub (or tree) canopies. Several works on the properties of fuel particles (Cohen *et al*. 2003) and fuel beds were carried out for the more widespread species and vegetation cover types.

The use of fire modeling systems, coupled with weather and terrain data (wind direction and speed, fuel moisture, elevation and slope conditions) provided fire behavior parameters in order to assess the combustibility of the fuel complex (McHugh 2006). Simulations of potential fire behavior carried out using American fuel types (NFFL) produced unrealistic outcomes in terms of fire behavior in Mediterranean countries due to unrealistic inputs in fuel description (i.e.

different species, no vertical continuity, etc.). Integration of the vegetation heterogeneity characterizing Mediterranean ecosystems resulted in more powerful simulations (Linn 2010), as done in the Firetec modeling system (Linn 1997; Linn and Cunningham 2005 and Pimont *et al*. 2009).

The aim of this work was to use descriptions of Mediterranean fuels at particle and stand levels as input data in fire behavior simulations using the Firetec simulation code, allowing the assessment of ROS. A classification of fuel complexes with similar potential fire behavior could be then proposed.

Material and methods

Study area

In order to prevent variability due to site fertility or physiography, data were collected on sites distributed throughout limestone Provence (southeastern France, Fig. 1) that were selected because of their homogeneity in terms of fertility (medium according to the forest site classification), elevation (less than 300 m), slope (less than 2°) and aspect (no aspect because of the very weak slope). A total of 39 study sites presenting the most common ecosystems in the area (pure pine stands, mixed pine-oak stands and shrublands so-called garrigue) with an array of fire regimes were selected in a GIS environment (Esri ArcGis 9.1) by intersecting the following layers: (1) an accurate vegetation map (National Forest Inventory, IFN), (2) fire boundaries for the period 1960[1]-2005, and (3) a Digital Elevation Model from the altimetric database provided by IGN (French National Geographical Institute).

Sampling: data acquisition

- At particle level

The sampling at particle level was carried out according to the 'Cube method' on the main species of the study area (Table 1). This method allowed the determination of the volume fraction and the spatial distribution of fuel particles within the plant canopy using a cube (25 x 25x 25cm) placed at three different heights (base, center and top) in the canopy of a plant (Fig. 2). Several classes of plant height were sampled depending on the species (Table 1).

[1] No spatial records are available on fires occurring before 1960 in the study area.

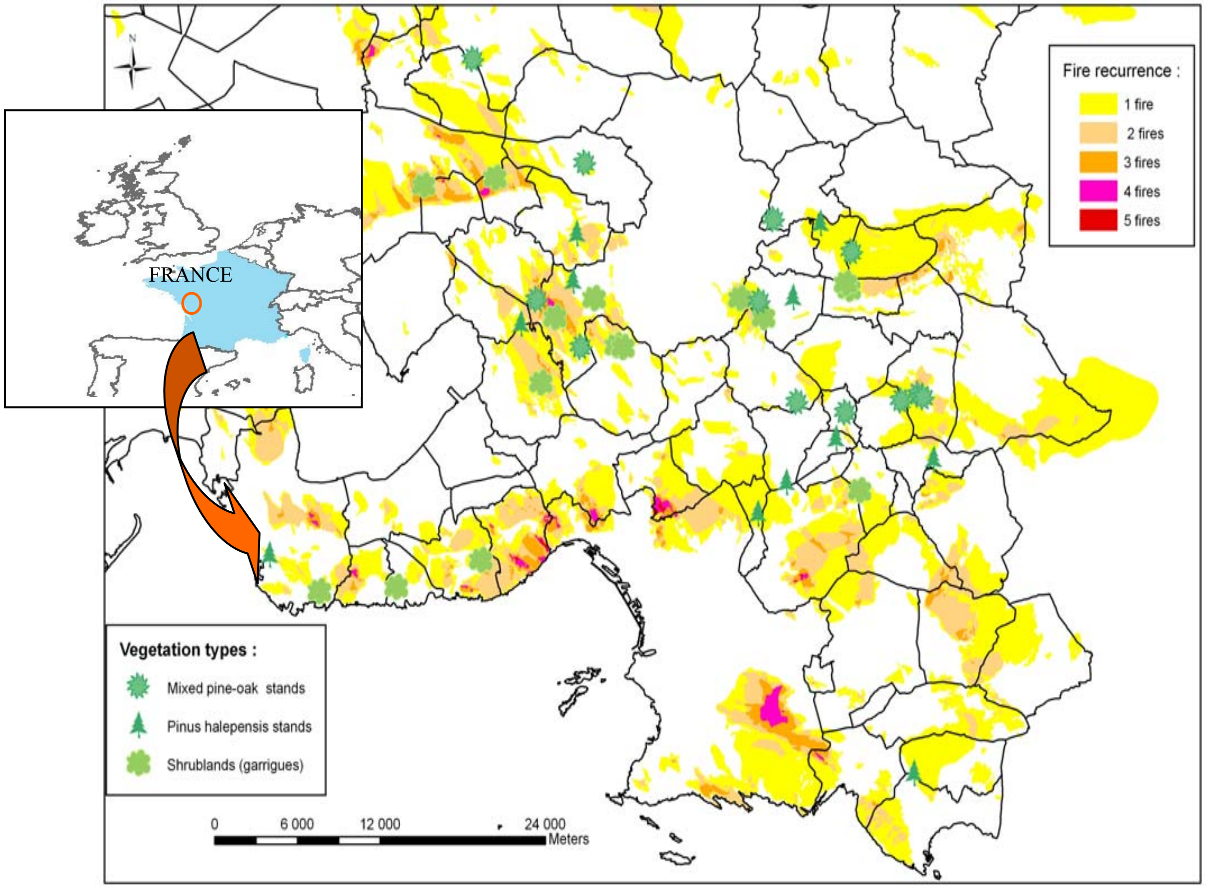


Fig. 1: Study sites and sampling plan according to vegetation type and fire regime in limestone-derived soils of Provence, France. Inner lines indicate municipalities (BD Carto ®

Table 1. Species and heights sampled using the 'Cube method' in the study area or stored in the 'particule' database (Krivtsov *et al*. 2009)(ND: no data).

Species	Height	Source
Brachypodium ramosum	0-25cm	Study area
Thymus vulgaris	0-25cm	Study area
Rosmarinus officinalis	0-25cm, 25-50cm, 50-75cm	Study area
Juniperus oxycedrus	25-50cm, 50-75cm, 75-100cm	Study area
Rhamnus alaternus	25-50cm, 50-75cm, 75-100cm	Study area
Phillyrea angustifolia	25-50cm, 50-75cm, 75-100cm	Study area
Quercus coccifera	0-25cm, 25-50cm, 50-75cm	'Particule' database
Quercus ilex	0-25cm, 50-75cm, 75-100cm, 100-150cm, 400-800cm	'Particule' database
Ulex parviflorus	ND	'Particule' database
Cistus albidus	0-25cm, 25-50cm	'Particule' database
Cistus monspeliensis	0-25cm, 25-50cm, 50-75cm	'Particule' database
Cistus salvaefolius	25-50cm, 50-75cm, 75-100cm	'Particule' database
Pinus halepensis	800-1600cm	'Particule' database

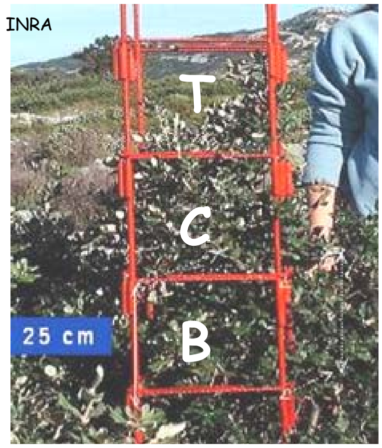


Fig. 2. Device used for the 'Cube method' sampling showing the three types of cubes (T: cube TOP, C: cube CENTER, B: cube BASE).

Four classes of particles were sorted and weighed (dry weight obtained after 48h at 60°C) in laboratory: (i) leaves, (ii) particles<2mm, (iii) particles 2-6mm and (iv) particles >6mm. For each species and at each cube height, the following fuel properties were measured or calculated: (i) volume fraction, (ii) mass to volume ratio, (iii) bulk-density (kg m^{-3}) equal to the volume fraction by the mass to volume ratio and (iv) the surface to volume ratio.

- At stand level

Sampling was carried out according to the fuel typology characterizing limestone Provence (Chandioux *et al*. 2006; fig. 3). Work by Ganteaume *et al*. (2009) described the vegetation structure in 400m^2 plots sampled in each fuel type in order to assess the spatial properties of each layer of vegetation such as fuel composition or fuel cover and height. Fuel horizontal and vertical continuities were described taking into account the overstory (>6m) and the understory (<6m), the fuel biomass, and the fuel cover and height. Parameters used to describe the vegetation structure (Ganteaume *et al*. 2009) were (i) covers and heights of vegetation layers, vegetation patches, shrubs and trees, (ii) covers of height strata 0-1m, 1-3m, 3-6m, 6-10m and >10m, (iii) tree density, (iv) total biomass, (v) biomass of vegetation <1.5m, (vi) biomass of vegetation >1.5m, (vii) tree crown diameter, (viii) vegetation patch diameter, and (ix) tree diameter at breast height.

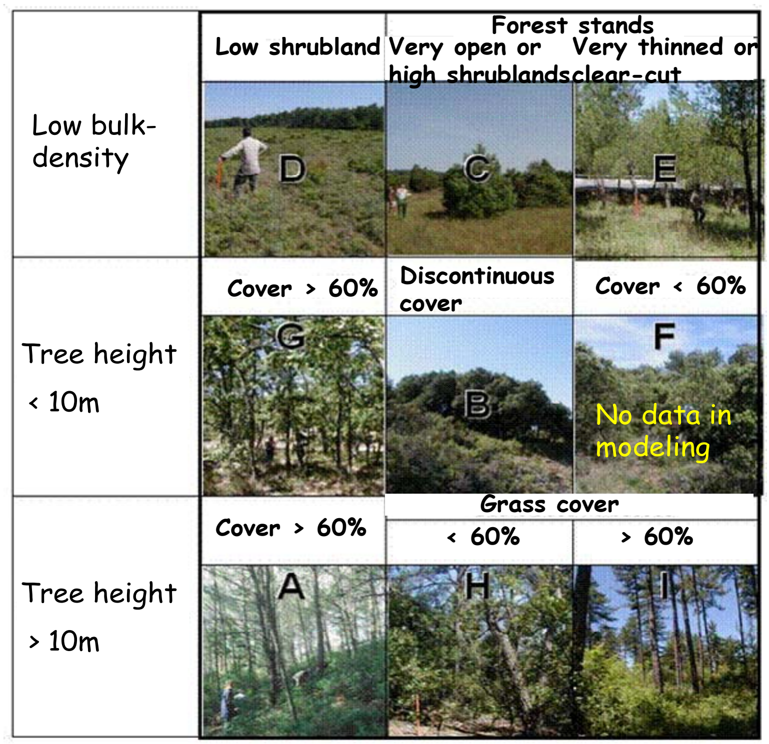


Fig. 3. Fuel typology used in limestone Provence taking into account fuel bulk-density, tree height and tree cover (Chandioux *et al*. 2006)

Modeling

- Modeling inputs

Different vegetation layers were taken into account depending on the stand height (Fig. 4). In each layer, the fuel parameters resulting from the sampling at particle level ('Cube method') and at stand level (plot description) were used as inputs in the model (Table 2). The fuel moisture content data came from a regional survey of dead and live FMC of different Mediterranean species.

Fuel properties and spatial properties, as described below, were needed for the modeling.

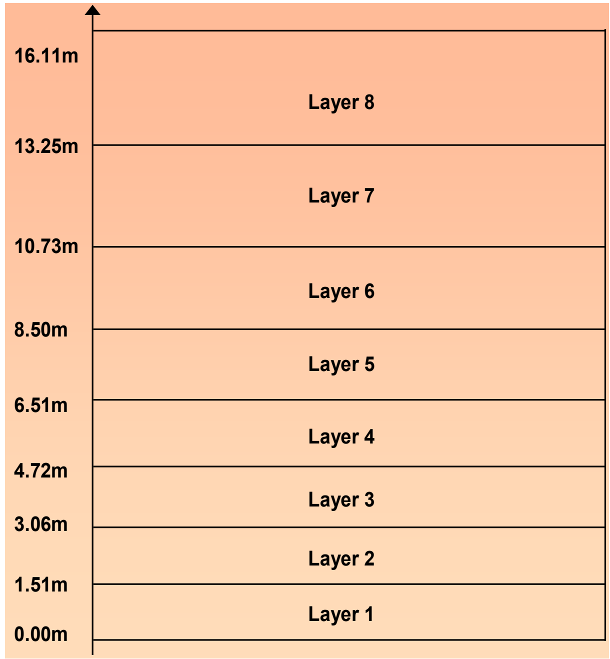


Fig. 4. Vegetation layers depending on the stand height taken into account in modeling.

Table 2. Type of sampling and fuel parameters characterizing each fuel layer (FMC: Fuel moisture content).

Sampling	**Fuel parameters**
Cube method	Total biomass (kg m^{-2})
Cube method	Biomass height<1.5m (kg m^{-2})
Cube method	Biomass height>1.5m (kg m^{-2})
Plot description	Maximum height (m)
Plot description	Maximum understory height (m)
Plot description	Tree cover (%)
Plot description	Shrub cover (%)
Plot description	Grass cover (%)
Regional database	Mean FMC (%)

The fuel properties used in the Firetec modeling system were derived from these fuel parameters. For a given layer i, the information required was:

- **rho(i)**: the bulk density of the fine fuel samples in layer *i* (in kg m^{-3}),
- **ss(i)**: a parameter characterizing the thickness of the fuel sample in layer *i* (in m),
- **MC(i)**: fuel moisture content in layer *i* (in fraction of dry mass).

The version of FIRETEC used in this study was 'monofuel within a cell', which meant that different cells could have different fuel properties but a given cell was supposed to be filled with one homogeneous fuel type. It was thus required to build average properties (**rho(i)**, **ss(i)**, **MC(i)**) for the layer that constituted an aggregation of fine fuel **families** (dead, live, leaves, needles, twigs<2mm).

The basic data needed for the specification of the spatial properties of a layer were:

- the **cover** C(i) fuel within the layer (in %),
- the **characteristic size** L(i) of the fuel clumps (if any) within the layer (in m),
- the **minimum and maximum heights** of the layer (cbh(i) and h(i)).

Data were available from the plot description.

Firetec simulation code

Simulations of fire behavior were carried out using the Firetec modeling system allowing the assessment of fire propagation at fine scale within and above heterogeneous vegetation canopies. These simulations were carried out under realistic conditions for Mediterranean summer period, with a 10 kmh^{-1} wind speed and no slope in the plot. The size of the voxel was 2m. A predictable ROS was identified in each fuel type, leading to a classification related to similar potential behavior.

Statistical analyses

The co-inertia analysis (Dolédec and Chessel 1994), using R software (ADE-4 package), was carried out on the dependent variables (rate of spread) and on the explanatory variables (fuel parameters) in order to assess the effect of the fuel parameters on the fire propagation.

Results and discussion

The simulations showed three classes of ROS could be highlighted (Table 3): (i) low ROS (<0.2ms^{-1}), (ii) medium ROS (from 0.2 to 0.5ms^{-1}) and (iii) high ROS (>0.5ms^{-1}).

Results of the multivariate analysis (Coinertia analysis) showed that, in each type of vegetation, the ROS could be explained by the vegetation structure (Fig. 5). Low ROS occurred in vegetation types characterized by a heterogeneous horizontal continuity and no vertical continuity with a low/medium tree density (open stands). This type of fuel showed a 'slow down' effect, trees burning only when the front fire passed by. In each case, the spread was steady for the whole layers (Fig. 6A). Medium ROS (from 0.2 to 0.5ms^{-1}) occurred in vegetation types characterized by a homogeneous horizontal continuity without trees (shrublands), even if the total biomass was low (Fig. 6B). High ROS (>0.5ms^{-1}) occurred in vegetation types characterized by either a high tree cover (trees>10m high) and a high biomass or a high tree cover (trees>10m high) and a high understory cover (3-6m stratum). When the tree cover was higher (≥60%; PC36-G, PC37-F, PC1-A, PC3-H, PC19-I), the ROS was faster (>0.5m/s) than in shrublands ('speed up' effect).

Moreover, simulations showed that, among the fuel types characterized by the fastest fire propagation, two types of high ROS could be differentiated:

(i) In the types characterized by a vertical discontinuity and a low horizontal continuity in the understory (mature pine stands: PC1-A and PC19-I), the ROS was heterogeneous according to the vegetation strata, faster in the upper layers ($0.73ms^{-1}$), like in case of crown fire, than in the lower layers ($0.15ms^{-1}$) where the biomass was lower (Fig. 6C). Indeed, in these plots, there was a big difference between the maximum tree height (>10m) and the height of the understory. The horizontal continuity was lower in the understory (more patchy) than in the overstory.

(ii) In the vegetation types characterized by a high overstory biomass and a homogeneous vertical continuity (mature mixed pine-oak stands: PC3-H), the ROS was the fastest and homogeneous regardless of the vegetation stratum (Fig. 6D). PC3-H was a plot composed of a mixed pine-oak stand with oaks in understory, with a very high biomass allowing high vertical and horizontal continuities. Thus, the rate of spread was high and steady in the whole layers, without any divergence as in the previous type.

A classification in three groups of vegetation types can be thus highlighted according to these three classes of ROS:

- Group 1 corresponding to a low ROS: low to high open stands with no vertical continuity,
- Group 2 corresponding to a medium ROS: shrublands with no tree, low biomass but with a strong horizontal continuity,
- Group 3 corresponding to a high ROS: high closed stands (high tree cover, tall trees, high biomass in the overstory).

This type of classification allows the assessment of fire risk through fire behavior, the higher the ROS, the higher the fire risk. Fernandes (2009) also assessed fire risk using forest structure and fire behavior. He showed that stand structure rather than cover types was the main determinant of fire vulnerability. Indeed stand structure was in most instances more important to fire behavior than tree species that comprised the stand. Fernandes's results showed that fire risk was lowest in both open and closed , tall stands (with a variable ROS) and highest in low stands (medium to high ROS). These two last results contradicted what we found.

Our results also agreed with other works carried out relating fire risk assessment and stand structure. For instance, Agee and Skinner (2005), Lentile *et al*. (2006), Pollet and Omi (2002) provided empirical evidence that open, tall conifer forests were less vulnerable to fire.

Conclusions

The aim of the present work was to analyze the potential fire behavior in eight fuel types characterizing the limestone Provence using Firetec simulations. The simulations needed two types of information: fuel properties coming from the sampling at particle level ('Cube method') and spatial properties coming from sampling at the stand level. The simulations allowed the assessment of fuel combustibility by the way of ROS. The classification of the fuel types according to this key parameter of fire behavior resulted in a new classification of Mediterranean fuels including 3 fuel types according to their potential fire behaviour.

This work can be improved by simulations of other fire behavior parameters such as fire intensity or flame height at the fire front. Replications of simulations within the same fuel type will be necessary to confirm these results.

According to Fernandes (2009), fire risk assessment cannot be inferred automatically from forest composition. So, this methodology allowed the comparison of the relative fire hazard potential of southeastern French fuels through fire behaviour.

Table 3. Parameters used in the modeling and resulting ROS for each type of fuel (FMC = fuel moisture content, ROS = rate of spread, ND = no data).

Plots and types	PC28-D	PC13-C	PC26-E	PC36-G	PC37-F	PC21-B	PC1-A	PC3-H	PC19-I
Vegetation Parameters	Shrubland	Shrubland	Pine stand	Mixed stand	Pine stand	Pine stand	Pine stand	Mixed stand	Pine stand
Total Biomass (kg/m^2)	0.67	0.92	1.03	1.80	1.46	1.86	2.01	3.14	2.00
Biomass<1.5m (kg/m^2)	0.67	0.92	0.84	1.12	0.91	1.54	0.78	0.94	0.96
Biomass>1.5m (kg/m^2)	0.00	0.00	0.19	0.68	0.55	0.32	1.23	2.20	1.04
Mean FMC (%)	0.72	0.65	0.76	0.74	0.79	0.74	0.88	0.78	0.74
Max Height (m)	0.80	0.99	7.00	8.33	7.59	11.20	16.81	16.14	13.67
Max Understory Height (m)	0.41	0.94	2.11	3.63	2.60	2.56	1.53	9.74	1.77
Tree Cover	0.00	0.00	0.26	0.58	0.57	0.28	1.00	1.13	0.85
Shrub Cover	0.62	0.97	0.67	0.83	0.73	0.93	0.54	0.61	0.98
Herbaceous Cover	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.06
ROS (m/s)	**0.24**	**0.39**	**0.13**	**0.53**	ND	**0.10**	**0.73**	**0.83**	**0.77**

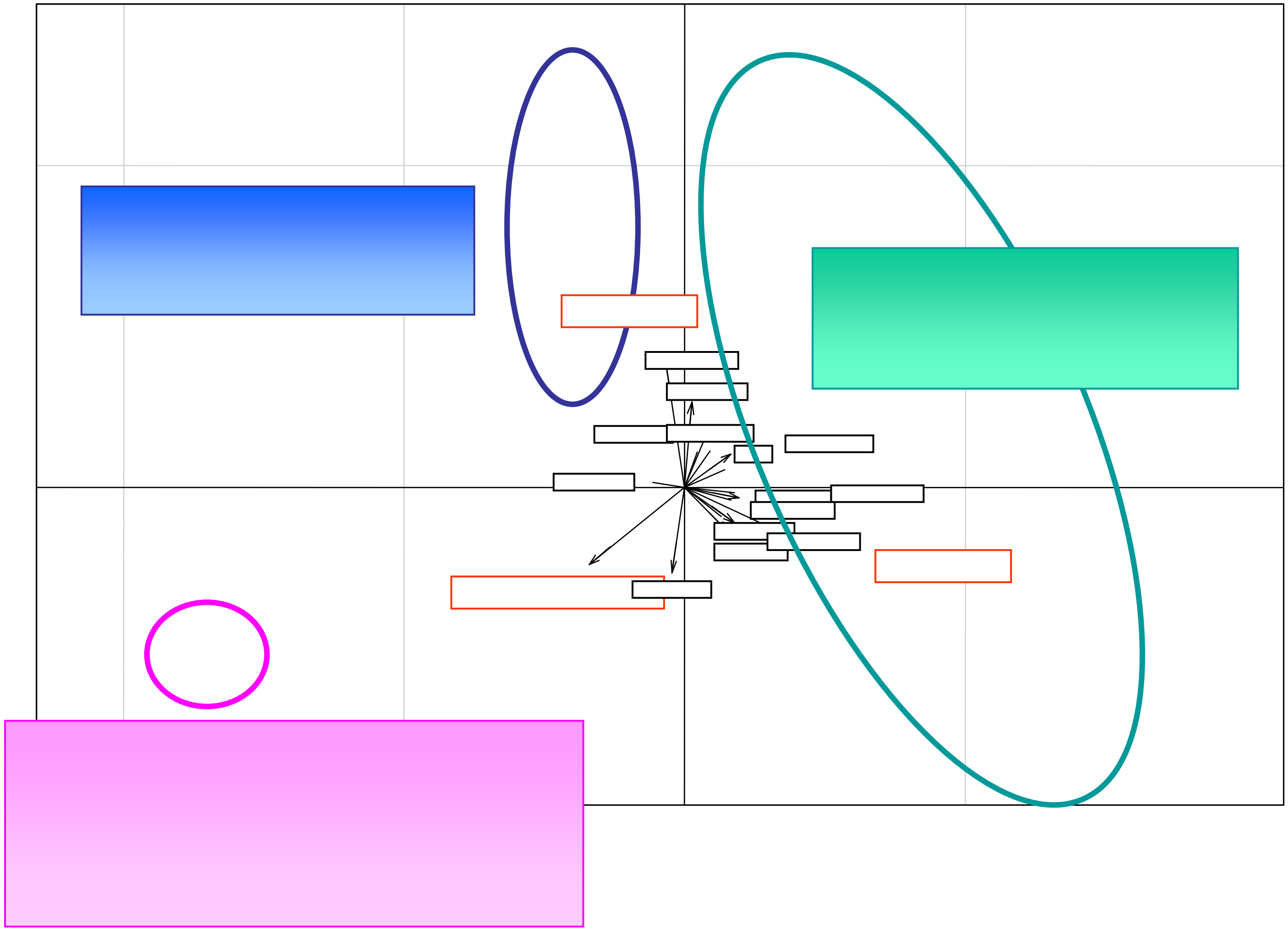
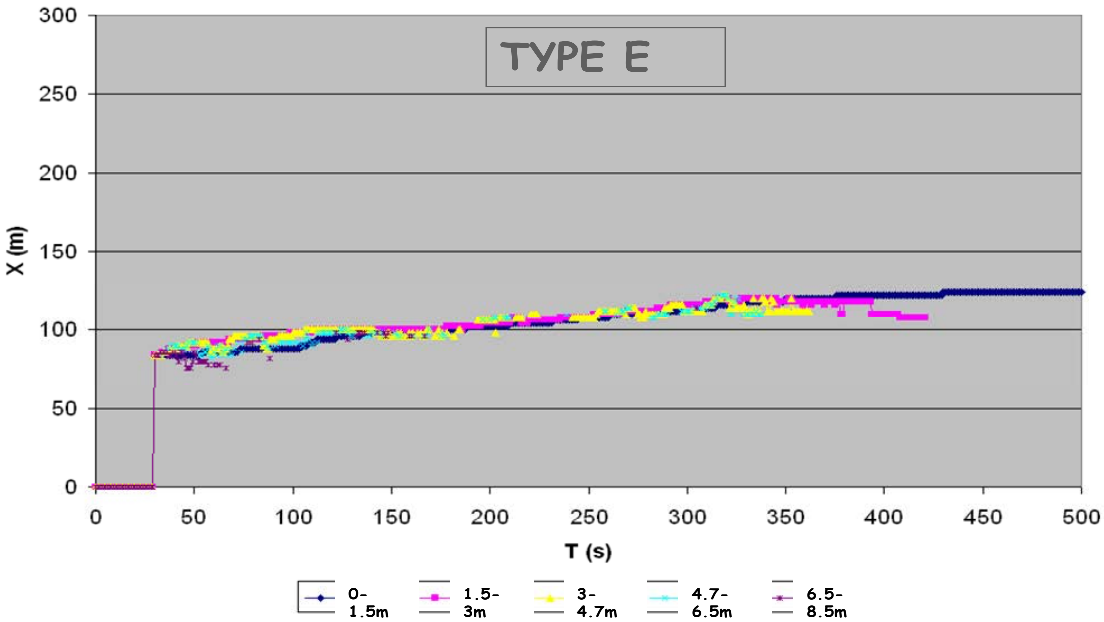
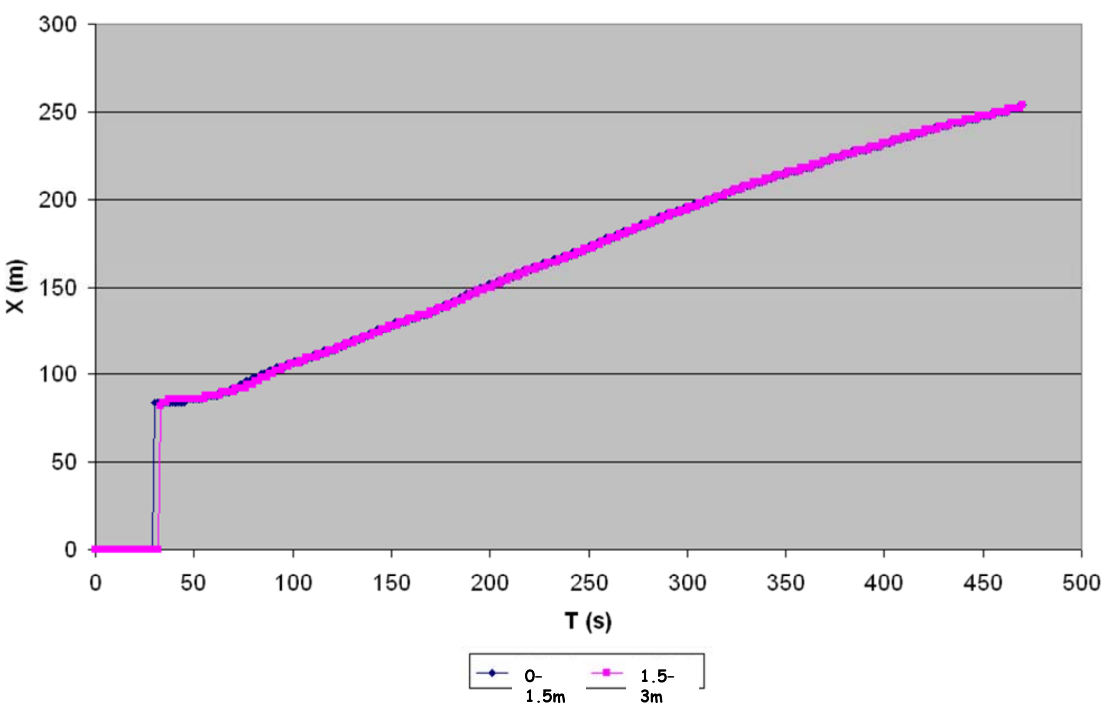


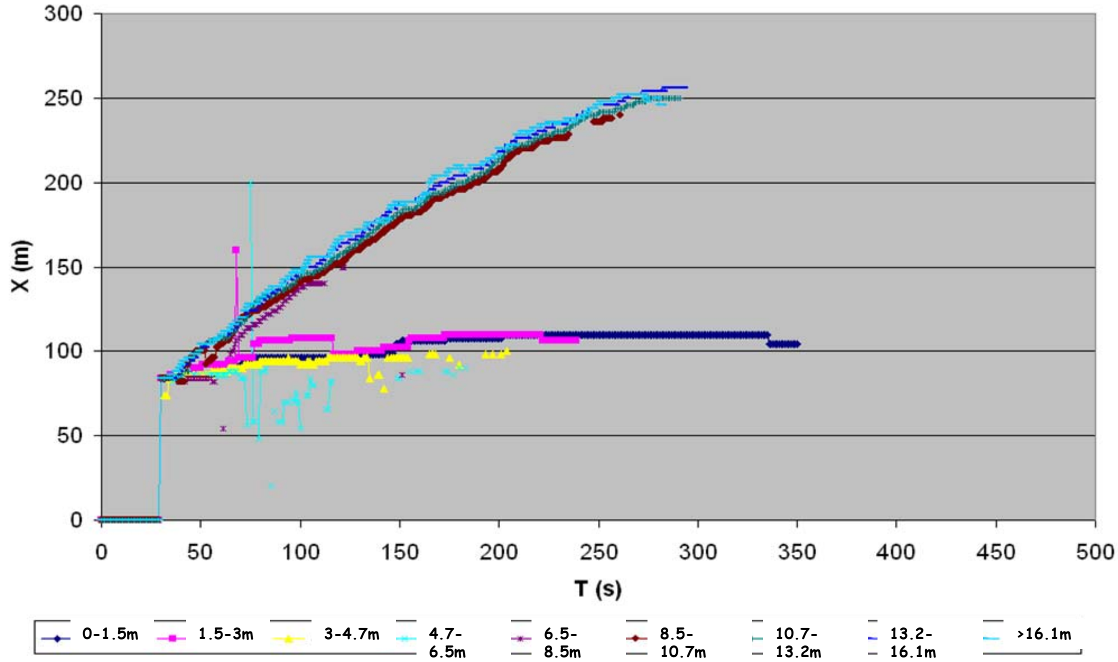
Fig. 5. Results of the Co-inertia analysis performed on 18 fuel parameters (explanatory variables) and on 3 classes of ROS (dependent variables): positions of plots, fuel parameters and classes of ROS on the F1xF2 co-inertia plane.



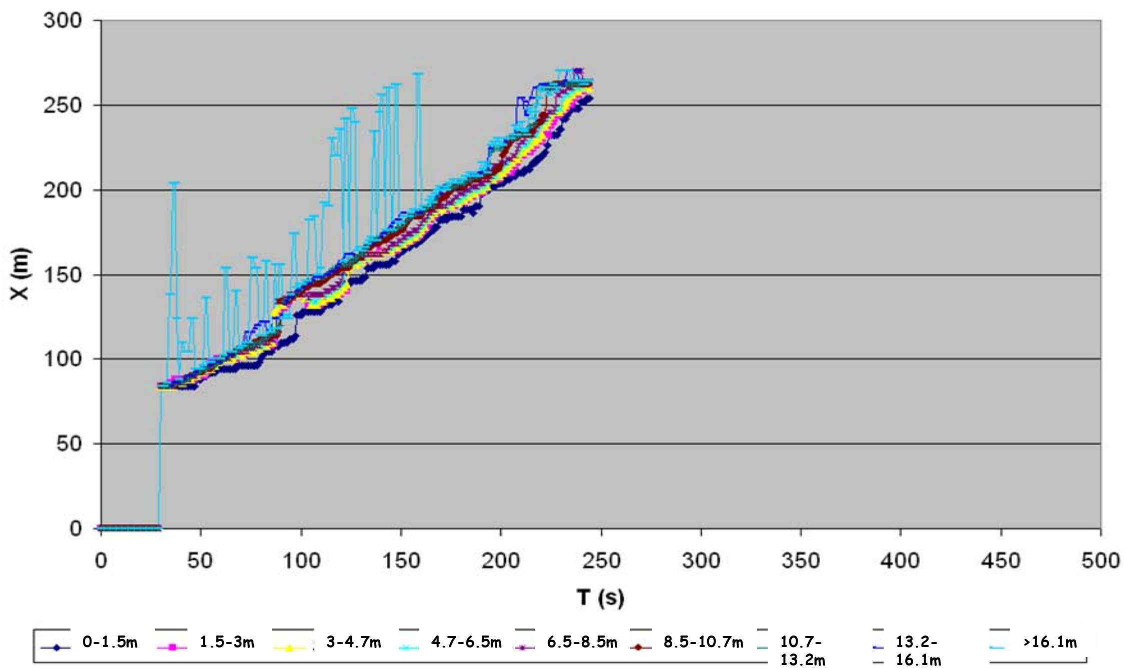
A. ROS simulation in open stand.



B. ROS simulation in shrubland.



C. ROS simulation in mature pine stand.



D. ROS simulation in mixed pine-oak stand.

Figs. 6 A-D. Results of the modeling simulation of ROS in different fuel types: (A: in open stand, B: in shrubland, C: in mature pine stand, D: in mature mixed pine-oak stand).

These results showed the importance of fuel and stand dynamics on proactive fuel and stand management; the fire hazard represented by the Mediterranean fuel types varying with the type and intensity of management they are subjected to.

Acknowledgements
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Modeling a Burning Shrub with and without Wind using a Semi-empirical Model

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Abstract:
Experimental data from individual leaf combustion experiments were used to develop a semi-empirical multi-leaf Manzanita shrub model. This model describes the propagation of a flame through a simulated manzanita shrub. Leaves are distributed evenly and randomly throughout a shrub structure. Individual leaf physical parameters are based on sample measurements and cross correlations. Experimentally-derived correlations predict the time to ignition, flame height, flame angle, and flame duration of each leaf based on physical parameters and the wind speed. The leaf nearest the bottom edge of the bush on the up-wind side is ignited and begins an ignition sequence illustrating the propagation of flame through the bush. Leaves ignite after being heated by surrounding flames for the predicted time to ignition. This model predicts burning rate, fire path, and the amount and location of unburned fuel remaining following combustion

Ignition thresholds for grassland fuels and management implications

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Abstract
In recent years in New Zealand, there has been an increase in the number of wildfires ignited in grasslands. Ignition sources have included off-road vehicles, sparks from machinery, and campfires, cooking stoves, etc. This research determined ignition thresholds for fully cured grasses commonly found in New Zealand. It aimed to provide a scientific basis for decisions around controls on recreational activities that could cause wildfire ignitions during periods of high fire risk. Five experiments (including laboratory and field trials) were designed to simulate ignitions in grass fuels from contact with: hot exhausts on off-road vehicles (hot metal); vehicle exhaust sparks (carbon emissions); metal sparks from grinding operations (metal sparks); smouldering debris dropped from hot vehicle parts onto grass fuels (organic embers); and flames from cigarette lighters, cooking stoves, etc. (open flame). Ignition probabilities were determined using logistic regression, apart from organic embers which failed to ignite any samples. The ignition threshold ($P = 0.5$) for the open flame model was 28% moisture content (MC) without wind, and 55% MC with light wind (1 ms^{-1}); for metal sparks 37% MC; for hot metal 1% MC at a wind speed of 2 ms^{-1} and metal temperature of 398ºC; and for carbon emissions 65% MC.

Additional keywords: fire behaviour, ignition probability, ignition sources, wildfire

Introduction

In New Zealand, fire managers and conservationists strive to protect highly valued grasslands from fire. On the other hand, many land managers rely on fire as a tool for management purposes such as promoting new growth and improving grazing quality, reducing fuel loads, and controlling weeds. Regardless of the management objective, it is imperative that research is focused on providing sound science to support fire management decisions. In New Zealand, the Department of Conservation (DOC) is responsible for fire protection over significant areas of grasslands, many of which have open access for public recreation (e.g. off-road vehicles, camping, hiking, etc.). The main objective of this study was to determine ignition thresholds for grassland fuels by testing five different ignition sources (Wakelin 2010; Wakelin *et al*. 2010). Results will assist fire managers in making decisions to control activities on public conservation land during periods of elevated fire danger. The results are also applicable to other management practices such as prescribed burning.

Background

Over thousands of years, natural and human influences have caused extensive areas of tussock grasslands to form in New Zealand. In many parts of the country they are maintained by fire and grazing (Ogden *et al*. 1998; McGlone 2001). Grasslands in Canterbury (located in the South Island of New Zealand, Fig. 1) are commonly exposed to drought and foehn winds. These conditions, alongside highly combustible fine fuels, trigger frequent fire throughout the region. Fire risk in these grassland areas is exacerbated by two key factors: increased recreational and occupational users and land-use change. Greater numbers of visitors are frequenting public grasslands due to easier access and increased knowledge of their existence. Fuel loads are increasing due to land-use change as large areas are retired from grazing, along with less prescribed burning. These factors, combined with severe fire weather conditions, raise the likelihood of high-intensity fires that are difficult to control and threaten important ecosystems.

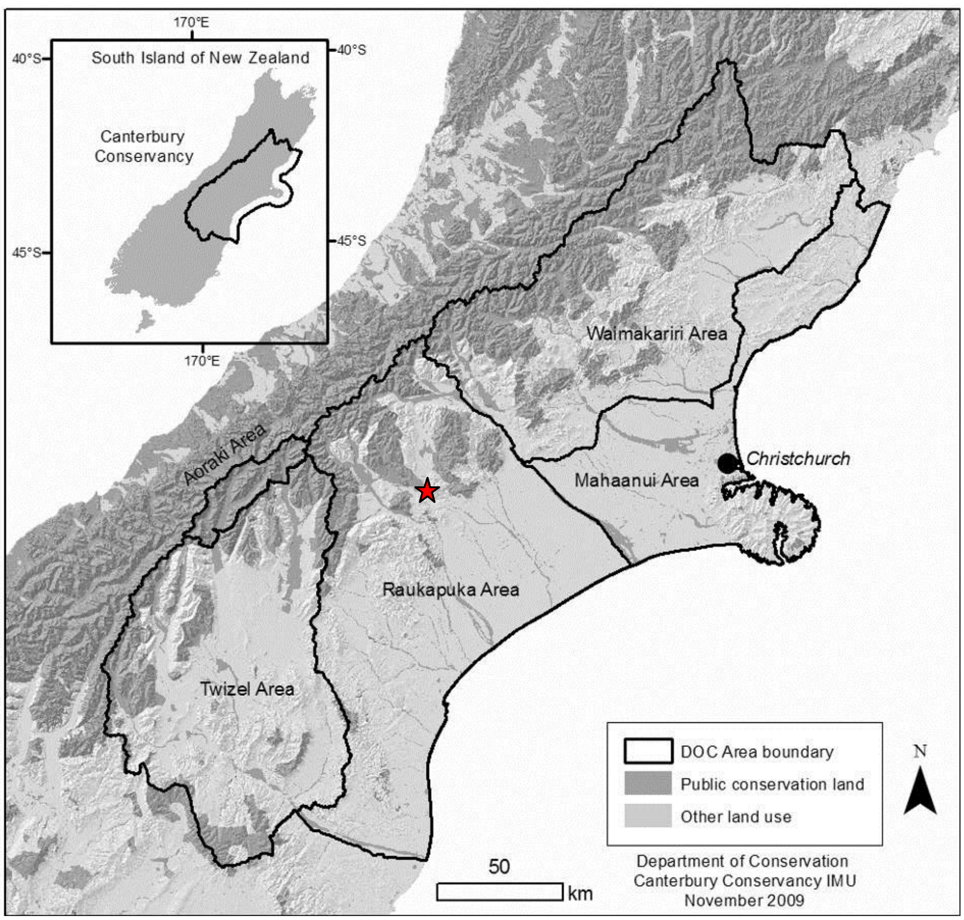

Fig. 1. The Canterbury region of New Zealand, showing Christchurch, where the research was based, and a star where fuel collection and field trials were conducted. (Source: DOC).

Compared with forest fuel types, there is little literature available about the ignition behaviour of grassland fuels when exposed to different ignition sources. This research contributed significant knowledge to the scientific community, as the findings provide relevant information about the ability of common ignition sources to ignite grassland fuels. The findings stem from innovative experiments conducted in the laboratory, and validated in the field.

General methodology

Ignition behaviour of 100% cured (dead) tussock (*Festuca novae-zelandiae*) and exotic (*Agrostis capillaris* with small amounts of *Anthoxanthum odoratum*) grass fuels was investigated by simulating five common ignition sources of concern:

- hot metal (hot parts from off-road vehicles);
- hot carbon emissions (hot particles from vehicle exhausts);
- metal sparks (from grinding operations);
- organic embers (smouldering debris dropped onto grass fuels from hot vehicle parts); and
- open flame (from matches or lighters).

The two grass types were chosen because their growth structures differ. Tussock grasses are perennial, have smooth blades, and grow in a tuft that spreads outward like a fan. Each year when tussock grasses die, the leaf bases and sheaths dry out, building up around the plant. This causes them to be highly flammable, even during winter. Exotic species do not exhibit this build-up, but are highly flammable when cured. Furthermore, exotics are shorter than tussocks, exhibit a rougher texture, and have a fine inflorescence at the top 15-20 cm of their stems.

Laboratory experiments were conducted for grass fuel moisture levels between 0.4% and 171.5% (based on oven-dry weight), as previous studies suggested that fuel moisture is the primary factor influencing ignition success (e.g. de Groot *et al*. 2005; Plucinski and Anderson 2008; Anderson and Anderson 2010). For each ignition source, ignitibility was assessed by leaving the grass sample in contact with the ignition sources for a specified time period. Field experiments were used to verify laboratory results. At the end of each test, ignition was classified as either success (flaming or glowing) or failure (non-ignition). The experimental design included the following conditions and assumptions:

- experiments tested for fuel ignition only and did not consider fire spread;
- arrangement of grass in the samples was consistent;
- if an ignition source was present (in the laboratory or the field), it would come into contact with grassland fuels;
- experiments tested for worst-case scenarios that would exist in the field, including fully-cured grass, and moisture content levels lower than 3%;
- ambient temperature (21.8ºC ± 0.1 s.e.) and RH (34.7% ± 0.2 s.e.) were relatively constant in the laboratory; and
- the effect of wind was simulated using a three-speed fan (0, 1, 2 ms^{-1} at experiment height).

Logistic regression was used to model the probability of ignition from each ignition source and ignition thresholds were reported in terms of 50% (possible) and 70% (likely) probabilities of ignition success. As in a similar study for gorse shrub fuels (Anderson 2009; Scion 2009), moisture content levels were converted to the equivalent Fine Fuel Moisture Code (FFMC) values from the Fire Weather Index (FWI) System (Van Wagner, 1987) component of the New Zealand Fire Danger Rating System. No difference in ignition behaviour was observed between the two grass types.

Hot metal methodology

This experiment simulated ignition through contact with hot metal surfaces, such as the exhausts from off-road utility and All-Terrain Vehicles (ATVs), or from other hot equipment such as industrial lawn mowers or brush cutters. This involved a copper hot plate (after Pitts 2007) heated to temperatures of 366 ï 493°C being held in contact with grass samples in both horizontal and vertical orientations (Fig. 2). Maximum contact time between the sample and the hot plate was five minutes, and wind speed was set at 0, 1 and 2 ms^{-1} (0, 3.6 and 7.2 kmh^{-1} respectively). Field experiments tested actual exhaust systems of an unloaded 2006 4WD Nissan Navara (turbo diesel with manual transmission, where temperatures ranged from 213 to 229ºC), and of an unloaded ATV (Honda Foreman 400, where temperatures ranged from 427 to 512ºC) (Fig. 2).

Fig. 2. Grass sample held in contact with the copper hot plate in vertical orientation (left) and horizontal orientation (middle), and field testing of a sample at the manifold of the ATV (right).

Hot metal results

Hot plate temperature, orientation (horizontal/vertical), and wind speed were the main variables that influenced ignition behaviour of the grass samples (Fig. 3). The model correctly predicted 77% of observations. Ignition curves and thresholds were determined for a fuel moisture content of 1%, but fuels are unlikely to dry to this level in field conditions, with the lowest moisture levels likely to reach 3% under extreme weather conditions (Pyne *et al.* 1996). Hot plate temperatures as low as 390ºC triggered successful ignition in both grass types. Ignitions were observed at moisture content levels up to 111%, indicating that the hot plate dried samples to their ignition point. Field experiments showed that contact with the exhaust of the unloaded Nissan 4WD posed little ignition risk in cured grasses. On the other hand, the unloaded ATV was found to pose a high ignition risk, as the exhaust system reached higher temperatures and all samples ignited in the field.

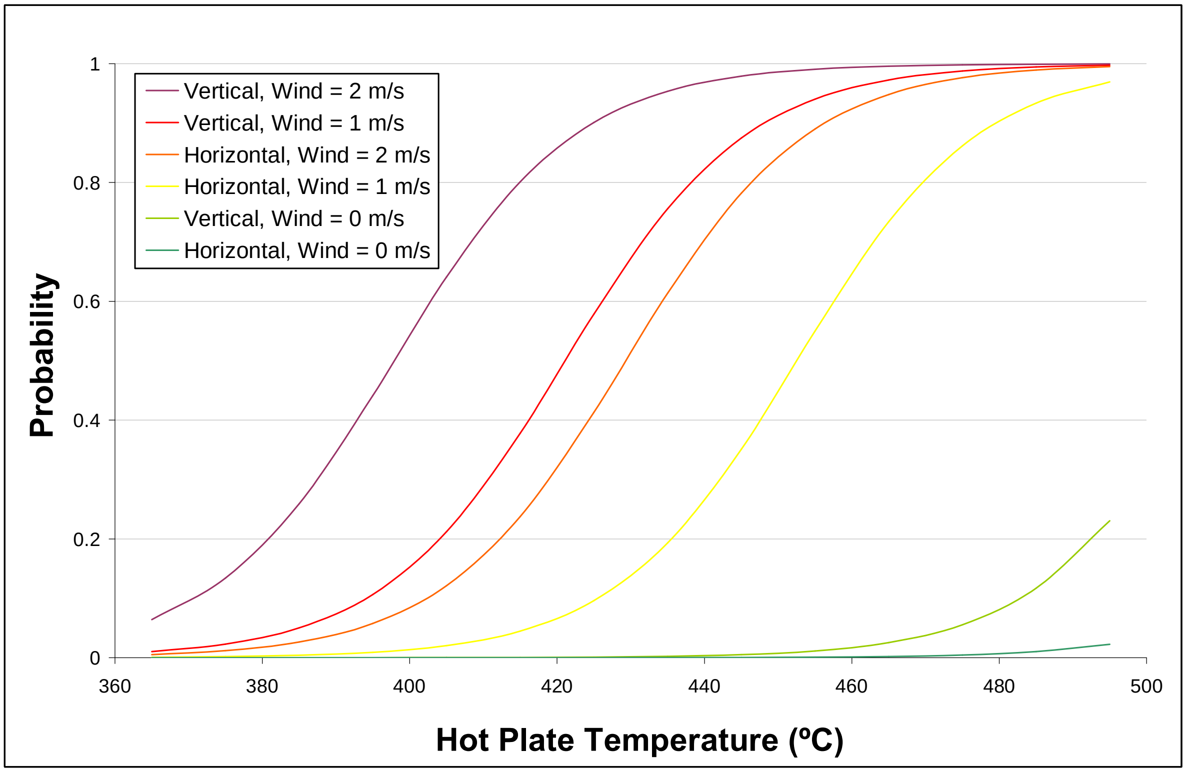

Fig. 3. Plot of probability of ignition success of grasses for six different plate orientation and wind speed scenarios tested in the laboratory, with moisture content set to 1%.

Hot carbon emissions methodology

This experiment simulated hot carbon particles and hot gases exiting a vehicle exhaust. This was achieved using a steel pipe with a funnel at the sample end. Hot carbon (ordinary wood pellets heated until glowing) was broken into particles of 1.0 mm diameter and dropped into the funnel every 30 seconds (Fig. 4). A hot air gun set at 200ºC blew the hot carbon particles onto the sample at a constant speed of 3.7 ms^{-1}. Trials lasted five minutes. In the field, the same 4WD Nissan used for hot metal testing was also used for hot carbon emissions testing; however, exhaust gas temperature did not exceed 115ºC, so results were difficult to compare with laboratory findings.

Hot carbon emissions results

Grass moisture content was the main variable that determined ignition behaviour of grass samples exposed to hot carbon emissions, with the model correctly predicting 69% of observations (Fig. 5). Predictions were better when ambient temperature and relative humidity were included in the model, with 78% of observations correctly predicted (Fig. 5). Ignition was possible for samples with grass moisture levels up to 116%, indicating that the exhaust gas dried samples their ignition point. No ignitions occurred in the field, indicating that the risk of ignition from the well-maintained Nissan 4WD vehicle was low; however, further vehicle testing is necessary.

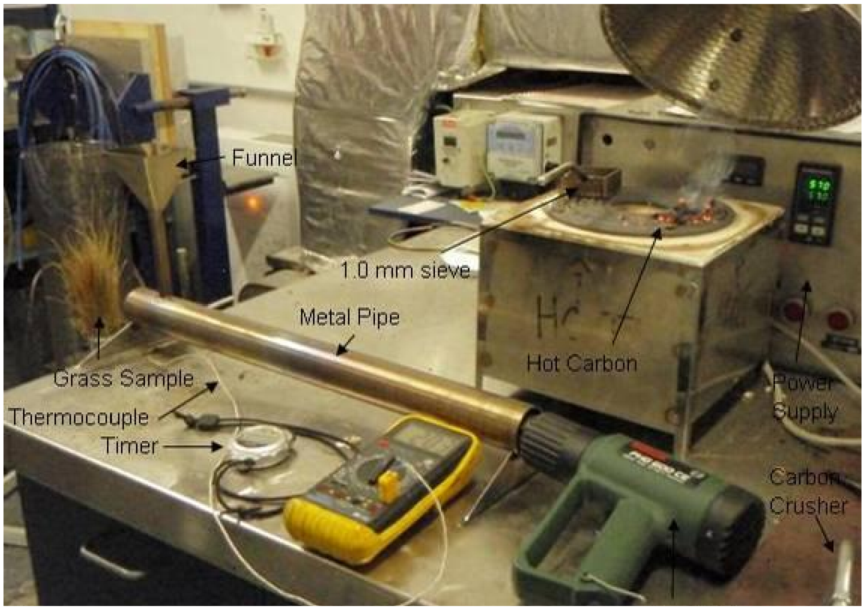

Fig. 4. Hot carbon emissions experimental set-up.

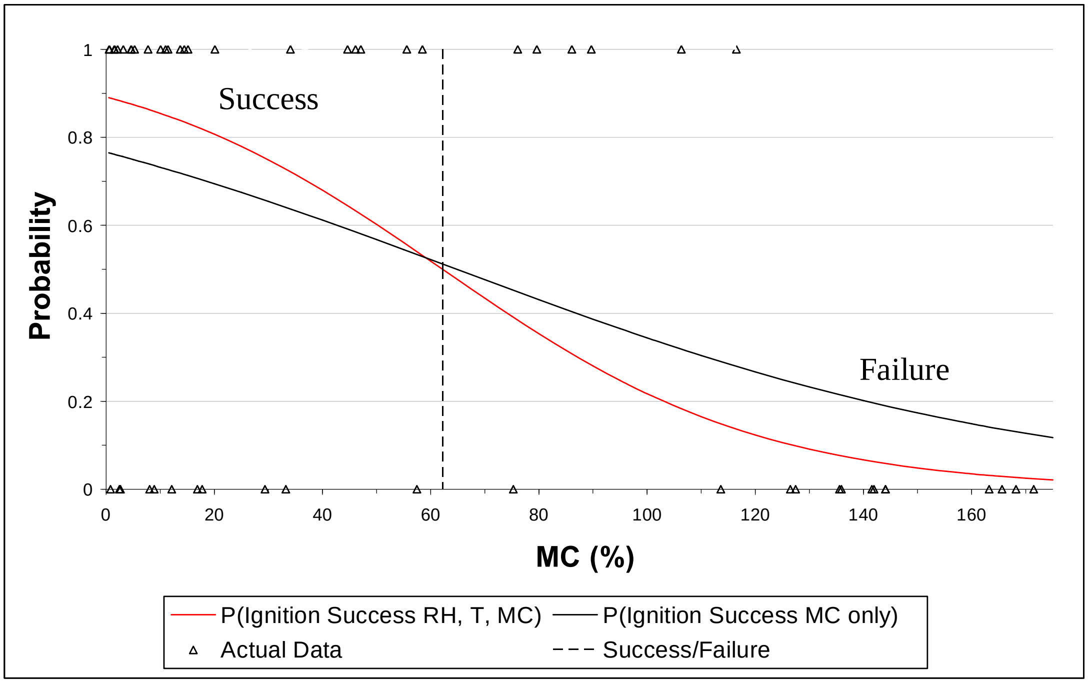

Fig. 5. Plot of ignition probability (categorised into success or failure) for grasses from hot carbon emissions, with the probability curves based on grass moisture content (MC) only (black line), and on ambient temperature (T) and relative humidity (RH) and grass moisture content (red line).

Metal sparks methodology

This experiment simulated hand-held grinding operations and/or sparks produced by outdoor power equipment and machinery. Steel was grinded at a surface speed of 80 ms^{-1} for a maximum of 30 seconds, showering the sample with sparks (Fig. 6). Wind speed was again set at 0, 1 and 2 ms^{-1}. Field trials were conducted in the same manner.

Fig. 6. Metal sparks experimental set-up in the laboratory (left) and the field (right).

Metal sparks results

Moisture content was the main variable that determined the ignition behaviour of grass samples exposed to metal sparks (Fig. 7) and wind speed did not significantly affect ignitibility. The logistic regression model correctly predicted 90% of observations. Ignition was possible for samples with moisture levels up to 69%. All ignitions were successful in the field, indicating that grinding operations pose a significant fire risk to fine grassland fuels.

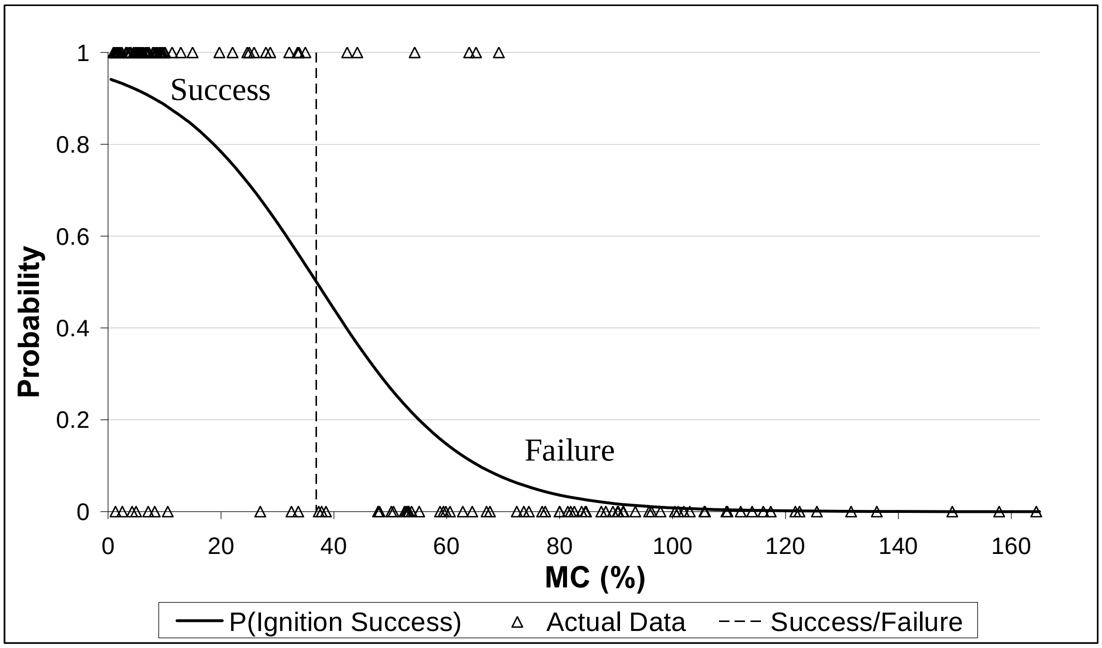

Fig. 7. Plot of ignition probability (categorised into success or failure) for grasses from metal sparks, with the probability curve based on grass moisture content (MC).

Organic embers methodology and results

This experiment simulated heated and/or smouldering organic material (usually encased in dry mud) that may fall onto dead grass after accumulating on a moving vehicle. Grass and soil were pre-moulded into disks (Fig. 8) that were heated to an average surface temperature of 400ºC. The disks were placed on top of the grass samples and left for five minutes. Wind speed was again set to 0, 1 and 2 ms^{-1}. Ignition of samples in the laboratory was not observed, so no comparative field experiments were completed. However, laboratory simulations are difficult for this ignition source, so subsequent research should focus on field experiments similar to Baxter (2002, 2004) and Palmu and Baxter (2008).

Fig. 8. A tussock sample with a disk placed on top (left), and organic embers in moulds (right).

Open flame methodology

This experiment represented careless use of an open flame, for example from a portable gas cooker being knocked over. A flame of 2 cm in length was produced using an ignition apparatus (representing an ordinary lighter) (Fig. 9) and wind speed was again set to 0, 1 and 2 ms^{-1}. Maximum contact time between the grass sample and the flame was 20 seconds. Field trials were conducted in the same manner.

Fig. 9. Open flame experimental set-up (left) and H. Wakelin with a burning sample (right).

Open flame results

Moisture content and wind speed were the main variables that determined ignition behaviour of grass samples exposed to open flame contact (Fig. 10). Without the presence of wind (0 ms^{-1}), ignition was possible for samples with moisture levels up to 32%. The presence of wind (1 ms^{-1}) increased the probability of ignition of samples at higher moisture levels, where all ignitions were successful at moisture contents less than 54%. The logistic regression model correctly predicted 97% of observations. For higher wind speed (2 ms^{-1}), results were variable due to the flame being blown out and requiring it to be relit. As a result, the probability curve for this wind speed is not reported. All ignitions were successful in the field, confirming that open flame ignition sources pose a significant fire risk to fine grassland fuels.

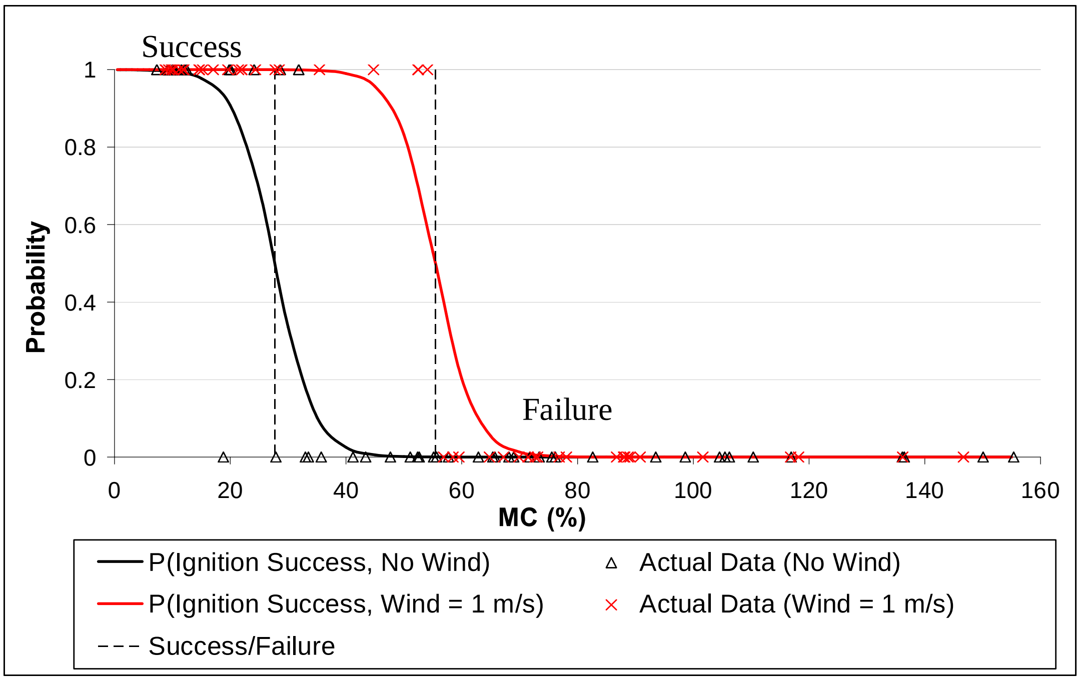

Fig. 10. Plot of ignition probability (categorised into success or failure) for grasses exposed to open flame contact, with the probability curves for wind speeds of 0 and 1 ms^{-1}, based on grass moisture content (MC).

Management implications

The results have been used to develop decision support tools that will improve fire management strategies and tactics, as decisions should be guided and supported by science-based knowledge and tools. Use of these tools will help to mitigate against wildfires before they start through a range of reduction and readiness activities. They could also help to determine appropriate conditions for prescribed burning or to support investigative procedures. It is important that managers understand the underlying assumptions of this study before using the tables provided below. Tables are supplied for hot metal (Table 1), hot carbon emissions (Table 2), metal sparks (Table 3), and open flame (Table 4), and include ignition probabilities for grasses with moisture content converted to Fine Fuel Moisture Code (FFMC).

Table 1 could be used to support decisions around closing off-road tracks to vehicle access once the FFMC reaches a certain level, or to predict the probability of ignition depending on FFMC and hot metal temperature. The other tables may be utilised in the same manner. Predictions are colour-coded for different ignition probability levels: 0 to 0.49, green (ignition unlikely), 0.50 to 0.70, yellow (ignition possible), 0.71 to 0.80, orange (ignition likely), and 0.81 to 100, red (ignition highly probable). When fire danger is elevated, these tools can support decisions to restrict the use of each ignition source, and can also be used to create guidelines for their safe use in grasslands. The information presented in this study can help educate recreational vehicle users of grassfire risk, and of the need for vehicle maintenance and other fire prevention actions.

Table 1. Decision support table of ignition probabilities for grasses from hot metal contact, with moisture content converted to Fine Fuel Moisture Code (FFMC) for management application.

Wind Speed = 2 ms^{-1} (Scenario with highest ignition risk - Full contact with grass fuels)	FFMC												
Temperature (ºC)	100	96	91	86	82	78	74	70	67	63	60	57	55
365	0.06	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02
375	0.13	0.12	0.11	0.10	0.09	0.08	0.08	0.07	0.06	0.05	0.05	0.04	0.04
385	0.26	0.24	0.22	0.20	0.19	0.17	0.16	0.14	0.13	0.12	0.11	0.10	0.09
395	0.44	0.42	0.39	0.37	0.34	0.32	0.29	0.27	0.25	0.23	0.21	0.19	0.18
405	0.64	0.62	0.59	0.57	0.54	0.51	0.48	0.46	0.43	0.40	0.37	0.35	0.32
415	0.80	0.79	0.77	0.75	0.73	0.70	0.68	0.65	0.63	0.60	0.58	0.55	0.52
425	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.81	0.79	0.77	0.75	0.73	0.71
435	0.95	0.95	0.94	0.94	0.93	0.92	0.92	0.91	0.90	0.89	0.87	0.86	0.85
445	0.98	0.98	0.97	0.97	0.97	0.96	0.96	0.96	0.95	0.95	0.94	0.93	0.93
455	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97
465	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98
475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99
485	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
495	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Wind Speed = 1 ms^{-1} (Full contact with grass fuels)	FFMC												
Temperature (ºC)	100	96	91	86	82	78	74	70	67	63	60	57	55
365	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
375	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
385	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01
395	0.11	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03
405	0.21	0.20	0.18	0.16	0.15	0.14	0.12	0.11	0.10	0.09	0.08	0.07	0.07
415	0.38	0.36	0.33	0.31	0.28	0.26	0.24	0.22	0.20	0.19	0.17	0.15	0.14
425	0.58	0.56	0.53	0.50	0.47	0.45	0.42	0.39	0.37	0.34	0.32	0.29	0.27
435	0.76	0.74	0.72	0.69	0.67	0.64	0.62	0.59	0.57	0.54	0.51	0.48	0.45
445	0.87	0.86	0.85	0.84	0.82	0.80	0.79	0.77	0.75	0.72	0.70	0.68	0.65
455	0.94	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.81
465	0.97	0.97	0.97	0.96	0.96	0.95	0.95	0.94	0.94	0.93	0.92	0.91	0.91
475	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.97	0.97	0.97	0.96	0.96	0.96
485	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98
495	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99

Wind Speed = 2 ms^{-1} (Contact with the tops of grass fuels)	FFMC												
Temperature (ºC)	100	96	91	86	82	78	74	70	67	63	60	57	55
365	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
375	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
385	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
395	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
405	0.12	0.11	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.04
415	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.13	0.12	0.10	0.09	0.09	0.08
425	0.41	0.39	0.37	0.34	0.32	0.29	0.27	0.25	0.23	0.21	0.19	0.17	0.16
435	0.61	0.59	0.57	0.54	0.51	0.48	0.45	0.43	0.40	0.37	0.35	0.32	0.30
445	0.78	0.77	0.75	0.72	0.70	0.68	0.65	0.63	0.60	0.57	0.55	0.52	0.49
455	0.89	0.88	0.87	0.86	0.84	0.83	0.81	0.79	0.77	0.75	0.73	0.71	0.69
465	0.95	0.94	0.94	0.93	0.92	0.91	0.91	0.90	0.88	0.87	0.86	0.85	0.83
475	0.98	0.97	0.97	0.97	0.96	0.96	0.96	0.95	0.95	0.94	0.93	0.93	0.92
485	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.97	0.97	0.97	0.96
495	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98

Wind Speed = 1 ms^{-1} (Contact with the tops of grass fuels)	FFMC												
Temperature (ºC)	100	96	91	86	82	78	74	70	67	63	60	57	55
365	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
375	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
385	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
395	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
405	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
415	0.04	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01
425	0.10	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03
435	0.19	0.18	0.16	0.15	0.14	0.12	0.11	0.10	0.09	0.08	0.07	0.07	0.06
445	0.35	0.33	0.31	0.28	0.26	0.24	0.22	0.20	0.19	0.17	0.15	0.14	0.13
455	0.55	0.53	0.50	0.47	0.44	0.42	0.39	0.36	0.34	0.31	0.29	0.27	0.25
465	0.73	0.72	0.69	0.67	0.64	0.62	0.59	0.56	0.54	0.51	0.48	0.45	0.43
475	0.86	0.85	0.84	0.82	0.80	0.78	0.77	0.74	0.72	0.70	0.68	0.65	0.63
485	0.93	0.93	0.92	0.91	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.81	0.79
495	0.97	0.97	0.96	0.96	0.95	0.95	0.94	0.94	0.93	0.92	0.91	0.91	0.90

Table 2. Decision support table of ignition probabilities for grasses from hot carbon emissions, with moisture content converted to Fine Fuel Moisture Code (FFMC) for management application.

IS THE AMBIENT TEMPERATURE BETWEEN 18.5ºC AND 20.1ºC **AND** IS THE RELATIVE HUMIDITY BETWEEN 31% AND 54%?

YES Scenario 1

NO Scenario 2

FFMC	Scenario 1	Scenario 2
100	0.89	0.76
96	0.87	0.75
91	0.85	0.73
86	0.83	0.71
82	0.81	0.69
78	0.78	0.67
74	0.75	0.65
70	0.72	0.63
67	0.68	0.61
63	0.64	0.59
60	0.60	0.57
57	0.56	0.54
55	0.52	0.52
52	0.48	0.50
49	0.43	0.48
47	0.39	0.45

Table 3. Decision support table of ignition probabilities for grasses from metal sparks, with moisture content converted to Fine Fuel Moisture Code (FFMC) for management application.

FFMC	Probability of Ignition
100	0.94
96	0.92
91	0.89
86	0.84
82	0.78
78	0.71
74	0.63
70	0.54
67	0.44
63	0.35
60	0.27
57	0.20
55	0.15
52	0.11
49	0.07
47	0.05

Table 4. Decision support table of ignition probabilities for grasses from open flame, with moisture content converted to Fine Fuel Moisture Code (FFMC) for management application.

FFMC	Probability of Ignition	
	No Wind	Wind = 1 m/s
100	1.00	1.00
96	1.00	1.00
91	0.99	1.00
86	0.98	1.00
82	0.91	1.00
78	0.69	1.00
74	0.34	1.00
70	0.10	1.00
67	0.03	0.99
63	0.01	0.96
60	0.00	0.83
57	0.00	0.53
55	0.00	0.20
52	0.00	0.05
49	0.00	0.01
47	0.00	0.00

Risk assessment and mitigation procedures are essential for effective fire management. In addition to the decision support tables, the ignition risk posed by the four ignition sources in grassland fuels was ranked from greatest to least: open flame > hot metal > metal sparks > hot carbon. Open flame represented the greatest risk, as it always ignited grassland fuels under favourable conditions. Hot metal was ranked second. If contact time is sufficient, it has the potential to ignite grassland fuels at high moisture levels. However, this is only likely if the hot metal ignition source reaches temperatures above about 400°C. ATVs pose a higher risk compared to modern and well-maintained utility vehicles. Metal sparks have the potential to ignite grassland fuels at surprisingly high moisture levels, so managers should seriously consider developing trigger points for restricting their use. Hot carbon was ranked last because more research is required to fully understand its ignition potential. Managers should require vehicles and machinery to have a fully functioning spark arrestor fitted before driving in grassland fuels. This proactive approach would prevent hot carbon from being expulsed out of tail pipes and limit potential ignition starts. Regardless of the ignition source and available decision support tables, managers should base decisions on a combination of science and experience, to suit local conditions.

Summary

This study provides an example of grass ignition research that is directly applicable to fire management planning. However, managers should understand the limitations of the research before using the results, and be cautious when applying them to conditions beyond those specified in the assumptions. A summary of ignition thresholds for a 50% probability of ignition is provided in Table 5. Future work investigating these thresholds would be useful, as described below, but managers in New Zealand and the United States have already begun to use the results for setting triggers and investigation purposes.

Table 5: Summary of grass ignition thresholds (50% probability) for each ignition source under different scenarios.

Ignition Source	Predictor Variables(s)	Scenario	Ignition Threshold	
			MC or ºC	FFMC
Hot Metal	MC (%), wind$_A$ (1 ms^{-1}), wind$_B$ (2 ms^{-1}) hot plate temperature (ºC) Orientation	Vertical, Wind = 2 ms^{-1}, MC = 1%	398ºC	100
		Vertical, Wind = 1 ms^{-1}, MC = 1%	421ºC	100
		Horizontal, Wind = 2 ms^{-1}, MC = 1%	429ºC	100
		Horizontal, Wind = 1 ms^{-1}, MC = 1%	452ºC	100
Hot CarbonEmissions	MC (%)	N/A	65% MC	52
Metal Sparks	MC (%)	N/A	37% MC	69
Open Flame	MC (%), wind (1 ms^{-1})	No wind	28% MC	75
		Wind = 1 ms^{-1}	55% MC	57

Recommendations for future work
Further validation and testing of the methods and results found in this study should be undertaken, including:

- **conducting experiments under a broader range of conditions, especially higher ambient temperatures and lower relative humidity levels;**
- **increasing the number of field tests, and testing grass samples *in situ*;**
- **extending the work to include samples under a range of curing values, different grass types/species, and investigation of fire spread once successful ignition has occurred; and**
- **validating or, if required, developing new models for predicting moisture content in grass fuels based on weather and/or FWI System components.**

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Remote Sensing Fire and Fuels in Southern California

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Abstract
Airborne remote sensing at infrared wavelengths has the potential to quantify large-fire properties related to energy release or intensity, residence time, fuel-consumption rate, rate of spread, and soil heating. Remote sensing at a high temporal rate can track fire-line outbreaks and acceleration and spotting ahead of a fire front. Yet infrared imagers and imaging spectrometers typically used for earth remote sensing are saturated by—and incapable of measuring—the very bright infrared light that radiates from wildland fires.

The Forest Service, Pacific Southwest Research Station, and its partners have addressed this problem by developing the FireMapper thermal-imaging radiometer for quantitative, high-resolution measurements of wildland fires. FireMapper has been applied to produce and disseminate accurate visualizations of large-fire activity, during active burning periods and for multiple fires, in near real-time.

Practical extension of measurements by the FireMapper to prediction of fire behavior on time scales from hours to days requires highly resolved information on fuels and wind across landscapes and changes to the basic Rothermel formulation for fire spread. Combined sampling in the field and by multispectral remote sensing for the 2006 Esperanza Fire have demonstrated that the latter may provide an improved means for acquiring the needed fuels data.

Additional keywords: chaparral, Esperanza Fire, FireMapper

Introduction

Very large and destructive wildfires are becoming common in the Mediterranean-type ecosystems of coastal southern California. Of the ten largest fire complexes recorded there over nearly a century, seven have occurred since 2003 (data *available online*[1]). Large-fire impacts on ecosystems and society have been high: more than 860,000 hectares have been burned, communities of 500,000 residents have been ordered evacuated, 9300 structures have been destroyed, and California mixed-conifer forest has been killed by crown fire with little or no subsequent regeneration in portions of San Diego, Los Angeles, and San Bernardino counties (data *available online*[1], Los Angeles Times 2007, Franklin *et al*. 2006). Absent adaptive changes in fire policy or management effectiveness, the trend might be expected to continue. Such adaptation will require timely fire intelligence data and more sophisticated fuel and fire behavior models to evaluate expected fire behavior in support of tactical fire suppression and decisions regarding strategic management of fuels by prescribed burning or other means. In this paper we describe recent applications of airborne remote sensing for fire measurements and monitoring

[1] < http://fam.nwcg.gov/fam-web/hist_209/report_list_209>

and the state of knowledge regarding chaparral fuel development as required for interpretation of those measurements and fire-behavior modeling.

Fire intelligence

Current knowledge of fire behavior in chaparral, which has been the plant community most involved in these large fires, is largely derived from simulation models and records of final fire location and area, from which have been derived fire-regime statistics involving distribution of fire size, season of occurrence, and frequency. Analyses of fire records lack specificity on fuel loading and fire behavior and do little to illuminate the forces behind an event. Operational fire-behavior simulation models and some research models are derived from the Rothermel model (Rothermel 1972), which was developed largely from laboratory-based measurements of fire spread in small, uniform fuel beds and a description of the effects of wind on fire spread in Australian grasslands. The applicability of the Rothermel model and its descendents to large-fire behavior in chaparral is uncertain, partly because of poor descriptions of extant fuels, non-linearity of scaling with fire size in the laboratory (cf, Fendell *et al*. 1990), order-of-magnitude extrapolations in energy release and rate of spread required to simulate large fires, inability to consider fire-atmosphere interactions, and the questionable application to live fuels of relationships based upon burning excelsior and pine needle beds. Most problematic for chaparral is the linkage of wind effects in the Rothermel model to the no-wind rate of spread, which in chaparral may be zero at higher fuel moistures and low dead-fuel loading. In the field, higher wind speeds may override these factors to produce substantial rates of fire spread even as the model must predict zero spread. Improvements in this prediction system clearly must come from measurements of real-world wildland fires at their full intensity and extent.

Fire intelligence regarding fire location and movement until recently has been derived largely from infrared line-scanner imagery collected in early evening, occasional mapping of a fire's perimeter based on the GPS-determined locations of a low-level helicopter flight along that perimeter, and ad hoc reports from ground- and aircraft-based observers. While these sources of information are valuable, especially on remote, slowly moving fires, they provide little information on current direction and rates of fire movement or homes and resources threatened during critical periods of fire activity, such as when the Cedar Fire burned into the City of San Diego, the Old Fire burned into San Bernardino, or the Jesusita or Tea fires burned into communities of Santa Barbara County. Similarly, traditional sources of fire intelligence provide little information of value in understanding fire behavior or effects or improving fire-suppression response.

The FireMapper thermal-imaging radiometer

The USDA Forest Service, Pacific Southwest Research Station (PSW), and its partners have developed and are applying new airborne remote-sensing technology to measure and understand wildfire behavior and impacts on the environment (Riggan and Tissell 2009). The FireMapper thermal-imaging radiometer has been designed to measure the very high infrared radiances of wildland fires (Riggan and Hoffman 2003) and is the only such system widely applied in fire research today. FireMapper has been deployed to multiple large fires during the 2003, 2006, 2007, and 2008 fire emergencies in California and often at times when fires were most active and high-value resources and communities were threatened (Figs. 1 and 2). FireMapper data allow quantitative measurements of fire-spread rates; fire temperatures, radiant-energy flux, and residence time; and fire-line geometry. Image products are made available at

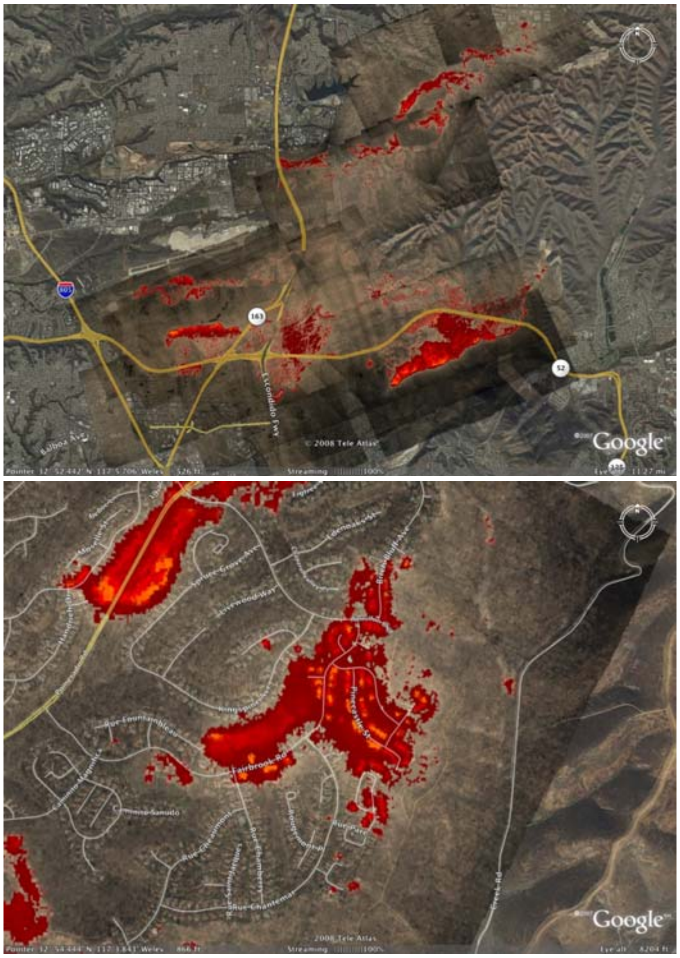
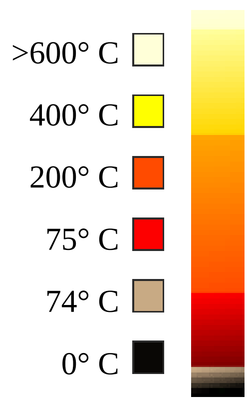


Fig. 1. Western portion of the Cedar Fire, San Diego County, California, as viewed from above by the PSW FireMapper, 26 October 2003. Color-coded surface temperatures, which reflect fire radiant-energy flux or intensity, are shown as posted as a Google Earth overlay at www.fireimaging.com. Here a Santa Ana wind is driving the fire to the west-southwest through chaparral and light fuels and across major freeways into portions of the City of San Diego (top image). Higher temperature objects at center of the detail



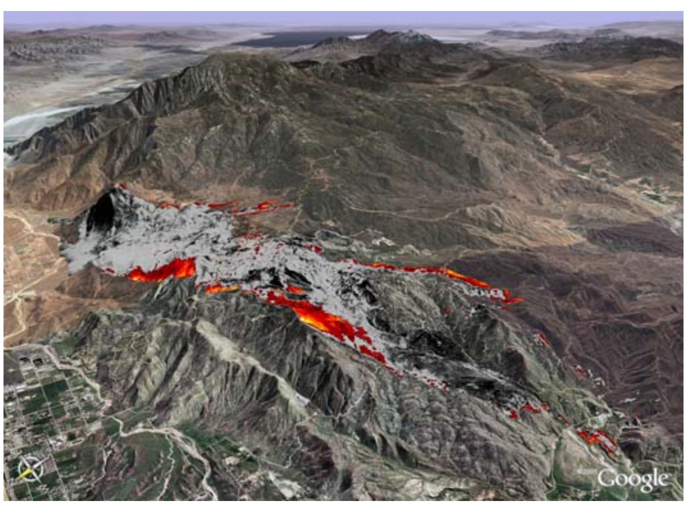


Fig. 2. Esperanza Fire, Riverside County, California, as first viewed from the northwest by the PSW FireMapper, 26 October 2006. Here a moderate Santa Ana wind is driving the fire to the southwest through chaparral and light fuels along the northwest flank of Mt. San Jacinto. Note the high temperatures and long residence time in heavy fuels at the center of the northern flank of the fire and the low values in light fuels at the fire's head (lower right).

www.fireimaging.com, in near-real time, for use by incident management teams.

The FireMapper system is now flown by PSW aboard Forest Service aircraft N127Z, an A100 King Air, which is operated in conjunction with the Forest Health Technology Enterprise Team. Incident management teams in California may order the FireMapper through the Southern Operations Coordination Center.

The PSW FireMapper system incorporates infrared cameras operated at one short-wave (1.6 μm), one mid-wave (3.9 μm), and two long-wave or thermal-infrared wavelengths (at 8.5 and 11.9 μm). Direct observations and modeling of fire radiances show that the radiance measured in the short-wave infrared primarily arises from emissions by very hot but optically thin flames within a fire front; those measured in the thermal infrared (at 11.9 μm) arise from the hot but lower temperature (and high emissivity) ground surface, even beneath active flames (Riggan and Tissell 2009). Both sources, flames and the hot ground surface, contribute strongly to the fire radiance measured at the mid-wave infrared wavelength. Fire radiance measurements at 1.6- and 3.9-μm wavelength have been combined to estimate flame properties including their temperature, combined emissivity and fractional area within a viewing pixel, and radiant-flux density – the rate of radiant energy release per area of ground and per second (see, for example, Riggan *et al*. 2004, Riggan and Tissell 2009). Furthermore, fire temperature and emissivity-fractional area have been correlated with heat and carbon fluxes from large fires and may be used to estimate rates of fuel consumption (Riggan *et al*. 2004).

FireMapper images are of high resolution: the thermal imager employs 1.8-milliradian optics, with a resulting pixel spacing of 1.8 m per 1000 m above ground level. A typical flight at 17,500 feet over 5,000-foot terrain would produce imagery of 6.9-m resolution at nadir.

In support of fire operations, we have disseminated fire-temperature maps derived from the long-wave infrared as measured by the FireMapper. These color-coded image mosaics depict current and recent behavior by active fires: very-high surface temperatures are typically associated with active and intense flaming combustion in heavy fuels; wide reaches of ground with elevated temperatures behind a fire front reflect recent fire movement through relatively heavy fuels (Fig. 2). Lower temperatures behind a fire front represent mixtures of small amounts of residual flaming combustion and cooling of the hot ground surface. In our scheme, we typically display progressive temperatures above residual heat from the fire in progressive colors of red, orange, and yellow. Black ash in the sun may be as warm as 75°C; we currently display surface temperatures below that point in shades of tan and gray.

Thermal-infrared imagery has also proven useful in tracking aerial applications of fire retardant; areas recently treated may be as much as 10°C cooler than the surroundings. Successive mapping of fire lines will show new applications and provide an opportunity to assess a measure of both the continuity and apparent density of retardant applications and the response of the fire to the application (Fig. 3).

FireMapper imagery is georeferenced, orthorectified, and disseminated in several map products including geoTIFF images, .kmz files for use in Google Earth, in a Google Maps viewer, and as shape files for incorporation in incident-team GIS databases. A Flash-based viewer at fireimaging.com allows an online user to zoom and pan fire imagery and record the latitude and longitude of selected points. This feature can be used to digitize a fire perimeter or record the location of critical fire activity, such as spot fires that have crossed a fire line, road, or natural barrier.

Although the behavior of active fires can be readily tracked by repeated flights with the FireMapper, both short-term prediction or extrapolation of fire behavior on time scales from hours to days and an understanding of why a fire evolves in a given pattern require highly resolved information on fuels and wind across landscapes. We have applied the Coupled Atmosphere Wildland Fire Environment simulation model (CAWFE) (Coen 2005) to understand atmospheric motions in terrain and interactions of fire with the atmosphere (Coen and Riggan 2010). Yet at present even such sophisticated modeling relies on the basic Rothermel formulation for fire spread and very coarse estimates of chaparral fuels.

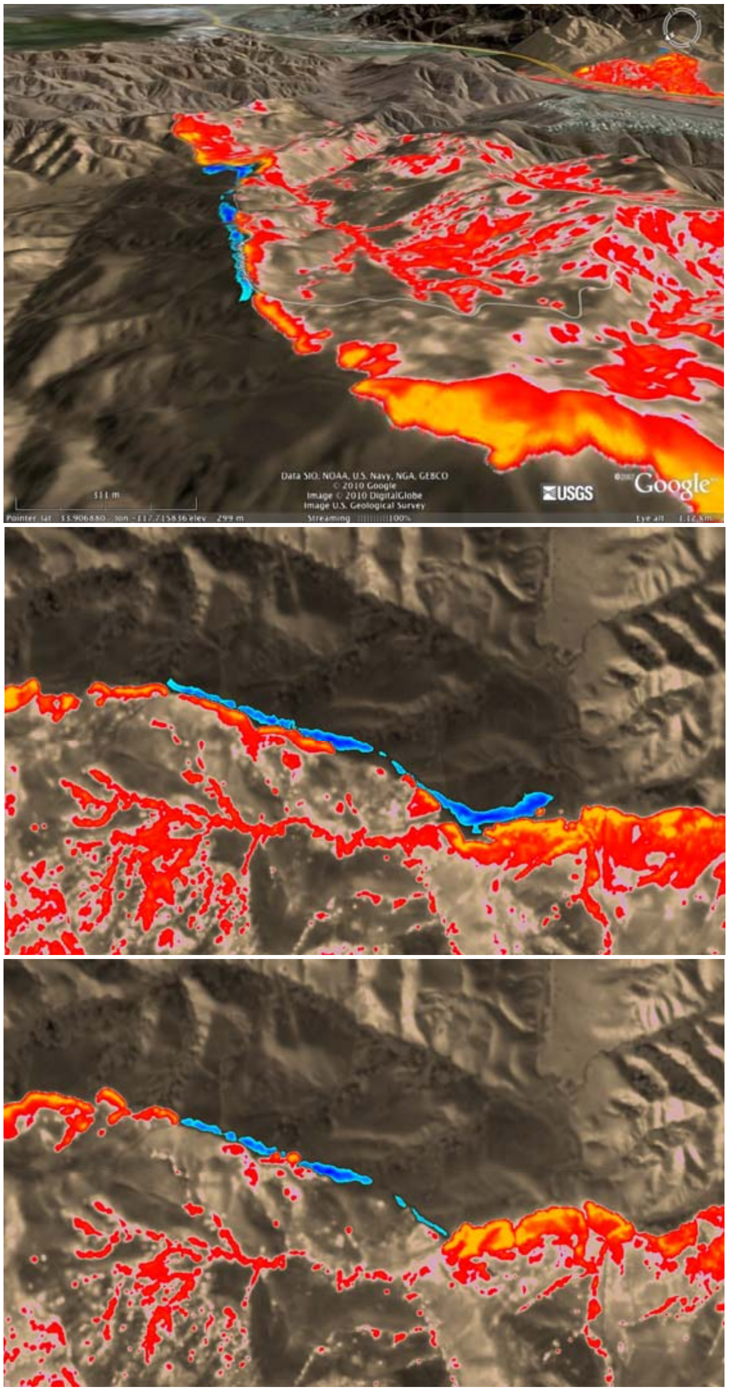


Fig.3. Freeway Fire, 15 November 2008, as viewed by the PSW FireMapper. Here a Santa Ana wind is driving the fhire west in grass and chaparral north of the 91 Freeway in Orange County, California. Fire temperatures are color-coded as in Fig. 1 (with a tan-to-red transition at 60°C). Recently applied fire retardant is shown in shades of blue according to the degree of depression in surface temperatures. In the upper image is a view from the northwest, showing the alignment of the retardant along a ridge trending east to west. A nadir view at 14:02 Pacific Standard Time (center image, oriented with north at top) shows small apparent discontinuities in the applied retardant. A nadir view at 14:32 (lower image) shows that the fire was indeed impeded along a portion of the retardant line on the west, burned across the retardant in heavy fuels at the east, and breached the retardant at west-center. Ultimately the line alone

Mapping fuels

Fuel properties are now commonly specified, for example by the LANDFIRE project (data *available online*[2]), using fuel models such as reported by Anderson (1982) or Scott and Burgan (2005). These models neither describe fuel development with time nor encompass the wide range of extant fuel conditions in chaparral. Fuel model 4, as reported by Anderson, was one of several models devised for fire-danger rating (Rothermel 1972). It has been widely and uncritically applied to chaparral (and is recommended as well for pocosin and southern rough). Fuel model 5 has been assumed as a description for younger chaparral with little dead fuel. We have been unable to discover the provenance of these models. Scott and Burgan (2005) specify four models for dry-climate shrub lands, two of which are appropriate for chaparral. Thus the available mapping data show primarily where there is chaparral fuel, but little about its variability. A photo-series guide to chaparral fuels (Ottmar *et al*. 2000) provides tables of measured loadings by size class and condition (dead or live) for 16 stands of chaparral and coastal sage scrub, with the intent that a user can visually compare a stand in the field with photos in the guide to select rough estimates of fuels. The procedure is useful but neither constitutes a measurement nor provides a means to estimate fuel distribution across landscapes or development with time. We note that in a few instances Scott and Burgan have obtained photos from Ottmar *et al*. to illustrate examples for their fuel models, but do not explicitly use the tabled fuel data from Ottmar *et al*.

Chaparral stand development

As with forest ecosystems, productivity and biomass accumulation in chaparral exhibit a wide natural range (Fig. 4) and are strongly affected by site quality or environment, community type, and possibly by stand density. The greatest rates of primary production at the San Dimas Experimental Forest (SDEF) in Los Angeles County rival those of the eastern deciduous forest (Riggan *et al*. 1988). For mature chaparral stands, say, near 20 years of age, total aboveground biomass may range from 2 to 12 kg/m^2! Variation across age must be even greater. Thus, a few stylized fuel models must be woefully inadequate to describe the range of biomass accumulation in chaparral.

Growth in chaparral is most limited by availability of water (or water stress), extremes of temperature, and possibly nitrogen or phosphorus availability (cf. Mooney *et al*. 1975, Oechel and Hastings 1983). Greatest rates of biomass accumulation have been recorded in *Ceanothus* chaparral in the San Gabriel and Santa Ynez Mts., and especially, on north-facing aspects (Riggan *et al*. 1988, Schlesinger and Gill 1980). Foliage biomass on a presumably mesic north-facing slope at a site in San Diego County was shown to be three times greater than on an adjacent, xeric, south-facing aspect, although soil moisture was seasonally depleted slightly more quickly on the northern aspect (Ng and Miller 1980). Leaf area on these sites apparently was adjusted during stand development to optimize water-use efficiency. Foliage mass in *Ceanothus* continues to accumulate at least through age 22 years, although the rate of accumulation begins to decline at around age 14 years (Riggan *et al*. 1988). The rate of total aboveground biomass accumulation shows no such decline prior to age 22.

Biomass accumulation during stand development has been approached by measurement of similar sites across age-class boundaries (e.g., by Schlesinger and Gill 1980) and by reconstruction of biomass accumulation for individual stands (e.g., by Riggan et al. 1988). These approaches are useful in providing expected trends in fuel properties with vegetation age.

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[2] <www.landfire.gov >

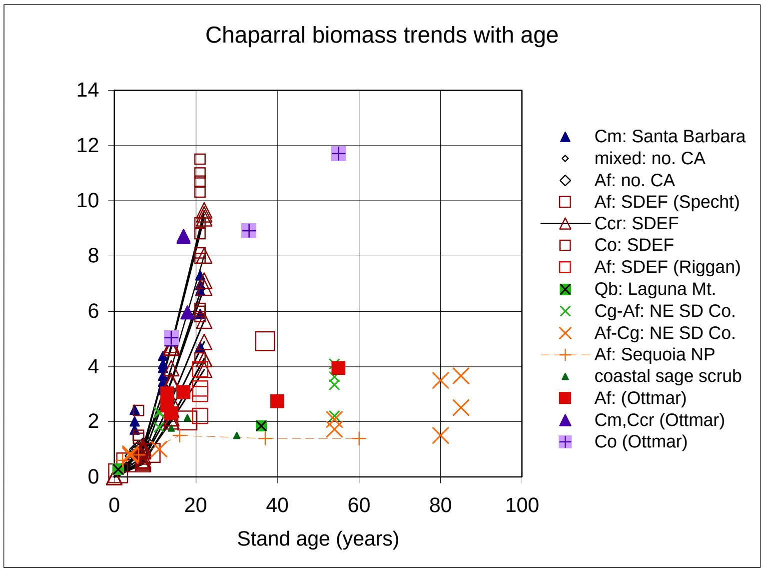

Fig. 4. Trends in chaparral biomass with age (adapted from Riggan *et al*. 1994). Aboveground biomass reflects a wide range of primary production across complex environments and community types in chaparral. Data are from Ottmar *et al*. (2000) and sources provided in Riggan *et al*. (1994). Identified species are *Af: Adenostoma fasciculatum, Ccr: Ceanothus crassifolius, Cg: C. greggii, Cm: C. megacarpus, Co: C. oliganthus, Qb: Quercus berberidifolia.*

Biomass as fuel

Not all chaparral biomass is likely to be consumed during burning. One expects a chaparral fire in stands of intermediate age to consume all foliage and deadwood, finer fractions of live wood, and dry leaf litter. Nine percent of live woody biomass was consumed by each of two prescribed fires of differing activity in 26- and 27-year-old chaparral at the SDEF (Riggan *et al*. 1994), yet stand age and associated fuel loading and condition apparently are important: For example, the 1985 Sherwood Fire in Los Angeles County produced a mosaic of burned and unburned vegetation and consumed foliage and only the finest of woody twigs, spreading in part through *Salvia mellifera* [black sage] and grass fuel in 8-year-old *Adenostoma fasciculatum* [chamise] and *C. megacarpus* chaparral. A black ash surface remained in burned areas. Concurrent burning in 50-year-old chaparral showed exceptionally high-intensity as all foliage, fine wood, leaf litter, and many live stems 5- to 10-cm in diameter were incinerated. Virtually no unburned vegetation remained within the fire perimeter in this age class, and the ground surface was uniformly covered with a deep white ash (Riggan *et al*. 1994). Thus an understanding of fuel requires both estimates of biomass accumulation and the proportion of the biomass that is consumed, and the latter probably changes with stand age or condition or fire intensity.

As chaparral stands age, deadwood accumulates through progressive shading (or aging) of lower branches, declines or dieback induced by extreme drought or pathogens, intra- or inter-specific competition, and random mortality such as that from snow or freezing (Riggan *et al*. (1994). The median deadwood fraction in chamise across 15 sites in southern California has been reported to be 0.23 (Paysen and Cohen 1990). Yet chamise has been observed to accumulate little deadwood in low productivity environments (0.07 of aboveground biomass) and a substantial fraction (0.45 to 0.48) in high-productivity stands where it is subject to competition from tall *Ceanothus* (Riggan *et al*. 1988). Note that although the *fraction* of biomass that is deadwood may not change substantially with age, biomass accumulation with aging would indeed lead to higher deadwood loadings. Some mortality may be rapid and episodic: A drought-related dieback in *C. crassifolius* at the SDEF was shown to kill 0.38 of the aboveground biomass within a few months in 1985 (Riggan *et al*. 1994). We also observed some stands of *C.*

oliganthus on north-facing aspects that had suffered almost complete mortality at about the same time.

By reference to controlled fires in the laboratory, the behavior of spreading chaparral fires also may depend on the physical arrangement of the fuel, especially the ratio of surface area to volume of fuel elements and the physical packing of the fuel, i.e., its volume fraction within the shrub canopy. Such fuel properties have rarely been measured or estimated for chaparral; Countryman and Philpot (1970) did so for a limited sample of 16 chamise shrubs from a single location at the North Mountain Experimental Area in Riverside County. Because the chaparral plant canopy carries a fire, effects of changes in bulk density with stand age are probably most important in that canopy; such changes with age are not well known. In 21-year-old C. crassifolius at the SDEF, ca. three-quarters of the foliage mass was located between 2 and 4 meters of the ground surface with one-tenth of the foliage above that height in stands averaging 4 m height (Riggan et al. 1988).

We envision that useful fire-behavior prediction in southern California will ultimately require landscape-level models of stand biomass accumulation as a function of environment and age with links to remote-sensing measurements of plant-community type, and plant-canopy development. *It may also be possible to directly relate remote sensing measurements of fire properties to prefire vegetation reflectance properties.* As an example of the latter concept, we note that the maximum temperatures observed along a fire line in chaparral often show a spatial correspondence with changes in apparent vegetation density as associated with different landscape aspects (Fig. 5).

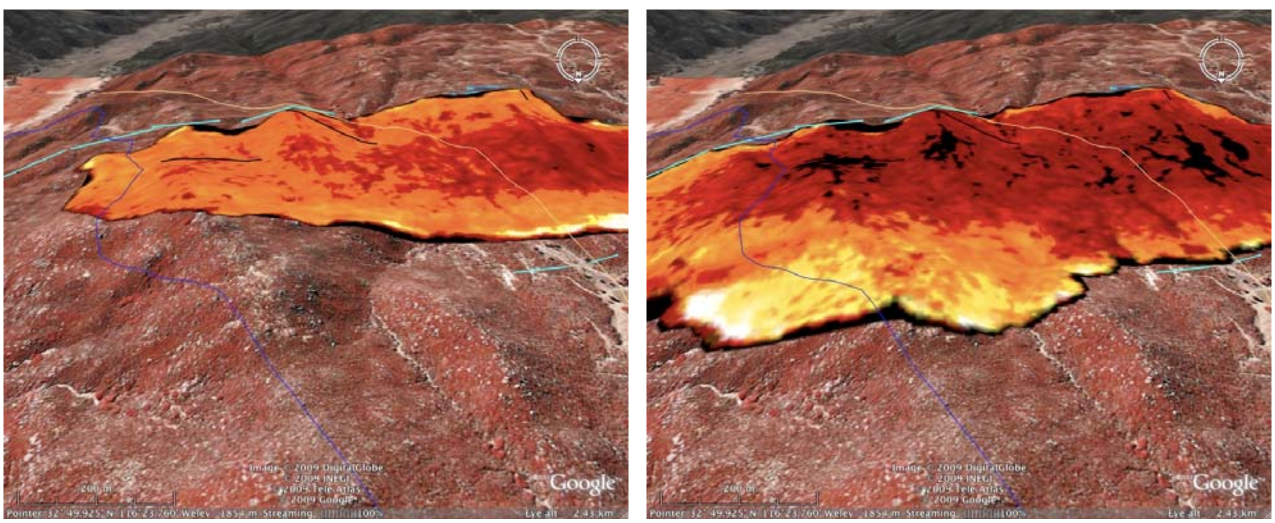

Fig. 5. Troy Fire, San Diego County, California as viewed from the north by the FireMapper thermal imaging radiometer, 19 June 2002, at 14:06 (left) and 14:53 (right) Pacific Daylight Time. Note that the maximum temperatures associated with the fire front (yellow and white tones) were greatly elevated when fire spread into chaparral on more northerly-facing aspects as indicated by the base false-color infrared photography.

Estimating fuels at the Esperanza Fire

To examine the use of multispectral remote sensing as an estimator of fuel properties, we have estimated chaparral fuel loading and likely consumption in the area of and surrounding the 2006 Esperanza Fire in Riverside County. Chaparral biomass was estimated from a combination of (1) post-fire measurement of the basal area of remaining shrub stems from 127, circular, 1/250-acre plots (D. Weise, *personal communication*) that were distributed in the area of active fire runs as observed by remote sensing with the FireMapper, (2) scaling relationships of biomass components to basal area for shrubs prior to burning and at different ages and for several species, and (3) correlation of pre-fire stand biomass estimates to broader averages of vegetation reflectance derived from Landsat Thematic Mapper (TM) imagery. Relations of prefire biomass components to stem basal area were obtained from measurements in the vicinity of the Esperanza Fire by C. Wright (*personal communication*) and earlier measurements in 55-year-old chaparral there by J. Regelbrugge (*U.S. Forest Service records on file, Riverside, CA*). Stand biomass estimates followed the approach previously described, for example, by Riggan *et al*. (1988), Schlesinger and Gill (1980), and Conard and Regelbrugge (1993).

The fine live biomass (B_f) estimated for Weise's 4.6-meter-diameter field plots showed, on a plot by plot basis, little correspondence to prefire estimates of the normalized difference vegetation index (NDVI), defined as (nIR-red)/(nIR+red) reflectances, as determined from 30-m TM data collected in either February or June 2006. However, averaging plot biomass and NDVI values by four ranges of ages and north and south aspects produced a good relationship between the variables with a power function regression accounting for 0.80 of the variance in $\ln(B_f)$ (Fig. 6a). Apparently, large differences in scale and uncertainty in location between the small field plots and much larger TM pixels obscured a large-scale relationship between the reflectance and vegetation measurements. Available data also showed that the ratio of fine live woody biomass to foliage biomass was very similar between 10- and 55-year-old stands, and deadwood biomass was similar and low in young *Arctostaphylos glandulosa* [manzanita] and chamise but substantially higher at age 55 years for either species (Fig. 6b). Accordingly, we fit a power function to these latter data so as to reasonably interpolate the rate of dead biomass accumulation with age.

The results of this analysis (Figs. 7 to 12) show a range of fuel loading associated with elevation and stand age that was not captured by application of the standard fuel models. The loading showed a general correspondence with observed fire behavior, specifically, the low energy release rates behind the main fire front in light fuels as shown in Fig. 2, high energy release on north-facing slopes, as along the north side of Mt. Edna, and high energy release associated with narrow reaches of old chaparral in the southwest of the fire adjacent to Poppet Flat (Fig. 11). The Esperanza Fire terminated in the southwest coincident with the boundaries of earlier fires and young fuels. Spatial discontinuities in surface temperatures after passage of the fire front were also noted to coincide with age-class boundaries. The Landsat NDVI measure showed skill in predicting broad classes of fuel accumulation and fire properties, yet sampling limitations precluded a more detailed analysis based on stand species composition and led to extrapolations at higher apparent biomass loading at higher elevations and low fuel loading in frequently burned and degraded landscapes.

Concluding remarks

Airborne remote sensing with the FireMapper thermal-imaging radiometer is providing unprecedented information on the short-term behavior and energetics of wildland fires in southern California. Extending fire measurements with predictive models will require extension of operational fire-behavior models to the extreme conditions of energy release of large wildland fires in chaparral and substantial improvements in measurement and modeling of chaparral fuel development with age and environment and rates of fuel consumption. Measurements of biomass in the field and by multispectral remote sensing have been combined to estimate fuel loading for the 2006 Esperanza Fire and these data are providing inputs for simulations with coupled fire-atmospheric dynamics models including NCAR's CAWFE model. We recommend extending this approach by applying fuel sampling and multispectral remote sensing across a wider range of environments and rates of chaparral productivity. Resulting fuel estimation models should then be combined with climatology and remote measurements of available moisture to model and map stand fuel development with age in important chaparral and grass fuel types in southern California. Measurements should characterize the ratio of foliage surface area to volume and trends with stand age in the development and vertical structure of foliage and fine live woody biomass, accumulation of live and deadwood by size class, and fuel-bed packing ratio. Modeled fuel and fire properties should then be independently evaluated against remotely sensed behavior of large wildland fires.

Resulting improvements in fuel and fire-behavior models will support tactical fire suppression by providing a basis to evaluate expected fire behavior and support strategic fuel management by allowing an evaluation of regional fire risk and the response of wildland fires to extant fuel condition and potential fuel treatments.

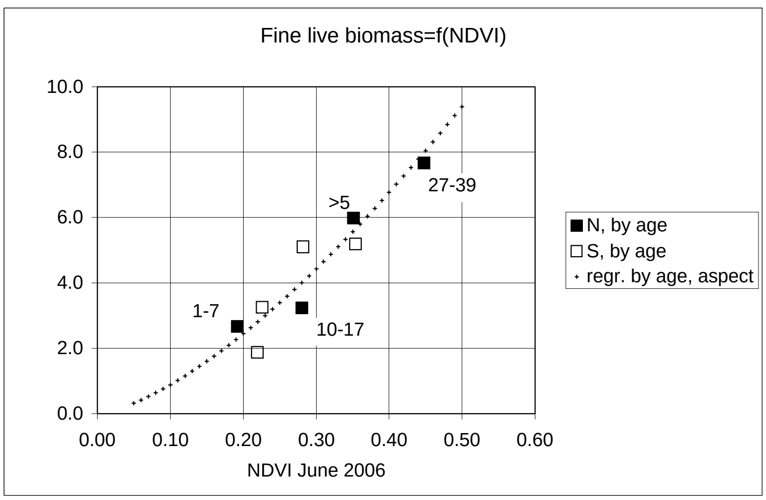

Fig. 6a. Relation of average fine live biomass (B_f) to NDVI for groupings of field measurements by categories of age and aspect at the 2006 Esperanza Fire. Age categories (in years) are labeled for the average values associated with north-facing aspects. A power-function model, B_f=26.0(NDVI)$^{1.47}$, estimated by regression of the average values is shown (+ symbols).

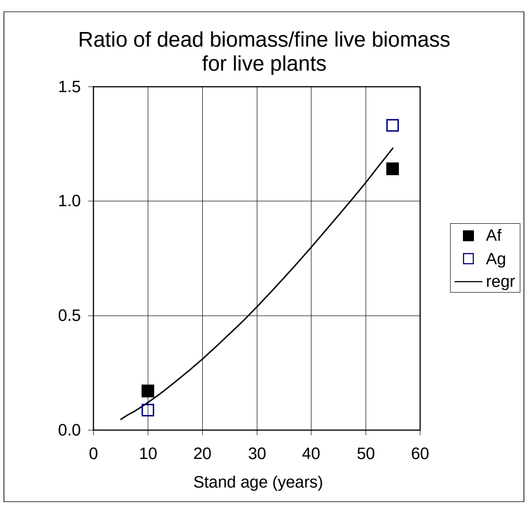

Fig. 6b. Changes with stand age in the ratio of deadwood biomass to fine live biomass for two chaparral species: Adenostoma fasciculatum (Af) and Arctostaphylos glandulosa (Ag). Data were collected from within the perimeter of the Esperanza Fire (*C. Wright personal communication, J. Regelbrugge U.S. Forest Service data on file, Riverside, CA*). A power function model was used here to interpolate by age.

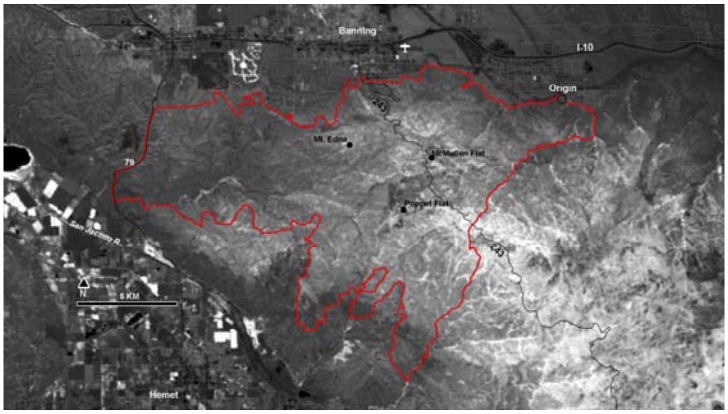

Fig. 7. Normalized Difference Vegetative Index mapped in the vicinity of the 2006 Esperanza Fire from pre-fire LANDSAT TM data, imaged in June 2006. All values in the area of interest are positive: scaling is such that an NDVI value of zero is mapped to black; a value of one is mapped to white. The fire perimeter is shown in red.

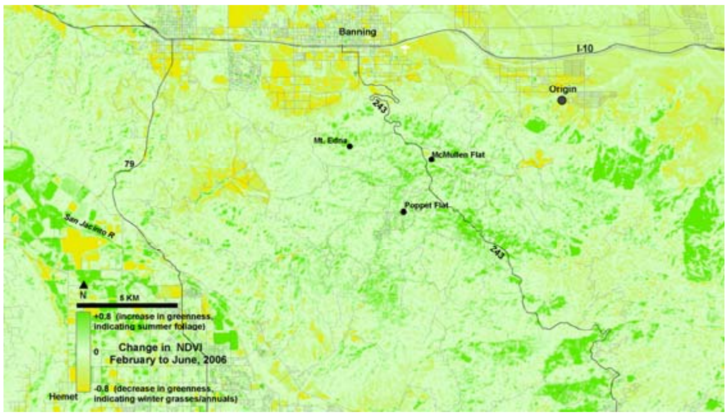

Fig. 8. Difference image of Normalized Difference Vegetative Index values between June and February 2006. Negative difference values, where values from February are greater than in June (assigned yellow tones) correspond to annual grasslands and herbaceous vegetation. Higher positive values (assigned deeper green tones) correspond to developing foliage in shrubs and woodlands.

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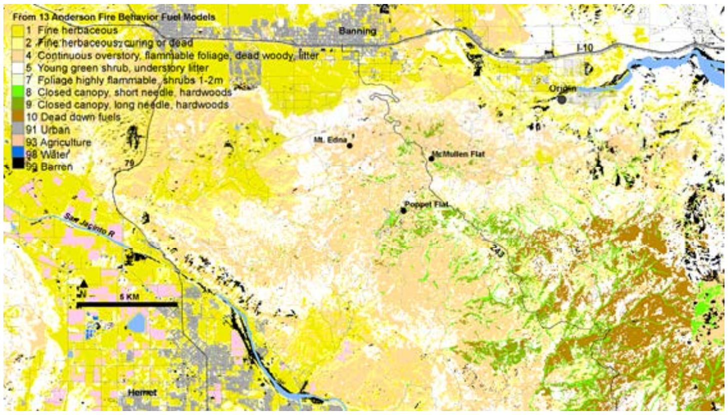

Fig. 9. LANDFIRE fuel models in the vicinity of the 2006 Esperanza Fire. The majority of the fire area falls into two classes of chaparral creating essentially a binary model for fuels: high and low.

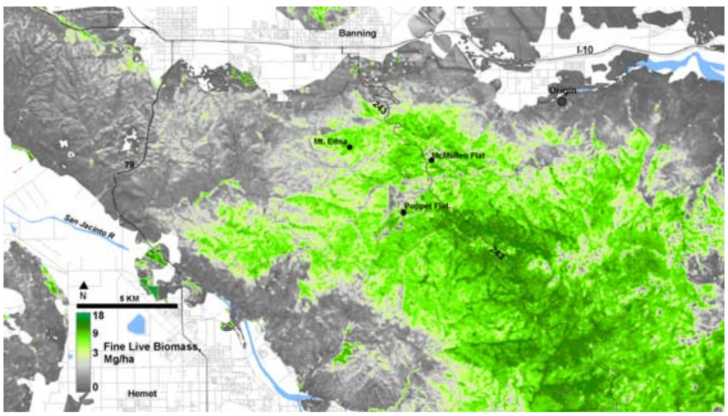

Fig. 10. Mapped fine live biomass (0-1/4 ‘ ‘ wood plus foliage) in the vicinity of the 2006 Esperanza Fire, as estimated from NDVI (Fig. 7) and the relation of B_f to NDVI (Fig. 6a). Highest values (dark green) are outside of the fire perimeter; together with the lowest values in grass and herbaceous types (darker grays), these constitute an extrapolation from available data based on chaparral.

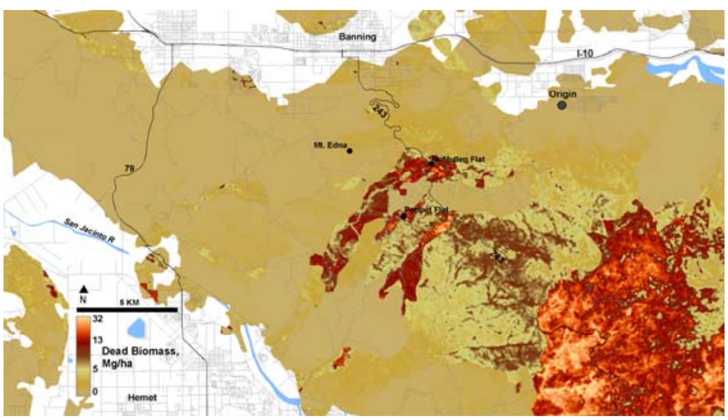

Fig. 11. Mapped deadwood-fuel loading for the area shown in Figure 10. Values are derived as a fraction of fine live biomass that varies with stand age (Fig. 6b). Highest values in the southeast are outside of the fire perimeter and correspond to more productive chaparral and oak woodlands with some conifers and no fire history. Strips of high deadwood loading at center correspond to high-intensity fire runs as observed with the FireMapper.

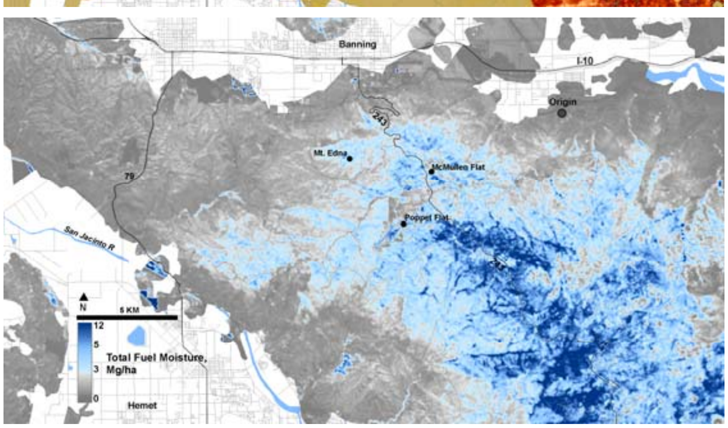

Fig. 12. Estimated moisture in fine live wood, foliage, and deadwood for the area of the Esperanza Fire. The latent heat of vaporization associated with this moisture will reduce the energy available to propagate the fire.

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Fuel consumption and particulate emissions during fires in the New Jersey Pinelands

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Abstract
We quantified loading and consumption losses of 1-hour and 10-hour fuels on the forest floor and understory vegetation during 24 operational prescribed burns conducted in the Pinelands National Reserve of New Jersey. PM 2.5 emissions were calculated using published emission factors, and atmospheric PM 2.5 was measured under ambient conditions and during prescribed fires. Pre-burn 1-h and 10-h fuel loading was greater in Pitch pine-dominated stands than in stands with a substantial biomass of overstory oak.

Forest floor and understory fuel consumption were a strong linear function of pre-burn loading, and forest floor consumption was often the predominate site of PM 2.5 production, even during crowning fires. These relationships allow a more accurate estimate of PM 2.5 production during fuel reduction treatments, based on knowledge of pre-burn fuel loading.

Additional keywords: Prescribed burning, , PM 2.5, Pinelands National Reserve, prescribed fire emissions, wildfire emissions, air quality, available fuel, fuel loading

Introduction

Prescribed fires are essential for the protection of homes and property from wildfires. Smoke from prescribed fires contributes to atmospheric pollutant loads, and where prescribed fires are conducted near urban centers or non-attainment areas, the potential exists for exceeding federal, state or local air quality standards (Tian *et al*. 2008). In addition, impairment of visibility by smoke on roads and highways can be a significant safety hazard.

The proximity of residential developments and commercial property to the nearly continuous fuel beds of the Pinelands National Reserve is a major concern for the New Jersey Forest Fire Service (NJFFS) and federal wildland fire managers. They have two major goals when using prescribed fire; to reduce fuels on the forest floor, and to reduce the occurrence of ladder fuels in the understory. Ladder fuels, consisting of shrubs and sub-canopy foliage and branches, increase vertical and horizontal fuel continuity, and can facilitate the transition of surface fires to the canopy, where they are much more difficult and expensive to suppress (e.g., Skowronski *et al*. 2007, Clark *et al*. 2009). In an effort to reduce the threat of crown fires impacting housing developments, commercial property and transportation corridors along the eastern margin of the Pinelands National Reserve, many prescribed burn blocks in the Pinelands have been burned at 5-8 year intervals since the late 1950ȇs. A number of these burn blocks are aligned along a north-south axis, and along with wetlands and stream corridors, serve as landscape-scale fire breaks under the prevailing NW winds.

Although a planning framework exists to mitigate the direct effects of smoke on communities and highways during prescribed burn treatments within the NJFFS and federal wildland fire management agencies, information is limited regarding fuel consumption and production rates of particulate matter less than 2.5 µg in size (PM 2.5) during prescribed burns in Pineland plant communities. Little ambient air data for PM 2.5 in the Pinelands exists, despite the fact that this region has one of the highest incidences of wildfires in the Northeastern US, and is located adjacent to large urban and industrial areas. Emissions from prescribed burns or other fuel treatments have rarely been compared to those from wildfires, precluding an evaluation of the tradeoffs between various hazardous fuels management strategies (e.g., Tian *et al*. 2008). Because prescribed fires are currently the most cost-effective method of treating hazardous fuels, a strong need exists to prioritize and maximize the effectiveness of fuel reduction treatments given the new 24 hour PM 2.5 ambient air standard is now 35 µg of PM 2.5 m^{-3} (EPA 2007a-c). Further complicating the situation is the fact that two counties in and surrounding the Pinelands (Burlington and Camden) were non-attainment areas for PM 2.5 in 2010 (http://ecfr.gpoaccess.gov/cgi/).

Our objectives were to:

1) Quantify fuel loading and consumption during operational prescribed fires conducted by the NJFFS in the Pinelands National Reserve.

2) Calculate PM 2.5 emissions from prescribed fires, and compare them to estimated PM 2.5 emissions from the May 2007 Warren Grove wildfire.

3) Monitor ambient air concentrations of PM 2.5 in the Pine Barrens throughout 2008 to determine seasonal patterns and seasonal occurrence of non-attainment days.

4) Measure PM 2.5 concentrations near and in a series of prescribed fires conducted by the NJFFS near the Cedar Bridge fire tower in March 2008.

Methods

Site Description

Research sites were located in Burlington and Ocean Co. in the Pinelands National Reserve in southern New Jersey. The Pinelands contain the largest continuous forested landscape on the Northeastern coastal plain. The climate is cool temperate, with mean monthly temperatures of 0.3 and 23.8 ºC in January and June, respectively (1930-2009; State Climatologist of NJ; http://climate.rutgers.edu/stateclim_v1/data/). Mean annual precipitation is 1142 ± 160 mm. Soils are derived from the Cohansey and Kirkwood Formations, and are sandy, coarse-grained, and extremely oligotrophic (Tedrow 1986). This landscape is also characterized by a high frequency and intensity of wildfires relative to other forest ecosystems in the northeastern US (Little & Moore 1948, Little 1998).

Wildland fire managers in the Pinelands conduct prescribed burns on approximately 8,000 to 12,000 ha of public forest per year (Table 1). Upland forests are the major focus of fuel reduction treatments in the Pinelands. These comprise ca. 62% of the forested areas in the Pinelands

National Reserve, and are dominated by three major forest communities; 1) oak - pine, consisting of black oak (*Quercus velutina* Lam.), chestnut oak (*Q. prinus* L.), white oak (*Q. alba* L.), and pitch (*Pinus rigida* Mill.) and shortleaf pine (*P. echinata* Mill.), 2) pine - oak, consisting of pitch pine with mixed oaks in the overstory, and 3) pine - scrub oak, dominated by pitch pine with scrub oaks (*Q. ilicifolia* Wang. and *Q. marlandica* Muench.) in the understory (McCormick & Jones 1973, Lathrop & Kaplan 2004, Skowronski *et al*. 2007, FIA data at www.fia.gov). A fourth forest community, the pine plains, consisting of short-statured pitch pine and scrub oaks, is also recognized in the vicinity of Coyle Field, Warren Grove Bombing Range, and Stafford Forge Wildlife Management Area. All stands have ericaceous shrubs in the understory, primarily huckleberry (*Gaylussacia bacata* (Wang.) K. Koch, *G. frondosa* (L.) Torr. & A. Gray ex Torr.) and blueberry (*Vaccinium* spp.). Sedges, herbs, mosses and lichens also are present (Wright *et al*. 2007).

Table 1. Acreage of prescribed fires conducted by the NJFFS in the Pinelands National Reserve from 2002 to 2008. Acres burned are from NJFFS. The sampled area is the sum of stand acreage sampled for fuel loading each year, and % is the percent of total burned area sampled each year.

Year	Hectares	Sampled area	%
2002	4898	-	-
2003	3849	-	-
2004	3250	918	28
2005	4065	295	7
2006	3150	404	13
2007	4720	202	4
2008	7520	459	6

Most upland forest stands in the Pine Barrens have regenerated naturally following cessation of logging and charcoaling activities in the late 1800ôs. Among mature upland stands of approximately the same age, understory fuel loading and óladder fuelsô are typically denser in pine - oak and pine ï scrub oak stands compared to oak-dominated stands (Skowronski *et al*. 2007).

Fuel Loading and Consumption Measurements

Fine (1-h), 10-h and 100-h fuels were sampled on the forest floor in 30 stands throughout the Pinelands. Stands were located in the Brendan T. Byrne State Forest, Greenwood and Stafford Wildlife Management Areas, Fort Dix Army Base, and Wharton State Forest, and encompassed a wide range of tree densities and fuel loadings. Pre-burn forest floor measurements consisted of 10 to 20 1 m^2 quadrats located at random points within each treatment block. We sampled the litter layer (L horizon) only, because the humus layer (O horizon), consisting of undifferentiated organic matter, rarely was consumed during prescribed fires. In the laboratory, samples were separated into 1-h, 10-h and 100-h fuels. All samples were dried at 70 ºC until dry, and then weighed. Shrubs, herbs, and understory oaks < 2 m tall were sampled in addition to forest floor fuels at twelve of the stands. Understory vegetation was cut at ground level, and separated into foliage and live and dead 1-h, 10-h, and 100-h fuels in the laboratory. Samples were dried at 70 ºC until dry, and then weighed.

Of the thirty stands initially sampled, twenty-four were burned in prescribed fires. These stands were re-sampled for unconsumed 1-h, 10-h, and 100-h fuels within one week of burning, using the same protocols that were used for pre-burn samples. On the days of many of the prescribed burns, fuel moisture content of 1-h and 10-h fuels on the forest floor and in understory vegetation was estimated using wet and dry weight measurements of samples collected in plastic bags. Meteorological data, 10-h fuel moisture contents and temperatures, and other ancillary data were recorded for each burn from fire weather towers in the Pinelands (http://climate.rutgers.edu/usfs/ monitoring.pfp). We also sampled a pitch pine ï scrub oak stand in the Stafford Wildlife Management Area that was burned in an intense crowning prescribed fire conducted on March 21, 2008 to estimate emissions from the 6,300 ha Warren Grove wildfire that occurred on May 15th-19th, 2007. In addition to forest floor and understory measurements, LIDAR data (described in Skowronski *et al*. 2007 and Clark *et al*. 2009) collected pre- and post-burn were used to calculate canopy fuel consumption.

PM 2.5 Emissions from Prescribed Fires

Emissions from fires were calculated as the product of the area of the burn, the fuel consumed per unit area, and an emission factor:

$$E = A \times F_{area} \times E_{factor} \qquad (1)$$

where A is the area burned, F_{area} is the amount of fuel consumed per unit area during the fire, and E_{factor} is the ratio of the mass of pollutant emitted per unit mass of fuel consumed. F_{area} and E_{factor} are functions of fuel conditions (e.g., availability and moisture content) and meteorological conditions during the burn. We used prescribed burn plans prepared by the NJFFS and burn perimeter measurements to calculate the area burned (A). Differences between mean pre- and post-burn fuel loadings were used to calculate the consumption of fine (1-hour), 10-hour and 100-hour fuels at each site (F_{area}).

Emissions (E_{factor}) from wildland fires and prescribed burns are well-characterized, and an extensive set of emission factors exist for EPA criteria pollutants and many hazardous airborne chemicals released from combustion of hardwood and coniferous fuels. We used EPA's Factor Information Retrieval Data System, FIRE 6.25 available from WebFIRE (http://www.epa.gov/ttn/chief/ efpac/index.html) and other literature values (Battye and Battye 2002) to estimate emissions of PM 2.5, CO_2, CO, and NMHC during combustion of forest fuels (Table 2). Mean emission factors for both wildfires and prescribed burns were used to calculate emissions of PM 2.5 from the intense crowning prescribed fire conducted in the Stafford Forge WMA in 2008, and estimated emissions from this burn were used to predict emissions from the Warren Grove wildfire.

Table 2. Mean emissions of fine particulates (PM 2.5), carbon dioxide (CO_2), carbon monoxide (CO) and non-methane hydrocarbons (NMHC) during wildfires and prescribed burns used for all calculations. Data are summarized from WebFIRE (http://www.epa.gov/ttn/chief/ efpac/index.html).

Fire type	PM 2.5	CO_2	CO	NMHC
	kg emitted per ton fuel consumed (kg ton^{-1})			
Wildfires	6.2 ± 0.5	1637	57.8 ± 15.3	4.3 ± 3.6
Prescribed fires	12.3 ± 1.0	1627 ± 50	140.5 ± 49.9	4.7 ± 2.0

We used the annual acreage burned from 2002 to 2008 in Table 1, mean consumption rates estimated from pre- and post-burn measurements, and emission factors in Table 2 to calculate annual emissions from operational prescribed fires conducted on public lands in the Pinelands by the NJFFS. Annual estimates of emissions released during prescribed fires were then compared to estimated PM 2.5 emissions from the Warren Grove wildfire in 2007.

PM 2.5 Measurements

Continuous PM 2.5 measurements were made at an oak - pine stand at the Silas Little Experimental Forest at the western edge of the Pinelands, and at a pine - scrub oak stand near the Cedar Bridge fire weather tower towards the eastern edge of the Pinelands in 2008. Two E-BAM beta particle attenuators (Met One Instruments, Inc., Grants Pass, Oregon) were fit with PM 2.5 sharp cut cyclone inlets, and operated using the manufacturerǿs specifications. When collectors were operated concurrently at Silas Little Experimental Forest, PM 2.5 concentrations were nearly identical. Both instruments were then located near fire weather or eddy flux towers (Clark *et al.* 2010), and operated according to the US EPA guidelines, and those in the instrument manual. Hourly or 24-hour averages of ε g m^{-3} PM 2.5 were used for all calculations.

In March 2008, the collector located at the oak-pine stand was relocated to an open area near the Cedar Bridge fire weather tower to monitor PM 2.5 concentrations during a series of prescribed fires. During these burns, one E-BAM was located within the burn block near the flux tower, and the second instrument was located in an adjacent feed plot clearing that was not burned (Fig. 1).

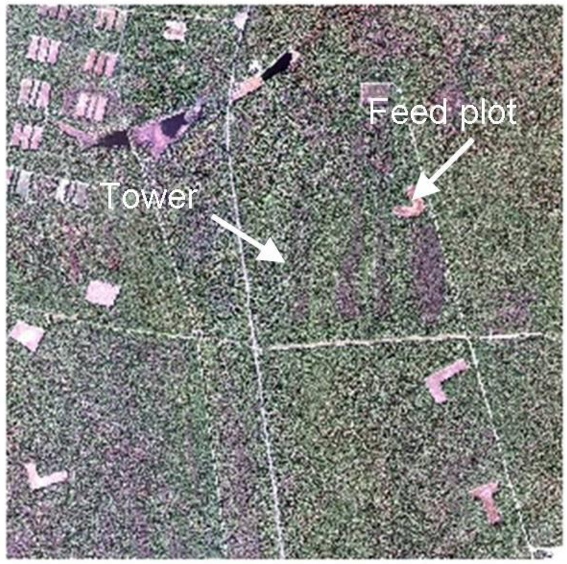

Fig. 1. Digital orthophoto of the Cedar Bridge area in Greenwood Wildlife Management Area following a series of prescribed fires conducted in March 2008. The tower and feed plot where the EBAM PM 2.5 instruments were located are indicated with arrows. Unburned crowns are green and areas of crown scorch appear dark grey and black. Area shown in the image is ca. 9 km^2.

Results

Fuel Loading and Consumption Measurements

Mean loading of 1-hour and 10-hour fuels on the forest floor was 12.8 ± 3.3 t ha^{-1} for the 30 prescribed burns blocks sampled from 2004-2009 (Table 3). Values ranged from 6.5 ± 2.1 t ha^{-1} in a fuel break that was burned at 2-3 year intervals (shown in the center of Fig. 1, running north to south between SR 539 and an unpaved road to the west) to 23.4 ± 5.8 t ha^{-1} in a pine-scrub oak stand that had not burned since a large wildfire in 1963. Differences in mean loading of 1-hour fuels but not 10-hour fuels were detected among forest types (ANOVAs, $F = 5.35$, $df = 29$, $p < 0.01$ for 1-hour fuels, and $F = 1.81$, $df = 29$, $p < 0.20$ for 10-hour fuels). Total fuel loading on the forest floor (1 hour + 10 hour fuels) was also significantly different among forest types (ANOVA, $F = 5.86$, $df = 29$, $p < 0.005$). Oak ï pine and pine ï oak stands had lower 1-hour and total fuel loading on the forest floor than pine ï scrub oak and pine plains stands (t-tests, $t = 3.87$, $df = 24$, $p < 0.001$ for 1-hour fuels and $t = 3.14$, $df = 24$, $p < 0.005$ for total fuel loading).

Table 3. Summary of 1-hour and 10-hour fuel loading on the forest floor in 30 upland forest stands in the New Jersey Pinelands. Data are mean t ha^{-1} ± 1 SD of mean values calculated from 10 to 20 1-m^2 plots located at random points throughout each stand. Stand types with different superscripts are significantly different at P < 0.01 for 1-hour fuels and P < 0.005 for 1hr + 10 hr fuels.

Forest type	n	1-hour	10-hour	1-h + 10-h
Oak - pine	5	8.4 ± 1.7[a]	1.7 ± 0.7	10.1 ± 2.1[a]
Pine - oak	14	9.8 ± 2.0[a]	2.1 ± 0.8	11.9 ± 2.3[a]
Pine - scrub oak	7	12.3 ± 1.8[b]	3.8 ± 3.3	16.1 ± 4.1[b]
Pine plains	4	11.6 ± 1.6[b]	2.5 ± 1.5	14.2 ± 2.7[b]

Mean live shrub and understory oak biomass in the twelve stands sampled was 5.4 ± 3.0 t ha^{-1}. Dead shrub and understory oak stems averaged 2.1 ± 2.4 t ha^{-1} across all stands sampled. The maximum live + dead understory loading was 11.7 ± 4.0 t ha^{-1} in a pine ï scrub oak stand that had not burned since 1962.

Fuel loading and consumption during prescribed burns

For the 24 prescribed burns sampled for pre- and post-fuel loading from 2004-2009, mean initial loading for 1-hour and 10-hour fuels on the forest floor was 12.4 ± 2.7 tons ha^{-2}. Mean post-burn loading of 1-hour and 10-hour fuels on the forest floor was 6.6 ± 1.5 t ha^{-1}, and estimated consumption during prescribed fires averaged 5.8 ± 2.9 t ha^{-1}. Mean consumption of 1-hour fuels represented 47.3 ± 15.5 % of pre-burn loading, while mean consumption of 10-hour fuels was only 24.9 % of pre-burn loading. Actual consumption of 10-hour fuels on the forest floor was likely greater, because some shrub stems likely fell to the forest floor during and immediately following prescribed burn treatments but were not consumed. For the subset of prescribed fires where shrub combustion was estimated, total pre-burn loading of live + dead shrubs was 7.5 ± 3.8 t ha^{-1} and post-burn loading was 3.3 ± 2.0 t ha^{-1}.

Consumption of fuels on the forest floor during prescribed fires was a strong linear function of initial fuel loading, which explained ca. 74% of the variability in consumption of 1-hour fuels, and ca. 72% of the variability in consumption of 1-hour + 10-hour fuels (Table 4, Fig. 2). Consumption of live + dead shrubs was also a significant linear function of initial fuel loading (Table 4). Because fuel consumption was a function of initial fuel loading, Pitch pine-dominated stands had greater consumption losses than stands with a significant biomass of overstory oaks (10.2 ± 2.7 ton ha^{-1} vs. 3.7 ± 1.3 tons ha^{-1} consumed; $t = 4.006$, $df = 21$, $P < 0.001$).

Table 4. Summary of equations for the relationship between pre-burn fuel loading and consumption estimated from post-burn measurements for 1-hour and 10-hour fuels on the forest floor, and woody stems of shrubs and scrub oaks in the understory. Units are mean tons ha^{-1}, and data were fit to linear equations with the form: Consumption = a (fuel loading) - b.

Fuel type	a	b	r^2	P
1-hour	0.839	3.508	0.736	<0.001
1-h + 10-h	0.898	5.317	0.722	<0.001
Understory stems	0.673	0.866	0.687	<0.01

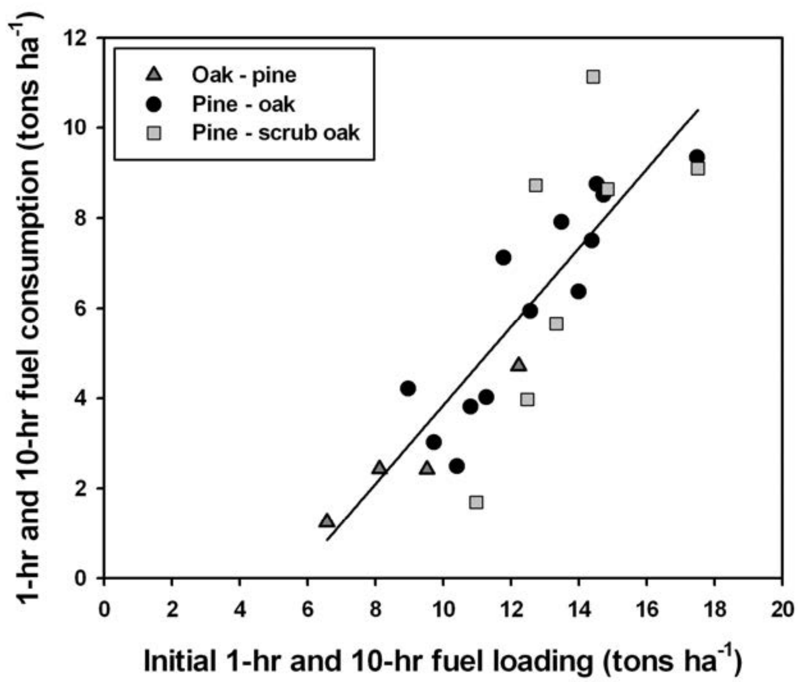

Fig. 2. The relationship between initial 1-h + 10-h fuel loading and amount of fuel consumed by forest type during 24 prescribed fires conducted in the Pinelands National Reserve in 2004-2009. Prescribed fires conducted in the Pine plains were included in the pine ï scrub oak category. Statistics for the regression line are in Table 3.

Mean fuel consumption during prescribed fires was much less than that estimated for the large crowning prescribed fire conducted in March 2008 near the site of the Warren Grove wildfire (Table 4). Consumption of forest floor and understory stems during this crown fire was estimated at 16.1 t ha^{-1}, and total consumption was 18.6 t ha^{-1}. Although this was a high intensity crowning fire, the majority of consumption loss was due to combustion of forest floor and understory fuels (ca. 87% of total consumption).

Table 4. Pre- and post-wildfire fuel loading in the canopy, understory and forest floor, and estimated consumption during an intense crown fire conducted on March 21, 2008, near the site of the Warren Grove wildfire. Measurements were made in 1 m^2 plots in high intensity burn areas. All units are tons biomass or mass ha^{-1} ± 1 SD. The amount of total consumption accounted for by the overstory, understory, and forest floor is shown as a percent of total consumption %).

Component		Pre-fire	Post-fire	Consumption	%
Overstory[1]	Foliage	3.0	0.5	2.5	13 %
Understory:	Foliage	0.4 ± 0.5	0.4		39 %
	Stems	11.1 ± 6.2	4.3 ± 3.5	6.8	
Forest Floor:	1-hour	12.7 ± 1.6	5.0 ± 1.1	7.7	48 %
	10-hour	2.2 ± 1.1	1.2 ± 0.6	1.0	
	100-hour	0.8 ± 1.1	0.5 ± 0.9	0.2	
Total		30.2 ± 7.9	11.6 ± 3.2	18.6	

[1]Foliage and twig biomass in the canopy as calculated from LiDAR canopy bulk density measurements (Skowronski *et al*. 2010).

PM 2.5 emissions from prescribed burns

The mean value for PM 2.5 emissions during all prescribed burns sampled was 111 ± 46 kg PM 2.5 ha^{-1}. Estimated mean CO_2, CO and NMHC emissions averaged 14,711 ± 6,036, 1,270 ± 521, and 42 ± 17 kg ha^{-1} for all prescribed burns sampled, respectively. When analyzed by forest type, PM 2.5 emissions from a fuel break that was burned at 2-3 year intervals was least, and emissions from pine-oak and pine-scrub oak stands were greatest (Fig. 3). PM 2.5 emissions from the forest floor during the subset of crowning fires in pine-dominated stands averaged 102 ± 20 kg PM 2.5 ha^{-1}, compared to 55 ± 30 kg PM 2.5 ha^{-1} for prescribed burns that did not crown significantly. Values for CO_2, CO and NMHC emissions from the forest floor during crowning fires were estimated at 14,828 ± 2,688, 1,280 ± 232, and 43 ± 8 kg ha^{-1}, respectively.

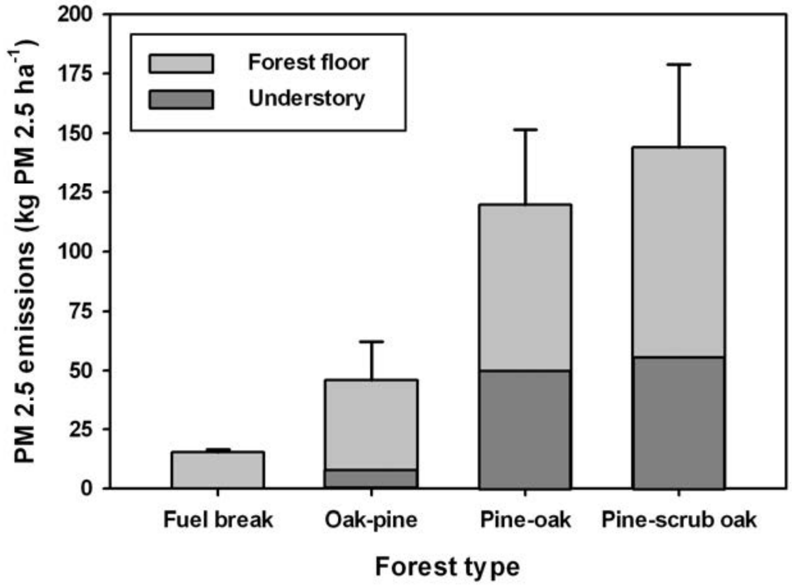

Fig. 3. Mean estimated PM 2.5 emissions during prescribed fires by forest type. Emissions are shown for 1-h and 10-h fuels on the forest floor, and understory vegetation separately.

PM 2.5 emissions from the Warren Grove wildfire were estimated at 115 ± 32 kg PM 2.5 ha^{-1} using the mean emission factor for wildfires listed in Table 1. If we assumed that half of the Warren Grove fire was characterized by smoldering fire due to protective backfire burning, then PM 2.5 emissions increased to 172 ± 46 kg PM 2.5 ha^{-1}.

For 2002-2008, estimated mean annual emissions of PM 2.5 from prescribed burns conducted on public lands by the NJFFS totaled 365 ± 121 tons PM 2.5 yr^{-1}. When variability in loading and annual area treated were considered, low and high estimates were 256 ± 95 and 611 ± 228 tons PM 2.5 yr^{-1} (Fig. 4). Total emissions from the Warren Grove wildfire in 2007, estimated from consumption data in Table 4 for the intense crowing fire that was conducted in 2008, was 727 ± 195 tons PM 2.5. Using mean emission factors for wildfires and prescribed fires together, total emissions from this wildfire were estimated at 1,084 ± 292 tons PM 2.5 (Fig. 4). These two mean estimates of PM 2.5 emissions from the Warren Grove wildfire exceed the average annual emission values calculated for prescribed fires by 2.0 and 3.0 times, respectively.

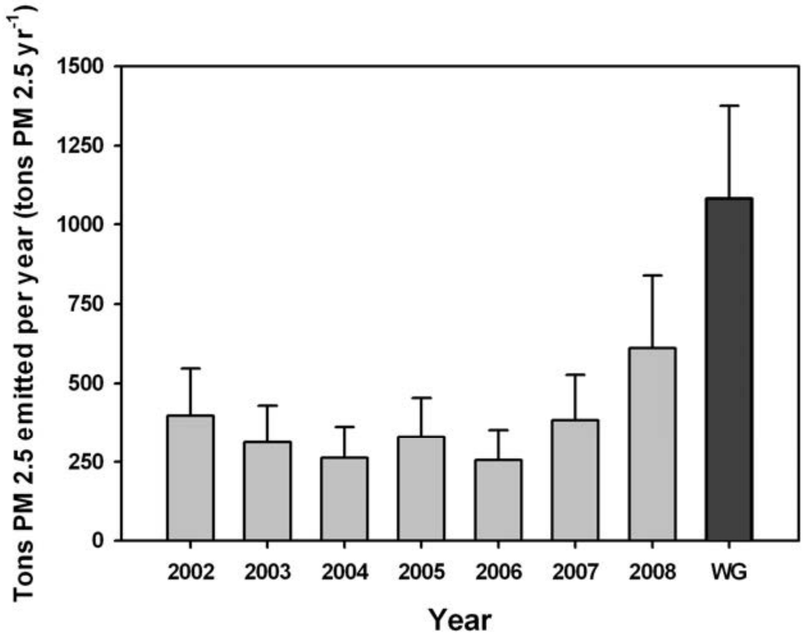

Fig. 4. Estimated annual PM 2.5 emissions for prescribed fires conducted on public lands by the New Jersey Forest Fire Service for 2002-2008. Estimated emissions from the Warren Grove wildfire (WG) on May 15-19th, 2007, are shown for comparison.

PM 2.5 in ambient air and during prescribed fires

Hourly PM 2.5 concentrations were generally less than the current EPA 24-hour standard of 35 εg m^{-3} during hourly measurements made in 2008 (Fig. 5). Three peaks in PM 2.5 concentrations occurred in 2008. The first peak was associated with the prescribed burns conducted near the Cedar Bridge fire tower during the end of March 2008, when we had the instruments near and in prescribed burns (data off-scale in Fig. 5). The second broad peak was associated with increased summer particulates in June-September, 2008, and the third peak in early October corresponds to wildfires in and near Wharton State Forest, when slightly enhanced PM 2.5 concentrations were detected at Silas Little Experimental Forest when prevailing winds were from the southwest. Seasonal mean hourly PM 2.5 concentrations reflected these patterns, with PM 2.5 concentrations averaging 4.40 ± 4.97 εg PM 2.5 m^{-3} from January through May (excluding data from the prescribed fires at Cedar Bridge), 8.53 ± 8.01 εg PM 2.5 m^{-3} during June through August, and 4.89 ± 8.01 εg PM 2.5 m^{-3} during September through December.

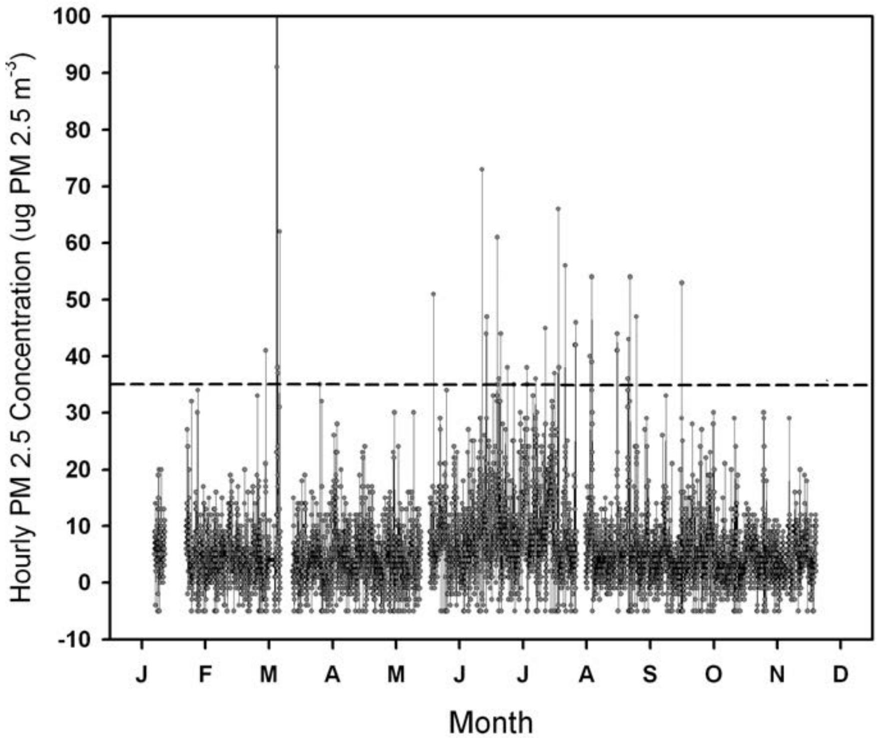

Fig. 5. Hourly PM 2.5 particle concentrations during January ï December 2008 in the Pine Barrens. Data are pooled from collectors at the Silas Little Experimental Forest and near the Cedar Bridge fire tower. The dashed line indicates the current EPA PM 2.5 standard for a 24-hour period.

Closer detail of 24 hour PM 2.5 concentrations measured during the prescribed burning season (January through April) indicates that other than during the direct effects of prescribed fires, fine particulate concentrations were below the current EPA standard of 35 εg PM 2.5 in 2008 (Fig. 6).

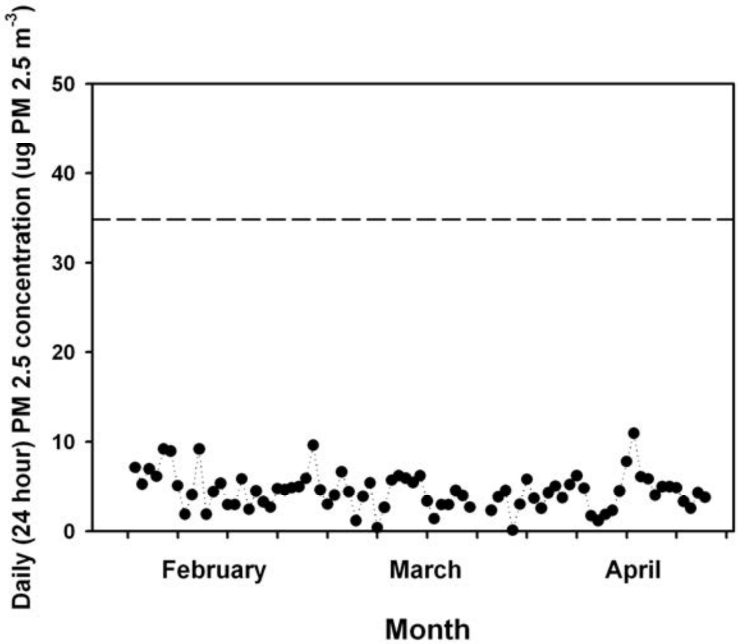

Fig. 6. 24-hour PM 2.5 concentrations for end of January through April 2008 at the Silas Little Experimental Forest, New Lisbon, NJ. The dashed line indicates the current EPA PM 2.5 standard for a 24-hour period.

Highest PM 2.5 concentrations in ambient air were measured during the end of March 2008, when both collectors were located near the Cedar Bridge fire weather tower during prescribed burning operations. A total of 1575 ha were burned in the Greenwood Wildlife Management Area during mid-March 2008, including the monitored stand on March 22, 2008 (Figs. 1, 7 and 8).

During the prescribed burn in the monitored stand on March 22, firing patterns differed between the tower and the feed plot measurement sites, with the burn initiated near the SE end of the feed plot at ca. 10:00 (Fig. 1). At ca. 12:00, the area near the main flux tower was fired. Hourly concentrations peaked at 4155 $\varepsilon g\ m^{-3}$ when the flame front and smoldering fire was burning within 1 m of the instrument, and then decreased exponentially (Figs. 7 and 8). At ca. 15:00 PM, the large block to the north and east of the feed plot was ignited. Hourly PM 2.5 concentrations at the feed plot instrument peaked at 873 $\varepsilon g\ m^{-3}$, coincident with the time that this large block was fired (Fig. 1). By 18:00, a backing fire approached the flux tower from the east. Burning operations continued on the western edge of the block, along SR 539, until well after sunset. Overall, hourly concentrations peaked when flame fronts and smoldering fire were burning close to the instruments, and then decreased exponentially to below ambient air standards within 11 hours (Figs. 7 and 8).

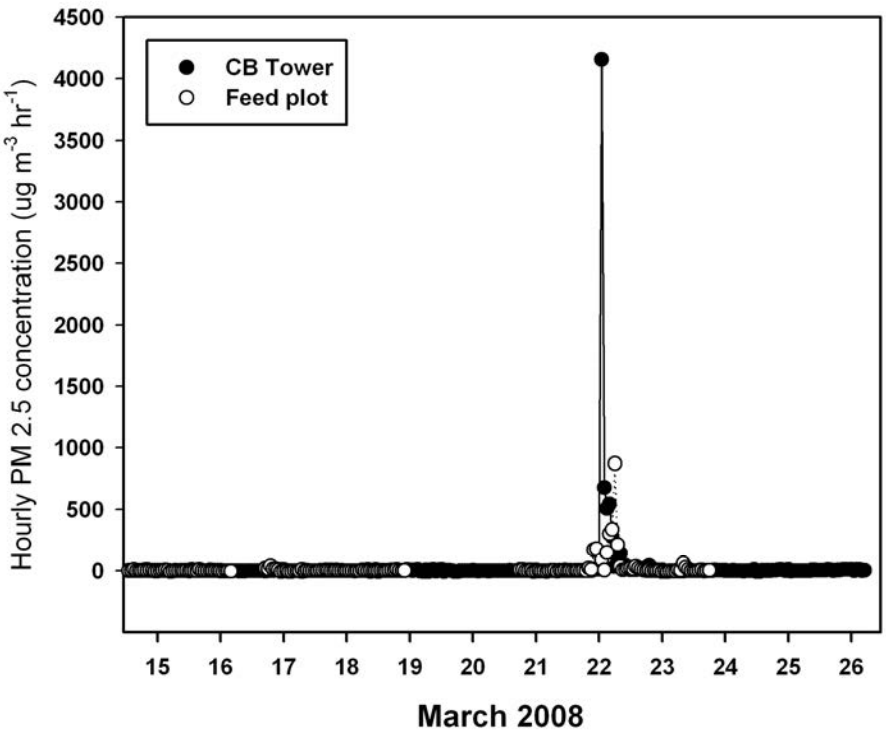

Fig. 7. Hourly PM 2.5 concentrations at the Cedar Bridge flux tower (ǒ) and the adjacent feed plot (ȝ) from March 15th to 26th, 2008.

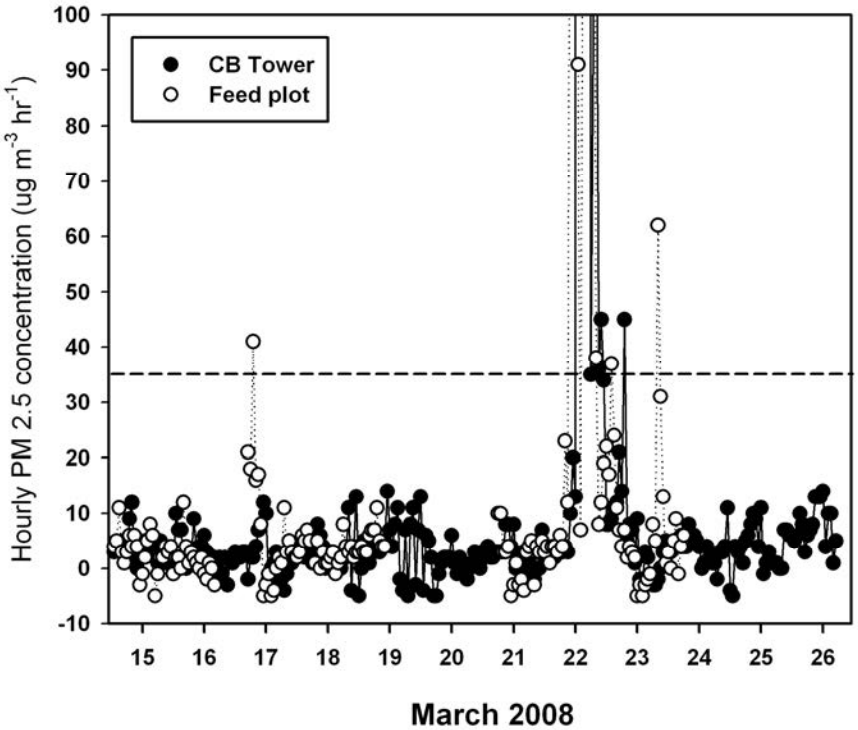

Fig. 8. Inset of hourly PM 2.5 concentrations at the Cedar Bridge flux tower (ŏ) and the adjacent feed plot (ʒ) from March 15th to 26th, 2008. Scale is -10 to 100 εg m^{-3}, and misses the large peaks during the prescribed fire on March 22, 2008, shown in Fig. 7. The dashed line indicates the current EPA PM 2.5 standard for a 24-hour period.

Discussion

The Pinelands National Reserve contains some of the most hazardous fuel types in the Northeastern US (Wright *et al*. 2007; Duvenek and Patterson 2007). We sampled a wide range of fuel loadings in the four upland forest communities, with time since last prescribed burn or wildfire ranging from two years in a fuel control strip, to ca. 45 years at two óoldô stands that had not burned since 1962 (prescribed burn) and 1963 (wildfire in April 1963). While the quantification of fuels in 1 m^2 plots is relatively straightforward, scaling 10 to 20 randomly located plots to the stand level introduces variability into the fuel loading estimates. Likewise, post-burn measurements made within the same stands in a similar manner but not made in the same spatial location as the pre-burn measurements potentially introduces some error into the estimation of consumption losses.

Fuel loading and consumption estimates reported here are generally consistent with previous work in the Pinelands (Burns 1952; Wright *et al*. 2007; Clark *et al*. 2009). For example, Wright *et al*. (2007) show similar forest floor loading for 10-hour fuels (1.86 ± 1.15 t ha^{-1}, t = 1.143, P = 0.246) and understory vegetation in the Pitch Pine photoseries data for the Pinelands. However, 1-hour fuel loading estimates were lower than our values (5.47 ± 1.57 t ha^{-1}, t = 4.770, P < 0.001), likely due to their use of fuel bed depth and bulk density estimates to calculate loading, rather than the use of fuel mass measurements as in our research. Burns (1952) sampled a number of prescribed burn blocks where fires had been conducted over a 15-year interval, and reported that loading of fuels on the forest floor was a strong function of prescribed burn history (Total fuel loading = -2.80 (number of prescribed burns) + 40.41 ton ha^{-1}, $r^2 = 0.79$, $P < 0.01$). His mass estimates for the forest floor were higher than those reported here, but he included duff mass in the O horizon with 1-hour and 10-hour fuel estimates. Taken together, our estimates for 1-hour and 10-hour fuels on the forest floor are intermediate between the Photoseries data reported by Wright *et al*. (2007) and those reported in Burns (1952).

Fuel loading, spatial arrangement, fuel moisture content, prevailing meteorological conditions (relative humidity, temperature, wind speed), and ignition patterns are critical factors controlling fuel consumption during prescribed fire treatments. Dry fuels enable ignition and subsequent fuel consumption. Meteorological conditions then become key factors in controlling fire spread rates and the amount of fuel consumed during prescribed fires. However, our results indicate that over the range of conditions that occurred during operational prescribed fires conducted by the NJFFS that we quantified from 2004 to 2009, initial fuel loading had an overriding effect on the amount of fuel consumed. Prescribed burns are conducted within a relatively narrow window of appropriate meteorological conditions, with air temperature typically not exceeding 16 °C, and RH above 40%. In our data, fuel moisture contents were variable, and soil temperature ranged from ca. 0 to 11 °C. Thus, it may be incorrect to apply the results reported here to prescribed fires conducted outside of this set of conditions.

In contrast to our results, Goodrick *et al.* (2010) reported a relatively weak relationship between initial fuel loading and fuel consumption ($r^2 = 0.34$) for a range of studies conducted in Longleaf pine-dominated stands in South Carolina. When components of the National Fire Danger Rating System, primarily the Burning Index (BI) were included in their regression equations, predictive power improved considerably ($r^2 > 0.8$).

Mean fuel consumption during operational prescribed fires reported here was much less than that measured during a large crowning prescribed fire that was conducted on March 21, 2008 near the site of the Warren Grove wildfire. Pre- and post-burn measurements indicated that this stand did have relatively high loading, but was reflective of much of the area burned in the 2007 wildfire, most of which had not burned since the early 1970ĝs (see Figure 1 in Clark *et al*. 2009).

We used standard emission factors to calculate the release of PM 2.5 and other constituents from prescribed fires. Factors which affect the actual release rates of PM 2.5 and other criterion pollutants include fuel moisture content and the efficiency of fuel combustion, both of which can affect the balance between flaming and smoldering combustion (see Table 2). Many of the fuel beds on forest floor sampled in these upland forests were generally uniform due to repeated prescribed fires conducted since the 1950ĝs, and emissions occurred over a relatively short period of time. The undifferentiated organic matter layer was rarely consumed, in contrast to the burning of thick duff and organic matter layers in lowland forests. Slow consumption of organic material lower in the forest floor of lowland and wetland forests can lead to much greater emissions of PM 2.5, due to smoldering over longer time periods (e.g., Mickler *et al*. 2010).

Total annual emissions from prescribed burns conducted by NJFFS in the Pinelands between 2002 and 2008 averaged 365 tons PM 2.5 $year^{-1}$, and ranged from 256 to 611 tons PM 2.5 yr^{-1}. When considered in the context of overall total PM 2.5 emissions in New Jersey (29,103 tons PM 2.5 yr^{-1} in 2002), prescribed fires conducted in the Pinelands contributed an estimated 1.3 %, with a range of 0.9 to 2.1 % of total PM 2.5 emitted to the atmosphere by all sources in the state in 2002. The three largest sources in 2002 were residential wood combustion (9,363 tons PM 2.5 yr^{-1}), restaurant operations (2,226 tons PM 2.5 yr^{-1}), and heavy duty diesel vehicles (1,329 tons PM 2.5 yr^{-1}). Total estimate PM 2.5 emissions from the Warren Grove wildfire in 2007 was estimated at 1,084 ± 292 tons PM 2.5, and represented 3.7% of total annual PM 2.5 emissions in New Jersey in 2002. When considered on a daily (24-hour) basis, emissions of PM 2.5 over the two major burning days during the Warren Grove fire (May 15th and 16th, 2007) were 6.7 times greater than the mean daily emissions reported for 2002 in New Jersey.

PM 2.5 Concentrations in Ambient Air

The temporal scales (sampling period, duration and frequency) of measurement are important for the assessment of human exposure to PM 2.5 and other EPA criterion pollutants. In many areas, PM 2.5 concentrations have been measured over a number of years, providing estimates of daily, seasonal and annual averages. In general, seasonal variations in PM 2.5 at many sites can be attributed to fluctuations in meteorological factors. In contrast, diurnal variations in PM 2.5 mainly depend on the fluctuations in the intensity of local pollution sources, e.g., fires, roads, air traffic, etc.

Ambient PM 2.5 concentrations in the Pinelands were highest on average from June through August, and were associated with photochemical smog and regional trends in PM 2.5 dispersion. Ambient ozone levels are also higher at this time of year, as a component of photochemical smog. Thus, trends in ambient PM 2.5 concentrations reflected seasonal synoptic weather patterns, especially patterns of mean above-canopy windspeed and direction, incident solar radiation, and air temperature. The patterns of seasonal variation in PM 2.5 concentrations in ambient air reported here for the Pinelands are consistent with data collected at Brigantine, NJ, which shows a similar summer peak in PM 2.5; seasonal daily (24-h) averages for Brigantine from 2000-2004 were 9.32 ± 4.78 εg m^{-3} for January to May, 13.86 ± 10.64 εg m^{-3} for June to August, and 8.28 ± 5.09 εg m^{-3} in September to December. Patterns in seasonal ambient PM 2.5 concentrations reported here are also consistent with a second PM 2.5 monitoring station to the east of the Pine Barrens in Toms River, NJ, where annual PM 2.5 concentrations averaged 11.8 εg m^{-3}.

Our data from the prescribed fires near the Cedar Bridge fire tower in March 2008 show that PM 2.5 concentrations at prescribed fires can be very high during burning operations, but also that plume dispersion occurs rapidly during the relatively windy periods in late winter and early spring, resulting in relatively low PM 2.5 emissions in less than 24 hours. Although a regional analysis of the impacts of prescribed burning on PM 2.5 concentrations in ambient air is beyond the scope of this research, other regions in the US have reported the effects of prescribed burns and wildfires on ambient PM 2.5 concentrations. For example, Zeng *et al*. (2008) reported that prescribed burning in the southeast US during the spring can account for up to 15% of total PM production, and that ambient PM 2.5 concentrations across the region can increase by 25 µg PM 2.5 m^{-3} during periods of intense prescribed burning. Jaffe *et al*. (2008) found statistically significant relationships between the area burned and seasonal PM 2.5 concentrations in ambient air, and between the amount of total fuel burned and seasonal PM 2.5 concentrations in ambient air in the western US. They used these relationships to calculate the addition amount of PM2.5 due to fires in Regions 1-5 in the western states, and reported summer-long enhancement of PM2.5 due to fires is 1.84, 1.09, 0.61, 0.81, and 1.21 εg PM 2.5 m^{-3}, respectively. Additional PM 2.5 levels were approximately twice these values during large fire years.

We are currently developing a more accurate GIS database of prescribed fire treatments conducted by the NJFFS and fire managers at Fort Dix from 1990-present, located in the forested areas of the Pine Barrens described above for fuel loading measurements (e.g., Clark *et al.* 2009). These will be used to estimate average amounts of fuel consumed more accurately than the method used above, and we can then refine our estimates of average annual emissions from stands burned by the NJFFS and federal wildland fire managers. In addition, we plan to monitor and model PM 2.5 emissions from prescribed fires more accurately in 2011-2013 (e.g., Heilman *et al*. 2010).

Summary

Consumption of 1-hour and 10-hour fuels on the forest floor and understory shrubs and oaks were quantified in 24 operational prescribed fires conducted by the NJFFS in the Pinelands of New Jersey. Emissions were calculated using emission factors, and atmospheric PM 2.5 measurements were made in ambient air and during prescribed fires.

Pre-burn 1-hour and 10-hour fuel loading was greater in Pitch pine - scrub oak stands than in stands that were characterized with a greater biomass of overstory oaks. Across all prescribed burns measured, consumption of fuels averaged 6.1 ± 3.2 t ha^{-1} on the forest floor and 3.5 ± 2.5 t ha^{-1} for understory vegetation, and consumption of both were strong linear functions of initial fuel loading. PM 2.5 emissions averaged 46 ± 15 kg PM 2.5 ha^{-1} from oak-dominated stands and 126 ± 33 kg PM 2.5 ha^{-1}from pine-dominated stands. For comparison, total fuel combustion and PM 2.5 release calculated from the Warren Grove wildfire in 2007 averaged 18.6 t ha^{-1} and 172 ± 46 kg PM 2.5 ha^{-1}. Our results indicate that forest floor consumption is often the predominate site of PM 2.5 production during prescribed fires, even during crowning fires in Pitch pine -scrub oak stands.

Estimated annual PM 2.5 emissions from prescribed fires were a small fraction of annual emissions from all sources in the state. Calculated PM 2.5 emissions from the Warren Grove wildfire in 2007 were 2 to 3 times greater than average annual emissions from prescribed burns in the Pinelands. During a series of prescribed burns in 2008, measured air concentrations spiked and then dropped exponentially to below 35 µg m^{-3} within 11 hours following the burns. Our research facilitates a more accurate estimate of PM 2.5 production during operational fuel reduction activities, based on knowledge of pre-burn fuel loading. Our data also suggests that annual emissions of PM 2.5 from prescribed fires would be less than years where wildfires burned > ca. 5000 ha in the Pinelands. Thus, it is likely that in addition to reducing wildfire risk to property and human welfare, prescribed burning may actually reduce human exposure to hazardous air pollutants.

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South-European firefighters' exposure to air pollutants

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Abstract
Smoke pollution due to wildland fire events can represent an important public health issue for communities directly affected and for personnel involved in firefighting operations. The current state of knowledge about firefighter's exposure to smoke and potential health impacts is still scarce, in particular within the European context. The main purpose of this work is to contribute to the scientific knowledgebase concerning firefighter's exposure to smoke, providing and analyzing exposure measured values during experimental field and wildfires. The measurements of individual exposure of firefighters were conducted before and during the 2008 and 2009 fire seasons, in Portugal, for experimental burns and wildfires, respectively. Data on individual exposure to CO, NO_2, VOC, and PM2.5 were obtained for firefighters equipped with portable 'in continuum' measuring devices. The air pollutant exposure values, acquired during fire experiments and wildfires were compared with the standard values recommended by the World Health Organization (WHO) and also with limits established in terms of Occupational Exposure Standard (OES). These measurements and analysis of firefighter's individual exposure to toxic gases and particles in fire smoke experiments in Europe indicate that urgent measures to avoid these levels of exposure are needed.

Additional keywords: wildland fires; field experimental fires; firefighter's exposure; occupational exposure standards; World Health Organization; south-Europe

Introduction

There is a growing awareness that smoke produced during wild-land fires can expose individuals and populations to hazardous concentrations of air pollutants. However, the current state of knowledge about the potential health impacts on firefighting personnel is still scarce, in particular within the European context. The most extensive measurements of smoke exposure among wildland firefighters were conducted in the United States of America (USA) and Australia (McMahon and Bush, 1992; Materna *et al*. 1993; Reinhardt and Ottmar 2000; Reinhardt *et al.* 2000; Reinhardt and Ottmar 2004; Reisen and Brown 2009). From these studies it was possible to conclude that firefighters can be exposed to significant levels of carbon monoxide (CO) and respiratory irritants, including formaldehyde, acrolein, and respirable particles (Reinhardt and Ottmar 2000; Reinhardt and Ottmar 2004).

In Europe, where an average annual value of 500,000 hectares of forest was consumed by fire in the last 29 years (EC 2009), there is a considerable lack of data on personal smoke exposure. Moreover exposure results from the USA and Australia experiments may not be applicable to the European wildland firefighters due to differences in vegetation, fire conditions and firefighting operations. Therefore it is crucial to assess exposure at the individual level and within the European context to determine whether exposure could result in health damage and what primary factors influence exposure. Based on previous smoke measurements along experimental field fires (Miranda *et al*. 2005) Miranda *et al.* (2010) presented the first smoke exposure measurements along experimental field fires in Europe concluding that urgent measures are needed to avoid the high levels of firefighter's exposure to air pollutants.

The main purpose of this paper is to go further in this research presenting and comparatively analyzing data on the individual exposure along experimental field fires and wildfire suppression activities and comparing them with the air quality thresholds established by the World Health Organization and with the Occupational Exposure Standard.

Methods

The measurement of firefighters individual exposure to smoke was conducted during: (i) 2008 and 2009 Gestosa fire experiments, in Central Portugal, at the end of the spring season; and (ii) 2008 and 2009 fire seasons (May-October) in districts of Central Portugal, namely, Aveiro, Coimbra, and Leiria. The experimental fires study area is located in the mountain range of Lousã, Central Portugal, at an altitude between 900 and 1,100 m. The vegetation is mainly composed of continuous shrubs of three dominant species: *Erica umbellata*, *Ulex minor* and *Chamaespartium tridentatum.* The forest in the areas affected by wildland fires is characterized by resinous, deciduous, and eucalyptus species, and shrubs.

Data on individual exposure to CO, particles with an aerodynamic diameter lesser than 2.5 µm (PM2.5), nitrogen dioxide (NO_2), and volatile organic compounds (VOC's) were obtained from a group of ten firefighters equipped with portable 'in continuum' measuring devices. More information about the monitoring devices can be found in Miranda *et al*. (2010).

Aiming to contribute to a better understanding of the smoke fire impacts on the firefighter's health, the measured results were compared to the values recommended by WHO (Table 1), which were established for the protection of human health from the effects of air pollution. These recommended values are time-weighted averages.

Table 1. Air quality limit values for the protection of human health recommended by WHO.

Air pollutant	WHO
PM2.5	25 $\mu g.m^{-3}$ (24 hours) 10 $\mu g.m^{-3}$ (1 year)
NO_2	200 $\mu g.m^{-3}$ (1 hour) 40 $\mu g.m^{-3}$ (1 year)
CO	100 $mg.m^{-3}$ (15 minutes) 60 $mg.m^{-3}$ (30 minutes) 30 $mg.m^{-3}$ (1 hour) 10 $mg.m^{-3}$ (8 hours)

Measured exposure values were also treated and compared to the OES limit values. According to the American Conference of Governmental Industrial Hygienists (ACGIH), Occupational Exposure Standard (OES) are presented as: (i) time-weighted average limit (TWA), (ii) short-term exposure limit (STEL), and (iii) peak limit. In Portugal, OES values for occupational activities are established by Occupational Health and Safety (OHS) regulations, namely through the Portuguese Regulation NP 1796:2007, which includes CO, PM, and NO_2

TWA values. The PM TWA value was defined for different types of particles and is not specific for smoke constituents. The NP 1796:2007 also includes the STEL value for NO_2. These regulations tend to follow those established by the ACGIH. Table 2 presents the OES values for the different air pollutants analyzed under this study. For some air pollutants, these values are not available (n.a.) in national or international regulations.

Table 2. OES limit values for different air pollutants contained in biomass burning smoke.

Air pollutant	TWA	Reference	STEL	Reference	Peak Limit	Reference
CO	25 ppm	NP 1796:2007	200 ppm	Australian legislation	400 ppm	Australian legislation
Respirable particles without other classification	3 $mg.m^{-3}$	NP 1796:2007	n.a.	n.a.	n.a.	n.a.
NO_2	3 ppm	NP 1796:2007	5 ppm	NP 1796:2007	20 ppm	NIOSH
VOC	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Results

Results are presented for experimental fires and wildfires fires and compared with air quality and exposure thresholds separately.

WHO standard values

To assess firefighter's exposure to smoke pollutants and taking into account the recommended air quality limit values (see Table 1), 1 hour averages for CO, VOC and NO_2 and 24 hours averages for PM2.5 were calculated for each monitored firefighter. Tables 3 and 4 present the maximum hourly-averaged values for CO, NO_2 and VOC and the daily averages for PM2.5 for Gestosa 2008 and 2009 experimental fires and for wildfires for the same two fire seasons, respectively. PM2.5 daily-averaged values were calculated considering zero PM2.5 values for the non-exposure time periods. Bold values in Tables 3 and 4 correspond to exceedances to the WHO thresholds.

Table 3. Highest hourly averages of CO, NO_2 and VOC and 24 hour averages for PM2.5 during Gestosa 2008 and 2009.

Firefighter	CO ($\mu g.m^{-3}.h^{-1}$)	PM2.5 ($\mu g.m^{-3}.day^{-1}$)	NO_2 ($\mu g.m^{-3}.h^{-1}$)	VOC ($\mu g.m^{-3}.h^{-1}$)
Gestosa 2008				
1	**32,479**	**260**	**2,163**	1,585
2	**73,033**	**184**	**4,172**	3,934
3	**47,223**	**306**	**3,641**	415
4	**50,881**	**240**	**274**	1,789
5	**33,178**	**738**	**709**	599
6	**49,078**	**735**	n.d.	2,917
7	n.d.	**684**	**2,599**	1,838
8	**35,847**	**479**	**609**	1,520
9	**48,259**	**610**	**4,571**	5,302
10	n.d.	**206**	82	2,097
Gestosa 2009				
1	12,586	**44**	**344**	54
2	22,814	**400**	**332**	526
3	**32,222**	**124**	**485**	496
4	**39,090**	**315**	142	343
5	**36,199**	**152**	**884**	337
6	**30,669**	**40**	**1,544**	10,342
7	4,903	**66**	132	62
8	**41,9389**	**396**	**788**	1,377
9	**42,023**	**176**	**802**	376
10	17,899	**358**	**1,091**	1,076

n.d. – no data

Table 4. Highest hourly averages of CO, NO_2 and VOC and 24 hour averages for PM2.5 during wildfires 2008 and 2009.

Firefighter	Date	CO ($\mu g.m^{-3}.h^{-1}$)	PM2.5 ($\mu g.m^{-3}.day^{-1}$)	NO_2 ($\mu g.m^{-3}.h^{-1}$)	VOC ($\mu g.m^{-3}.h^{-1}$)
3	01/08/2008	3,039	**42**	**3,807**	5,929
4	02/08/2008	**105,428**	n.d.	**6,481**	1,180
5	17/08/2008	14,185	**118**	**1,167**	2,078
6	19/08/2008	**50,830**	**83**	**1,173**	n.d.
7	31/07/2008	**39,778**	**28**	72	2,224
9	18/07/2008	-	**2,149**	**5,584**	476
14	28/07/2009	15,033	**157**	86	575
17	08/09/2009	**67,172**	5	**2,229**	2,184

n.d. – No data

For all the monitored firefighters, a considerable number of the air pollutants concentration values acquired during their activity was beyond the limits recommended by WHO (see bold values in Tables 3 and 4), namely for PM2.5, CO and NO_2.

Daily averages of PM2.5 concentration values as high as 700 $\mu g.m^{-3}$, for the fire experiments, or 2,000 $\mu g.m^{-3}$ for the wildfires, were obtained, well above the recommended limit of 25 $\mu g.m^{-3}$, even considering that during the non-exposure hours the concentration was 0 $\mu g.m^{-3}$. In terms of CO, hourly averaged values higher than 73,000 $\mu g.m^{-3}$ were monitored, clearly above the 30,000 $\mu g.m^{-3}$ recommended by the WHO. In the case of the wildfire exposure measurements values even reached 105,000 $\mu g.m^{-3}$. Once again the highest NO_2 hourly averaged measured value was measured along the wildfires reaching 6,000 $\mu g.m^{-3}$, and a little bit smaller 4,500 $\mu g.m^{-3}$ for the fire experiments. In both situations, values are much higher than the recommended hourly value of 200 $\mu g.m^{-3}$. Due to the lack of recommended or legislated values for total VOC it is not possible to evaluate the measured values in terms of human health protection.

OES standard values

Regarding OES values, Table 5 (which only concerns Gestosa 2008) shows for each firefighter and each pollutant, the TWA values, the number of exceedances of the peak limit (and the maximum value), and indicates if the STEL was exceeded or not.

Table 5. TWA, number of peak (n), peak values, and TLV-STEL fulfilment for CO, NO_2, VOC, and PM2.5 during Gestosa 2008.

Firefighter	Parameter	CO (ppm)	PM2.5 ($\mu g.m^{-3}$)	NO_2 (ppm)	VOC (ppm)
1	TWA	7.60	773.40	0.90	0.19
	n (Peak value)	**1 (493.30)**	(13,593.00)	0 (3.00)	(88.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
2	TWA	9.60	551.00	1.90	0.28
	n (Peak value)	**9 (486.60)**	(13,768.00)	0 (9.00)	(35.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
3	TWA	10.70	917.10	1.80	0.03
	n (Peak value)	0 (198.80)	(15,590.00)	0 (8.00)	(4.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
4	TWA	13.10	1,439.60	0.10	0.16
	n (Peak value)	0 (386.60)	(19,953.00)	**1 (33.00)**	(11.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
5	TWA	14.80	2,196.40	0.10	0.12
	n (Peak value)	**2 (499.80)**	(19,134.00)	**1 (22.00)**	(12.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
6	TWA	19.80	2,187.50	n.d.	0.47
	n (Peak value)	**6 (454.40)**	(16,516.00)	n.d.	(63.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	n.d.	n.a.
7	TWA	n.d.	2,052.80	1.10	0.22
	n (Peak value)	n.d.	(17,635.00)	0 (10.00)	(23.00)
	Fulfillment of TLV-STEL criteria	n.d.	n.a.	Yes	n.a.
8	TWA	11.80	1,435.40	0.10	0.19
	n (Peak value)	0 (376.70)	(14,969.00)	0 (4.00)	(15.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
9	TWA	13.70	1,829.30	2.20	0.69
	n (Peak value)	**2 (421.00)**	(18,286.00)	0 (5.00)	(20.00)
	Fulfillment of TLV-STEL criteria	**No**	n.a.	Yes	n.a.
10	TWA	n.d.	618.50	0.02	0.25

n (Peak value)	n.d.	(13,989.00)	0 (4.00)	(15.00)
Fulfillment of TLV-STEL criteria	n.d.	n.a.	Yes	n.a.

n - Number of exceedances to the peak limit
n.a. - Not applicable
n.d. – No data

From the analysis of the results presented in Table 5, it can be seen that there are no exceedances of the TWA value for any of the monitored pollutants. However, TWA was calculated considering time periods which are non-burning periods and with very low exposure or even zero values. The authors believe that the eight hours time weighted averages may not be suitable for this kind of occupation, due to the high variations of concentrations in relatively short term exposure periods. For instance, the peak limits were surpassed for the pollutants with available limit values (see Table 5), namely CO and NO_2.

In fact, during Gestosa 2008 the CO peak value was exceeded for five firefighters (ranging from 1 to 9 times each). The highest recorded peak was 499.80 ppm, near the maximum value of the working range of the equipment (0 – 500 ppm). When analyzing the NO_2, only two values higher than the peak value are observed with a maximum of 33 ppm.

There is no National or International legislation that sets TWA, STEL or peak limits for the total VOC, although peak limits are set for specific compounds. Thus, it is not possible to compare the monitored concentrations with any limit value. Previous studies (Reinhardt *et al.* 2000; Reinhardt and Ottmar 2004) have identified formaldehyde, and acrolein as the main toxic VOC emitted by bushfire; other studies (De Vos *et al.* 2009; Reisen and Brown 2009) have also identified those compounds as well as acetaldehyde, benzene, toluene, xylenex, and phenol. Those authors found that these compounds were in concentrations below 1 ppm. We measured total VOC peak concentrations as high as 88 ppm; further research would be interesting for identifying the concentrations and speciation of VOC.

Since there is not a specific value of TWA for particles emitted by wildfires or prescribed burns, the ACGIH's TWA of 3 $mg.m^{-3}$ for respirable particles was selected for the analysis. However, because ACGIH assumes respirable particles as PM3.5 (sampled with a 50% efficiency at 3.5 µm), and this study considers PM2.5 (sampled with a 50% efficiency at 2.5 µm), the ACGIH's TWA will only be used as a reference value. All the monitored firefighters are within the allowed OES for particulate matter; the highest calculated TWA was 2.196 $mg.m^{-3}$ and occurred in 2008. The maximum measurable instantaneous concentration of 20 $mg.m^{-3}$ was reached several times. Therefore, it is possible that values higher than the measured peaks have occurred during the experiments because the concentration was out of the equipment measurement range.

Once again and using the same procedure described for the experimental field fires, individual exposure values acquired by the ten firefighters during wildfires in 2008 and 2009 were compared with the OES. None of the exposure periods lasted for a period of 8 hours. Table 6 lists the TWA values, the number of exceedances of the peak limit (and the maximum value), and indicates if STEL criteria is fulfilled or not, for each pollutant. Bold data mean exceedances to the OES.

Table 6. TWA, number of peak (n), peak values, and TLV-STEL fulfilment for CO, PM2.5, NO_2 and VOC during wildfires 2008 and 2009.

Firefighter	Date	Parameter	CO (ppm)	PM2.5 ($mg.m^{-3}$)	NO_2 (ppm)	VOC ppm)
3	01/08/2008	TWA	5.8	0.5	1.9	2.3
		n (Peak value)	0 (143)	6.9	0 (3)	5
		Fulfillment of TLV-STEL criteria	Yes	n.a.	No	n.a.
4	02/08/2008	TWA	22.8	n.d.	0.17	0.9
		n (Peak value)	**6 (684)**	n.d.	0 (6)	21
		Fulfillment of TLV-STEL criteria	**No**	n.a.	No	n.a.
5	17/08/2008	TWA	12.6	0.9	1	0.8
		n (Peak value)	0 (367)	11.3	0 (3)	34
		Fulfillment of TLV-STEL criteria	**No**	n.a.	No	n.a.
6	19/08/2008	TWA	**53.4**	1.9	n.d.	0.8
		n (Peak value)	**1 (410)**	6.7	n.d.	12
		Fulfillment of TLV-STEL criteria	**No**	n.a.	n.d.	n.a.
7	31/07/2008	TWA	2.8	0.2	1.1	0.04
		n (Peak value)	0 (128)	4.2	0 (5)	5
		Fulfillment of TLV-STEL criteria	Yes	n.a.	No	n.a.
14	28/07/2009	TWA	7.9	1.4	0.1	0.2
		n (Peak value)	**1 (413)**	11.8	0 (0.9)	42
		Fulfillment of TLV-STEL criteria	Yes	n.a.	No	n.a.
17	20/09/2009	TWA	5.1	n.d.	n.d.	n.d.
		n (Peak value)	**1 (893)**	n.d.	n.d.	n.d.
		Fulfillment of TLV-STEL criteria	Yes	n.a.	n.d.	n.a.
18	13/08/2009	TWA	23.8	n.d.	n.d.	n.d.
		n (Peak value)	**1 (405)**	n.d.	n.d.	n.d.
		Fulfillment of TLV-STEL criteria	**No**	n.a.	n.d.	n.a.

n - Number of exceedances to the peak limit.
n.a. - Not applicable.
n.d. - No data.

For CO there are several exceedences to the TWA, STEL and peak values, with the highest peak value of 893 ppm. For 47% of the reported occurrences, the CO peak limit concentration was exceeded and for some of them more than once. The STEL also exceeded the TLV for almost 40% of the monitored situations. Regarding longer exposures and the TWA analysis, only two firefighters (numbers 5 and 6) registered values higher than the threshold. For these firefighters the other parameters (STEL and peak value) also indicate a high exposure to CO.

Therefore, they have been exposed to very high values of CO for short periods, and also to not so high values, but still serious, over a long period of time.

All the monitored firefighters are within the allowed occupational exposure standard for particulate matter. The highest calculated TWA and peak value were 2.1 $mg.m^{-3}$ and 19.7 $mg.m^{-3}$ respectively and occurred in 2008.

The NO_2 results for all firefighters indicate no exceedances of the TWA, STEL and peak values. The highest peak value was 9 ppm, well below the 25 ppm peak limit.

Conclusions

Usually, the amount and characteristics of noxious exposure of wild-land forest firefighters is not widely recognized; more attention has been drawn upon the risks of urban firefighting. This work indicates that wildland firefighters can be exposed to very high concentrations of CO, PM2.5, and also to high concentrations of NO_2 and VOC, with potential harmful effects on their health, even on relatively small prescribed fires and wildfires. Particular concern has to be given to exposure to CO, namely to the peak and short-term very high exposure values that can occur. This type of exposure can create disorientation and even for short-time periods this can lead to firefighting decisions that are not 100% based on clear thinking.

Firefighter exposure cannot directly be associated to the size of the area burned by a wild-land fire. Sometimes firefighters are exposed to higher doses on small wildfires because the strategy could be to contain the fire and not to make a direct attack as is usually the case on smaller fires. Another important aspect that influences exposure levels is the firefighter position and function of his activities.

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BlueSky-enabled Smoke Tools

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Abstract:
Smoke and air quality information has an important role in wildland fire decision making. The BlueSky Smoke Modeling Framework has provided a basis for many different national and regional smoke and air quality forecasts. Several new tools were brought online this spring, allowing fire managers and decision makers to better access and user interactivity. These tools include an enhanced national forecast and several improved regional forecasts in the west, as well as better user interfaces for accessing smoke information through Google Earth and GIS. In addition, a new tool, BlueSky Playground, lets users interact with the BlueSky Framework in real-time, choosing the models best suited to their application, and customizing information throughout the process. Through the Playground, users can create a smoke dispersion forecast, then change values and see the difference all within a few moments and without the need to download any models or data. These tools are ushering in a new, more interactive and more responsive mode of exploring and utilizing smoke model forecasts.

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Sub-canopy Transport and Dispersion of Smoke: An Overview of the Observation Dataset Collection and Future Model Development

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Abstract:
A research prescribed burn was accomplished on The Nature Conservancy's Calloway Forest/Sandhills Preserve on March 7, 2010. The burn was done to achieve land management objectives and to provide observational data that will help with the development of prescribe burning oriented tools in the BlueSky Smoke Modeling Framework (BlueSky Framework). Fuel loadings were measured prior to the burn to provide accurate inputs for the consumption and emission models used in the daily 1 km BlueSky Framework run, which predicted smoke dispersion for the burn unit. Three towers, two inside the burn unit and one outside were set up and instrumented with meteorological and tracer-gas sensors. Observations of the small scale changes in winds, temperature, relative humidity, and trace gasses within and outside the burn unit were made. These data were used to characterize sub-canopy turbulence and smoke plume thermodynamic structure as the fire progressed through the unit. Carbon monoxide sensors deployed inside and PM2.5 monitors deployed outside the burn unit provided additional information, including the presence or absence of smoke. All of these data were collected to characterize the smoke emissions and dispersion from low intensity fires and smoldering fires. The object of this research was to gather the necessary data required to develop a new capability within the BlueSky Framework that is geared specifically towards low-intensity/smoldering emissions often found during and after prescribed burning.

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Uncertainties in Fuel Loading, Fire Consumption, Plume Rise, and Smoke Concentration Calculations

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Abstract:
Many models exist for calculations of fuels, consumption, emissions, plume rise, and smoke impacts from fire. Recent work done through the Smoke and Emissions Model Intercomparison Project (http://semip.org) has shown that inter-model differences can have a profound effect on the resulting answers. Additionally, interactions between models can also result in unexpected or unwanted dependencies between model choices at different steps (e.g. fuel loadings and fire consumption). We present an overview of the work done by the SEMIP project to date, including the cross comparisons between LANDFIRE, the new FCCS fuel maps, and other fuel loading maps, as well as analyses of fire location and plume rise calculations based on their effect on modeled ground smoke concentrations. A companion poster presents these results in greater detail, as well as how to access the full set of results via the SEMIP Viewer website. For users interested in information from a specific fire or in a regional inventory or smoke analysis these comparisons can be useful in understanding the uncertainties resulting from different model choices.

Bushfire politics and management in Australia: where are the gatekeepers?

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Abstract

Bushfire management in Australia is traditionally governed by ‘the Bushfire Cycle’ï the revolution of a wheel of boom and bust in which calamitous fires are followed by inquiries, upgraded bushfire management systems, absence of calamities, apathy, system degrade and another calamity. In the second half of the 20th century this cycle was derailed. A fundamental truth was acknowledged: without effective bush fire management, no other objective can be achieved. The unsung heroes, who I call the bushfire gatekeepers, were successful in minimising the damage caused by high intensity forest fires for the best part of a generation. They used prescribed fire to reduce fuels so that when wild fires occurred they could be more easily suppressed.

Across forested Australia, this system was largely abandoned during the 1990s. The emphasis shifted from preparedness and damage mitigation to suppression. The result was a series of terrible bushfires. Subsequent Inquiries have invariably promoted the need for increased fuel reduction burning.

However, prescribed burning is an anathema to environmentalists and many academics. Australia now lacks strong, politically-neutral leadership that would drive a fire policy based on fuel reduction, and experienced people on the ground to carry it out. It is the people on the ground, the gatekeepers, who will be hardest to replace in the short term.

The bushfire outlook for Australia is bleak, but long-term change is possible. An optimistic scenario can be visualised.

Additional keywords: wildfire preparedness, damage mitigation. Fuel reduction burning,

Australian bushfire management; bushfire history

Introduction

I was taking my grand-daughters for a swim in the Swan River one hot day last summer when a trio of water-bombing helicopters flew over, buckets swaying. They were on their way to a small scrub fire down the coast somewhere. To my surprise, the crowd on the beach stood as one, and cheered resoundingly, as if sending heroic troops off to war. It made me think about one of the great ironies in the Australian bushfire scene: the attitude to heroes.

Australians have always loved their heroes. At one time they were explorers, pioneers, settlers, poets and soldiers. Today mostly they are football players. But also high on the list of national heroes are our firefighters. Every summer we celebrate them: the water bombing pilots swooping down into the flames, the yellow-jacketed fire crews saving the occupants of a burning house, the grizzled fireman nursing a charred koala, or the emergency service chief, resplendent

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in a glittering uniform, calling the shots in a glittering control centre. Australian firefighters are justifiably admired and respected. The men and women at the fire front are tough, resourceful and courageous; their work is dangerous and unpleasant. A great many (probably a majority) are volunteers and they make a selfless commitment.

Australian bushfire management also has its pantheon of unsung heroes. Although they are virtually unknown outside the narrow confines of our tiny fire community, they have a revered status within it. Among ourselves we often remember with admiration the pioneering fire research scientists like Alan McArthur and George Peet, the brave and innovative forestry leaders of the 1920s and 1950s, and the technological wizards, aviators and engineers who gave us our modern fire prevention and firefighting capabilities.

But there is another category of unsung bushfire heroes. They are the focus of my paper today. These heroes are not just unsung, but are also unrecognised and unknown to the public; they are even largely unremembered within the modern fire community. And they are on the verge of extinction. I call them the gatekeepers. They are the people who óminded the farmô while there was no-one else at home, the people who focused on bushfire management when no-one else much cared. To use my favourite medical metaphor, they were doctors who chose the unglamorous task of preventative medicine over treating disease epidemics, who understood that wildfires, like disease outbreaks, go through an incubation period.

Over the decades from the 1950s to the 1990s Australiaøs bushfire gatekeepers numbered perhaps less than five thousand for the whole country. They were mostly foresters and were public servants in the employ of State forestry or land management agencies. They lived in small forest communities or timber towns, and had titles like Divisional Forest Officer, District Forester, Fire Operations Officer, and Forest Ranger. Their most distinguishing feature was not just that they were responsible for a patch, but that they accepted accountability for the fire protection of this patch, and the communities within it. Individual patches, usually called districts, were part of regions, which in turn were part of a State jurisdiction. Added up, they covered virtually the entire forest estate of the nation.

The gatekeepers were also firefighters, and they were usually good ones. They had numerous other responsibilities, including forest industry supervision, recreation and wildlife programs, catchment management, forest regeneration, community relations. But their most critical role was fire management. This was the year-in and year-out work involved in running a land management system with a focus on bushfire preparedness and damage mitigation. The job was not to prevent fires from occurring; this was known to be impossible. Rather it was to put in place, *and to keep in place*, a series of measures so that when a fire did occur, even under the most trying circumstances, it would be relatively safe and easy to control, and would do little damage.

The gatekeepers understood the most fundamental principle of land management in a fire-prone environment. This is: without effective fire management, no other land management objective can be achieved. It is all very well to dedicate forests for wildlife, for water catchments, for recreation or for timber production, but none of these objectives are possible if fire management fails.

These were the gatekeepers of Australian forests for most of the second half of the 20^{th} century. You will note that I speak of them almost in the past tense. This is because in many places in Australia they no longer exist, and in others they have become an endangered species.

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The changing scene in Australian forests

Forest management in Australia has changed radically over the last 15 years, and one of the most dramatic changes has been the depopulation of the bush, the steady extinction of the on-the-ground forest manager, the dirt forester and his fire-tempered bush crews. The Western Australian situation is typical: many districts have been shut down or amalgamated, the staff moved to large and remote regional centres; permanent career staff living and working in the bush have been replaced by seasonal workers and contract staff. There were perhaps 70 professional foresters working in forest districts in south-western WA in the 1970s. Today the number would be less than 5 or 6, and most of these work out of the larger regional centres.

Accompanying the decimation of the field staff has been the worst of all institutional re-arrangements: all over Australia we are seeing the progressive transfer of responsibility for fire from forest and land management agencies (who are interested in ecosystem management) to emergency authorities (who are interested only in fire suppression).

None of these changes has led to more successful fire outcomes. On the contrary, Australia has experienced one large, damaging bushfire after another over the last decade, culminating in the ghastly fires of February 2009 when 173 lives were lost and whole towns were incinerated. In 2003 a wildfire burnt right into the suburbs of our national capital city, killing 48 people. In succeeding years there have been devastating bushfire calamities in Victoria, New South Wales, South Australia and Western Australia.

Why is this so?

The authorities and the environmentalists are blaming all this on climate change. However, there is no evidence of dramatic or unprecedented warming in Australia to date. Indeed, the most superficial study of Australian climate history reveals a high natural variability, including warm periods and severe periodic droughts[1]. No-one who knows anything about fire believes that to blame the current spate of serious fires on climate change is anything other than dishonest sophistry, an attempt to wriggle out from taking accountability.

Nevertheless, the idea that all is not well in the Australian fire scene is at last beginning to dawn on governments and communities, and a number of inquiries and re-evaluations are underway as we speak, or have recently reported. The over-riding conclusion emerging is that the new institutional arrangements and reliance on modern fire suppression technology have not delivered on their promise.

I welcome the re-evaluations and official reports, although I do so somewhat cynically. There is a phenomenon known as the Bushfire Cycle that revolves implacably in Australia. It runs like this: First you have a bushfire disaster. This is followed by a plethora of inquiries and policy and technological reviews. These lead to system upgrade, heightened awareness of fire risks and improved outcomes. A period of freedom from bushfire disasters follows. However, a lack of fires leads in turn to apathy, over-confidence, political foolishness, budget cuts, system

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1 The Australian poet Dorothea Mackellar succinctly summed up Australian climate variability in a verse from her celebrated poem ôMy Countryô (once learned verbatim by every schoolchild):

'I love a sunburnt country, a land of sweeping plains
Of ragged mountain ranges, and drought and flooding rains'

downgrade and finally another bushfire disaster. This kicks off the cycle anew. Over the years, the wheel of the Bushfire Cycle has turned relentlessly.

However, quite recent history has also given us a clear example of how the Bushfire Cycle can be derailed. Derailment was accomplished by the gatekeepers, the experts in preventative medicine, plying their trade behind the scenes year-in and year-out, not simply in a burst of enthusiasm in the wake of a Royal Commission, to hold the disease epidemic at bay.
In none of the current bushfire re-evaluations in Australian have I seen any recognition of the need to resurrect the role of the gatekeepers and the principles and systems that supported them. Unless this is done, no other measures will succeed, and the Bushfire Cycle will continue to revolve. Iôll go into this in more detail in a moment. But first I need to digress briefly and sketch in the historical perspective. How did we get to this point?

An historical digression

The fire history of Australia follows a similar pattern to that of North America. There was a ópre-historyô (before European settlement in the late 18th century), which reached back thousands of years in which fire was common across most of the continent. The bulk of the Australian landscape is either arid, or seasonally dry, and mostly the native vegetation is highly flammable.

Aboriginal people occupied the whole of the Australian continent, perhaps for 40,000 years. While data or physical evidence of fire prehistory is limited and often contested, the situation is easy to infer from the merest knowledge of our vegetation, climate, ecology and anthropology. All conspire to conjure a continent-wide situation in which fire found a welcome home. Thus, over millennia, fires occurred frequently and were widespread. They were started either by lightning, or more commonly by the indigenous people who used fire skillfully for a wide range of purposes. In the savannah grasslands and woodlands of the tropics and sub-tropics, fires occurred annually or biennially across vast areas; in the arid central rangelands and deserts fire occurrence was periodic, responding to irregular cycles of rainfall and regeneration. In the temperate dry eucalypt forests and woodlands of the south-east and south-west, mild fires probably occurred as frequently as every 3-5 years, while the wet eucalypt and temperate rainforests of the south-east and Tasmania burned less frequently. The only parts of the Australian landscape that were not periodically burned were the coastal mangrove forests and the tropical rainforests of far north Queensland. Elsewhere, the ecosystems found today have a biodiversity that has been screened by thousands of years of repeated, frequent fire. [2]

Settlement of Australia by Europeans in the late 18th and early 19th century wrought wide-scale, rapid and dramatic changes to rural landscapes and to fire regimes. Most of the temperate woodlands and significant parts of the high forest were freeholded and converted to cropland and pasture, both comprised of exotic species. A large and unmanaged (until about 1920) timber industry developed within remnant native forests. Aboriginal populations were decimated by dispossession and disease, and their traditional land use practices, in particular their regular mild burning, soon disappeared. Townships, settlements and community assets grew apace, often within or in close proximity to the bush. There is a phrase that sums it up: *'European settlement of Australia represented the insertion of a fire-vulnerable society into a fire-prone environment'*. Not surprisingly the early history of rural post-settlement Australia is also a history of repeated

[2] The most readable account of fire pre-history and of Aboriginal burning in Australia can be found in Part II of *The Burning Bush* by Stephen Pyne.

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bushfire disasters, as non-Aboriginal humans experienced the inevitable confluence of a hot, dry climate, flammable vegetation, plentiful sources of fire, and human impotence in the face of bushfire fury.

Fire history and forestry history are intrinsically intermixed in Australia. This is explained by two factors:

(a) The distribution of forests and of people largely overlap - both are concentrated in the higher rainfall east coastal and south-west coastal regions of the continent; and

(b) After about 1918, the responsibility for management of Australian forests and therefore for management of Australian fire, fell largely into the hands of Australian foresters. This followed from the establishment of the first forestry agencies by State governments and the dedication of forests on crown land as State Forests.[3]

Unfortunately, when it came to the management of fire in the native eucalypt forests, our first foresters were groping in the dark. These were men mostly trained in forestry principles and practices developed in 17th and 18th century Germany and France where fire is not a problem; or they inherited the attitudes towards fire that had evolved in Imperial British India in the mid-late 19th century. These attitudes reached Australia in exactly the same way they reached the USA ï through people like Dietrich Brandis, a German forester who had been Chief of the Forest Service in British India and who was a powerful hater of fire. Brandis significantly influenced Gifford Pinchot and helped guide the policies of the fledgling US Forest Service. These policies were, in turn, taken as a model by early Australian foresters setting up their own forest services in the years just after World War I.

Underpinning early forestry policy all over Australia, then, was the firm belief that fire was the enemy of the forest; it could not be accommodated, so must be expunged. Not just wildfire, but *all fire* was regarded as destructive, an interloper into what should be a pristine, fire-free environment.[4] The management approach that emerged was attempted fire exclusion.

Throughout the 1920s and 1930s Australian forestry was abuzz with actions that would allow this policy to be implemented. District forest stations were established and foresters and

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[3] Two further fire control systems slowly developed at about this time: the uniformed career fire fighters stationed in cities and larger towns, and the volunteer bushfire brigades in agricultural Australia. Both had an emphasis on suppression, but the members of the volunteer brigades were also mostly farmers who usually included fuels management, either by grazing or burning, as a routine part of land management on the properties they owned or managed. The sharp line between urban and rural areas in Australia is now blurred, producing a zone at the outer edge of all the major cities where neither the uniformed career firefighters nor the volunteer bushfire brigades are effective. These are the killing fields for the bushfires of the future.

[4] The ex-Indian Forest Service forester David Hutchins visited Australia in 1916 and produced a highly influential paper with recommendations on the management of Australian forests. Hutchins believed that the infertility of Australian soils was caused by Aboriginal burning (he had no idea of the weathering processes they had been subjected to over geological time), and that it was desirable and possible to extinguish all fires.

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field staff appointed. Ranger staff and crews were trained to attack and suppress fires. Lookout towers, telephone networks, and roads and trails were constructed. Fire Control manuals were written, with protocols covering everything from eyesight tests for fire lookoutmen, to the correct method of raking a fire trail and building a field telephone line.

The emphasis was on early detection and aggressive response to fires. Although forest and fire management were the responsibility of the States, not the Federal government (we have no ónational forestsô in Australia), there was a uniformity of adoption of the system that amounted virtually to a national approach. By the mid-1940s, it applied more or less nation-wide. For a while, pre-World War II, foresters were confident that the answer to óthe fire problemô had been found.

But there were unintended consequences of the fire exclusion policy. The most obvious of these was the inexorable build-up of flammable fine fuels (dry leaves, twigs, and bark) in the forests where the policy had been successful. Eucalypts are described as óevergreenô but in fact mostly they replace their leaves and outer bark every 12-18 months; nor does it help that leaf shed occurs in mid-summer. Litter is slow to decompose, and even in the dry schlerophyll forest it can reach 10 tonnes to the hectare within five years of a fire, and go on to top out at 25 tonnes to the hectare, all of it highly flammable when cured. In the more productive wet schlerophyll forests these figures can be doubled.

By the 1940s a point was reached where fuel levels in forests across the nation were so high that fire suppression had started to become difficult even under mild weather conditions. Under severe conditions, it had become impossible. Large, intense and damaging bushfires were the result, the most famous being the Black Friday fires in Victoria in 1939, when 78 lives were lost and many hundreds of thousands of hectares of prime forest and farmland were decimated.[5]

It was at this point that the fire policies in Australia and the United States diverged sharply. In the face of increasingly unwinnable wildfire battles, Australian forestry authorities resisted the temptation to redouble investment in fire suppression forces and technology. Instead they turned to fuel reduction. In Western Australia for example there was a radical reversal of policy in 1954, and broad-acre prescribed burning commenced.

The reasons for the change were pragmatic: first, it was much cheaper to manage than to control fires; and second, it worked. The new approach also had its champions, most notably Alan McArthur, a pioneer fire scientist who was well-known and highly respected amongst the State agencies, and Alan Harris, the Conservator of Forests in Western Australia. Harris was a determined and aggressive leader. He had, in his own words, been ótempered in the great fires of the 1940s and 1950sô, and he was not prepared to see them return.[6]

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5 Fuel build-up resulting in rapid escalation of fire intensity after ignition was a key factor in the great fires of the 1930s and 1940s in Australia, but the other was lack of a matching growth in suppression capability. What had worked earlier in lighter fuels, i.e., headfire or flank attack by crews with hand tools, was no longer reliable or possible. This situation persisted until well after World War II when tracked bulldozers and 4WD trucks first started to become available for use in fire suppression.

6 There was another factor at play in the Australian decision not to pursue the option of all-out suppression based on aerial water, or retardant-bombing at that time. Australian bushfire authorities did not have access to large numbers of cheap ex-military aircraft after World War II.

There was a further reason for the re-introduction of fire, although this was not acknowledged explicitly at the time. It had become obvious that forests left long-unburnt started to decline in health.

The transition from a suppression-dominated culture to a damage-mitigation culture did not happen overnight. It took nearly a generation, and during this time there were some nasty fires. The summer of 1960/61 for example, was the worst in Western Australiaó bushfire history, and as late as 1983 Victoria and South Australia were ravaged by the Ash Wednesday fires. The 1961 fires in WA were our Great Teaching Event, equivalent in their impact on policy and institutions to the impact in the USA of the fires of 1910.

The new culture was fundamentally a professional one, driven by people with first-hand experience in the forest. It incorporated an emphasis on fire behaviour research and adaptive management. The 1950s and 1960s saw the emergence of our first bushfire scientists, disciples of Alan McArthur, studying and documenting fuels, measuring experimental fires, studying fire weather and fire danger forecasting, developing fire behaviour equations and burning guides and promoting the technology of broad-acre, mild-intensity, rotational prescribed burning.[7]

What emerged was a new paradigm: the fire suppression capability was retained and refined, but it was underpinned by a systematic fuel reduction program aimed at making the suppression effort easier, safer and more effective. [8]

The 1961 fires in Western Australia were followed by a Royal Commission. The Commissioner found that fuel reduction burning was essential to minimise the risk of future bushfires. This was not surprising. What was surprising was the rapidity with which his finding was translated into action on the ground, and its outstanding success.

The new system was firmly in place in Western Australia by 1970. At that stage, the annual program of fuel reduction prescribed burning covered 12-14% of the entire forest estate. The burning interval in the drier jarrah forest averaged 5-6 years and in the wetter karri forest 8-10 years. Similar (but less comprehensive) programs were undertaken in State Forests in the other

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Water bombing trials using civilian aircraft were deemed unsafe by the Civil Aviation Authority, the nationó aviation watchdog, and were not persisted with. Water-bombing of bushfires in Australia did not take off until the 1990s when specialist aircraft were acquired.

7 By the early 1970s, fire behaviour and operations research was being accompanied by research into fire ecology, so that questions about the ecological impacts of fuel reduction burning could be properly understood. There are now 40 years of results of this work, and none of it indicates that there is any ecological problem associated with fuel reduction burning at intervals of about 8-10 years.

8 In this paper I have equated fuel reduction with burning, but it needs to be noted that fuel reduction by grazing was once very important in Australia. Many State forests, especially in NSW, were leased for cattle grazing, and the high sheep numbers on private agricultural land in the decades after World War II had a significant impact of fuels on most of the lands adjoining State forests, and on regional bushfire spread and intensity.

states.[9] In every region where fuel reduction was methodically and routinely practiced, the occurrence of serious wildfires fell away dramatically.

What made this new system so effective? I believe there were three factors:

- it was driven from the top;
- it was supported by research; and
- the work on the ground was in the hands of agency staff who lived and worked in the forest, and were experienced in the use of fire.

A personal perspective

I was a district and regional forester in Western Australia in the 1960s, 1970s and early 1980s. I was part of the system described above, one of the bushfire gatekeepers. As a student I had worked summers in fire crews in the era before the new fuel reduction policy had become effective, and I had been at the sharp end in several serious fires. When I became responsible for a district and later a region, I shared with my colleagues an intense dedication to preventing large, intense wildfires through a fire management system that incorporated fuels management.

The burning was physically and technically demanding, and it was relentless. Each year we updated the 5-year plan that established the strategic priorities, and from which the annual plan was drawn. All burns required a detailed prescription. The burning program came around every spring, starting in about October and finishing the following April. We were set clear targets in terms of area burnt and high standards in terms of burning quality and cost. Our work was closely monitored by senior and specialist staff.

I was never in any doubt what was expected of me: this was to implement a systematic and professionally managed prescribed burning program covering at least 12% of my districtøs forests every year. My bosses were uncompromising, but they gave me the staff, funds and equipment to do the job.

I made some mistakes, especially in the early days of aerial prescribed burning in the karri forest when our capacity to micro-forecast the weather and predict fire behaviour was primitive by todayøs standards, but I was lucky: not only was there a learning culture in the agency, there was also a tolerance for error.....provided you only made the same mistake once!

As a district forester I had many responsibilities and priorities, but bushfire preparedness and damage mitigation through fuel reduction burning was my highest. I always knew I would be judged according to how well I handled it. My situation was replicated in forest districts all over the nation.

The wheel turns

By 1985, foresters believed that this time, the answer to óthe fire problemô in the bulk of the Australian eucalypt forests had *really* been found. Fires would still occur, and sometimes they would be difficult and damaging, especially in the areas where forests, farmlands and rural settlements intersected, or in the wake of a prolonged drought. But on the whole, we were

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9 There remained areas where fuel reduction was difficult or impractical, principally the wet sclerophyll forests of Victoria and Tasmania. But even here it was possible to develop an effective protection system in surrounding drier forests, thus affording overall benefits to the regions in which ash forests occurred.

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confident that if we maintained our fuel reduction program and continued to refine our suppression capability, the really bad ókillerô fires (or ómegafiresô as they are called today), would be a thing of the past.

Again, however, there were unexpected consequences. From about the mid-1980s, just as it reached its peak of efficiency and effectiveness, fuel reduction burning in Australian forests started to become politically difficult, and then to unravel.

The most serious changes occurred in Victoria and New South Wales, but Western Australia was not immune.

With hindsight, it is easy now to see what happened. Five forces were at work:

1. Humans are conditioned to respond to threats. What the fuels management program achieved in the second half of the 20th century was to significantly reduce the threat of large, intense wildfires. A version of The Bushfire Cycle cut in, breeding complacency and overconfidence. Budgets were cut, field stations closed down, recruitment of professional and field staff slowed or ceased. Fuel reduction burning was no longer given the highest priority ï ówhy do it when we donõt have any bad wildfires?ô was a recurring theme. In a nutshell, we became victims of our own success.

2. Forestry (or more correctly timber harvesting) became politically unpopular, and because of the way the two were linked on the ground through the forestry profession, so did fire management. By the 1980s, urban Australians had discovered óthe environmentô and it became a new religion. Forests were no longer óthe bushô but fragile ecosystems, precious icons, natureõs cathedrals, to be ósavedô from destruction by evil foresters. The old threat of the destructive bushfire was replaced by a new threat: fuel reduction burning! It was (and still is) routinely described by environmentalists as ófire-bombingô or ónapalmingô, conjuring up images of Dresden or the Vietnam War.

3. The Australian political and electoral system allows small well-organised lobby groups disproportionate capacity to influence government policies. From the mid-1980s onwards, environmental groups opposed to prescribed burning began to control election outcomes. Both of the major political parties, one or the other of which was always in power, became hostage to green lobbyists. Forest and fire management was one of the first things to suffer.

4. In the 1980s there was a profound change in the Australian public service. Up until that time, the so-called óWestminster Systemô applied, in which public servants were appointed on the basis of their know-how and experience, not their politics. Responsibility for public administration in areas such as forest management was in the hands of professional men who had come up through the ranks, not political appointees parachuted in from above. Under the new arrangements, the role of the senior public servant was no longer to give options and professional advice, but to toe the line of the political party in power. Departmental heads were placed on short-term contracts to ensure they could be easily dispensed with if they stepped out of line. This

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situation made it easy for environmentalists, operating through a political party which they controlled through the electoral system, to manipulate forest policy and land management practices.

5. Finally there were the two great transfers. The first was a massive rededication of State forests as national parks and their falling under new administrations. The bulk of the national parks administrators in Australia (especially in the eastern States) at that time did not have backgrounds in forest or land management, but were zoologists, botanists or environmental scientists. They tended to fear fire, and did not want responsibility for it. They supported the second great transfer: this was shifting the responsibility for fire from those responsible for forests to those responsible for emergency response.[10]

The traditional bushfire gatekeepers in their remote ranger stations were at an enormous disadvantage in all this. They were few in number, were politically naive, and had no-one to speak for them or support them politically. Right across Australia during the 1990s, they began to disappear, transferred to desk jobs in the city, retired and not replaced, and starved of resources as well as moral support. The once-routine programs of systematic fuel reduction collapsed. Even in Western Australia where there was a continued agency support for burning, the annual program began to wind down. By 2003 it had reached a point at which it began to become ineffective: large, intense forest fires began to re-occur for the first times since the 1960s.

The downgrading of a prescribed burning program is worse than its closure. It is a double blow. A program of fuel reduction burning will not do the job if it does not meet a certain threshold in terms of area covered annually, and strategic distribution.[11] Big fires which have worked up a head of steam in long-unburnt bush simply go over the top or around small, scattered or inadequately fuel-reduced areas. When this occurs it enables the opponents of fuel reduction burning to portray it as not only environmentally damaging, but worse, *ineffective in preventing fires.* The fact that we had never said that it would ‘prevent’ fires was conveniently overlooked.

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10 The exceptions were in Western Australia, where an integrated land management agency emerged and bushfire management stayed largely in the hands of foresters for another decade, and in Tasmania where the timber industry was an important element in the State’s economy. It is no coincidence that these are the two jurisdictions in which fuel reduction burning persisted, and wildfire occurrence was minimised. Elsewhere in Australia the forestry profession sank without trace, a situation now also applying in Western Australia.

11 Fuel reduction burning of 10% of the forest each year, which equates to a rotation time of 10 years), means that up to 50% of the landscape will have fine surface fuels less than 5 years old. Provided burns are thoughtfully distributed in terms of assets and values to be protected, prevailing wildfire winds etc, and if individual burns are large and intense enough, the potential for a severe wildfire is dramatically reduced. Any wildfires will soon run into an area of fuels aged 0-5 years.

Another factor emerged at about this time, promoted by the emergency authorities: this was the belief that aerial water bombing would provide the ultimate solution to the bushfire threat. The water bomber would replace the fire bomber, and a new technological era would render the old land manager obsolete at last.

The dawning of a new era

This brings us to the modern, or what I call the ótechnological eraô of bushfire management in Australia.

I am the first to admit, and I do so proudly, that Australian fire authorities have made a number of significant steps in technological development in fire suppression in recent years. Aerial detection, commenced in the 1970s, has become routine and very efficient. Remote sensing and mapping of fire fronts has become possible. Research studies have provided world-leading insights into fire behaviour, including fires at the upper ends of intensity. Computer technology has brought new dimensions across the spectrum from weather and fire forecasting to bushfire threat analysis. On the ground, crews have access to the most up-to-date vehicles, pumps, and communications, and they are directed from modern, purpose-built fire control centres that hum with technological wizardry. Water bombing capability, either from fixed wing aircraft or helicopters, including Skycrane helicopters hired each summer from the USA at enormous expense, now reaches right across the high rainfall forest and heavily populated regions of the nation. Firefighter mobility had been developed to the point at which interstate movement of firefighters has become routine, and indeed now extends to the importation on occasions of firefighters from New Zealand, Canada and the USA.

By 2003 it is probably fair to say that Australiaôs fire response system was more technologically advanced and more efficient than ever before in the nationôs history.

Nevertheless, the decision to abandon or wind back fuels management, and replace it with a technology-based suppression approach produced an inevitable and predictable consequence. Instead of getting better, things began to get worse. From about the year 2000 there was a rash of very nasty fires[12], culminating in the disaster in Victoria in 2009. The highly vaunted suppression technology was found to be powerless when faced with fires burning in heavy dry fuels and high winds, and under their onslaught, the suppression system collapsed.

There was no Plan B. Many people perished trying to defend or shelter in homes that were wholly undefendable, or were actually fire traps, as they were nestled under the canopy of long-unburnt forest.

As the Bushfire Cycle dictates, the rash of fires has been followed by a rash of inquiries, commissions, conferences, seminars, workshops and recriminations. Books, letters, submissions and articles have been written, speeches made and óin-depthô analyses conducted by expert panels and committees. Overseas experts (including from the USA)[13] have been brought in to advise us. Separate and independent inquiries have been made by the House of Representatives, the Senate, the Victorian Parliament, State Coroners and a Royal Commission (presided over by a judge).

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[12] In 2003 a bushfire actually burnt into the suburbs of Canberra, our national capital.

[13] A notable contribution came from former US Forest Service fire specialist Jerry Williams. Mr Williams is deservedly held in very high regard by Australian bushfire managers.

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As each report is published, nothing is found within them to surprise the well-informed observer. Many findings are concerned with ósmall pictureô issues or with the minutiae of local situations, for example what sort of fire siren to put up in small country towns. However, without exception, every independent study has come to the same conclusions about the most important óbig pictureô issue. These are:

(i) Fuel levels in eucalypt forests must be kept below certain threshold levels and fuel reduced areas thoughtfully distributed across the landscape;

(ii) The way to achieve this is through a program of periodic, planned burning under mild conditions that reduces fuels systematically over about 8-10% of the burnable forest every year;

(iii) If we do this, and continue to maintain a sound bushfire suppression system, wildfires will be easier and safer to control, and will do less damage, even under the most severe weather conditions; and

(iv) The community must have a Plan B, enabling evacuation to safe places when all else looks likely to fail.

This is all very well and good and the old hands have all cheered as the findings are made public.

However, the depressing reality for the most fire-prone areas (especially in the south-east), is that neither a new policy nor its implementation are likely to follow. Opposition to fuel reduction burning remains virulent in environmental organisations and within academia in Australia. This opposition is incurable, because it is not based on science, but on ideology, and a change of position would involve a loss of face.[14]

However, neither the activists nor the academics are the main problem. The main problem is the vacuum left by the removal of the gatekeepers and their supporting leadership; this has not, and is unlikely to be filled. This issue is not even discussed. And the situation is made worse by the increasing bureaucratisation of prescribed burning. So many constraints have been erected it is becoming very difficult to actually do a burn. This is a clever strategy as it allows those who oppose fuel reduction burning to claim publicly that they support it, while simultaneously making it nigh impossible for burning to take place through the imposition of bureaucratic processes that the public never sees.

To revive the system under which the gatekeepers flourished and to dismantle the bureaucratic morass in which fire operations people find themselves entangled, would require significant cultural changes within current environmental agencies and in our emergency services authorities. This will not come without major surgery at the top, and in this era of a political, rather than a professional public service, it is hard to see this happening.

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[14] Despite the protestations of environmentalists and academics, no evidence has ever been presented that suggests that a program of prescribed burning involving mild fire at intervals of 8-10 years has any deleterious effect on the biodiversity of Australian eucalypt forests. On the contrary, forests subjected to diverse fire regimes are healthier and more diverse than those subject either to fire exclusion or periodic high intensity wildfire.

Without the drive from the top to establish the culture, and to insist that the staff in the districts are devoted year-in and year-out to achieving their fuel reduction targets, the job will not get done.

The missing pieces of the jigsaw

It is important to remind ourselves of what is now missing from the Australian bushfire scene.

- No longer are forest and land management agencies 100% committed to a fuel reduction program from the top down.
- the people at the top did not start at the bottom.
- No longer is there a constant injection at the bottom of young professionals with training in forest or land management who can then be exposed to coaching and mentoring from the old hands, gain practical experience with fire, and learn basic personnel management.
- Also fading into the sunset are the old hands themselves: the locally-trained sub-professional ranger staff with their intimate knowledge of the forest, the weather, and the people of the district. They not only worked in the bush, they had their homes there, and they knew that if they didnøt get their fire work right, their own families, friends and assets would be at risk. They are being replaced by young graduates with a degree in ecology or environmental science, all too often more interested in sitting at a computer than in getting out into the bush[15] and mostly with a strong prejudice against the use of fire, inculcated back at University.

These institutional and cultural changes have occurred at a time when large numbers of Australian are moving out of the cities to live at the interface, and where it is becoming increasingly difficult for leaders to lead. Nothing can be done in Australia any more without calling for public submissions, consulting stakeholders, preparing draft plans, conducting public meetings, test cases, pilot studies. Regrettably we are also seeing a growing threat of litigation the moment something happens that someone does not like.

All of this has produced a sort of bureaucratic paralysis that hangs like a dead weight around the necks of the nationøs bushfire managers.

Finally, there is the inability of the community and media to see beyond short-term losses to long-term gains. The concept of the trade-off seems no longer to be comprehended.[16]

There are many good men and women still working as bushfire managers and in fire research in Australia. Their devotion to duty and their professionalism is unquestioned. The

15 I accept that society has changed, and that few young people today are prepared to put up with the sort of living and working conditions that were the norm in the bush when I was a young forester. Australia is one of the most urbanised and affluent societies in the world. Attracting young professionals to work in the bush, leaving behind the comforts, bright lights and financial rewards of city life, is a universal problem not confined to forest and fire management.

16 In the aftermath of the Victorian bushfire tragedy in 2009 I was invited to debate a leading member of the Australian intelligentsia on national radio. He was opposed to fuel reduction burning, he said, because he didnøt like the aesthetics of recently burned areas.

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trouble is, increasingly they are being constrained, corralled, repressed, outvoted or stood up in witness boxes in courtrooms. The tolerance for error that I experienced as a district forester has disappeared, replaced by a fear of trial by media or of having to take the rap for an incompetent Minister. What particularly alarms me is that this is occurring at a time when expertise in the field is declining to vanishing point, so that errors will become more commonplace.

Returning to the discussion about heroes at the start of this paper, it is fascinating to observe a new trend out in the bush, especially within the Australian national parks agencies. The refrain has become: *why should I do a fuel reduction burn, and draw the wrath of the greenies and media down on me for being a villain, when I can sit back, wait for the inevitable wildfire and become a hero as a firefighter?* [17]

Where to from here for bushfire management in Australia?

I predict that the spate of interest in bushfire management in the wake of the 2009 disaster will last for maybe 5 years at best. After that, memories will fade and other political priorities will arise. The Bushfire Cycle will revolve inexorably.

In the past, it was precisely at the moment when political and community interest was at the lowest point in the cycle that the role of the gatekeepers became most important. It was the gatekeepers who kept the bushfire management machine well-oiled and chugging along, year-in and year-out. Running an effective bushfire management system when everyone is interested and activated is relatively easy. The hard job is running it when nobody cares.

Unless the political and institutional system in Australia changes, and there is a return to responsible gatekeeping, I can see no alternative to more megafires, more calamities, more deaths, more communities up in smoke. Leadership is absent or hopelessly constrained. We are desperate in Australia for a leader to arise who will make a stand: to decide what has to be done and to insist that it be done, so as to minimise bushfire calamities. But we also need inputs at the bottom. The best people at the top will be ineffective if we do not have people in the field who know how to get the job done on the ground, and to stick with it year by year, as the seasons roll by.

Foresters in my day had a saying when it came to bushfires. I suspect it was a sort of global philosophy amongst people in that game: *hope for the best, but prepare for the worst.* It was this approach that, for a generation, shut the gate on the megafires now killing Australians and damaging the Australian environment. I believe this has been replaced by a new saying: *hope for the best.*

The real tragedy in Australian bushfire management today is not that we do not know what to do. The solution is at hand, but the hands are tied behind the backs. If only we could find a way to couple the brilliant developments that have been made in suppression technology to a professionally planned fuel reduction program that ticked over permanently across the landscape

[17] Usually overlooked is that it takes personal courage to give the order to commence a fuel reduction burn, for example a 2000 hectare burn in mid-summer of an area of prime forest containing a mixture of fuel types and with high value neighbours. Even with todayꞌs knowledge of fire behaviour and weather forecasts, things can go wrong. This puts a premium on experience and the ‘feel for fire’ which only comes with years in the business, the two qualities most under threat under new institutional arrangements in Australia.

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without attracting the slings and arrows of outrageous criticism, we would become a land of bushfire heroes.

In the end, of course, it will be our political and community leaders who determine whether a winning strategy is adopted or rejected, but they will only do so if supported by the wider community, a proposition that emphasises the real game being played here.

The real game

Australian land and bushfire managers have always been too preoccupied with fighting fires to face up to the real battle, which is political, not operational.

Consider the fact that we have never addressed, through effective programs of research and community education, the three most fundamental of political issues relating to fire management:

- Documenting and publicising the benefits of fuel reduction burning in terms of reducing the damage caused by megafires. It is a tragedy that a tiny handful of academic theorists can hijack this ultimate truth;

- Discrediting the mythology that a professionally conducted fuel reduction program is ó destroying the biodiversityô. There is no evidence to support this idea, yet it continues to be promoted and widely believed; and

- Documenting and publicising the human, economic and social costs of megafires as well as their damage to ecosystems, water catchments, soils and the atmosphere. The fact that megafires come at a huge cost has never been publicly understood in Australia, nor do people in fire-prone areas foresee the immense post-fire problems associated with the sudden disappearance of their entire social infrastructure (roads, power, water, schools, hospitals, churches).

This brings me to The Bushfire Front, the organisation I am representing at this conference.

Who are or what is The Bushfire Front? We are a small group of retired foresters in Western Australia passionate about bushfire management and determined to fight the current trends. We decided that we were too old to volunteer as firefighters, but we had enough accumulated experience, wisdom, cussedness and old-fashioned rat-cunning to make us fairly effective on political battlegrounds.[18] For a while we muttered amongst ourselves, and then in the wake of the 2003 Canberra fires we decided we would have a go. We developed a *modus operandi* based on the successful campaigns waged against us in earlier years by the environmentalists, started a campaign, and found to our surprise that the old weapons were still sharp.

The response has been interesting. First, we quite rapidly developed political credibility, as it was recognised by politicians who were not part of government that they could come to us for independent advice. Second, we began to be sought out by the media, who wanted to hear from

[18] Three members of the Bushfire Front were formerly Heads of Departments in Western Australia, one was formerly a Regional Manager, one a Research Director, and one the Manager of a land management planning division. Two are highly credentialed fire fighters and we have a communications and public relations specialist.

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people with something to say, but who did not chant the tired old mantras, as did the green groups and the agencies.

Needless to say we became quite unpopular with the green groups and the agencies, and especially with the emergency services, of whom we are most critical. Amusingly, they have attempted to discredit us by labeling us óyesterdayös menö.

Well, of course we are! Of course we look back with nostalgia to the time when we were running the show, and everything was better. But we also remember what it was like in the 1950s and 1960s when fires in heavy fuels were unstoppable, we remember the effort that went into designing and implementing a system that turned this situation around, and we despair to see the re-emergence of a 19th-century approach to fire in our schools and universities, and a fascination with the full-bore suppression approach in the emergency services authorities.[19]

Although, sad to relate, the 2009 Victorian tragedy did a lot to help our public profile (we had predicted it infallibly), we have started to make a difference at the political level. In addition to providing an alternative public voice, we have been relentless in pointing out to our political leaders that, having been warned, they cannot escape accountability for preventable bushfire disasters. We have also pointed out, repeatedly, that in a do-nothing scenario, the outlook is bleak, just ómore of the sameô in the years ahead, and having been warned, that they will have to take the blame.[20]

We also critique the so-called ónew approachesô emerging from Australian universities, with their emphasis on decision-theory equations and computer-modeled scenarios, and point out how profoundly the proponents are divorced from the real world, but here we have had no success. The academic establishment simply draws its wagons into an impenetrable circle. I should emphasise here that I am not against computer modelling *per se*; I use models all the time, for weather forecasting, fire behaviour prediction, in burning guides and so on. These are models built with the aim of helping the man in the field. The modelling approaches I abhor are those designed to make our life more difficult, or to conjure up false fears about the impacts of fuel reduction burning.

Is there room for optimism?

I would not like to conclude this paper on a down-note. I occasionally allow myself a brief fantasy and would like to share it with you. What if the human survival instinct kicked in for people living at the urban interface who find themselves threatened by increasing numbers of unstoppable fires coming at them from long-unburnt forests? This instinct would surely drive

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19 A fire management system with emphasis on suppression and inattention to preparedness and damage mitigation has come to be known in Australia as óthe American Approachô, reflecting the admiration emergency service chiefs have for US campaign fire style operations with their squadrons of aircraft and thousands of firefighters in smart uniforms equipped with the latest in expensive equipment.

20 This is not a popular message. Following a meeting with the Western Australian Premier a few years ago, at which we told him his personal accountability was on the line if there was a bushfire tragedy, he remarked to his staff (we heard later) óIôm glad those guys are not still part of the public service: they tell me things I donôt want to hearô. This Premier resigned shortly afterwards, suffering from depression.

them to seek effective measures to cut the rate of death and destruction. Then, just as an early generation of Australian foresters did, they will discover that the only way to do this is through a program of fuel reduction prescribed burning. This would start to shift the balance of political agitation from anti- to pro-burning.

What if rural Australians suddenly started to feel empowered to deal with their own bushfire destiny? To build fire-resistant homes and to keep them free of hazards?

What if the environmental movement in Australia realised, finally, that biodiversity is enhanced by habitat diversity which in turn is enhanced by fire diversity. Would they not then realise that mild frequent fire is a driver towards healthier, more ecologically resilient and more beautiful bushland? Would not the stories and legends of the Aboriginal people and their use of fire then be resurrected and supported, rather than denied and rejected.

And finally, what if Australian academics suddenly emerged from their leafy inner-city campuses and started to actually study fire in the field, rather than through the construction of computer models at their desks? Might they not start to learn something about the real world, as compared with the hypothetical one they invent and report upon, replete with garbage-in and garbage-out.

Such a coalition of interests might well result in the community starting to condemn forest managers for not keeping up with their burning programs, instead of trying to stop them burning. This would swing the pendulum away from an unmanaged to a managed fire regime, and would prove difficult even for the intelligentsia to overcome.

Itøs a good fantasy, and one that sustains me when I lie awake in the small hours despairing over the way in which chaos so often triumphs over order and the fact that, as that great forester and administrator Alf Leslie once said: ó*when it comes to public policy, stupidity nearly always wins*ö.

And I also remind myself that Australians have made many magnificent advances in many fields over the decades. We are still a lucky country. Yes, bushfire management has gone backwards in recent years, and it is going to be a big job to get it back on the rails. The key requirement is a new generation of bushfire gatekeepers who will devote their professional lives to building and maintaining an effective bushfire system, not just seeking hero status putting fires out.

And what the gatekeepers need is organisations like The Bushfire Front, able to offer independent political support. Our little group of old guys (there are only seven of us), has taken on a big job, and so far, we have punched above our weight. But we also have fun and relish the recapture of the camaraderie between fire people that was once part of our daily life. And, of course, being in the Bushfire Front has got me to this wonderful conference and an opportunity to meet and interact with so many inspiring people. It has been a privilege to share my thoughts with you.

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When death rides the forest: Can satellite imagery help resolve interactions among insects, fuels, and fire?

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Abstract
Historically, people have tended to perceive forest disturbance as a negative force, epitomized by vivid posters representing insects and wildfires as the grim reaper, wild animals, national security threats, and more. This presentation attempts to reconcile those perceptions with the reality that native insects and fire are natural and highly variable agents of forest health. We draw examples from our observations of insect disturbance via field, aerial survey, and satellite remote sensing in Pacific Northwest conifer forests. Focusing on two insect agents (mountain pine beetle *[Dendroctonus ponderosae]* and western spruce budworm *[Choristoneura occidentalis]*), we compare field measurements at 38 survey plots with Landsat TM/ETM+ spectral trajectories since 1985 and with cumulative mortality estimates from forest health aerial detection surveys (ADS) since 1980. Our analytical approach captured both bark beetle and defoliator effects in the satellite time-series, but the temporal evolution of the satellite signal varied by insect agent and forest type. In many cases, insect impacts appeared as persistent mortality signals evolving over many years, making it critical that insect mapping methods capture a wide range of potential signals. Field-measured overstory tree mortality ranged widely and was generally partial to moderate (well less than 100% tree mortality). The ADS maps provided valuable identification of specific insect agents, particularly in areas with multiple consecutive years of detection, although they tended to underestimate stand-level tree mortality. These results demonstrate the diversity of insect effects on conifer forests, confirming that satellite imagery does indeed have a key role to play in quantifying and informing society's perceptions of the interactions among insects, fuels, and wildfire. Given the likely increase of fire and insect activity in western North American forests, accurately characterizing insect effects on fuels—and clearly communicating those effects to the general public—will become increasingly important.

Additional keywords: fire ecology, fire behavior, fuel profiles, insect-killed forest, mixed conifer, multiple disturbance interactions, Pacific Northwest, remote sensing, social perceptions

A comparative wildfire risk assessment framework for the cohesive strategy

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Abstract
As part of the recently passed Flame Act, Congress has mandated that the Forest Service and Department of Interior develop a new Cohesive Strategy for Fire and Fuels Management. Congress has requested that the new Cohesive Strategy include the following elements: 1) Cost effectiveness in the allocation of the fire management budget in a risk based framework; 2) Appropriate management response to wildfire; 3) Risk to communities, 4) Allocation of hazardous fuels funds within a priority framework; 5) Impacts of climate change on wildfire; 6) Effects of invasive species on wildfire risk; 7) Fuel treatment effectiveness in terms of risk reduction. We will discuss the potential applicability of a recently completed national wildfire risk assessment (Calkin *et al*. 2010) as a framework for a new Cohesive Strategy and its ability to address the identified 7 elements. The described framework is based upon fire behavior simulation developed for the Fire Program Analysis (FPA) project interacted with spatially identified Highly Valued Resources (HVR) through the use of response functions that translate fire intensity to benefits and losses for specific resources. Scalability of the proposed framework from project level fuels planning to national scale assessment will be demonstrated as well as the relationship between the risk assessment and the Wildland Fire Decision Support System. Future research to refine and improve protocols and assessments will be discussed.

Additional keywords: Fire and fuels management

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Incentivizing Wildfire Cost Containment via Assignment of Actuarially-based Premiums

Abstract:

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Abstract:
Large fire suppression costs may be the most pressing issue facing the Forest Service today. Excessive suppression expenditures have resulted in high cost fire seasons, budget shifts toward fire suppression and away from other priorities, and a possible lack in the balance of capital expenditures among agency priorities. A posited contributing factor to excessive expenditures is that fire managers face a misaligned incentive structure that does not incentivize cost containment. We offer a novel approach to restructuring incentives based on actuarial principles that would require national forests to pay a wildfire management premium commensurate with statistical expectations of annual suppression cost. We describe how premium rates can be calculated using existing fire simulation software and regression cost models, demonstrate how this approach would properly incentivize cost containment, and offer preliminary results.

Prescribed fire applications in Forest and Woodlands: Integration of models and field studies to guide fire use

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Abstract
Globally prescribed burning is widely used for agro-forestry, restoration, and conservation to modify species composition and stand structure. Commonly stated goals of prescribed burns include to reduce hazardous fuels, improve species' habitat,   reduce the potential for severe fires in the wildland urban interface or protect municipal watersheds. Treatments may focus primarily on modifying conditions at the stand level or to change the mix of mosaic patches at the landscape level. Given the wide range of vegetation/fuel types, management objectives, and human resources it is not possible to conduct field studies to acquire the empirical data to guide fire use in the full range of applications. The integration of empirically-based models with biophysical process models holds promise for being able to extend our knowledge, develop interim guidelines for prescribed fire applications in novel situations, identify knowledge gaps, and set future research priorities. Based on their experience in forests from North America and Eurasia, the authors have begun to synthesize the fire effects literature and identify common data sets for comparative analysis. This paper reports preliminary results of this effort.

Additional keywords: conifers, fire effects, fuel treatment, restoration

Introduction
Vegetation/fuels, climate, and disturbance processes, particularly fire, are dynamically coupled. People, through their impacts on vegetation/fuels, climate and disturbances, as well as their responses to disturbances, are an integral part of the global system. Twenty-first century land management requires a higher level of interdisciplinary integration of the physical, biological, and social sciences than ever before. Vegetation/fuel management activities can no longer be based on single- or narrowly-focused resource outcomes. It is now necessary to integrate multiple resource and societal benefits including species viability, clean air, clean water, public

safety, and sustainable human livelihood. Activities need to integrate across increasingly large spatial and temporal domains. This requires that managers and policy makers have ready access to the best available science and decision support tools to guide their planning and implementation. Because management is today more complex than ever before, it is imperative that it be based on sound foundational science.

Fire is a natural ecosystem process and many vegetation types have recognized fire regimes that describe the frequency, timing, and severity of the fires that created the dominant stand conditions, whether these resulted from natural ignitions or a pattern of repeated human ignitions. Many species evolved in such close association with fire that they possess attributes specialized for exploiting the post-fire environment either through survival (resistance) or rapid regeneration (Gill *et al.* 1981; Wein and MacLean 1983; Goldammer and Furyaev 1996; Sugihara *et al.* 2006; Paula *et al.* 2009). For woody vegetation, adaptations include specialized morphological characteristics such as thick bark, high open crown, large buds, and epicormic buds that are adapted to reoccurring fire (Hare 1961; Ryan 1982; Peterson and Ryan 1986; Ryan 1990). Controlled burning under prescribed conditions is commonly used to alter species composition, reduce competition, enhance wildlife habitat, improve forage, and reduce the risk of catastrophic wildfires. Likewise mechanical treatments are often applied with the intent of reducing either the likelihood or severity of future disturbances. Designing treatments that effectively increase the residual forest's or woodland's resilience to future fires requires robust models that integrate fire behavior with tree injury and postfire survival and growth (Butler *et al.* 2010; Dickinson and Ryan 2010; deGroot 2010).

The authors have begun a review and synthesis of existing fire injury-response science. This synthesis and review builds on the authors' years of experience in Eurasian and North American fire ecology. The purpose of this activity is to develop interim models and guidelines for fuels treatment and restoration activities and to identify research needs. The purpose of this paper is to review basic principles.

Synthesis

Fuels treatment and restoration projects are developed either to modify the potential impact of fire on individual sites or fire's effects at the larger landscape scale. Whether a project is classified as a fuel treatment or restoration depends primarily on the project's objective(s). Similar scientific information and logic need to be applied in either case. Landscapes are made up of sites, each site having its own particular species composition, stand structure, disturbance history, and fire regime. Sites have unique histories resulting from past grazing, hunting, harvesting (fuel, fodder, timber), tilling-farming, and settlement-abandonment. Each sites has a specific rate of change which reflects the underlying site properties (soils, nutrition, precipitation, insolation), specific responses to disturbance, specific response to removal of disturbance, and unique fire relationships. Likewise sites and landscapes have strong social relationships owing to the history of land use and local attitudes towards fire (Daniel *et al.* 2007; Montiel and Kraus 2010; Silva *et al.* 2010). All of these factors should be considered when developing fuel treatment and restoration projects.

Fuel treatment and site restoration employ mechanical manipulation/removal, chemicals, controlled grazing, prescribed burning, or combinations thereof. Where the desired historic stand conditions were strongly influenced by repeated fires, whether by natural or human ignition, prescribed fire is often the most likely process to restore the desired conditions. In addition to being the most ecologically sound treatment, prescribed fire is often the most cost effective means of fuel treatment and restoration. However, excessive fuel build-up can lead to excessively severe fire effects which may compromise treatment goals (Rego, 1991; Rego *et al*. 1993; Vega *et al*. 1994; Botleho and Rigolot 2000). Thus mechanical pretreatment or multiple light burns may be necessary to reduce fuels prior to resuming the desired burning regime, or in some cases to enhance fuels to achieve objectives. In order to achieve management objectives it is necessary to develop and implement a burning prescription tailored to the specific site/stand. Prescriptions for burning define the set of fuel and weather conditions and the ignition pattern that will yield the desired effects. The final outcome of a burn treatment is influenced by pre- and post-burn conditions in addition to the actual fire (Fig. 1). All these factors should be considered in an iterative problem resolution framework. If the current fire environment, principally vegetation/fuels precludes achieving resource objectives during probable fire weather then one or more non-fire treatments will be needed before intentional fire can be introduced. . The same suite of factors needs to be considered when formulating the burning prescription.

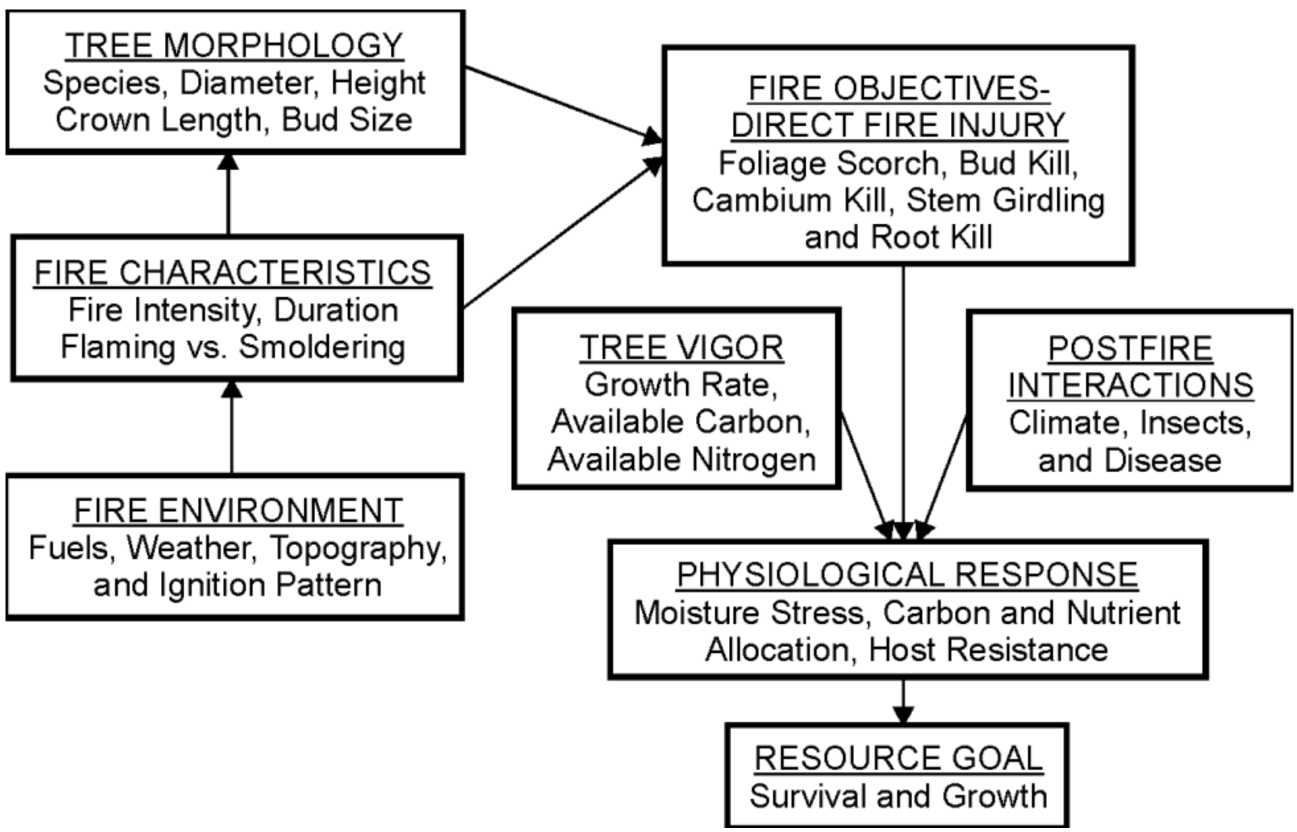

Fig. 1 Schematic illustrating the partial suite of factors that affect the behavior and effects of fire and necessary considerations in the achievement of fuel treatment and restoration goals in forests and woodlands.

The term *fire effects* simply refers to the observable alterations—permanent or temporary, reversible or irreversible—to the physical properties or biogeochemistry of the flora and fauna of terrestrial and aquatic ecosystems, the earth's atmosphere, and their implications to society. All fire effects may be relevant to varying degrees in any vegetation/fuel treatment. For prescription development purposes, it is important to clearly distinguish three classes of fire effects. First, the direct, first-order effects are those that result from combustion and heat transfer process during the burn. Combustion and heat transfer are the direct agents of change and vary with the specific fire environment (vegetation/fuel, weather, and terrain) as well as the kind of fire (heading fire, backing, fire, flanking fire) and the speed of application (c.f., Ryan 2002 for review). Direct effects to trees include crown, stem, and root injuries that the prescription is designed to manage (Fig. 1). Next are the indirect effects of fire. Indirect effects are those effects that are derived from or dependant on the fire's occurrence. If the fire had not occurred, indirect effects could not occur. Indirect effects are of two types: biophysical processes acting on the fire-altered environment and human responses. These include the post-fire biophysical processes such as nutrient cycling, insects, disease, and weather which affect the final outcome (second-order effects) as well as the real and perceived benefits or losses associated with the fire or its management (third-order effects). Tree growth and survival can be directly and indirectly affected by fire. Direct effects result in tissue death. Such death may be readily visible as in the case of crown consumption (burned foliage) and crown scorch (browned/dead foliage). However, bud, crown branch/twig cambium, stem cambium, or root injury may also occur. These latter injuries may be difficult to detect and quantify. The bulk of fire effects knowledge and decision support tools come under the first- and second-order effects and that is the primary focus of our synthesis.

Trees consist of three highly integrated organs: crown, roots, and stem or bole (Table 1). These organs have differing physiological functions and morphological properties that are important considerations in prescribed burning. First, there is the crown. For prescription purposes the crown is defined to include the foliage, buds, and branchwood. The crown is a resource assimilation organ that produces carbohydrates that are the source of all of the energy to meet the demands of the tree including maintenance, tissue growth, injury repair, and chemical defenses against insects and diseases. Second, there is the root system that supplies most of the raw materials (water and nutrients) essential for all metabolic functions and stores carbohydrates/starch. For prescribed burning purposes, the roots include the entire rhizosphere which is made up of the coarse storage and structural support roots, the fine 'feeder' roots, and the associated mycorrhizae. Third, there are the xylem and phloem of the stem that transport water and nutrients from the roots to the crown, and carbohydrates from the crown to the roots; the stem cambium allows the tree bole to expand in girth and is protected by the bark.

The stem also serves as a minor storage organ for water, nutrients, carbohydrates, and defensive chemicals. Under normal conditions in trees that produce annual rings, the stem increases in volume each year. However, new crown and root growth take precedence over stem growth in the hierarchy of carbon allocation (Waring 1987; Waring and Running 2007). The only allocation of carbohydrates that is of a lower priority to a tree is the production of defensive chemicals to protect against insects and disease.

Table 1. Tissue injury results from the interaction of critical fire environment variables with species and age/size morphological characteristics (adapted from Ryan 1998; Ryan et al. 2010).

Physio-morphological Unit	Critical Fire Environment Variables	Factors Affecting Response
Crown	Fuels: • mass & depth of fine (<5mm) fuels Weather: • wind, temp. (°C), %RH • short-term(≤ 3 days) drying Fire Behavior: • peak surface fire intensity • head-fire > backing-fire • convection > radiation	• foliage kill vs. bud kill • crown vigor (color, length, density, architecture) • bud size (mm) • phenology (active vs. bud set) • epicormic buds vs. none, • single vs. multimodal
Stem	Fuels: • mass & depth of coarse (≤7cm) fuels Weather: • mid-term(2-20 days) dryness Fire Behavior: • head-fire ≥ backing-fire • conduction , radiation & convection	• circumference killed • height killed • bark moisture (%) • bark thickness (cm) • phenology (growing vs. dormant season)
Root Crown/Roots	Fuels: • duff depth (cm) • duff moisture (%) ○ Weather: • long-term(> 30 days) dryness ○ Fire Behavior: • ground-fire duration (hr) • conduction	• root-crown bark thickness (cm) • rooting depth

Fire Injury – Resistance and Response

Living tissues of higher plants die when exposed to excessive heat. How long tissues can survive high temperatures depends on 1) the initial temperature of the tissue (i.e., starting air or soil temperature); 2) the amount and rate of heat supplied by the fire which depends on the amount of available fuel and its combustion rate.; 3) how well the tissue is insulated (e.g., by bark and/or soil), and 4) the tissue's specific heat capacity which is largely dependent on how much water is held within the tissue. Approximately, vascular plant tissues survive 1 hour at 50°C, 1 minute at 60° C, and 1 second at 70°C (Nelson 1952; Hare 1961; Peterson and Ryan 1986; Wade 1986; Botelho and Rigolot 2000; Rigolot 2004).

Crown injury is the most commonly observed fire injury. It is easy to visually detect and quantify. During acceptable prescribed burn conditions, crown injury generally determines overstory tree mortality, although as the days since rain increase and the duff dries, root and lower bole damage become increasingly important (Wade and Johansen 1986; Ryan and Frandsen 1991; Varner *et al.*2007). Crown injury occurs when heat energy released during combustion raises the temperature of a crown component above the lethal threshold of about 60°C.The level of damage depends on the amount of heat and the rate at which it is received from the combustion zone, the amount necessary depends upon the initial temperature of the foliage (Byram 1958). The initial leaf temperature is generally assumed to be the ambient air temperature which is a close approximation for conifer needles (VanWagner 1973; Peterson and Ryan 1986) although unpublished results of measurements by Paul Ryan in the early 1960's showed the uppermost canopy foliage of southern pines in direct sun could exceed ambient Fahrenheit temperature by over 20º (Wade personal communication 1965). Such observations could be important to predicting scorch height if subsequent research verifies the observation. Crown scorch has three components, death of foliage, death of branch/twig buds, and death of branch/twig cambia. Based on earlier work and for discussion purposes we distinguish between foliage kill, typically referred to as crown scorch (VanWagner 1973) and crown kill which refers to death of both foliage, buds, and twig cambia (Wagner 1961; Peterson and Ryan 1986; Ryan and Reinhardt 1988). Foliage is relatively small and poorly insulated. Thus it is relatively easy to kill and is **always** a precursor to bud and branch cambial damage within a given conifer species (Wade and Johansen 1986). Buds are somewhat more resistant to heat, particularly if they are large (e.g., *Pinus ponderosa*) and after bud scales have formed. Crown heat resistance depends on bud size, the amount of protection provided by needles and moisture content (Byram 1948; Wagener 1961; Peterson and Ryan 1986). Bud kill is more critical to tree survival than needle consumption and species with well protected buds are much less likely to be affected by fire (Wade 1985); Peterson and Ryan 1986). Experiments of lethal temperatures for needles and buds of *Pinus pinaster*, *Pinus nigra*, *Pinus brutia*, *Pinus halepensis*, *Cupressus arizonica*, *Quercus ilex*, and *Cupressus sempervirens*, showed that buds were less sensitive to heat than needles, and *Pinus pinaster* was a somewhat more heat resistant species (Alexandrian and Rigolot 1992; Rigolot 1992; Duhoux 1994). The cambium of branchwood is relatively resistant to heat.

Heat injury affects the physiology of the plants and the plant's physiological condition at the time of injury affects its response (Hare 1961; Kramer and Kozlowski 1972; Kozlowski 1985; Chambers *et al*. 1986). Tree response to crown kill varies with the vigor of the tree (Ryan 1990, 1998). Tree survival with respect to crown injury depends primarily on bud survival (Wagener 1961; Dieterich 1979; Wade 1985;Wade and Johansen 1986; Wyant *et al*. 1986; Ryan 1990; Hood 2010). Bud kill is more serious than foliage scorch because lost foliage cannot be replaced if the buds are killed. The crown may recover from foliar death if the buds survive and the branch contains sufficient non structural carbohydrates to initiate and sustain new foliar growth. Coniferous species can better withstand crown kill during the dormant season (Craignead 1940; Wagener 1961; de Ronde *et al*., 1986). *Pinus ponderosa* tree buds are large and relatively heat resistant (Wagener 1961; Ryan 1993, 2000) but quite vulnerable to fire damage in the growing season (Wagener 1961).

Bud kill generally occurs at a lower height in the tree than foliage scorch, particularly in trees with large or dormant buds (Fig. 2). In such cases the height of bud kill may be 2 or 3 meters less than the height of foliage scorch. In species with an indefinite terminal bud (e.g., *Thuia plicata*, *Juniperus* spp.) or with small actively growing buds (e.g., *Picea* spp. *Abies* spp., *Tsuga*, spp., *Pseudotsuga* spp.), buds are typically killed to the same height as the foliage (Peterson and Ryan 1986). In species with small set buds (i.e, leader growth has stopped and bud scales have formed) and those with large or shielded buds (e.g., *Pinus ponderosa*, *Pinus contorta*, *Pinus monticola*, *Larix occidentalis*) that are actively growing, buds will be killed to about 10 percent lower height than foliage. In species with large or shielded buds expect crown kill to be about 20 percent lower height than the height of foliage scorch once leader growth is complete and the buds are set.

Vigorous young trees often survive complete foliage scorch if the buds survive. At high crown kill levels surviving trees often exhibit little or no radial growth after burning. Reduced growth may last several years. At low crown kill levels, the remaining foliage may actually experience increased photosynthesis resulting in no growth loss (Wade 1985, 1986; Weise *et al*. 1987, 1989; Ryan 1993, 2000). In trees of average or better vigor, and in the absence of other significant injuries, empirical observation (Ryan 1998; Landsberg 1994) and physiological process modeling (Ryan 1990) suggests that:

- < 30 % crown kill – few problems, minor growth losses, minimal mortality
- 31-60 % crown kill – modest growth losses, increasing insect attack, modest mortality
- 61+% crown kill – major growth losses, insect attack and mortality rapidly increases.

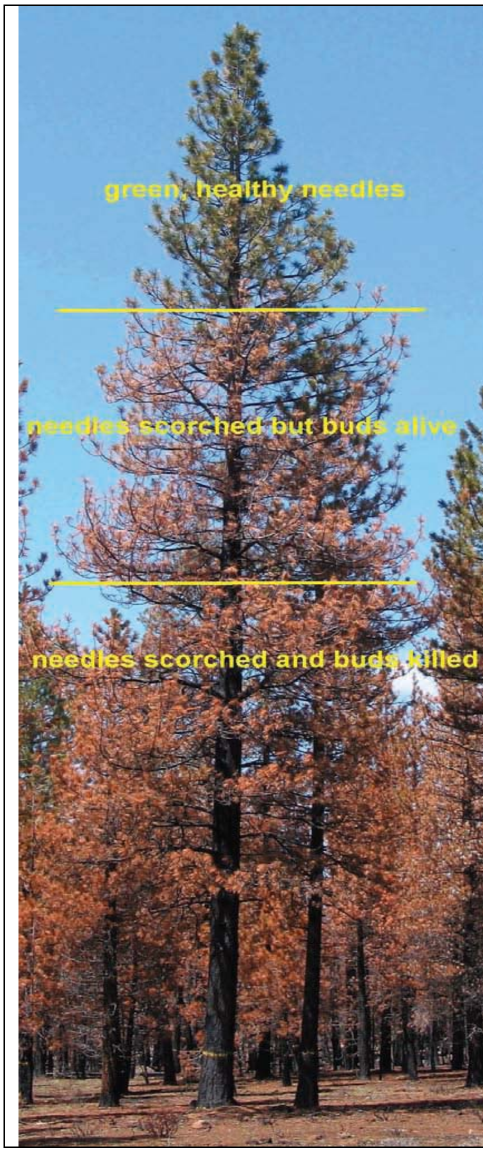

Fig. 2 Ponderosa pine showing the different types of crown injury. The uppermost, green portion of the crown was unaffected by the fire. The middle portion of the crown's needles were scorched and killed, but the buds survived. The lower portion of the crown's needles was scorched and both the needles and buds were killed. (from Hood 2010)

Crown scorch depends primarily upon the rate at which fine fuels ignite and burn. The most important fuels to consider when evaluating potential crown scorch are the stand's average mass of fuel $\leq$ 5 mm in diameter and its moisture content. Discontinuities such as openings in the forest canopy, ridges, and mid slope benches tend to favor ventilation of smoke. Scorch may be higher in these areas (Ryan 1982). It may be necessary to slow the rate of ignition around the edges of these areas. Heat from backfires normally does not reach high enough to significantly defoliate the trees. Headfires can be expected to casuse more injury in a given fire environment (vegetation/fuels, weather, and terrain) where crown base height is less than predicted scorch height. Currently, the best available technique for estimating the amount of foliage that will be killed in a fire is based on Van Wagner's (1973) scorch height model (Fig. 3). Figure 3L may be used to find the scorch height associated with a particular flame length and vice versa given a standard 37^{o}C day (e.g., summer wildfire conditions) and an observed or predicted mid flame wind speed. Crown scorch also depends on air temperature (Byram 1948; Van Wagner 1973) (Fig. 3R). Cooler temperatures yield lower scorch heights, which is of paramount importance when considering prescribed burning weather conditions as opposed to summer wildfire conditons. For example at 15^{o}C scorch height is 50 percent of that predicted in figure 3L. A variation of this model is also presented in Albini (1976), Reinhardt and Ryan (1988). Fig. 3 can be used to visualize flame lengths and wind speeds that will yield a specified level of foliar injury.

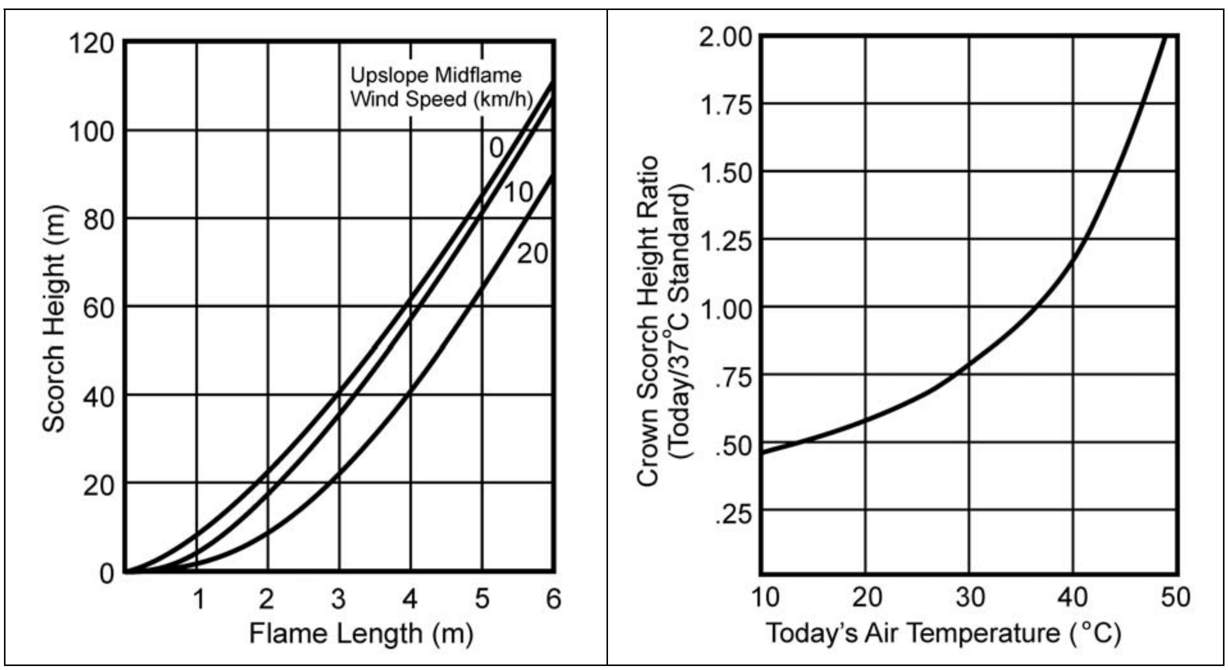

Fig. 3. Foliar scorch height (m) as a function of flame length (m) and wind speed (km/h) when today's ambient air temperature is 37^{o}C (left). Relative height of foliar scorch as a function of ambient air temperature ^{o}C (right). In the graph at the right ambient air temperatures < 37^{o}C correspond with height ratios <1, i.e., lower foliar scorch height. Conversely air temperatures > 37^{o}C correspond with higher foliar scorch. (adapted from Albini 1976, Cochrane and Ryan 2009)

Root damage is determined by the amount of heat conducted into the soil, but the depth of roots should also be considered. For purposes of prescribed burning roots include the root-crown, i.e., the area at the ground-line where the main stem transitions into the roots. The reason for including the root-crown as part of the rhizosphere as opposed to the main stem is because the fuel, fire behavior and heat transfer factors most critical to root-crown injury are more similar to those of the rhizosphere than of the stem exposed to the atmosphere above the forest floor during burning. Basal injury at the ground line is a common injury in fires (Ferguson *et al.* 1960; Ryan and Frandsen 1991; Hood 2010). Although basal injury may be caused by flaming in heavy coarse woody surface fuels at the base of the tree, injury is more typically caused by smoldering in the duff, particularly in long-unburned forests (Fig. 4). The amount of heat conducted downward into roots and laterally into the root-crown is dictated primarily by the amount of duff (fermentation and humus) consumed and soil properties, principally moisture content. Smoldering ground fires in conifer duff have been measured as having temperatures in excess of 400^{o}C (Ryan and Frandsen 1991). Such temperatures have persisted for as long as 30 hours but durations of 3 to 6 hours are more typical. Thus, the amount and moisture content of the duff are the primary factors to consider in prescribed burning. In general duff moisture contents above 120 percent minimize duff consumption so should also minimize root injury. Below about 30 percent duff moisture content most duff is consumed so potential root injury is maximized. Between these is a range of intermediate duff consumption and potential root injury. Duff moisture content changes slowler than the litter. Diurnal changes in fine fuel moisture or changes in the ignition pattern are not likely to affect duff consumption and potential root injury unless they result in a patchy burn. If the surface fuels are ignited the duff beneath them will likely burn about as well at night as in the day. Light wind may improve duff burnout somewhat. If duff moisture is out of prescription it will require to wait for substantial precipitation or drying before there will be much affect on duff consumption and potential root injury.

There are few studies that have attempted to quantify fire-caused damage to fine and coarse roots in the soil. When roots are injured by fire, trees may grow slowly or die (Ryan, 1990; Abaimov *et al.* 2004), but root injury is rarely described due to the difficulty of assessing root distribution (Wade 1986; Swezy and Agee, 1991; Zeleznik and Dickmann 2004; Hood 2010; Noonan-Wright *et al.* 2010). The amount of root injury that occurs and its effect on survival and growth has not been quantified adequately.

Coarse or large roots function both as structural support and as carbohydrate storage organs. They are generally deep in most pioneer species and are not likely to be directly killed by fire unless considerable duff is consumed. Early successional conifers generally are shade intolerant and prefer a mineral seed bed. These species tend to be more deeply rooted than the late successional, shade tolerant species. In contrast late successional species tend to be shallow rooted. For example, *Sequoia sempervirens*, *Larix occidentalis*, and *Pinus ponderosa* naturally regenerate following fire and are generally deep rooted. *Pseudotsuga menziesii* and *Pinus contorta* are moderately deep rooted. *Pinus monticola* and *Pinus lambertiana* have an intermediate root depth. *Abies concolor* and *Abies grandis* are moderately shallow rooted. *Thuja plicata*, *Tsuga heterophyla*, *Picea engelmanni*, *Picea sitchensis*, and *Abies lasiocarpa* are shallow rooted species. *Pinus pinaster* has a deep-root habit with extensive lateral branches (Maugé, 1987). Seventy to ninety percent of the total root system is located below 60 cm under the surface soil level (Fischesser, 1981). Soil/site characteristics such as permafrost and high water table also affect rooting depth. Regardless of the initial rooting pattern most fine-feeder roots and their mycorrhizae are found in the duff and surface several centimeters of the mineral soil. As the duff gets deeper more roots are found in the organic soil layers. These are susceptible to injury by a prescription that results in heavy duff consumption.

When developing a burning prescription it is necessary to evaluate the potential for root injury by looking at the duff right around the base of the tree (Fig. 4). It is usually deeper and dryer than the average duff in the rest of the stand. This is because much of the needle litter and most of the bark flakes fall near the tree. The canopy intercepts rain until it is saturated. Only then does the rain fall through to the litter below. As a result the amount of rain received by the duff right beneath the tree is reduced. Usually long duration storms of 1 cm or more are needed to begin significant wetting of the duff mound beneath the tree. If the duff is deeper than 8 cm and dryer than 50 percent on an oven dry basis basal girdling may be a problem for all but the thickest barked trees. High mortality should be expected for shallow rooted species in any prescription that calls for more than 4 cm of duff consumption. Unless high mortality is a goal, fires causing deep ground char should be avoided. Mortality is not apparent immediately and may be delayed as sometimes occurs when smoldering duff either girdles the root crown or excessively prunes roots. Trees with sub-lethal tissue injuries have an increased likelihood of successful insect attack (Ryan and Amman 1993, Hood and Bentz 2007).

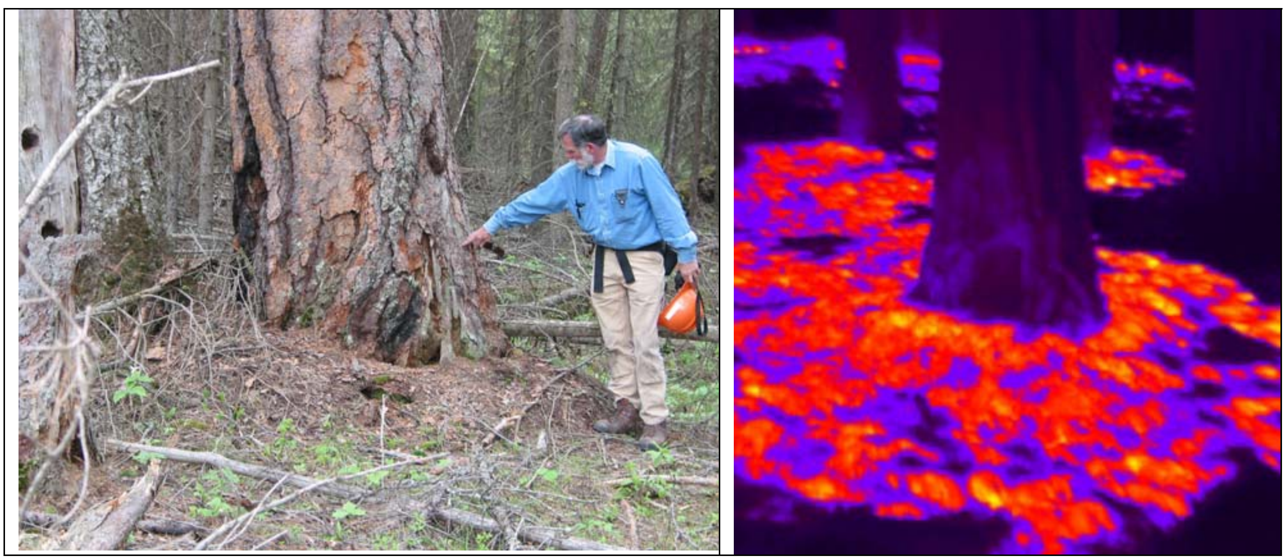

Fig. 4. Duff mound (l) beneath old growth ponderosa pine (*Pinus ponderosa*) in Glacier national Park, Montana and thermal infrared image (r) of smoldering duff (from Hood 2010)

For fire effects prediction purposes the stem includes the main bole/trunk above the duff surface where the primary heat source comes from flaming in surface fuels. Stem heating during a fire is complex heat transfer process involving radiation, convection, and conduction. First the surface of the stem is heated by radiation and convection. Then heat is transferred from the dead outer bark to living tissues (phelogen, phloem, and xylem) within the stem by conduction. Prediction of potential stem injury requires information about fire behavior in proximity to the tree and the tree's bark properties (Peterson and Ryan 1986; Rego and Rigolot 1990; Jones *et al.* 2004, 2006; Butler and Dickinson 2010). The two factors that are most important for determining the likelihood of trees suffering cambium injury are the thickness of the bark and the duration of burning in surface fuels. Bark thickness increases approximately linearly with stem diameter and it varies by species (Peterson and Ryan 1986; Ryan and Reinhardt 1988, Ryan *et al.* 1994a) (Fig. 5A). Resistance to stem injury varies with the square of the bark thickness (Fig. 6). The factors controlling the duration of burning include the fuel-bed particle sizes, arrangement, moisture content (Albini 1976; Albini *et al.* 1995a, b; Albini and Reinhardt 1997), and ignition pattern.

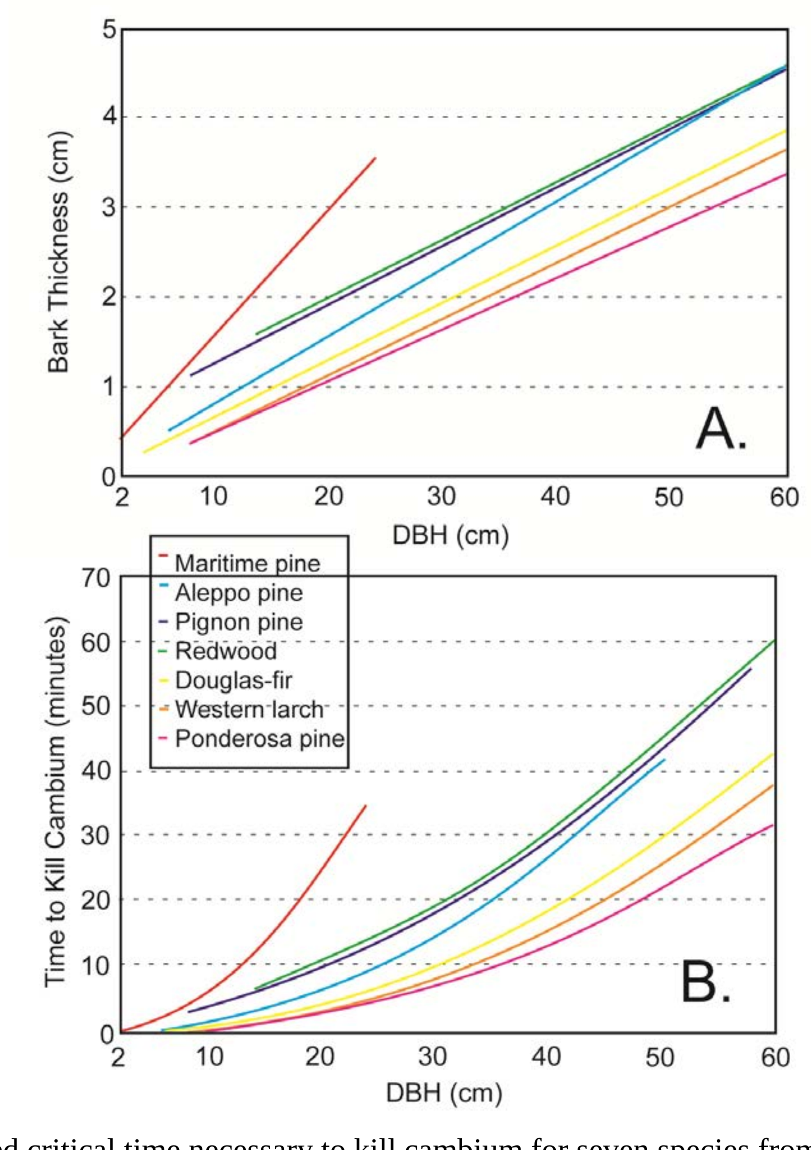

Fig. 5. Calculated critical time necessary to kill cambium for seven species from western North America and the Mediterranean Basin based on heat transfer relationships (from Ryan *et al.* 1994a). Maritime pine (*Pinus Pinaster*), Aleppo pine (*Pinus halepensis*), Pignon pine (*Pinus pinea*), redwood (*Sequia sempervirons*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and ponderosa pine (*Pinus ponderosa*).

The duration of burning that a tree can withstand is approximately 3 times the squared bark thickness (i.e., time to kill {min} = 3 x bark thickness {cm}^{2}) under common prescribed burning conditions (Peterson and Ryan 1986). The heating duration necessary to kill will be shorter for higher intensity fires and longer for very low intensity fires (Fig 6). Bark thermal properties vary somewhat from species to species but available literature suggests that the differences are unlikely to be a major factor in predicting the effects of fire when compared to the uncertainty in stem surface temperature.

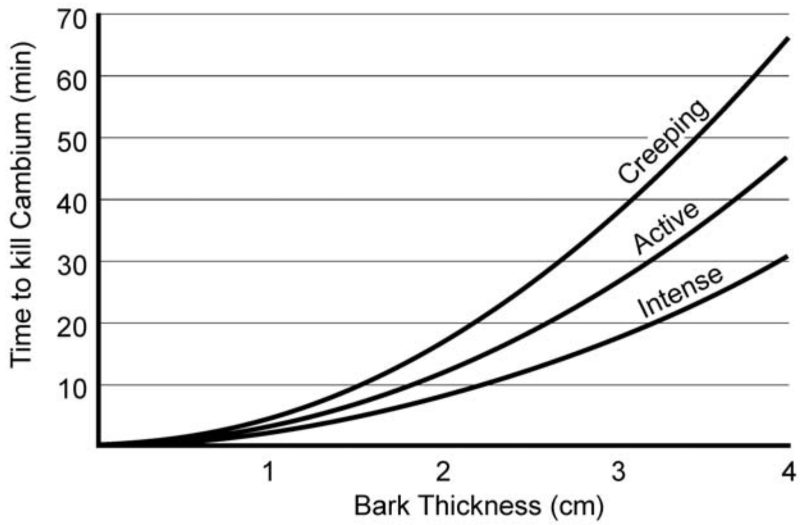

Fig. 6. The time to kill cambial tissue varies with the square of bark thickness and the difference between the stem's initial temperature (~ambient) and the stem's surface temperature due to radiant and convective heat transport from the flames. Stem surface temperature varies somewhat with the emissivity of the flames. Emissivity in turn increases with the flame depth as fire intensity increases until it approaches unity at around 1 meter flame depth. (from Ryan 1998, Cochrane and Ryan 2009)

If the duration of the fire is above the point on the curve representing your species and diameter in figure 5B, expect cambium injury. In general trees with bark less than 5 mm thick are poor candidates for survival in prescribed burns because it is difficult to consistently find suitable fuel and weather conditions for such short duration fires. Cambium beneath moderately thick bark (bark thickness 10 to 25 mm) is likely to survive light surface fires but not moderate surface fires or moderate ground char fires (e.g., where duff depth > 5 cm and dryer than 50 percent). Cambium beneath bark thicker than about 25 mm should survive most surface fires, with the exception of dry heavy coarse woody debris. The primary source of cambium damage on these larger trees results from smoldering ground fires in the duff. As previously pointed out basal girdling may be a problem if duff is deeper than 8 cm and dryer than 50 percent. If crown kill is less than about 30 percent and root injury is minimal, trees often survive with cambium killed in two quadrants up to breast height. If crown kill is between 30 and 60 percent trees often survive with dead cambium in one quadrant. The probability of survival is low for any tree with dead cambium on more than half of the circumference at breast height.

When sizing-up potential fuel situations the fuels within one- to two-meters are of primary concern. More distant fuels generally only cause problems when concentrated into piles that can burn for long durations. If the fuels are mostly $\leq$ 1 cm diameter expect the duration of burnout to be about 4 minutes. If there are a lot of 1 to 5 cm fuels expect the duration to be about 10 to 12 minutes. If there are enough 5 to 15 cm diameter fuels to make a sustained fire expect the duration to be about 20 to 30 minutes. Heavy coarse woody debris, i.e., large logs, is usually a problem only when they are resting against the bole or if clumped nearby.

Bark thickness, tree height, and crown ratio are all factors in determining susceptibility to fire injury and mortality(Fig. 7). Reinhardt and Ryan (1988) developed a graphical nomogram for predicting the effects of fire on conifers in western USA. This can be used in prescription development. The equations for the nomogram also are included in the fire effects section of the BEHAVE-Plus fire behavior and effects model (Andrews 1986; Heinsch and Andrews 2010, http://fire.org/index.php?option=content&task=category&sectionid=2&id=7&Itemid=26) FOFEM (Reinhardt *et al*. 1997; http://www.fs.fed.us/ccrc/tools/fofem.shtml), and CanFIRE (deGroot 2010) fire effects prediction systems. Numerous post-fire tree mortality models have been developed for the United States (Woolley *et al.* 2011), Canada (deGroot 2010), Europe (Fernandes *et al.* 2008; Catry *et al.* 2010), and Russia(Voynov and Sofronov 1976; Voynov *et al.* 1980; Abaimov *et al.* 2004).

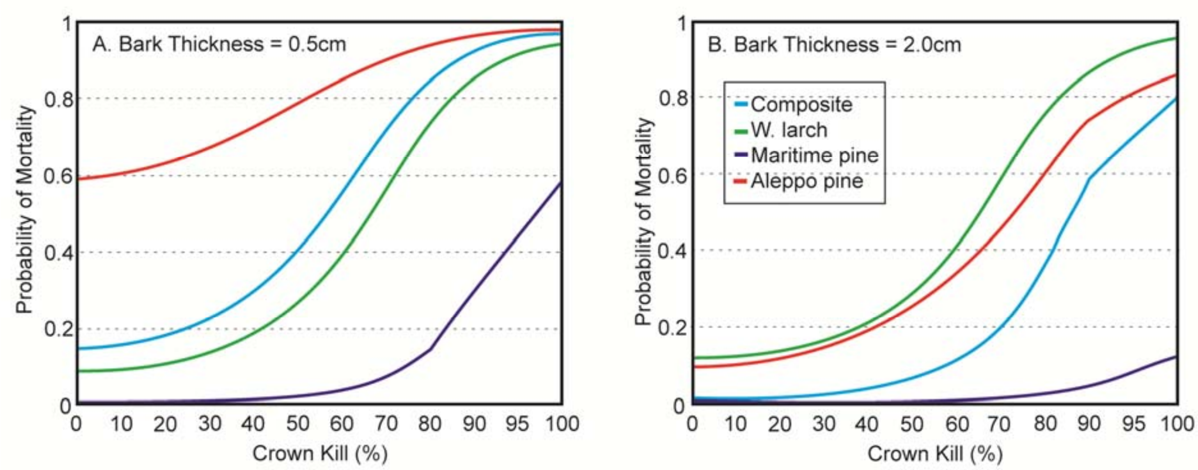

Fig 7. Predicted mortality for Aleppo pine (Pinus halepensis), Maritime pine (Pinus pinaster), western larch (Larix occidentallis), and a composit equation for all three species for thin (a) vs. thick (b) barked trees. (from Ryan *et al.* 1994b)

When conducting a prescribed burn it is necessary to size-up the fuels all around the tree and determine their burning characteristics. If, after having used a decision support aid (Reinhardt and Ryan 1988; Reinhardt et al. 2004; Fernandes et al. 2008, de Groot 2010) to calculate expected mortality the level of mortality is unacceptable, i.e., too high or too low then you have three choices: First, change the amount of fuel that can burn (commonly called available fuel) either by modifying the total amount of fuel (e.g., modify the harvesting, utilization, or removal standards to achieve the proper fuel load), or by modifying the moisture content of one or more elements of the fuel complex, raising or lowering moisture content to decrease or increase, respectively the amount of fuel consumed and energy released. Second, you change the prescribed weather conditions. Aside from effects due to fuel moisture changing the air temperature and wind speed will modify fire effects, particularly crown scorch. Diurnal changes in temperature and wind are not likely to have big effects on bole or root injury and the resulting growth losses or mortality. Third, you can modify the ignition pattern to either increase or decrease the amount of fuel on fire at any one time. For example, several strips ignited close together in time and space result in increased surface fire intensity. This increases crown scorch height but may result in bole damage to thinner-barked trees. Backing fires result in lower surface fire intensity but longer duration. This can result in lower scorch height but greater bole damage. When using strip head-fires intensity can be reduced without effecting duration by igniting one strip at a time and making the width of the burn strip less than the maximum flame zone depth. For example, if a free burning head-fire has, or is predicted to have a 5 meter flame zone depth, igniting strips less than 5 meters will result in lower flame lengths. Flanking fires result in varied fireline intensities. Initially, intensity is relatively low but increases as strips converge. This may be useful for increasing the amount of diversity on a burned area.

If the amount of fuel around a tree is too much for desirable leave-tree to survive, it is necessary to accept a higher level of mortality, change your prescription, or take supplemental measures to protect the trees. To change the prescription implies that you burn when duff and large woody fuels are wetter. Supplemental protection involves either pretreating the fuels or insulating the tree. Examples of fuel pretreatments include wetting the fuels using a fire hose or sprinkler; treating fuels with ground application fire retardants or foams; or removing fuel (Ryan and Steele 1989). Treating with fire retardant chemicals is not effective against large concentrations of logs or deep dry duff. The limits of usefullness of foams are presently unknown. Many new foam products recently have been developed for fire suppression but they have not been evaluated for their ability to protect trees. If you have large concentrations of fuels < 25mm diameter, think about burning when it is wetter unless only a few trees require clearing. Remove 25 mm to 75 mm fuels only if there is a clump of them. Remove large fuels within 2 times the log diameter (e.g., remove all 25 cm logs within 50 cm of the tree). It is difficult to say just how far to clear around a tree. Economics often dictates how much mitigation is possible. Usually 1 meter is sufficient but that depends on the amount of fuel and the thickness of the bark. The thinner the bark and the heavier the available fuel the further the fuel must be moved. When clearing fuel around trees broadcast the fuel to the side, never up hill or down hill (or on the windward side).

In western North America species with shallow roots also tend to have thin bark. This pattern also occurs throughout much of the Eurasian boreal forest (Melekhov 1980; Melekhov *et al.* 2007). It is unclear whether it is the dominant pattern in other parts of the world, particularly where genotypes have been planted off-site. It is consistent, however, to expect that species that evolved with infrequent fire would not invest the energy in producing thick fire-resistant bark if they were likely to suffer extensive root damage from a smoldering ground fire. Later successional species tend to be susceptible to both root and stem injury. As a result shallow rooted trees rarely survive surface fires with more than 50 cm high flames or those that consume more than the fresh litter (e.g., light ground char). The exception to this is when the fire is patchy and does not uniformly burn around the tree.

Scolytid bark beetles (Family *Scolytidae*) often attack trees following reintroduction of fire, compromising restoration goals. Because, stem growth and production of defensive chemicals are relatively low priority for a tree's carbohydrate allocation (Waring 1987, Waring and Running 2007) significant injury to crown or roots will result in reduced stem growth (radial or basal area growth). There will also be at least a temporary reduction in a tree's ability to defend itself from insects and disease. The relationships between fire injury and host susceptibility to insect and disease attack are poorly known. The need to understand beetle dynamics suggests we need more research and development in the physiological ecology of trees and insects.

Conclusions

Knowledge of the interactions between vegetation/fuels, fire behavior, and fire injury is integral to controlling direct fire injury thereby affecting the survival and growth of trees. Prescriptions for burning can be developed to minimize or enhance the type and degree of fire injury thereby favoring certain species and size classes of trees. It is important to realize, however, that most prescribed fires will cause at least minor injuries and temporary reductions in tree vigor and growth (Landsberg 1994). One of the premises of prescribed burning is that improved ecological conditions and the reduced risk of stand destroying wildfires justify investments in burning and minor growth losses. The application of prescribed fire beneath standing timber is challenging but integration of fire behavior knowledge with an understanding of the fire injury process and plant response to injuries can maximize desirable results.

When one looks across the globe at the near-infinite number fire environments it is easy to appreciate the impossibility of conducting robust empirical field studies on a large number of them. The many sites and species-fire relationship combinations, and the locally-variant social constraints argue in favor of taking a process-based approach to developing treatment prescriptions. Vegetation/fuels are highly variable in time and space leading to a wide range in fuel consumption/energy release and fire behavior. Fire weather is highly variable but the patterns are quite well known. Tree morphology is quite variable but there is a large body of physiognomic and mensurational data in the literature upon which one can draw inferences. While the body of knowledge on tree physiology is not robust evolutionary constraints argue that there are a limited number of plant responses to injury. The response of insects and diseases to fire injury to their host organisms has received only limited attention in the literature. By synthesizing our understanding of the biophysical processes associated with fire injury, survival, and growth we hope to develop interim models to guide safe effective fire use in vegetation/fuel treatments and restoration projects. We also expect to identify knowledge gaps that will help to prioritize subsequent research and development.

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Friendly fire: assessing the effects of firing operations in managing wildfires

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Abstract
Over the last quarter century, there has been a perceptible increase in the frequency of large-scale high-intensity wildfires. This rise in wildfire activity has mainly been attributed to the effects of excessive fuel accumulations from past fire suppression coupled with the effects of climate change that is causing prolonged droughts and longer fire seasons. Some of this recent increase in wildfire size and severity may also be the result of *current* fire suppression actions using indirect attack strategies with firing operations called backfires and burnout. This paper will present a critical discussion the possible role of suppression firing operations in recent large wildfires, the significant environmental and ecological effects of backfires and burnout, some examples of the negative social impacts when firing operations óbackfire,ô and conclude with a call for increased documentation, monitoring, and analysis of the role of suppression firing operations in large fire management. The goal of this discussion is to inspire greater mindfulness of the need to integrate safety, ethical, and ecological concerns in ó*managing fire with fire*.ô

Introduction
The technique of ó fighting fire with fireô has long been part of the toolbox of fire management, and was likely first learned by early foresters from Native Americans. Indeed, Pyneôs (2001) ó *Year of the Fires*ô and Eganôs (2009) ó *The Big Burn*ô provide numerous examples of backfires ignited by firefighters in desperate attempts to save towns during the 1910 Fires in the northern Rockies. In some cases these backfires successfully halted the advance of wildfires, but in other cases the backfires were ineffective or actually óbackfiredô on firefighters and destroyed some or all of the towns that they were attempting to save. These opposing outcomes of suppression firing operations underlie my use of the term, ófriendly fire,ô which has a double meaning. On one hand, friendly fire refers to the notion of a ógood fireô that accomplishes its intended beneficial purpose, e.g. to protect a threatened community or restore a degraded ecosystem. On the other hand, friendly fire also refers to notion of ó bad fireô in the same sense that the military uses it to refer to intentional firing that accidentally causes death or destruction of oneôs own forces. The concept of friendly fire in this paper thus symbolizes suppression firing operations that are always ignited with the best of intentions but can lead to either good or bad outcomes.

Mega-fires and the 'hidden hand' of fire management
For several years both fire scientists and fire managers have been reporting that there is a growing frequency of large-scale high-intensity wildfires including what the newsmedia have dubbed ómega-fires.ô For example, in the last decade, Arizona, New Mexico, Colorado, Oregon, and California have had the largest wildfires in their statesô recorded histories. Global warming-induced climate change that is creating prolonged droughts and longer fire seasons, or excessive fuels accumulations resulting from past fire suppression have been the most common explanations for the relatively sudden appearance of these fast-spreading mega-fires. Scientists have studied nearly every relationship between biophysical variables in the fire environment

(fuels, weather, and topography) to understand wildfire dynamics and craft better models for predicting fire spread, fire behavior, and fire effects. They have researched all variables except one: what I liken to Adam Smithôs óhidden handô of firefighters and their firing operations.

Most people associate fire suppression with stopping fires, not starting them, but as every firefighter knows, there is a considerable amount of fire-lighting involved in firefighting. But with few exceptions, fire researchers and managers have rarely considered the relationship of fire management actions to other variables affecting fire spread, nor designed a study to monitor or analyze the role and effects of firing operations on wildfire size and severity. Anecdotally, firefighters report that they are increasingly employing indirect attack strategies with lots of firing operations, especially on large wildfires in unroaded areas with steep slopes, dense fuels, or extreme fire weather conditions. This is not surprising, since these strategies and tactics are generally the safest methods for firefighters to contain wildfire spread under these conditions. Nevertheless, when the newsmedia breathlessly report that a given wildfire has grown an alarming number of acres in a given day, never do they ask if any of this rapid growth in wildfire size was due to firing operations. If reporters did ask this question, fire managers would have no reply since they almost never document the data needed to track the location and spread of firefighter ignitions.

In places where the newsmedia did report that the Forest Service or other agencies were igniting backfires or large burnouts, this became an issue of public interest and concern. For example, in the aftermath of the 2008 wildfires in northern California where extensive firing operations were conducted, local Native American tribes charged that some of their sacred sites were severely burned by backfires, forest conservation activists accused the agency of deliberately burning old-growth stands in order to later offer salvage timber or hazard tree sales, private timber owners complained that backfires burned up valuable commercial timber stands on both public and private lands, and rural homeowners charged that backfires ignited by CALFIRE actually destroyed several homes in the community of Concow. Fire managers needed to respond to these concerns and criticisms, but because the agencies do not track the locations or spread of suppression ignitions, they had no real data to use to refute some of the more ó incendiaryô claims made by local citizens. Both fire researchers and managers need to address this data deficit and absent analysis.

Fire suppression does not equate with fire exclusion

Over the last two decades many people have implicitly assumed that fire suppression is the main cause of fire exclusion, and in fact, the former concept has been used almost interchangeably with the latter concept as if they were the same thing. The argument has been made that by fighting fires this has excluding fire across the landscape, which in turn has allowed excessive fuel loads to accumulate and feed increased wildfire activity including mega-fires. On the contrary, because firefighters routinely ófight fire with fire,ô fire suppression involves a fair amount of human-caused fire *reintroduction* rather than absolute fire exclusion. The ironic fact that firefighters start fires in order to stop wildfires is counter-intuitive and misunderstood by much of the public. Some people must wonder, why are firefighters putting *in* more fires when theyôre supposed to be putting them *out*? A brief introduction to some of the motives and methods of suppression firing operations follows.

There are two main types of firing operations: backfires and burnout. Backfires are high-intensity fires designed to consume all available fuels in front of an advancing wildfire, and apply force to change the wildfireôs intensity or direction. Burnouts are low-intensity fires that remove fuels adjacent to firelines, and thus help widen and secure them. Burnouts are also ignited deep within wildfire interiors on ógreen islandsô of unburned vegetation and fuel. Increasingly, the two types of firing have become conflated with the advent of large-scale burnouts that some Forest Service fire spokespersons dubbed óbackburnsô during the 2008 wildfires in northern California. So-called backburning has become common practice on wildfire ócomplexesô (a cluster of adjacent wildfires) to merge separate smaller fires into a single large wildfire. It is generally far safer and more efficient for firefighters to work on one large fire perimeter than to send them in between several smaller fires trying to contain and control each one individually. Given that most of the recent mega-fires started out as fire complexes that later merged into huge wildfire areas, it raises the question: compared to natural fire spread, what role did backburning did play in the formation of these mega-fires?

The 1999 Big Bar Fire in northern California and the 2002 Biscuit Fire in southern Oregon were the largest and most expensive wildfires in the nation in their respective years. Both were lightning-caused fire complexes that burned mostly across designated wilderness and inventoried roadless areas, and firing operations were used extensively on both wildfires. Two unpublished reports (Ambrose 2001; Ingalsbee 2006) examined the scale of backburning on these fires: an estimated 44,000 acres out of 144,000 total acres on the Big Bar Fire, and over 100,000 of the total 500,000 acres of the Biscuit Fire resulted from backburning operations. Although there have been no systematic studies of firing operations and no hard data available to either support or refute this statement, an educated guess is that generally 30% of the total burned acreage on large wildfires result from firing operations. This is not an insignificant amount of land being burned by the óhidden handô of fire management!

Beyond questions of size or scale, questions remain as to the environmental and ecological effects of firing operations. If they successfully contained the wildfire, then no further questions are asked and they are assumed to be beneficial actions. But this *assumption* that firing operations are always good or better for the ecosystem than unfettered wildfire spread needs to be put to a scientific analysis comparing fire effects. A discussion of some of the potential adverse environmental and social impacts of firing operations follows.

Scorched Earth suppression: the environmental impacts of firing operations

One of the most obvious environmental impacts of firing operations is that they kill vegetation and consume fuel. Typically small-diameter understory fuels are the target, but sometimes large overstory trees are killed by backburns. Given the pretense that firefighting is supposed to protect forests and saves trees from wildfire, backburns that kill large numbers of big old trees represents one of the clearest examples of (bad) friendly fire. Creating large patches of big, old dead trees may not necessarily be a significant impact, though, if the amount of high-severity acres are within the natural range of variability within a given watershed. In fact, large-diameter snags and logs are highly valuable as wildlife habitat structures, but if the legacy of commercial logging in the surrounding landscape had already reduced the number or extent of old-growth stands, then further losses from backburns might be a significant long-term impact. Moreover, even if the percentage of high-severity acreage is within a watershedös natural range of variability, it is not simply a matter of size but also the pattern of fire spread that is important. Backburns that cause unnatural sizes, shapes, or locations of high-severity patches may have adverse impacts that are more significant on a qualitative if not quantitative level.

Another environmental impact of suppression firing operations is that they kill wildlife. While most species that evolved in fire-prone environments have developed various adaptations and instincts that help them escape, survive, or recover from wildfire disturbances, the location, timing, pattern, or intensity of backfires may alter what would otherwise be natural fire spread, causing higher mortality of individuals than might have occurred naturally. Animals that are adept at evading slow-moving wildfires such as deer may become entrapped between a wildfire and a backfire they lose their ability to escape. In the ókill boxô between the two flame fronts, fireline intensities can reach extreme levels, where it must be assumed there are few survivors.

One of the benefits of wildfire burning at various intensities and severities is that across the landscape it creates a multitude of habitats referred to as the ófire mosaic.ô It is trite but true: pyrodiversity enhances biodiversity. Thus, from an ecological standpoint, one should not assume that low-severity burnout is always (good) friendly fire. Large-scale burnouts that create uniformly burned large patches, or target ógreen islandsô of unburned vegetation within wildfire interiors, can eliminate vital refugia for some plants and animals, and result in a homogenization of fire effects that diminishes the fire mosaic. Thus, both high and low intensity firing operations can have paradoxical beneficial or adverse effects.

Backfires that backfire: the social impacts of firing operations

When the conditions for igniting backfires are just right, they get pulled into the main wildfire and slow or stop its spread, but when something goes wrong, they can literally backfire and either fail to meet up with the main fireð becoming their own new wildfireð or even turn against firefighters, putting them in peril. One of the more notorious firing operations that went awry is the 2000 Cerro Grande Fire. Speaking at the Association for Fire Ecologyôs Third International Fire Ecology and Management Congress, former Interior Secretary Bruce Babbitt admitted that it was a backfire ignited to contain an escaped prescribed fire that, in turn, escaped firefightersô control and destroyed over 200 homes in Los Alamos, New Mexico. At the International Association of Wildland Fireôs 2008 conference in Jackson, Wyoming held on the 20th Anniversary of the Yellowstone Fires, former president of the Association for Fire Ecology, Dr. Michael Medler, made the startling confession that it was an ill-planned backfire ignited by his Forest Service firefighting crew that had roared towards Old Faithful lodge, nearly destroying it.

The 2009 Station Fire presents an excellent example of the paradox of firing operations and the two kinds of good and bad friendly fire. On the one hand, backfires saved the community of La Crescenta from certain wildfire destruction, but on the other hand, two firefighters were killed from a backfire they ignited. Use of extensive burnout enabled firefighters to eventually corral the blaze that burned for weeks on steep, extremely rugged, densely vegetated slopes. However, Forest Service Chief, Tom Tidwell, in testimony before Senator Feinsteinôs Interior Appropriations Committee stated that it was the burnout operation conducted by initial attack crews that had escaped their control, later becoming that huge wildfire. The Station Fire has been the focus of harsh media criticism and several Congressional investigations revolving around the charge that the Forest Service was not sufficiently aggressive enough during initial attack and let the wildfire grow to its huge size. But, ironically, one could also argue the opposite: the agency was possibly *over-aggressive* and *made* it a mega-fire with its use of burnout and backfires.

To burn or not to burn? that is not the question!

According to Pyne (1995), we are a fire-tending species--the only creature on Earth with the ability to both stop and start fires. Indeed, it may be our speciesô ecological role as a disturbance agent to supply ignitions at the times, places, patterns, and frequencies that would not occur by natural lightning alone. In many areas around the world, individual species, biological communities, and entire landscapes have co-evolved with human-caused ignitions as a recurring part of the local fire regime. Firing operations thus may help maintain our role as fire-tenders, paradoxically igniting fire in the act of suppressing it, reintroducing it to areas where it has been excluded in the past while limiting some of its spread or severity in places where burning is socially unacceptable.

There is no escaping the inherent paradoxes of suppression firing operations: firefighters starting fires in order to stop them, putting in more fire than they physically put out, and in the process sometimes killing or destroying the very things they are striving to protect. Consequently, it is time to ask some tough questions: are natural resources and rural communities that are meant to be protected by these (good) friendly fires more often than not falling victim to (bad) friendly fire? We cannot answer that question because we have yet to even ask it! Ignitions are set on wildfires with a single-minded focus on containing fire spread, but managers rarely if ever ask themselves if their firing operations will cause more severe fire effects than if they simply let the wildfire spread to the same area on its own.

There has been little research interest and no management attempt to conduct a systematic scientific analysis of the influence of firing operations on wildfire size, spread, behavior, or effects, but it is time for such an analysis to begin. With the development of the new Wildland Fire Decision Support System, there will be new opportunities to generate and record essential data on the locations of firing operations, and the environmental variables of fuels, weather, and topography that influence their behavior and effects. Increasingly sophisticated mapping and monitoring tools, and more accurate modeling programs are being developed that will enable us to track the spread of backburn operations, and better predict their effects. At the present, documentation of suppression actions is currently very sketchy, and there are serious concerns over the validity and reliability of this data, but with these new research and management tools now is time to start generating, recording, and analyzing data from suppression incidents in order to answer this óburning questionô of growing public interest and concern.

Firefighters United for Safety, Ethics, and Ecology strongly advocates the use of fire to *manage* instead of ófightô wildfires. Indeed, our pro-fire use philosophy is best symbolized by our organizationôs acronymð FUSEE--and our motto: óWeôre *torchbearers* for a new fire management paradigm.ô Suppression firing operations that are done the right way can accomplish both protection objectives (e.g. stopping wildfire from spreading toward a community, or limiting its intensity in a sensitive natural area or endangered species habitat), and restoration goals (reintroducing fire of appropriate intensities to places it has been excluded). There is no escaping the inherent risk and multiple paradoxes of using fire to suppress fire, but at least some of this risk can be mitigated if firefighters are more mindful of the positive and negative effects of their firing actions. With the right management motives and methods, firing operations could be the least damaging and most ónaturalô way to manipulate fire spread and mitigate fire severity so that the ecological benefits of burning are maximized while the environmental impacts of suppression are minimized.

Given the multiple legal and social constraints against proactive prescribed burning, wildfires are the most opportune venues for conducting ócontrolled burnsô to restore the role of fire as a vital ecological process. Indeed, using wildfire ignitions as trigger points for the times and places to burn, firefighters could utilize burnouts and backfires to steer flames into areas that fire planners have previously identified as needing to burn for various ecological restoration reasons, while stopping fire from spreading into areas that for social reasons should never burn, such as near human communities. With ecologically appropriate firing operations, the whole distinction between prescribed burning and wildfire use may even dissolve as firefighters implement an integrated, holistic fire management praxis.

Conclusion

Under the Obama Administrationøs new guidance for implementing the Federal Wildland Fire Policy, fire managers are empowered to use all the tools in the management toolbox to manage fires for multiple social and ecological objectives simultaneously. Thus, we may see an increase in Fire Use strategies and tactics to accomplish both fire restoration goals and fire suppression objectives. But what will we be accomplishing when weøre simultaneously suppressing and using wildfire for multiple resource objectives? There is no way we can account for successes or learn from mistakes unless and until we begin to critically examine the effects of suppression actions, especially firing operations. Along with the greater managerial discretion that the new policy guidance provides comes the need for more transparency and accountability in wildfire management including firing operations. Above all, a greater intentionality or mindfulness needs to guide our use of backfires and burnout so that they are oriented towards a wider set of social and ecological objectives besides simple fire containment.

As Pyne (2004) would put it, weøre igniting the ófires of choiceô (backburns) in order to avoid the ófires of chanceô (wildfire); however, it is time to acknowledge that while we have little choice whether or not to use fire to manage wildfire, we take chances with every firing operation. The key is to become more mindful of the risks of the two kinds of friendly fire, and strive for the right mixture of human and natural fire spread that yields the kind of fire behavior and effects that society wants and nature needs. In FUSEEøs vision, some day in the future the term ófire fighterô will become as anachronistic as the term ósmokechaserô is today. Instead, we will be using terms like fire-lighters, fire-guiders, or possibly fire-rangers to better describe the occupation and the way we safely, ethically, and ecologically manage wildland fire.

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Predicting Prescribed and Wildland Fire Behavior in Deep Organic Soils

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Abstract:
Fire has played a major role in determining the distribution of plant communities across the forest ecosystems of the southeastern US. Ground fires ignited by lightning and prescribed fires can result in wildfires that have historically combusted organic soil to depths of one meter or more and put communities in the wildland urban interface at risk from particulate matter and trace gas emissions. Wildfire behavior on deep organic soils changes from a low intensity burn to a virtually uncontrollable burn until weather conditions change or the fire has run out of fuel. The fuel and weather conditions that determine whether fires will ignite, and are associated with transitions between combustion stages, are not easily measured. This is due partly to the highly variable nature of fuels on the coastal plain landscape, and the lack of a dense network of sensors to monitor weather and fuel conditions. Installation of portable weather stations equipped with TDR sensors placed at various depths in the organic soil profile has provided insight into conditions that contribute to the ignition of organic soil ground fires. We report on two prescribed fires. One which met the burn plan objectives and had minimal organic soil ignition and a second prescribed fire which resulted in extensive organic soil ignitions that consumed 30 cm of the soil profile. We report weather station data that includes daily and yearly trends in air temperature, relative humidity, wind speed and direction, and duff moisture from the TDR sensors. In addition, the stations include fuel stick moisture and fuel stick temperature sensors, and barometric pressure and precipitation sensors. We report on the relationships between meteorology, litter/duff moisture, and fire behavior in flaming and smoldering combustion stages. Additional data is reported which characterizes smoke and photochemically/radiatively important trace gases during flaming and smoldering stages of prescribed burns and ground fires in organic soils.

A landscape-scale wildland fire study using a coupled weather-wildland fire model and airborne remote sensing

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Abstract
We examine the Esperanza fire, a Santa Ana-driven wildland fire that occurred in complex terrain in spatially heterogeneous chaparral fuels, using airborne remote sensing imagery from the FireMapper thermal-imaging radiometer and a coupled weather-wildland fire model. The radiometer data maps fire intensity and is used to evaluate the error in the extent of the simulated fire perimeter and to reveal dynamically active regions of the fire fronts, their intensity, and their depth. The simulations use a numerical weather prediction model tied to a fire behavior model to simulate fire growth, its impact on the atmosphere through heat release, and the feedback of these fire-induced winds on fire behavior. The model was initialized with a regional weather simulation and fuel mapping data enhanced by additional sources to examine the meteorological flow in the vicinity of the wildfire, the fire growth and interaction with the atmospheric flow, and compare with airborne measurements collected during the first days of the fire. Model results capture the rapid spread to the east-southeast, flank runs up canyons, bifurcations of the fire, and rough agreement in area, shape, and spread direction. The west-southwesterly spread of the fire and acceleration of winds near the surface result from complex, transient, three-dimensional atmospheric wave dynamics that transport higher momentum east-northeasterly winds down to the surface in combination with other topographic dynamic effects.

Additional keywords: fire behavior, fire mapping, coupled atmosphere-fire model

Introduction
This work examines our current ability to model landscape-scale wildland fires using a coupled weather-wildland fire model. Computer simulations with the Coupled Atmosphere-Wildland Fire-Environment (CAWFE) model tie numerical weather prediction models to fire behavior models to simulate the impact of a fire on the atmosphere and the subsequent feedback of these fire-induced winds on fire behavior - i.e. how all fires, to some degree, 'create their own weather'. Here we describe simulations of the October 2006 Esperanza wildfire, which was ignited near Cabazon, California, and spread during a moderate Santa Ana wind event through chaparral and coastal sage vegetation along the northern flank of the San Jacinto Mountain range. We present simulations and sample airborne infrared imagery with which detailed comparisons are being made.

Background

The Esperanza wildfire was ignited on October 26, 2006 at 0112 local time in a river wash outside Cabazon, California, during a Santa Ana event at the upwind edge of the San Jacinto mountain range. It spread rapidly uphill to the west-southwest under the influence of steep slopes, dry flammable brush, single-digit relative humidity, and gusty winds, burning approximately 9700 ha in 18 hrs (Esperanza Fire investigation Team 2007). Winds measured nearby in Banning Pass (a west-east oriented pass between the San Jacinto and San Bernardino mountain ranges) were easterly with average velocity of 6-10 mph and gusts of 20-25 mph. By containment on October 30, 2006, the fire had burned approximately 16300 ha (40,200 acres).

Model description

The CAWFE modeling system contains two parts: a numerical weather prediction model and a fire behavior model that simulates the growth of a wildfire in response to weather, fuel conditions, and terrain (Clark *et al*. 2004; Coen 2005). These are two-way coupled so that heat and water vapor fluxes from the fire alter the atmospheric state, notably producing fire winds, as the evolving atmospheric state and changes in humidity (including effects from the fire) simultaneously affect fire behavior, notably how fast and in what direction the fire propagates. This wildfire simulation model can thus represent the complex interactions between a fire and the atmosphere.

a. Atmospheric model

The meteorological model is a three-dimensional non-hydrostatic numerical model based on the Navier-Stokes equations of motion, a thermodynamic equation, conservation of mass equations using the anelastic approximation, and equations for conservation of several phases of water vapor, summarized previously in Clark (1979) and Clark and Hall (1991). Vertically stretched terrain-following coordinates allow the user to simulate in detail the airflow over complex terrain. The numerical weather prediction model is capable of modeling fine scale atmospheric flows (horizontal resolution of 10s-100s of m) in very steep terrain where the inclination may exceed 30^o. Forecasted changes in the larger-scale atmospheric environment are used to initialize the outer of several nested domains and update lateral boundary conditions. Two-way interactive nested grids capture the outer forcing domain scale of the synoptic-scale environment while allowing the user to telescope down to tens of meters near the fireline through horizontal and vertical grid refinement. Weather processes such as the production of cloud droplets, rain, and ice are parameterized using standard cloud microphysical treatments (Clark *et al*. 1996).

b. Fire model

Because the modeling system is trying to represent fires at spatial and temporal scales too coarse to simulate combustion, the wildland fire component of the model treats these subgrid-scale processes with parameterizations and semi-empirical relationships.

One algorithm defines the burning region within each grid cell. At the surface, each atmospheric grid cell is further divided into two-dimensional fuel cells with fuel physical characteristics and fuel loads specified by the user, the defaults being those of the 13 standard fuel models (Anderson 1982). Four points within each cell (called tracers) make up a quadrilateral that contains the burning region of the cell. Together with neighboring cells, these define the fire front, which is the interface between burning and unburned fuel. A local contour advection scheme assures consistency along the fireline.

Another algorithm relates fire properties such as rate of spread to local wind, terrain slope, and fuel characteristics through the Rothermel (1972) surface-fire algorithms. Fire spread rates are calculated locally along the fire front as a function of fuels, wind speed and direction from the atmospheric model (which includes the effects of the fire), and terrain slope.

A third algorithm implements a canopy fire model that calculates the energy used to heat and dry any canopy above a surface fire. The canopy is ignited if the residual heat flux, after heating and drying the canopy, exceeds a specified threshold value. Any canopy fire is assumed to remain collocated with the surface fire.

A fourth algorithm treats the post-frontal heat release rate (Albini, 1994) which characterizes how the fire consumes fuels of different sizes with time after ignition, distinguishing between rapidly consumed grasses and slowly burned logs.

A simple radiation treatment distributes the sensible and latent heat and smoke into the

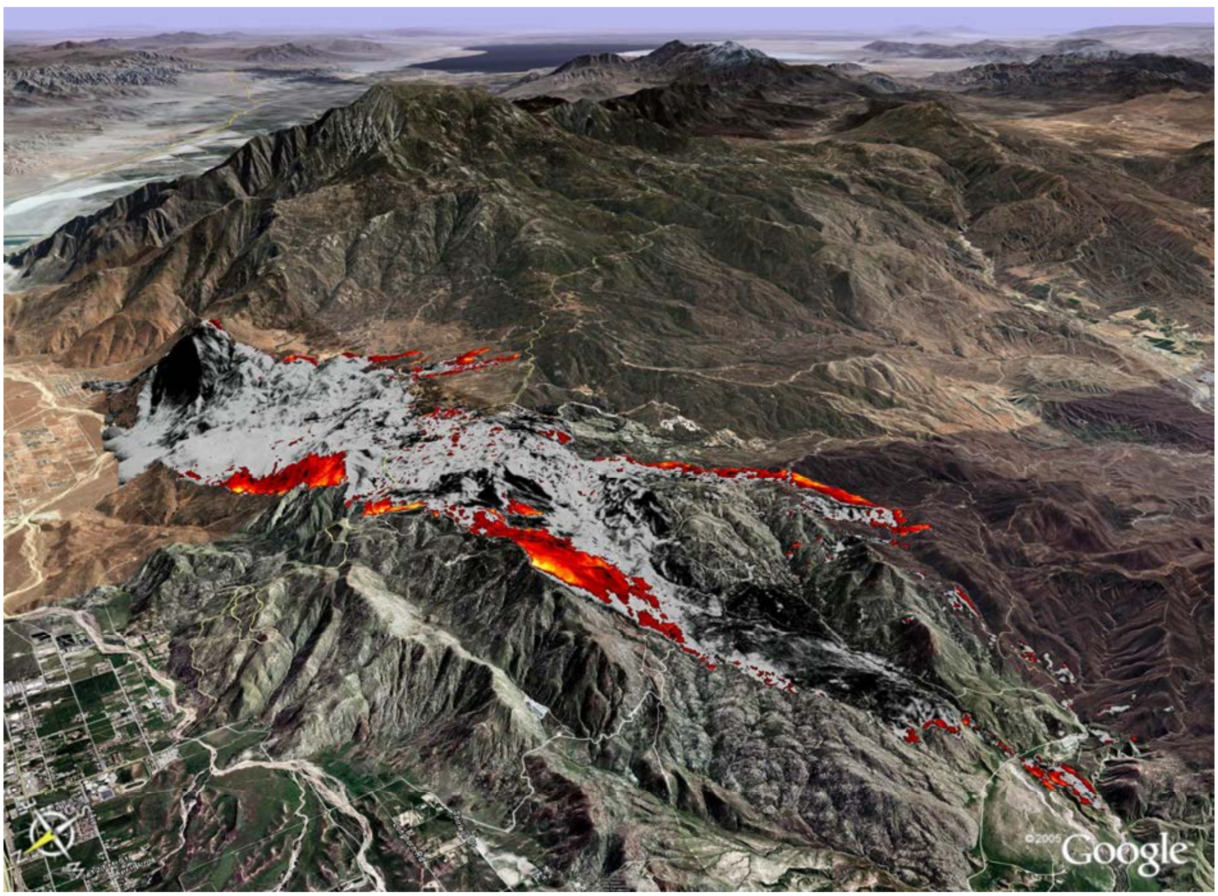

Fig. 1. Esperanza Fire, Riverside County, California, as viewed from the northwest at 11:15 local time, 26 October 2006, by the FireMapper thermal imaging radiometer. Color-coded surface temperatures, which reflect fire intensity, are shown as imaged in the thermal infrared and displayed in Google Earth. Here a moderate Santa Ana wind is driving the fire to the southwest through light fuels and chaparral.

lowest atmospheric grid levels. The e-folding height over which the heat is distributed is specified by the user ï typically 10 m for grass fires and 50 m for crown fires, based on analysis of fire observations (Clements *et al*. 2007; Coen *et al*. 2004).

The fire behavior is coupled to the atmospheric model: low level winds drive the spread of the surface fire, which releases sensible heat, latent heat, and smoke into the lower atmosphere, in turn feeding back to affect the winds directing the fire. Although this influence is most dramatic near the fire, model simulations show this influence can change the wind speed by several kilometers per hour even kilometers from the fire (Coen 2005).

Case study

A 10-km horizontal resolution 48-hr MM5 mesoscale simulation of the region initialized at October 26 2006 0 Z (October 25 2006 1700 local time) was used to initialize the finer resolution CAWFE. This was done by interpolating the MM5 forecast state onto the CAWFE three-dimensional grid at the time the finer-scale CAWFE simulation starts and used at later times in the MM5 simulation to specify the boundary conditions of the CAWFE domain.

CAWFE terrain used 1 or 1/3 arcsec terrain data (USGS 2010), smoothed with a pass of a 1-2-1 bidirectional filter to remove high frequency noise. The distribution of fuel models was taken from the LANDFIRE Fire Behavior Fuel Models data server (LANDFIRE 2010). The characteristics for the fuel types used, primarily grass (Fuel Model 1), shrubs (Fuel Model 4), and forest litter, were adjusted based on local on-site measurements (Weise *et al* 2005). We simulated 17 hrs of weather and fire behavior beginning at October 25, 2006, at 2100 local time. CAWFE refined the resolution from 10.0 km horizontal resolution in the coarsest domain to 3.33 km, 1.11 km, 0.370 km, and 0.123 km in the finest resolution domain, with corresponding refinement in the vertical grid. We examined the meteorological flow in the vicinity of the Santa Ana-driven Esperanza wildfire, modeled the fire growth and interaction with the atmospheric flow, and compared with measurements collected during the first day of the fire.

Airborne fire remote sensing

The Pacific Southwest Research Station of the U. S. Forest Service develops and applies specialized remote-sensing systems to measure and understand wildfire behavior and impacts in the environment and provide fire intelligence needed to improve fire suppression operations, fire-fighter safety, and strategic fire management. One such system, the airborne FireMapper thermal-imaging radiometer, employs a BAE Systems microbolometer focal-plane array with two levels of onboard calibration to measure and map thermal radiation across a wide range of radiances in a broad-band channel encompassing wavelengths from 8 to 12.5 mm and narrow-band channels at 8.8 to 9.1 and 11.3 to 12.4 mm. The narrow-band channels each provide unsaturated data over large wildland fires. Images of wildland fires have been transmitted by satellite communications, geo-referenced to a map base, assembled into photo mosaics, and displayed via the Internet at http://www.fireimaging.com to provide fire fighting personnel with a current, detailed, and synoptic view of fire spread and activity. During the Esperanza Fire, the California Department of Forestryôs incident command used FireMapper imagery in part to visualize and predict active fire spread so as to prioritize deployment of firefighting resources and to direct mop up during latter stages of the fire. The imagery also has provided unprecedented measurements of the behavior of a wildland fire under the influence of Santa Ana winds.

The upwelling radiation from wildland fires is comprised of emissions from a complex of high temperature flames, ash, residual flaming combustion, smoldering of larger biomass elements and unburned vegetation. Radiation from flames, which are of high temperature but low emissivity, is thought to be dominant in the remote sensing signal at short-wave infrared wavelengths. At long-wave infrared wavelengths, as measured by the FireMapper, radiation from fire fronts is likely dominated by emissions from lower temperature ï yet very hotï ash of high emissivity (Riggan and Tissell 2009). Thus, FireMapper imagery depicts not only the location of fire fronts, but based on the temperature of the underlying ground surface, provides a measure of the fireõs intensity. The duration of high temperatures behind the fire front reflects the sum of energy absorbed and emitted from the ground surface, so that the breadth of high temperature zones along a fire perimeter provides an indication of the amount of consumed fuel in the area. For more details on mapping of the fire and fuels with this instrument in this and other fires, see Riggan *et al*. (2010).

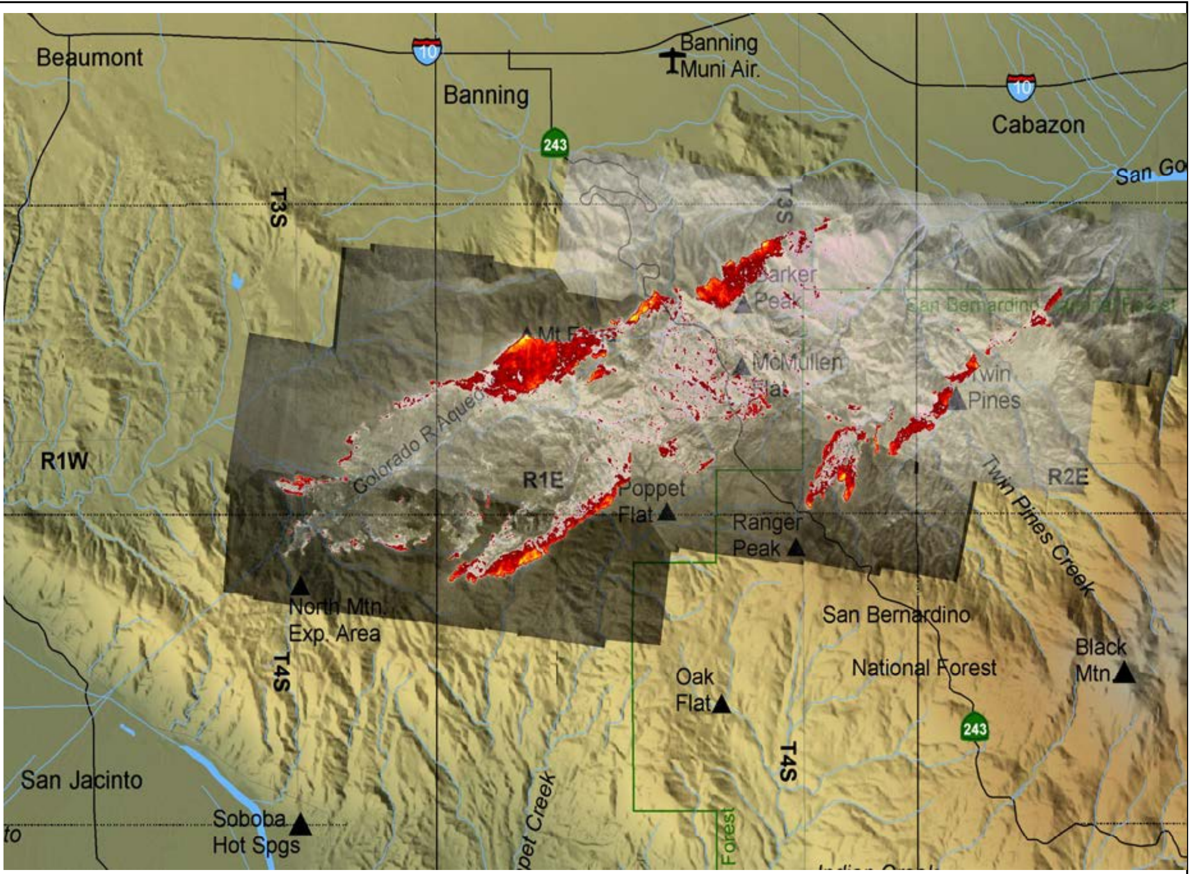

Fig. 2. Nadir view of the 2006 Esperanza Fire on shaded relief, as viewed by the FireMapper thermal imaging radiometer, at 1117 local time on Oct. 26.

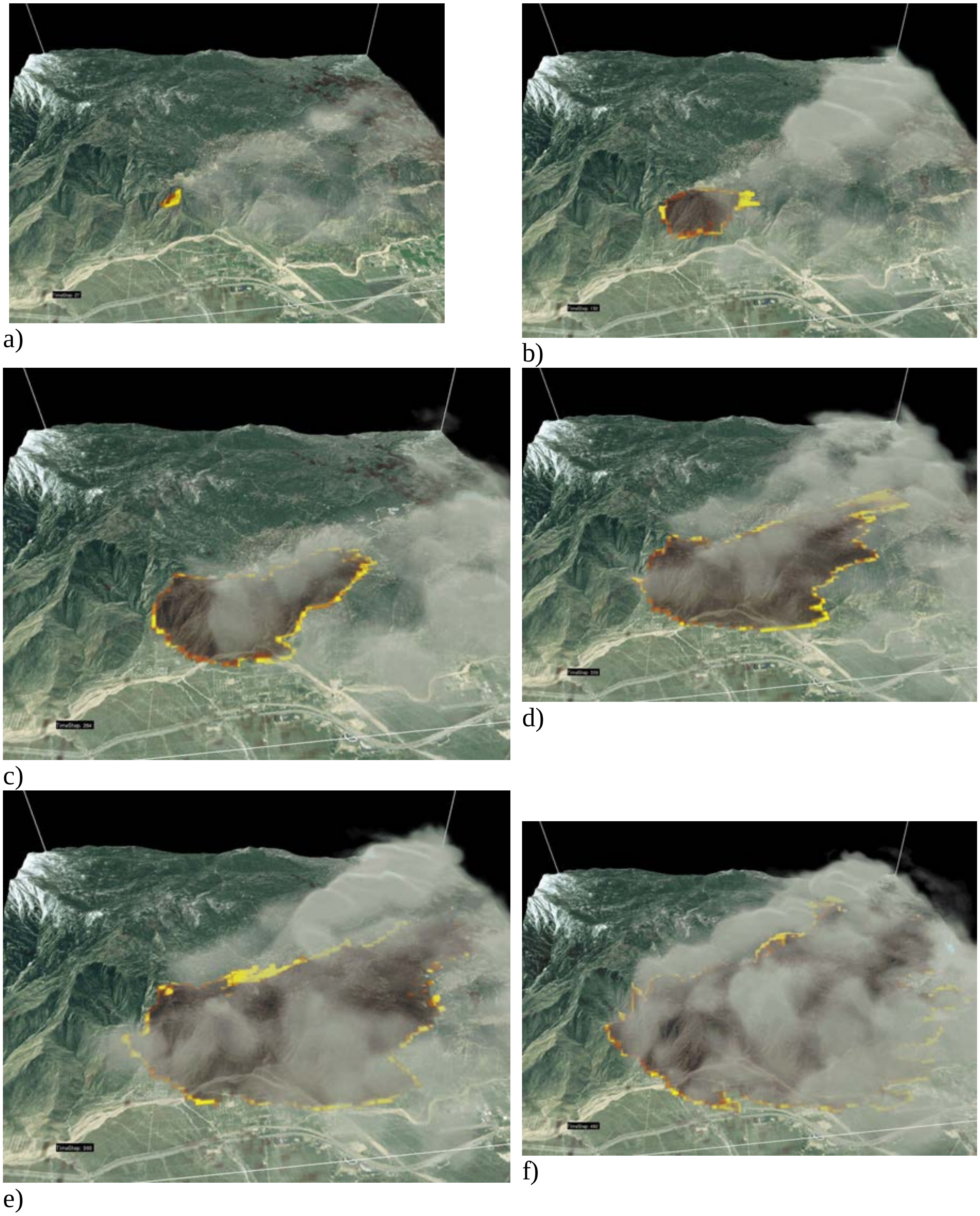

Fig.3. View toward south. Cabazon, CA, is in the foreground. Simulation on Oct. 26 at a) 0127, b) 0333, c) 0524, d) 0639, e) 0733, and f) 0923 local time. The misty field is smoke, colored by concentration. Higher concentrations are darker and more opaque. The colors identifying the burning areas correspond to radiant temperature color bar in Fig. 1. (brighter colors like yellow: higher surface fire sensible heat fluxes; darker browns: lower fluxes). Another field on the surface is the 'fuel load remaining'. Where the fire has passed, the surface is dark brown. Boxiness to the fireline shows the atmospheric grid sizes onto which the fire fluxes on the fire fuel cell scale (5x5 in each atmospheric cell) have been summed.

Results

At the time of the first observation at 1117, the primary run of the Esperanza Fire had traveled 16.5 km to the west-southwest (WSW) from the point of ignition. The primary run encountered vegetation there that was 6 to 10 years old and displayed little energy release as evidenced by low observed temperatures at the front of the fire line and lack of continuity across areas of elevated surface temperature. Substantial temperatures were evident primarily on north-facing aspects and higher productivity vegetation along the north flank of the fire and in vegetation older than 50 years in the southwest of the perimeter. A separate fire run developed in the southeast; it may have been isolated by fire fighting action and cleared ground in the vicinity of structures along Twin Pines Road. Other isolated runs with the wind were initiated along the southern flank of the fire such as immediately east of the main head of the fire in vegetation

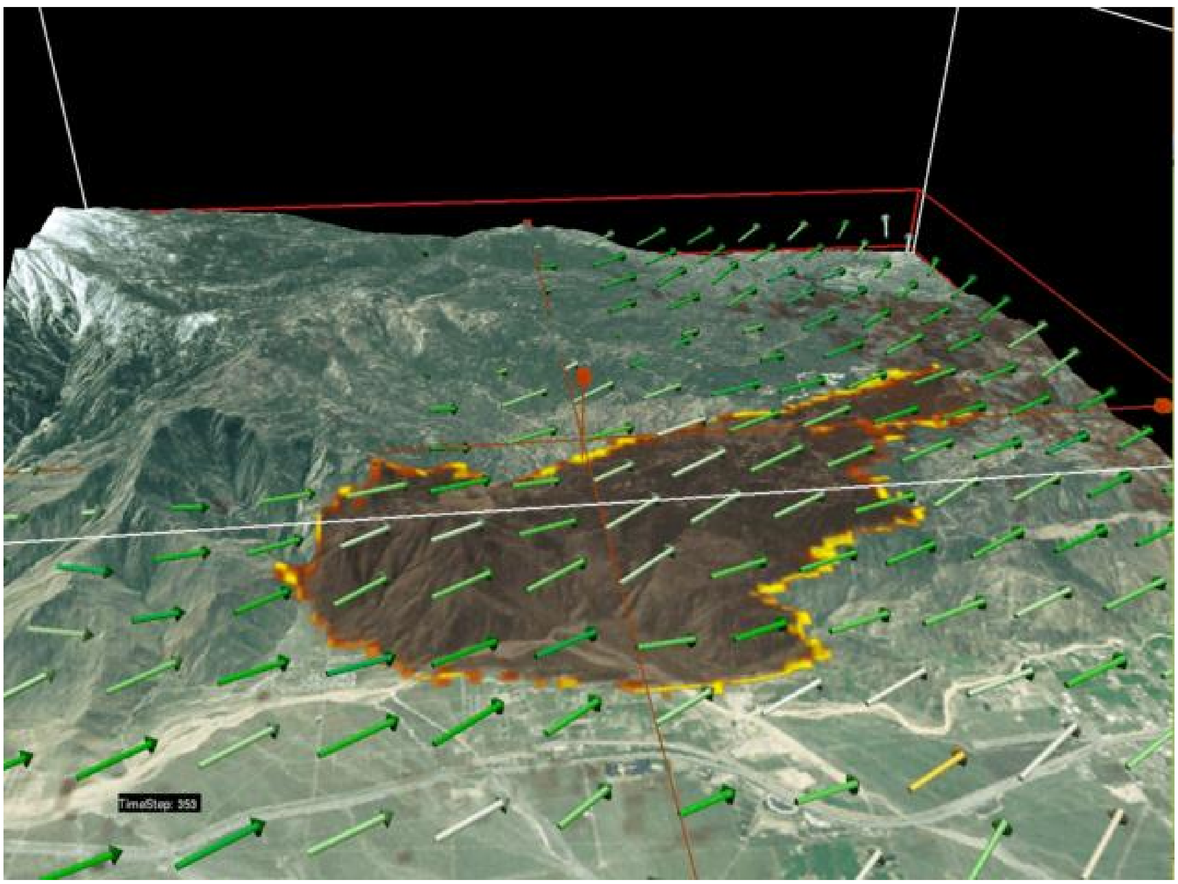

Fig. 4. The simulation at 0652 local time. The fire heat fluxes and fuel remain the same as Fig. 3. The vectors show the winds at a constant elevation 1500 m above sea level. The length and direction of the vectors show the strength and direction of the horizontal winds. The colors superimposed on the arrows represent the vertical velocity: white is 0, warm colors (yellow to orange to red) reveal updrafts, cold colors (green increasing to blue increasing to violet) represent downdrafts. Over the fire area, the arrows are greenish, which is interpreted as a slight downdraft at this elevation. Some areas are mostly white, which means there is no up or down component there. A few vectors near lower right and sometimes over Cabazon Peak (center left) show upward motion.

older than 50 years. Little long-range fire spread by development of spot fires was evident at the head of the fire. Only one spot fire, disconnected from the fire front, was observed and that was located only 90 meters ahead of the front. This imagery is shown in Figs. 1 and 2.

The simulated airflow during the incident was complex. As expected in a typical Santa Ana event, winds turn counterclockwise with height, such that surface winds in the pass were easterlies and at the elevation of the fire were northeasterly. Compounding that, there were

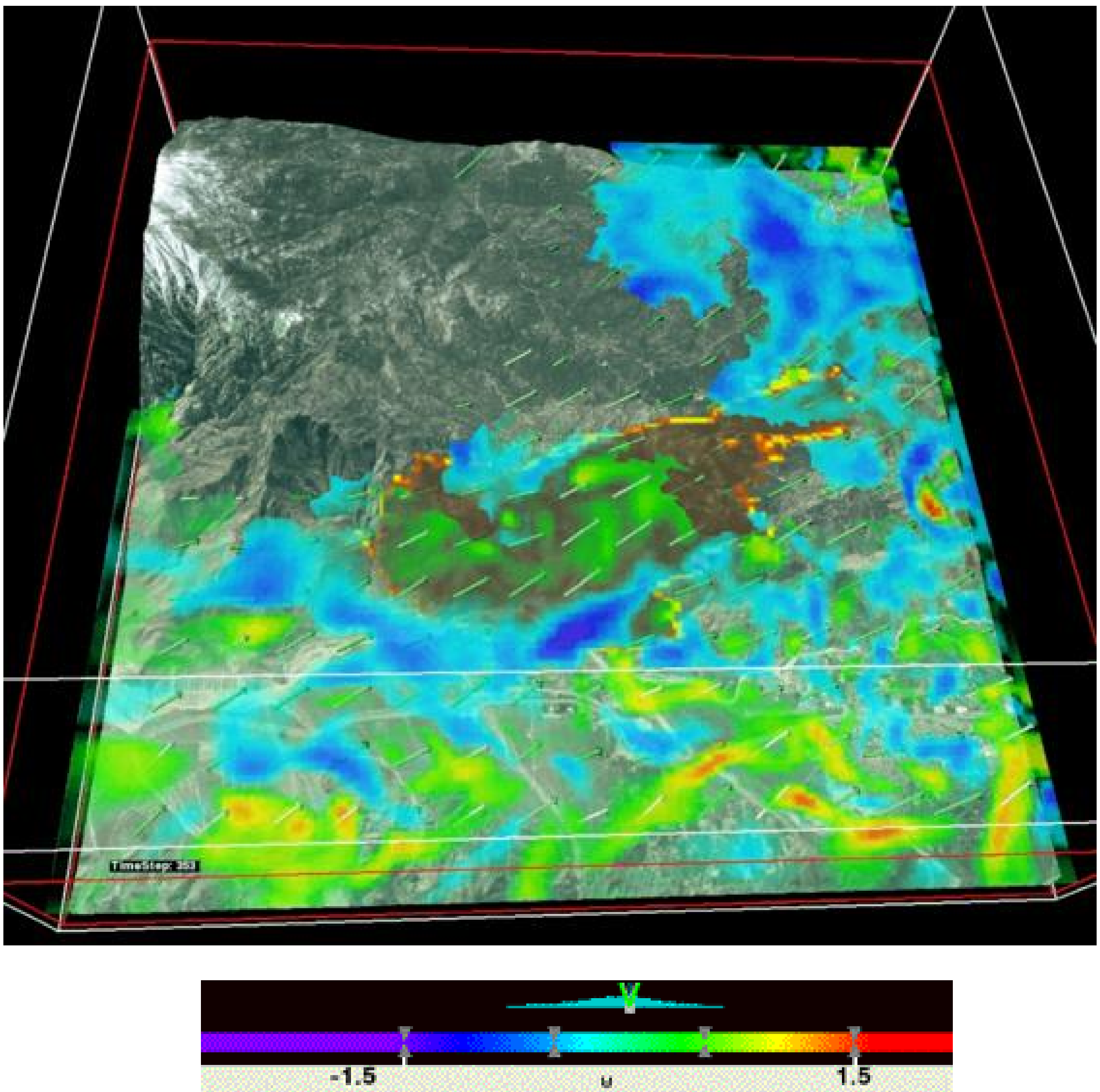

Fig. 5. In this image at 0653 local time, a contour of the vertical velocity field (see legend, values in m s^{-1}) at 1500 m is superimposed and shows the transience in the terrain-induced gravity waves from upstream San Bernardino mountain range encountering the San Jacintos, complicated by smaller-scale terrain features, shear-generated motions, and convection generated by the fire.

complicated three-dimensional terrain induced flow effects, including gravity waves bringing higher-momentum east-northeasterly airflow from upper levels down to the fire. Moreover, these effects varied in time and space, as the locations of the updrafts and downdrafts moved and evolved as the Santa Ana event moved and altered the wind direction with respect to the terrain ridges and local topographic features.

The simulated fire behavior captured the rapid spread to the WSW and had rough agreement in area, breadth, shape, and direction of spread at periods for which fire location data were available, although it overestimated the rate of spread over the first 10 hours by arriving 2 hours early. The simulated fire spread out onto the low elevations of Banning Pass because firefighting efforts to hold line there were not simulated. Simulations capture flank runs up canyons, bifurcations of the fire into two heads, and feathering into fingers in sparse fuels at the leading edge of the fire which can surround features and rejoin. The simulated fire progression and smoke is shown in Fig. 3. Secondly, results show that the acceleration of winds near the surface can be understood as resulting from complex three-dimensional atmospheric wave dynamics (Figs. 4 and 5) set up by the Santa Ana events flowing over upstream mountain ranges that are a common component of many of the largest fires in this fire-prone region. As in the airborne remote sensing observations, the most intense burning areas simulated were along the flank of the fire, where we see flank ŕunsô that were supported by satellite and aircraft imagery.

Discussion

It is significant that the simulations captured WSW spread of the fire because all available surface stations (the standard mechanism for predicting fire growth), located at lower elevations in Banning Pass, measured easterlies due to the west-east orientation of the pass and backing of winds with height in standard Santa Ana flow. We note this is not a matter of terrain extending up into elevations where winds were stronger, but a result of atmospheric gravity waves bringing the higher-momentum ENEly air down to the surface. It is encouraging to capture many elements of the phenomenology of fire spread in a landscape scale fire where the weather, terrain, and fuels are so complicated. We think the rate of spread at the head and flanks could be overestimated due to a number of factors, including errors in the large-scale forecast, errors due to assumptions in the vertical interpolation of winds from the current lowest CAWFE model level (67 m) to the height of the fuel, errors in representing the fuel available for burning, conceptual errors in using a rate of spread calculation designed for a heading fire at all points along the fire front, and the conceptually difficult assessment of which wind elevation and location relative to the fire to use for calculation of fire rate of spread. Even with these very high-resolution simulations, it is still undetermined what effect even finer unresolved terrain features, such as small drainages, which are common in this area, had on the airflow directing the fire.

Acknowledgements

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The effect of terrain slope on firefighter safety zone effectiveness

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Abstract
The current safety zone guidelines used in the US were developed based on the assumption that the fire and safety zone were located on flat terrain. The minimum safe distance for a firefighter to be from a flame was calculated as that corresponding to a radiant incident energy flux level of 7.0kW-m^{-2}. Current firefighter safety guidelines are based on the assumption that radiant energy transfer is the dominant energy transfer mode. Intuition, professional observations, and the few experimental measurements that have been reported indicate that when fires are located on slopes or ridges convective energy transfer may reach distances equal to 2 to 4 or more flame lengths ahead of the fire front. This implies that the current safety zone guidelines may be invalid in some situations where the safety zone and/or fire are on slopes. A research project supported by the Joint Fire Science Program is underway to measure convective energy transport and use those measurements to develop safety zone guidelines for slopes. The new guidelines will depend on multiple variables including: fire characteristics (flame length or height), site characteristics (e.g. slope percent), and relative location (i.e. chimney, ridge, midslope, ridgetop).

Additional Keywords: Fire behavior

Introduction
Perhaps one of the most critical decisions made on wildland fires is the identification of suitable safety zones for firefighters during daily fire management operations. To be effective (timely, repeatable, and accurate), these decisions rely on training and judgment. The current safety zone guidelines used in the US and published in the Incident Response Pocket Guide (IRPG) and Fireline Handbook were developed based on the assumption that the fire and safety zone were located on flat terrain. The minimum safe distance for a firefighter to be from a flame was calculated as that corresponding to a radiant incident energy flux level of 7.0kW-m^{-2} which was determined to be the level at which exposed human skin will develop a 2nd degree burn in less than 90 seconds. An approximate correlation was derived from this model that indicated a minimum separation between the firefighter and fire should be equal to four times the flame height. For a circular safety zone this would be equal to the safety zone radius. When fires are burning on flat terrain, convective energy transfer is primarily upward in the plume while radiant energy transfer occurs out ahead of the fire front. Current firefighter safety guidelines are based on the assumption that radiant energy transfer is the dominant energy transfer mode. Experimental measurements have verified the accuracy of this assumption but have also indicated that when fires are burning on slopes convective energy transfer can be significant. Intuition, professional observations, and the few experimental measurements that have been reported indicate that when fires are located on slopes or ridges convective energy transfer may reach distances 2 to 4 or more flame lengths ahead of the fire front. This implies that the current

safety zone guidelines may be invalid in some situations where the safety zone and/or fire are on slopes. It is also clear from site visits to designated safety zones on numerous wildland fire incidents that considerable ambiguity exists regarding identification or creation of true ósafety zones,ô versus ódeployment zones.ô

A new research project supported by the Joint Fire Science Program is underway to measure convective energy transport and use those measurements to develop safety zone guidelines for slopes. We expect the guidelines will depend on multiple variables including: fire characteristics (flame length or height), site characteristics (e.g. slope percent), and relative location (i.e. chimney, ridge, midslope, ridgetop). Special emphasis is focused on the effect of óchimneysô and other terrain features that produce dangerous levels of convective heating ahead of the fire front.

Approach

The approach for this study followed several phases:

1) Measure convective/radiant energy transport in fires across a range of slopes and fuel types. Two instrument packages have been developed: 1) The Fire Behavior Flux Package (FBP) and 2) the Video Acquisition Box (VID). The FBP packages measure 27cm by 15 cm by 18 cm and provide an insulated protective enclosure for datalogger, sensors and other electronics. The standard instruments consist of radiometers that measure total and radiant energy fluxes, small-gauge thermocouples (nominally 0.13mm diameter wire) that sense flame and air temperature, and pitot-static type velocity probes that sense the magnitude and direction of airflow before, during, and after the fire passes. The VIDs are approximately ½ have the size of the FBP and provide digital video imagery of the fire as it burns past the FBPs. Collecting video imagery not only allows us to observe the actual footage of the fire behavior, but also provides insight into our data analysis.

2) Numerical Simulations: We are using measurements to ótuneô and validate theoretical heat transfer models. Simulations of fire on slopes are being conducted (fig. 1). The fire is simulated as low velocity jet in a cross flow. The calculations are being explored to develop relationships between fire intensity, slope, cross wind flow strength and fire intensity. Fire growth is being explored using existing spatial fire models like FARSITE and the newly available Wildland Fire Dynamics Simulator (WFDS) developed at the National Institute for Standards and Technology (NIST). Measured and modeled convective and radiant energy distributions around the fires will be applied to human burn injury limits to determine appropriate separation distances and associated safety zone sizes.

3) Survey of firefighters: Fire managers and fire crews will be surveyed to determine what they believe is the most effective method for communicating the results of the analysis. It is likely that the results will depend on a number of variables including slope angle, wind speed, fire intensity, and slope shape. Because there are multiple variables, a model with multiple variables will be required. This precludes a simple model like that derived from the original safety zone analysis (Butler and Cohen 1998).

Below we discuss the methods that are being used to analyze firefighter safety zones on slopes. The results will be used to develop guidelines for wildland firefighters in the US.

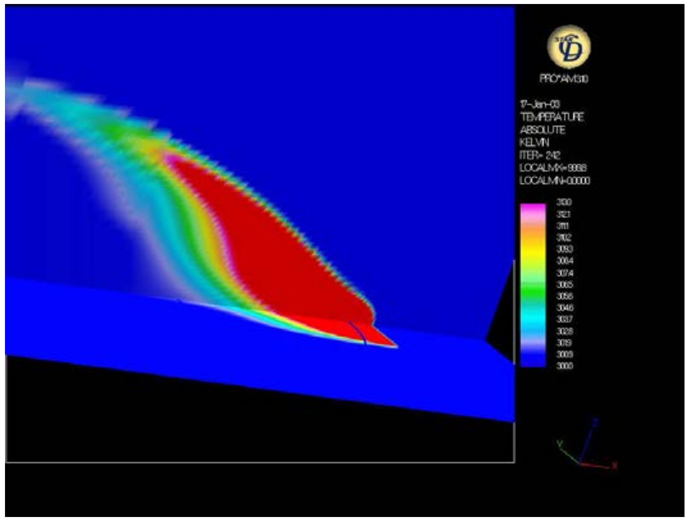

Fig. 1--Image of numerical simulation of jet in cross flow used to simulate a fire on slope under influence of wind**.**

Discussion

Injury can occur by one or several means in fire. It is primarily associated with the maximum incident flux and is not necessarily aligned with the primary modes of energy transport: radiation, convection, and conduction (DiNenno *et al.* 1995). The data presented in table 1 below identify the limits of exposure.

Table 1—Summary of heat injury modes and limits.

Heating Mode and Indicator	**Injury type and time**
Conduction	
43 (110F)	Pain
60 (140F)	Pain in 1 s, burn in 10s, severe burn in 100s
100 (210F)	Severe burn in 1 s
Convection	
180 (350F) dry	Burns in 3 minutes
120 (250F) dry	Burns in 7 minutes
32 (90F) 100% rh	Burns in 30 minutes
150 (300F) 100% rh	Max breathing temperature according to Nat. Res. Council of Canada
Radiation	
4.2 Kw/m^2	Pain in 10s
10 kW/m^2	Pain in 5 s, 1% fatality in 40s
25 kW/m^2	Severe pain 10s, 100% fatality in 60s
30 kW/m^2	Pain in 1-4s, full burn in 10-15s

Note that injury by conduction occurs at relatively low temperatures. Injury by convection occurs through two means: both heating of the external surface of the body and injury to the throat and mouth. Convective injury is sensitive to air temperature and relative humidity. Higher relative humidity results in more severe injury at lower temperatures. Injury from radiant heating is dependent on incident energy flux.

Measurements of energy release from fires are being used to develop new understanding into the distribution of radiant and convective energy in and around naturally spreading fires. Fig. 2 is a summary of heat flux measurements reported (Frankman *et al.* 2010). In general the heat flux measurements suggest that convective energy is 75% of radiant energy. There seems to be a correlation between slope and radiant energy flux. However, little or no correlation between slope and convective energy flux. The convective and radiant heating rates are more than sufficient to generate injury. The primary challenge is to predict the distribution of that energy around the fire front. This is the objective of the numerical simulations.

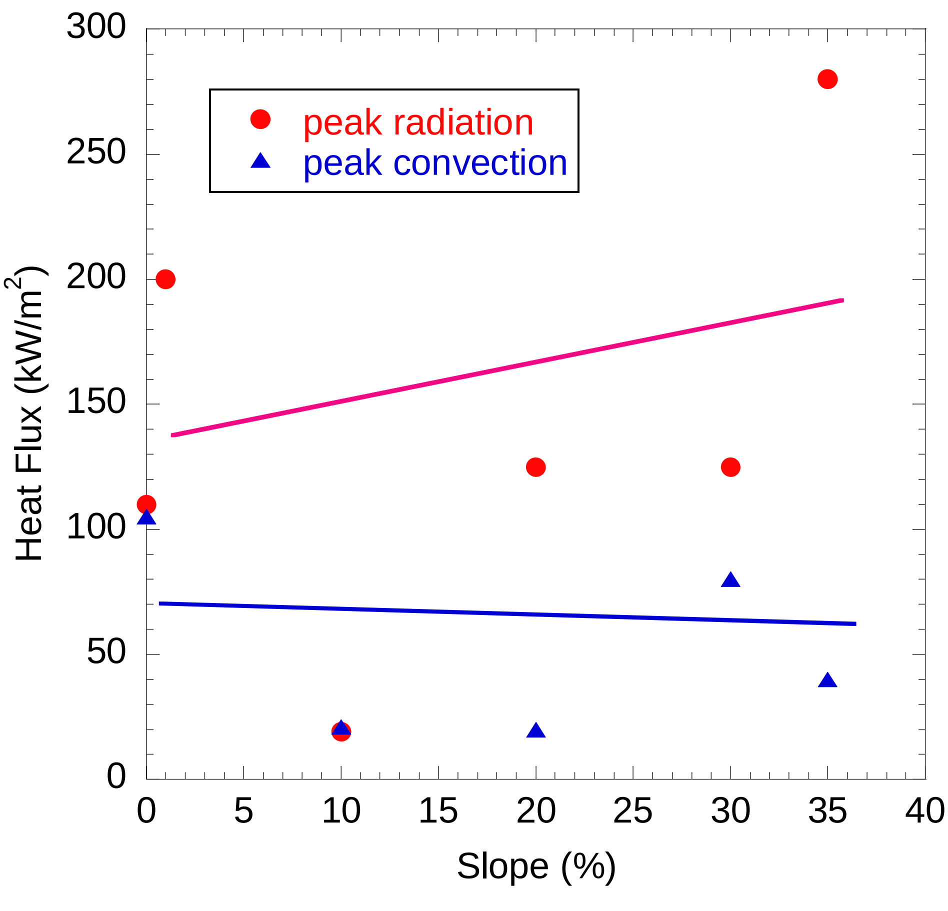

Fig. 2ð Peak radiant and convective fluxes from field based measurements

Air temperatures associated with convective energy heating are difficult to determine. Measurements of air temperatures measured within a forest canopy as a crown fire burned over the sensors have been presented (Butler *et al.* 2004) (see Fig. 3). The temperatures are all significantly higher than the minimum survivable temperatures presented in table 1 suggesting that at least in the flaming region air temperatures exceed survivable limits.

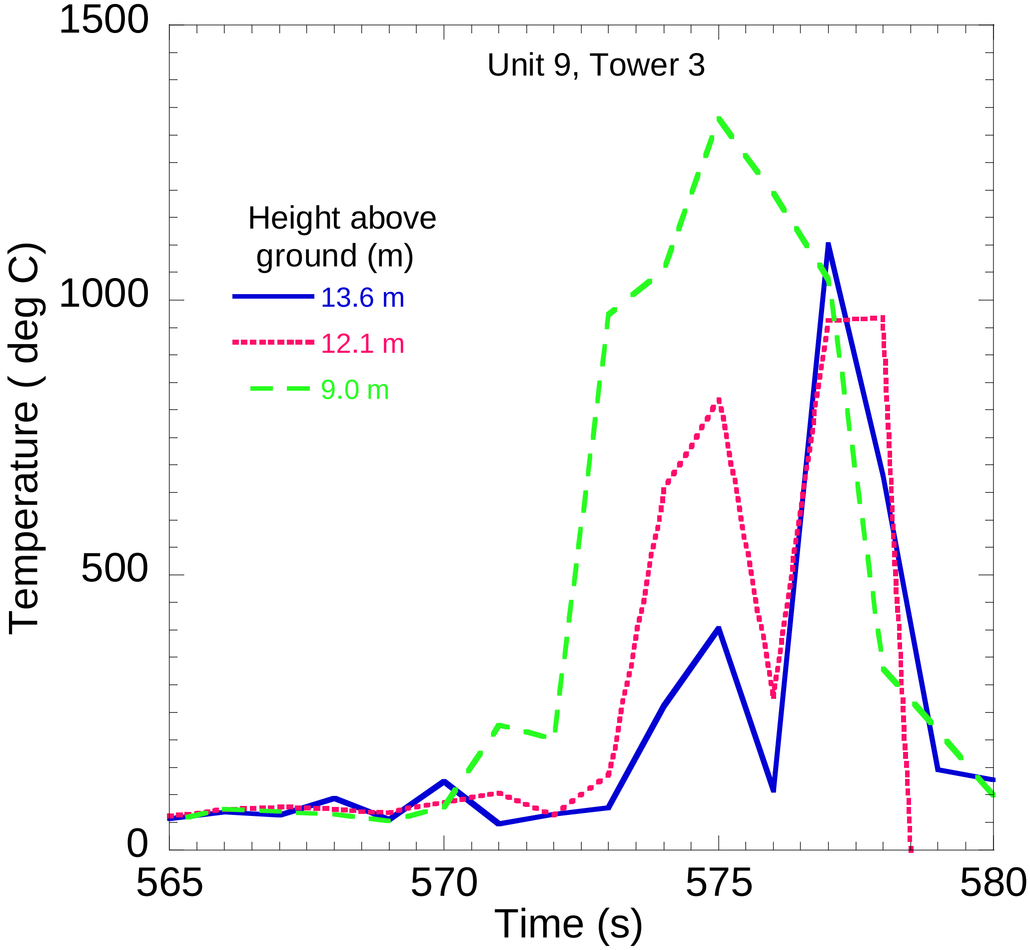

Fig. 2--Summary of measured air temperatures collected from International Crown Fire Experiments.

The challenge over the next year is to use numerical models to simulate the distribution of radiant and convective energy around the fire front. Once this distribution is known then injury limits can be related to distance from the fire front to recommend safety zone size

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Rabbit Rules Tells Us about the Esperanza Fire

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Abstract:
On 26 October 2006 an intense "fire run" on the Esperanza fire in southern California killed five fire fighters. The event was simulated by Rabbit Rules – an experimental recursive fire spread model– which has shown skill at simulating some extreme aspects of coupled fire/atmosphere behavior. The intense run was the outcome of three fire/fuel/atmosphere conditions: (1) a mostly flanking fire line with a small head fire component directed to blowing the fire down the east slope along much of the extent of an unnamed creek valley, (2) a change in fuels from mostly grass on the slopes to mostly chaparral in the valley, and (3) terrain-induced shifting of winds to blow from the northeast up the unnamed valley.

Rabbit Rules found that the event was not a "run" in accordance with typical understanding. The strong up-valley winds drove the flanking fire across the valley igniting chaparral almost simultaneously. A fire 'head" or unusual surge in the fire line did not develop. The fire line instead pushed across the valley and into grassland on the western side.

Given that a typical fire run did not develop in Rabbit Rules, we used the model results and photographs of the even to infer that large quantities of unburned volatile gases were released within an oxygen-starved atmosphere where large areas of chaparral ignited almost simultaneously. These gases ignited as they were carried up-valley by strong winds and blasted past the fatality area and beyond.

Wildland fire behavior modeling: perspectives, new approaches and applications

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Abstract
The last 15 years have seen the development of wildland and wildland-urban interface fire behavior models that make use of modern numerical methods in wind and combustion physics. Currently, these approaches are too computationally expensive for operational use and, as for any fire behavior model, require validation through comparison to full-scale measurements. However, these 'physics-based ' models have the potential of providing a more complete understanding of fire behavior over a wider range of environmental conditions than empirically based models. The promise of physics-based models is not to replace the use of simpler and faster models, but to provide a well founded understanding of their limitations and a means of improving them. An example of this is to use the physics-based wildland-urban interface fire dynamics simulator (WFDS) to develop and evaluate a simpler level set model of surface fire spread. A basic implementation of the level set model performs reasonably well but requires further evaluation when applied to scenarios that include heterogeneous fuels and the potential influence of fire induced winds.

Additional Keywords: fire modeling, fire spread, fire behavior, CFD, numerical combustion

Introduction

Wildland fire modeling, considered in its entirety, is a very challenging task. The challenge arises from the range of physical processes and the temporal and spatial scales over which they operate. These processes range from the small-scale (~ 1 mm) ignition event to the large-scale (~100 km) transport of smoke. The focus of this presentation paper will be on the modeling of fire behavior. By this we mean the initiation of fire spread and the subsequent development of a fireline and fire plume as determined by the coupled processes of combustion, buoyancy induced flow, and thermal degradation of vegetation through radiative and convective heat fluxes. Smoke generation and transport, while modeled, is not considered here. Modeling approaches will be discussed and distinguished from each other according to the degree to which the physical processes are explicitly handled. Simple models are those that do not attempt to model the physical processes. Instead, they use formulas for the spread rate, and other quantities, derived from measurements (empirical based) or from observation and experience (rule based). Complex, physics-based, models do attempt to capture the physical processes through the numerical solution of equations governing the physical processes in question. Of special importance is the fact that physics-based models include the interaction and coupling of the driving processes (wind, buoyancy induced flow, combustion, thermal radiation, thermal degradation of vegetation, etc.). As a result, the same model can be used to investigate the relevance of wind, fuel structure, fuel moisture, terrain, etc. on fire behavior over a range of environmental variables. This is not possible with empirical or rule based models of fire behavior. Each environmental scenario requires sufficient, repeatable, measurements (or observations) to form a legitimate basis for developing the model or formula.

Simple models have the advantage that they can provide faster than real-time predictions. However, simple models are derived, when empirically based, from measurements over a limited range of environmental conditions. Strictly speaking, their application to environment conditions outside of those for which they were derived is not justified. Ideally, physics-based models would not have this limitation. The governing equations, upon which they are based, would capture the basic physical processes regardless of the scale of the process (for engineering applications). In reality, however, physics based models are subject to two types of limitations in this regard. The first is a need for empirically derived information, such as the radiation absorption coefficient or the convective heat transfer coefficient, for component physical processes. Because these empirical relations are derived or applicable over a wide range of conditions this is not too severe a limitation. Also, by their nature, physics-based models are constructed such that the importance of component models can be tested in a consistent manner. In particular, targeted experiments in the laboratory and the field can support this testing.

A second limitation of physics-based models is due to limited computational resources. A numerical simulation that attempts to capture, with equal fidelity, the range of processes from ignition to fire plume dynamics would require a computer with prohibitively large memory and processor demands. For example, the physics-based fire simulation tool called the Wildland urban interface Fire Dynamics Simulator (WFDS) (Mell *et al*. 2007; Mell *et al*. 2010) developed by the National Institute of Standards and Technology (NIST) requires approximately 1 kB of memory per grid cell. It is reasonable to assume that resolving the processes of ignition would require a grid cell resolution of approximately 1 mm. At this resolution, a WFDS run with the computational domain that is 1 m on the side would require 1 billion grid cells or 1 TB of computer memory. Present-day supercomputers have on the order of a few hundred terabytes of memory. Thus, it is beyond the capabilities of even today's most powerful computers to capture, with high fidelity, the processes of ignition and larger scale fire dynamics using the same computational grid resolution. The methods of adaptive mesh refinement offer one way to address this problem. In this approach, a sufficiently refined computational grid follows physical processes that require a relatively fine grid. Elsewhere in the computational domain the grid can be less refined. This allows a high fidelity physics-based simulation to occur with much less computational expense. However, these methods are still in the stage of research and development for application to wildfire simulation. Currently, the limitations imposed by insufficient computational resources are addressed through what are called sub-grid scale modeling. In this approach, processes that occur at scales that are not resolved by the grid are handled through separate terms in the conservation equations. An overview of different approaches to sub-grid scale modeling in present-day physics-based wildland fire behavior simulations (including WFDS) is given by Morvan (2010). Details on the sub-grid scale modeling approach used in WFDS are given in Mell *et al*. (2010).

Table 1 lists some general characteristics of complex and simple fire behavior models. The implementation and programming of simple models can be complicated. An example is the extension of a single point fire spread prediction formula used in BehavePlus (Andrews 2007) to predict the spread of a wildland fire over landscapes in FARSITE (Finney 2004). In most applications of FARSITE, the wind field is not calculated and assumed to be uniform in space. Fast turnaround time wind models, that can provide spatially variable winds, have been developed (Forthofer and Buler 2007). Since physics-based models compute three-dimenional fields of wind, temperature, and other variables they can have significantly higher output demands.

Table 1: General characteristics of complex and simple fire behavior models.

Complex Fire Behavior Models (more physics)	**Simple Fire Behavior Models** (less physics)
Physics-based	Heavily empirical or rule based
Potentially high input/output data demand	Usually low input/output data demand
Computationally expensive (usually slower than real time computations)	Computationally cheap (usually faster than real-time computations)
Directly provides heat fluxes, winds, firebrand transport and deposition	Cannot directly provide heat fluxes; winds are usually prescribed; empirical firebrand modeling
Directly handles variable fuels, terrain, weather	Influence of variable fuels and terrain is handled empirically

In the remainder of this write-up, examples of results from a physics-based model and a simple model will be given. The physics-based results will be from the WFDS model (Mell *et al.* 2007; Mell *et al*. 2010). Other physics-based models exist and can be applied to many of the example scenarios shown. These include FIRESTAR (Morvan *et al*. 2009), FIRETEC (Linn *et al*. 2002) and FIRELES (Tachajapong *et al*. 2008). An overview of these models is given in Morvan (2010) and Mell *et al*. (2007). With regard to the range of application of these models, FIRESTAR is limited to two-dimensions, FIRETEC is designed to operate with computational grid cell sizes on the order of 1 m, and FIRELES has, to date, been applied to laboratory scale fire experiments. In reported applications to date, therefore, WFDS appears to have the widest range of applicability. The simple model examples given below will be from a level-set based approach under development at NIST.

Results from the physics-based WFDS model can be used to determine head-, flank-, and back- fire spread rates for input into the simple level-set model (in much the same manner as laboratory measurements were used to determine the head fire spread rates used in the FARSITE model). By basing the spread rates used in the level-set model on WFDS results (which account for a wide range of physical processes) it is possible to investigate the importance of various physical processes in fire behavior and, potentially, identify the level of physical modeling required for a given application. For example, if the level-set model is implemented with a constant uniform wind and well matches WFDS results, this implies that, for the scenario simulated, the influence of the terrain and the fire atmosphere interaction were not significant.

Examples from a physics-based model (WFDS)

Fig. 1 shows images from a grass fire simulation using WFDS. Ignition occurs in a localized region (i.e., spot ignition as opposed to line ignition). The top figure shows the fire line and the smoke plume. The middle figure shows the radiant heat flux on the grass fuel and the bottom figure shows the convective heat flux. The region of the head fire can clearly be seen to have larger heat fluxes compared to the flank fires. No backing fire occurs because the grass plot was ignited along a fire break. In the region underneath active flaming the heat fluxes are positive; while in the region of previously flaming fuel the heat fluxes are negative (corresponding to a net heat loss). The actively burning head fire is larger in extent than the flanking fires, as is seen in the field. This figure illustrates the ability of physics-based models to calculate the driving mechanisms in fire behavior.

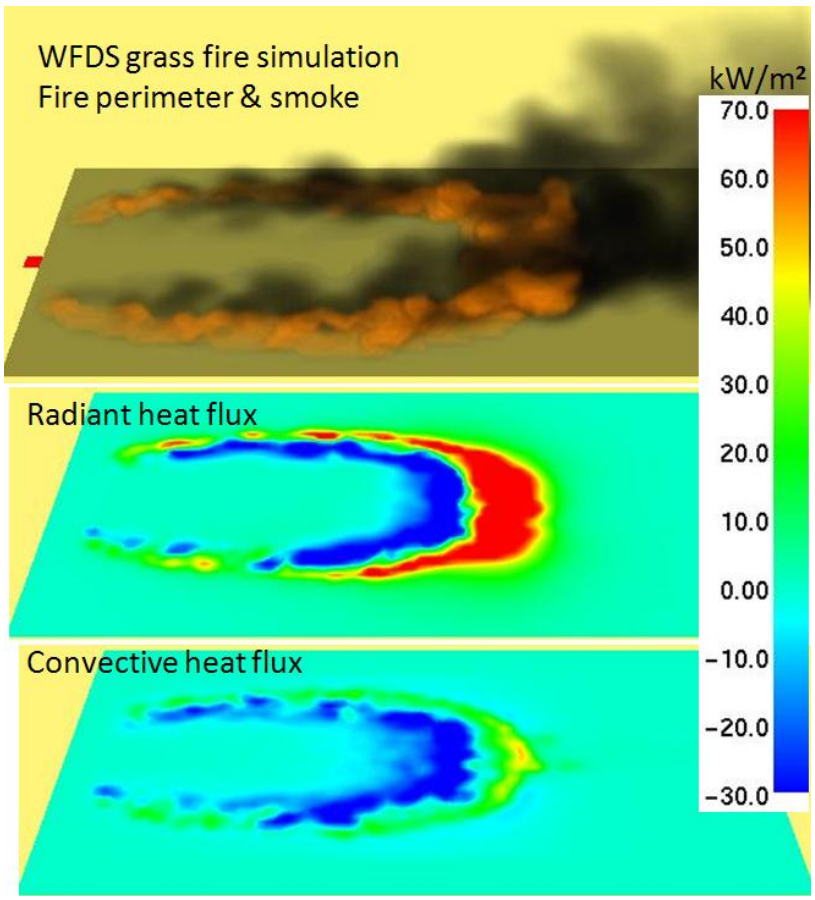
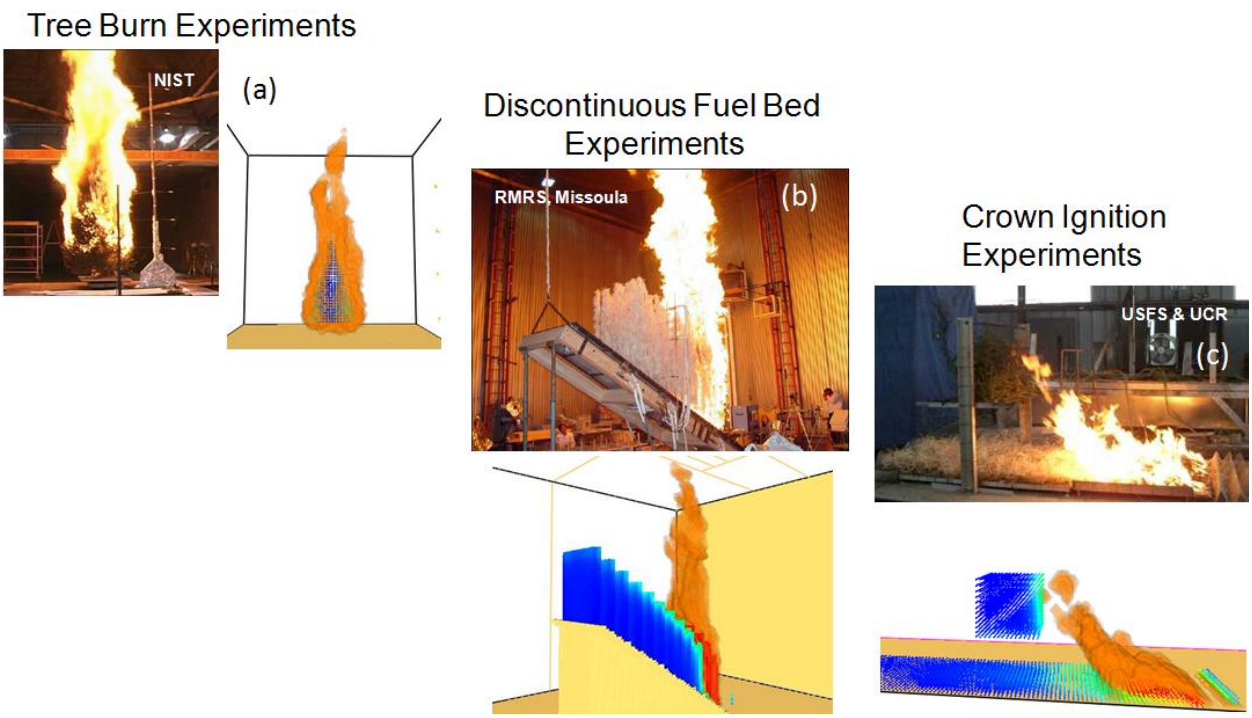


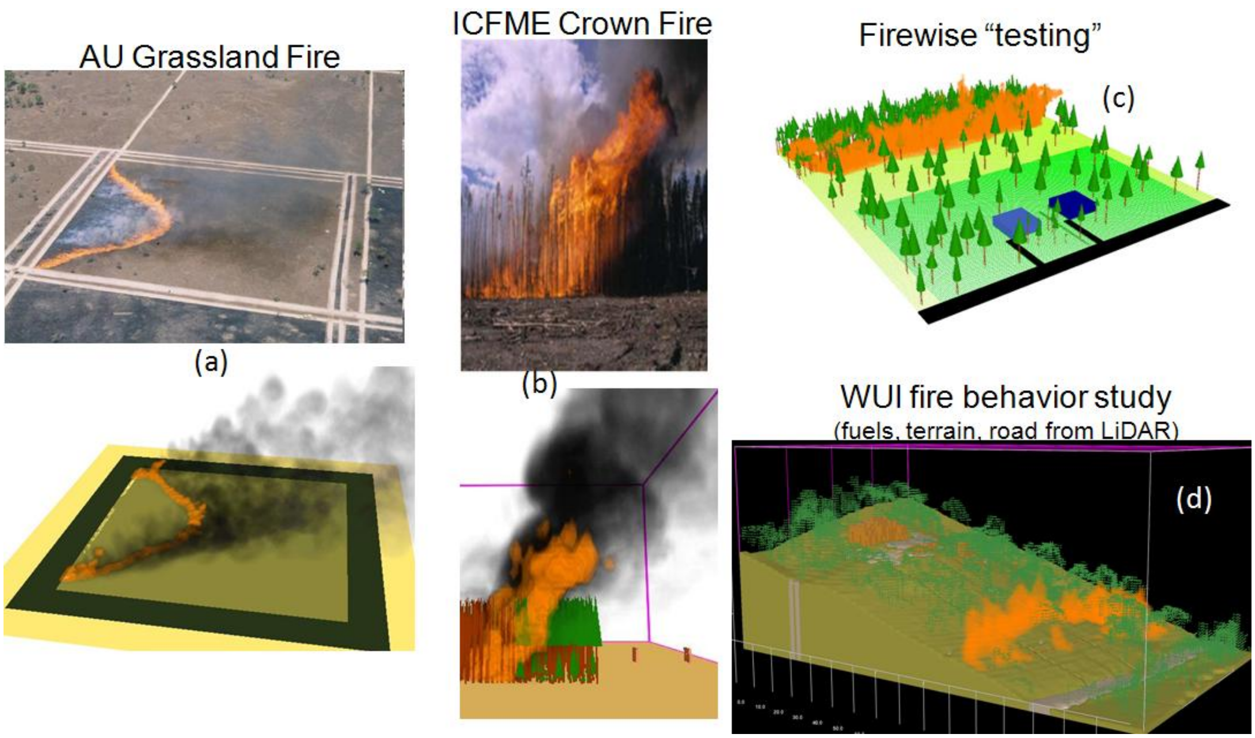
Fig. 1: Three images showing results from a grassfire simulation using WFDS. The grass land plot is 150 m long and 50 m wide. All figures correspond to the same time. From top to bottom: the fire perimeter and smoke plume; radiant heat flux; convective heat flux are shown. The scale for the heat fluxes also shown.

The next two figures illustrate the application of WFDS to laboratory-scale and stand-scale fire scenarios. In Fig. 1 laboratory cases are shown. Fig. 2a shows a snapshot in time from Douglas fir tree burning experiments and simulation. Trees of two different heights and a range of fuel moisture values were burned and simulated (Mell *et al*. 2010). In Fig. 2b a snapshot from the deep fuel bed experiments conducted in the USFS burn chamber in Missoula, Montana, and numerical simulation are shown. In these experiments rows of vertical steel rods, wrapped with excelsior fuel, were mounted on a platform. The spacing and height of the fuel rows was varied, along with the slope of the platform, to determine threshold conditions for fire spread along the entire platform. Experimental results are reported in Finney *et al*. (2010). In Fig. 2c a snapshot from the crown initiation experiments, conducted in the USFS laboratory in Riverside, California (Tachajapong *et al*. 2008 & 2008), is shown along with a result from WFDS numerical simulations of the experiment. These experiments are designed to investigate conditions under which an excelsior surface fire will ignite a raised fuel composed of chaparral branches and foliage. Papers reporting WFDS simulations of the experiments shown in Figs. 2b-c are in preparation. Predictions from WFDS for the cases shown in Fig. 2a-c are in reasonable agreement with measured results. These simulations were slower than real time and conducted using computational grid cells on the order of centimeters. See the Fig. 2 caption for further details on the simulations.



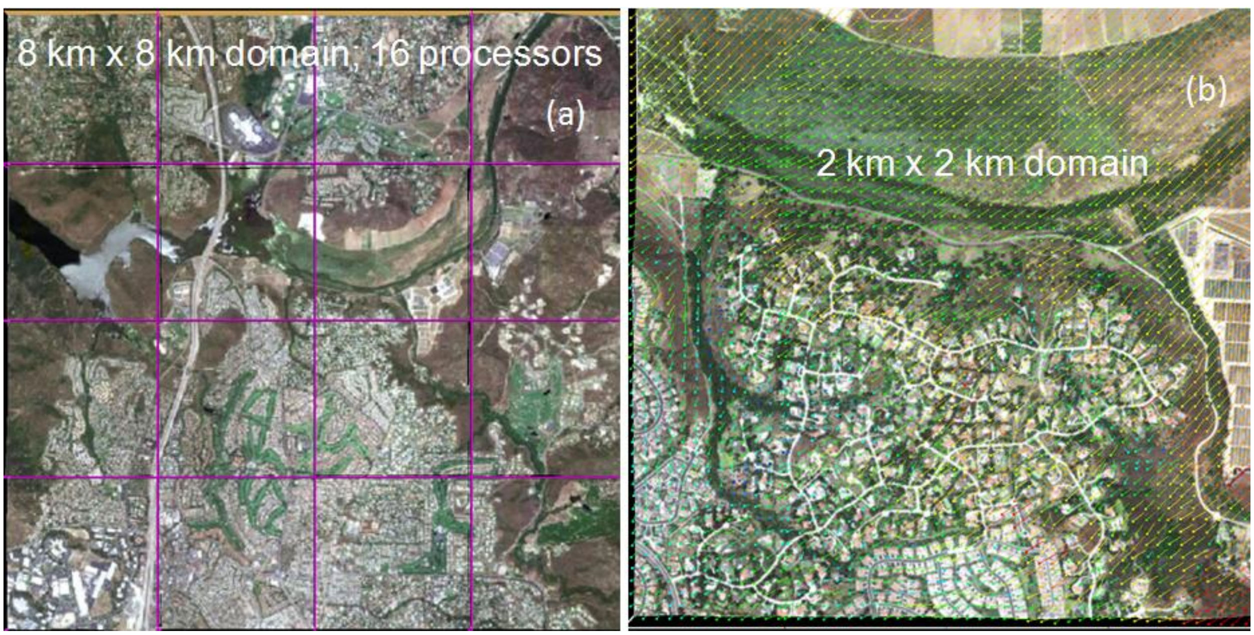
Figs. 2a-c: Examples of WFDS applied to laboratory scale fires: (a) Douglas tree burn experiments conducted at NIST (10 cm grid; 6 m x 6 m x 9 m domain; 300 times slower than real time with 4 processors). (b) Deep fuel bed experiments conducted in the USFS Missoula burn chamber (5 cm grid in fire region; 12 m x 10 m x 6 m domain; 180 times slower than real time with 10 processors). (c) Crown fire initiation experiments conducted in USFS Riverside laboratory (2 cm grid; 1.2 m x 1.2 m x 1.2 m domain; 80 times slower than real time with 6 processors).

Figs. 3a-d display results from WFDS as applied to stand-scale fire behavior scenarios. Fig. 3a is an Australian grassland fire spreading within the plot that is 200 m x 200 m in extent. The parabolic shape is a result of the ignition procedure. Two igniters begin at the middle and walked in opposite directions with drip torches. At the time of the photograph the ignition procedure had just ended. This ignition procedure was reproduced in the simulation. Results from the application of WFDS to this scenario are in Mell *et al*. (2007). In fig. 3b a snapshot from the international crown fire modeling experiments is shown. In the simulation, walls can be seen which reproduce a scenario in which the ignition of walls by the crown fire was studied (Cohen 2004). Fig. 3c is a result of a modeling study to compare the effects of different fuel treatments on fire behavior and heat fluxes on structures (Ginder *et al*. 2010). Results of this study are consistent with findings of the international crown fire modeling experiments (Cohen 2004). Fig. 3d is an example of using WFDS to simulate fires spreading over realistic terrain and vegetative fuels obtained from LiDAR data. The simulation studies shown in Fig. 3b and Fig. 3d are works in progress. The simulations in Fig. 3 used computational grid resolutions of approximately 1 m on 5 to 10 processors; these simulations were slower than real time. It is important to note that the same physics-based model (WFDS, in this case) was used to simulate the fire behavior across all the cases shown in Figs. 2 and 3. This is in contrast to empirical modeling where each scenario requires a different and independently derived empirical model.



Figs. 3a-d show stand scale examples of fire behavior and applications of WFDS: (a) Australian grassland fires (Mell *et al*. 2007) on 200 m by 200 m plots (1.7 m computational grid in fire region; 1500 m x 1500 m x 200 m domain; 125 times slower than real time with 10 processors). (b) Crown fire experiments conducted in the Northwest Territory of Canada (Cohen 2004). (c) Simulation only study of fuel treatment effectiveness in preventing structure ignition (Ginder *et al*. 2010) (0.5 m grid; 150 m x 112 m x 30 m domain; 200 times slower than real time with 8 processors). (d) Example of fire behavior simulation using terrain and vegetation obtained from LiDAR data.

Figs. 4a-b show examples of landscape-scale wind simulations from WFDS. The wind enters the computational domain from the northeast at a speed of 20 m s^{-1}. In Fig. 4a the computational domain is 8 km x 8 km in extent; in Fig. 4b instantaneous wind vectors 5 m above ground level are plotted and the domain is 2 km x 2 km covering a WUI community in the central region of Fig. 4a. The community shown in Fig. 4b was burned in the 2007 Southern California wildfires under Santa Ana wind conditions and is currently the subject of an in-depth study (Maranghides and Mell 2010). Both simulations shown in Fig. 4 used 16 processors. The spatial domains for each processor (2 km x 2 km) for the 8 km x 8 km case are shown as red squares in Fig. 4a. Depending on the grid cell size, wind simulations can be faster than real-time. For example, the 8 km x 8 km simulation with a horizontal grid resolution of 40 m and a vertical grid resolution of 20 m is 10 times faster than real-time. If the grid resolution is increased by a factor of two in each direction the simulation runs three times slower than real-time. The 2 km x 2 km case in Fig. 4b used a 3 m horizontal and 2 m vertical resolution and ran 180 times slower than real-time with 16 processors. The influence of the terrain on the wind can be clearly seen in the valley on the western edge of the community where the wind is redirected to the south.



Figs. 4a-b: Examples of landscape scale wind simulations from WFDS. (a) An 8 km x 8 km domain. Computations used 16 processors whose spatial domain is outlined by the red squares. (b) A 2 km x 2 km domain over a community in the center of Fig. 4a. Wind vectors at 6 m above ground level are plotted. The ambient wind enters the domain from the northeast at 20 m s^{-1}. See text for a discussion on simulation specifics.

Figs. 1 - 4b illustrate that physics-based models have developed to the point where they can be used to investigate fire behavior trends and even, to some degree, quantitative measures of fire such as heat fluxes and spread rates. While these models do not operate faster than real-time they can be used to develop and assess simpler fire spread (faster than real-time) models, as will be discussed in the next section. As affordable computers continue to improve in speed and memory capacity, the capabilities and range of applicability of physics-based models will improve. In addition, unlike empirical models, the accuracy of well-designed physics-based models will improve due to increased spatial resolution. As a benchmark, when the Rothermel (1972) surface fire spread model was published, IBM's flagship computer (IBM 370) cost 500 times more, and had one 1/6000 the memory and 1/800 the processing speed of current top-of-the-line laptops.

Example of a simple fire spread model (level set)
The simple fire spread model considered here is based on a level set method (Rehm and McDermott 2009) and is currently under development at NIST. This method is based on solving the equation for the evolution of a scalar field, ϕ, which has values -1 to 1:

$$d\phi/dt + \mathbf{R} \,.\, \mathrm{grad}(\phi) = 0 \qquad (1)$$

where $d\phi/dt$ denotes the partial derivative of ϕ with respect to time; **R** is the spread rate vector; and grad(ϕ) is the gradient of ϕ. In fluid mechanics Eq. (1) is the material derivative of ϕ, where **R** would be the fluid velocity vector. Thus, an element following the 'streamline' of ϕ which is initially zero (i.e., the fireline location) will remain zero. The spread rate vector **R** is a prescribed function of environmental variables (e.g., wind, slope, vegetative fuel).

In the examples presented here, **R** is a function of the local slope (using rules from the McArthur Forest Fire Danger Meter [McV, 2010]), the angle (θ) between the normal to the fire line and the direction of the wind (see Fig. 5), and prescribed values for the head-, flank-, and back- fire spread rates (here these are obtained from WFDS simulations). **R** is not a function of the fuel type, in the examples below, because only one fuel is considered: grassland. It is also assumed that the spread rate depends on the magnitude and direction of the ambient wind, as opposed to the local wind in proximity to the fire line. This implementation of the level set is commensurate with FARSITE as applied to surface fires. An implementation that includes more environmental information would, for example, use the direction and magnitude of the wind in proximity to the fire line (instead of the ambient wind). This local wind field could be obtained from separate wind simulations such as those shown Fig. 4a-b, above. In this case, the resulting implementation of the level set method would be commensurate to the use of FARSITE and WindNinja (for wind fields) (Forthofer and Butler 2007).

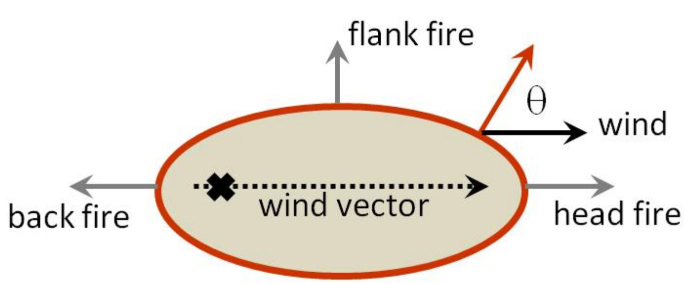


Fig. 5: Schematic illustrating the components of the level set model for fire spread. The red line represents the fireline. The direction (obtained from the model) and magnitude (prescribed) of the head-, flank-, and back- fires are required.

This level set model approach is 'empirically-based' (with the measured data obtained from numerical experiments), faster than real-time, and can predict the spread of the fire line using spread rate 'maps'. These maps would define the spread rates on a landscape for many environmental scenarios (e.g., various fuel, wind, whether, and terrain conditions) and could be based on observations, measurements, or model predictions. The predictions are only as good as the rules and the rules themselves can become complicated, as with any approach that links rule-based or different empirically-based models together. An example would be rules that attempt to capture the complex processes involved in the transition from a surface fire to a crown fire and vice versa.

Fig. 6 plots the fire line location, in an Australian grass fire experiment (Mell *et al*. 2007), at three different times as measured (symbols) and predicted by the level set model (solid lines). For this implementation of the level set model, the head fire spread rate is obtained from the empirical model derived from experimental database and the flank fire spread rate is prescribed. A photograph of the fire line, at the time of 56 seconds, is shown in Fig. 3(a). The level set model does a good job of predicting the spread rate of the head fire (as expected given that the empirical spread rate is used) and a reasonable job of predicting the rest of the fire line. A break in fire line symmetry about the head fire point (in both the measured and simulated fire lines) occurs after 86 s due to a wind shift (which was not measured). The level set simulation was 25 times faster than real time using one processor. Note that the WFDS simulation (not shown, see Mell *et al*. 2007), with the same grid resolution, was 125 times slower than real time with 10 processors.

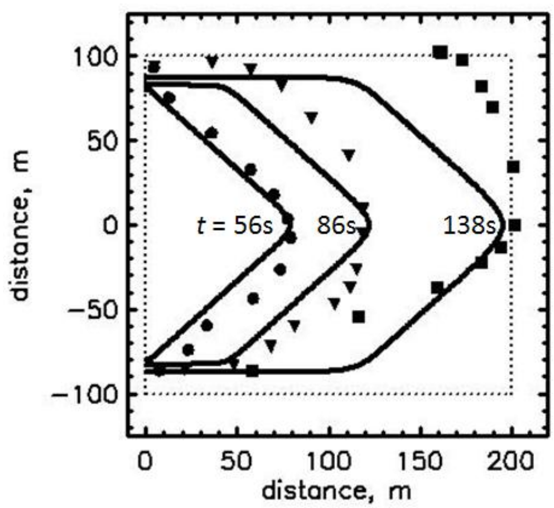


Fig. 6: Level set (solid lines) and experimentally measured (symbols) fire lines at three different times for an Australian grass fire (Mell *et al*. 2007). Grass plot and computational domain is 200 m x 200 m. Level set simulation with a 1.7 m grid resolution was 25 times faster than real time with one processor.

Developing and testing the level set model using the physics based model (WFDS)

This section presents some preliminary results from an approach which uses the physics-based model, WFDS, to determine the head- and flank- fire spread rates for use in the level set model. The level set model was then tested for transition scenarios in which the fire spread from natural to treated grasslands and vice versa. No backing fire was present because ignition took place along a firebreak. The ambient wind speed was 10 m s^{-1}. The WFDS simulations for determining spread rates were made in a computational domain of dimensions 300 m x 150 m x 25 m and a grass plot of dimension 100 m x 50 m (the computational domain must be sufficiently large to ensure that the boundary conditions do not influence the fire behavior). WFDS simulations on much larger domains (2700 m x 2700 m domain and 900 m x 900 m grass plot) were also conducted and compared to level set predictions to determine if spread rates obtained from simulations on small domains would be applicable (this is discussed in the following section). Fuel characteristics for natural grass were based on field measurements: 0.3 kg/m² loading, 0.5 m height; 120 cm^{-1} surface area to volume ratio; 6% moisture (Cheney *et al*. 1998; Mell *et al*. 2007). Treated (cut) grass had a fuel loading and height reduced by cutting the grass to 1/5 its height (0.1 m) and removing the clippings (0.06 kg m^{-2} fuel loading).

Fig. 7 shows results from WFDS and level set model predictions of a fire spreading through natural (untreated) Australian grass from a point ignition. Color contours show WFDS burning rates and the red lines show the fire line position as predicted from the level set model. The head- and flank- fire spread rates from WFDS were used in the level set model. It is known from field measurements (Cheney *et al*. 1998) and reproduced in physics-based models (e.g., Mell *et al*. 2007) that the head fire spread rate increases until the width of the head fire is sufficiently large (~50 m). For this reason, this WFDS simulation will be used to obtain the flank fire spread rates for the level set model.

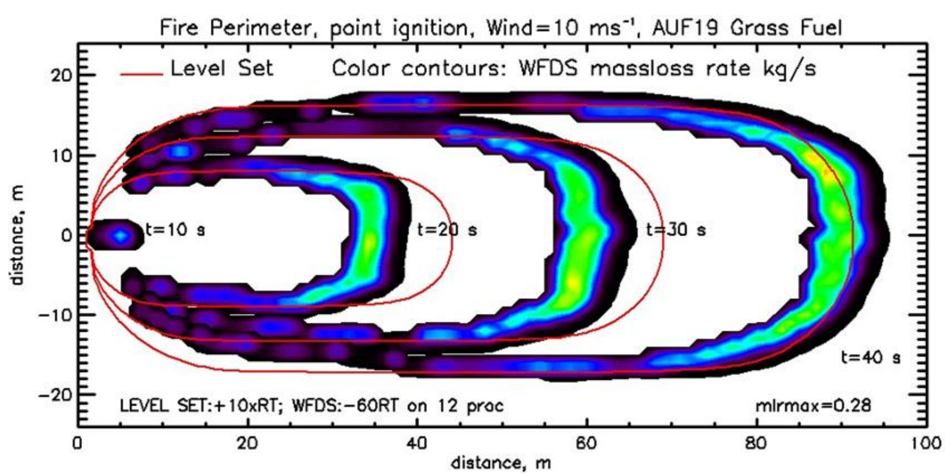
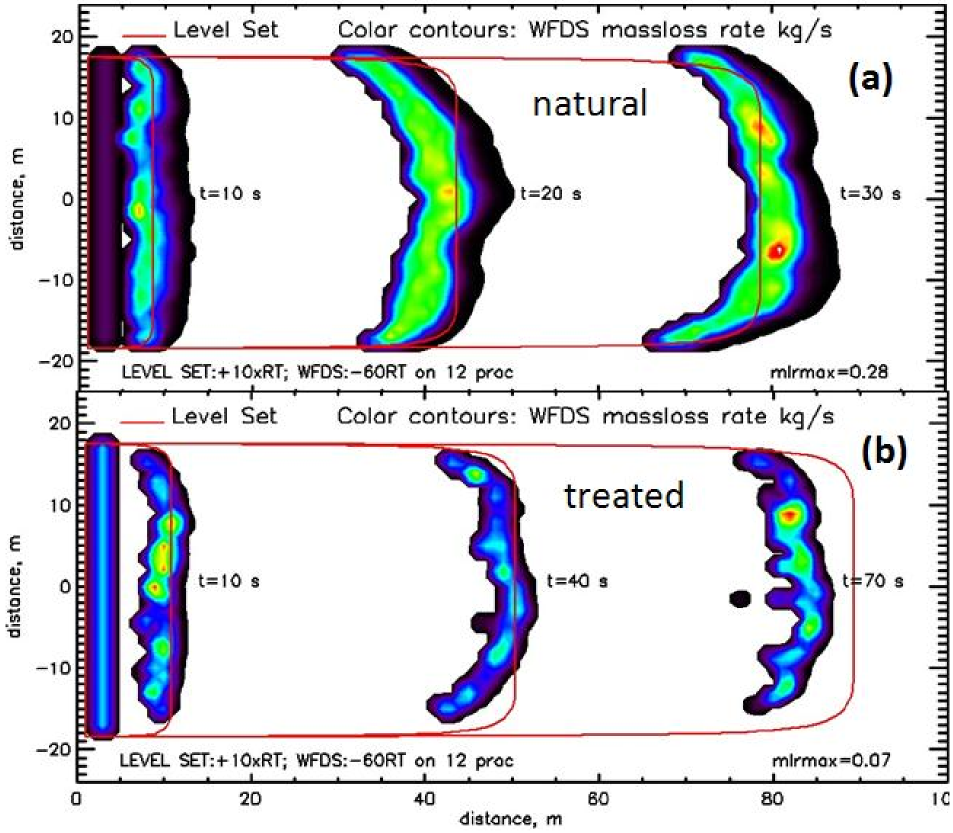


Fig. 7: Results from a WFDS and level set model simulations of fire spread through Australian grass (fuel properties are listed in the text). Color contours are mass loss rate from WFDS; red line is the fire line from level set. Ambient wind in 10 m s^{-1} and a point ignition was used. Level set was 10 times faster (one processor) and WFDS was 60 times slower (12 processors) than real time. The head and flank fire spread rates from WFDS were used in the level set model.

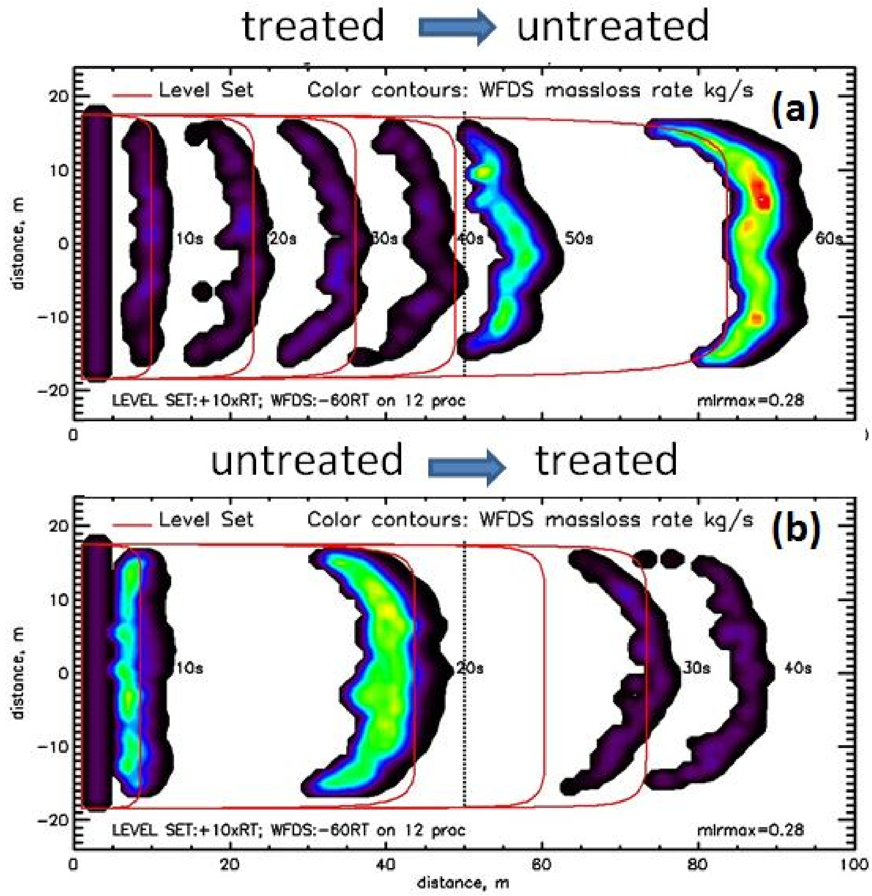
Head fire spread rates for the level set model were obtained from WFDS simulations of grassland fires using a line ignition (no flank fires were present). Figs. 8a-b show the results of these simulations for natural (Fig. 8a) and treated or cut (Fig. 8b) grass. As in Fig. 6, color contours show the burning rate (kg s^{-1}) from WFDS and red lines show the location of the fire line from the level set model. Fire spread and mass loss rate in the treated grass was significantly lower than in the natural grass. Spread rate in the treated grass is about half its value in the natural grass. The maximum burning rate in the untreated case is 0.28 kg s^{-1} and 0.07 kg s^{-1} in the treated grass. The area of active burning is also significantly larger in the natural grass case. The level set model head fire spread rate was obtained from WFDS after a quasi-steady spread rate was established, well past any period of time required for ramp-up from ignition.
Predictions from both models for the case when the fire spreads through a change in fuel loading are shown in Figs. 9a-b. The location of the fire line is plotted every 10 s; time labels are positioned next to the WFDS fire locations. A vertical dotted line gives the location of the fuel loading change. Prior to the transition in fuel loading, the level set and WFDS models are in good agreement. In Fig. 9(a), the fire spreads from treated to untreated grass. The WFDS mass loss rate contours clearly show the increase in fire intensity when spreading from treated to untreated grass. The level set significantly over-predicts the spread rate after the transition because it is based on the quasi-steady spread rate in WFDS and so does not account for the ramp up from ignition to established spread rate. This fire acceleration period is a known fire behavior phenomenon and FARSITE (Finney 2004) has an adjustable parameter to account for it with default values based on field observations of fires in different fuels, etc.



Figs. 8a-b: WFDS (color contours of mass loss rate) and level set (red lines) model results for fire spread in Australian grass. (a) natural grass, (b) treated grass (natural grass cut to 1/5 its height, clippings removed). Note that the maximum mass loss rate was 0.28 kg s^{-1} for the natural grass and 0.07 kg s^{-1} in the treated grass; the color contours are scaled to show red for the maximum mass loss rate in each case.

In Fig. 9(b) the fire spreads from untreated, natural, grass to treated grass. In this case, the level set location of the fire line lags the WFDS location (opposite of Fig. 9(a)) even though the quasi-steady spread rate from WFDS is used in the level set model. This occurs because, in WFDS, the treated fuel is pre-heated by the approaching, high intensity, fire in the untreated fuel. This causes the fire in the untreated fuel to accelerate rapidly and outpace (note the separation distance between WFDS fire locations in the 10 s interval between 20 s and 30 s) the level set predictions. However, by 30 s the WFDS fire has decelerated and, although it leads the level set fire, is spreading at a rate equal to the level set (as can be seen by comparing the separation distance between the fire locations at 30 s and 40 s in both models). In FARSITE it is assumed that the fire will decelerate instantaneously (Finney 2004).

The results shown in Figs. 8a-b and 9a-b are meant to be illustrative of one type of fire transition that cannot be captured by simple models without additional ‘tuning ‘ or calibration. How important these particular fire behaviors, and others, are requires further study. This type of study is especially important if simple models are to be applied to complex, realistic, landscapes with heterogeneous fuels (such as fuel treatments).



Figs. 9a-b: Results showing the model predictions when the grassland fuel loading changes: (a) from treated to untreated treated (1/5 fuel height and loading) and (b) from untreated to treated. A vertical dotted line denotes the boundary between fuel loadings. The location of the WFDS fire line is shown every 10 s. WFDS results are color contours of mass loss rate (scale of contours is the same for both figures) and level set model results are the red lines showing fire line location. See text for discussion.

Application of the level set model to landscape scale fires

The last section presented preliminary results from the application of the level set and the WFDS models to relatively small domains (200 m x 150 m computational domain). A question relevant to the development of empirical models of landscape fire spread is: Can spread rate formulas based on measured data sets from relatively small-scale field experiments be legitimately applied to large landscape scale fires? (The same question is even more pressing when laboratory measurements form the basis for the empirical model – but that issue is not considered here.) This question also holds for the modeling approach used here: Can WFDS simulations over relatively small domains be used to develop a level set model for application to landscape scales? A first step to investigating this was performed by simulating a much larger grassland fire.

The landscape-scale grassland plot is 900 m x 900 m and the fire was ignited along a 400 m ignition line (this should be viewed as an approximation to a fire that developed from a much smaller ignition). The head and flank fire spread rates from the smaller scale WFDS simulations in untreated grass fuel (discussed in the previous section) were used in the level set model. A comparison of the WFDS and level set models is shown in Fig. 10. The level set predictions, although based on smaller scale WFDS simulation, well predicted the large-scale fire perimeters. In as much as WFDS is capturing the physical processes driving fire behavior for this larger scale fire these results imply that smaller scale simulations, and field experiments, can be used to develop simple fire spread models applicable to landscape scales. It should be kept in mind that the scenario considered here is about as simple as you can get: flat terrain, a single thermally thin fuel type, and a constant wind. There is a great need for a well conceived, coordinated, and comprehensive field measurement effort to test these conclusions.

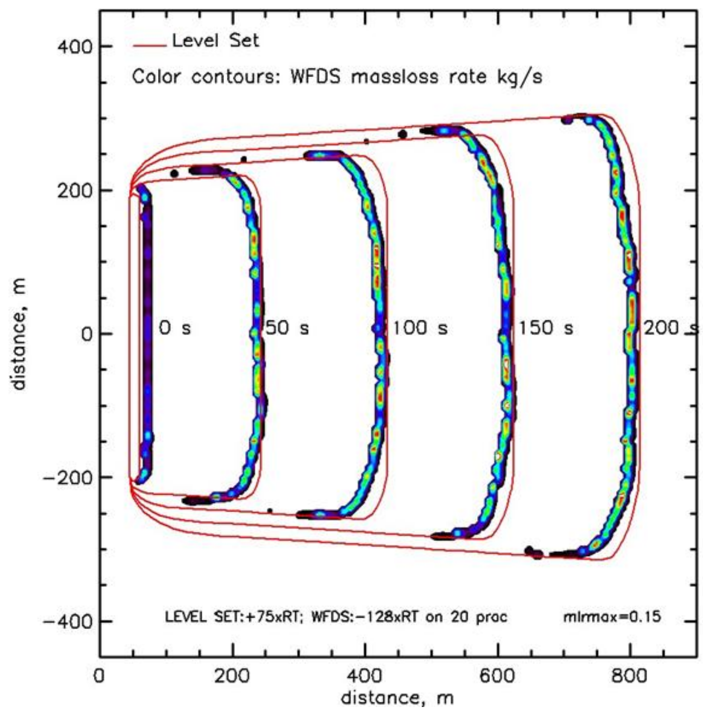


Fig. 10: Comparison of the WFDS and level set model predictions of grassland fire perimeters. The computational domain is 2700 m x 2700 m x 200 m with a grassland plot of 900 m x 900 m (area of figure). Fire perimeters are shown every 50 s. Level set head and flank fire spread rates were obtained from smaller scale (100 m x 50 m grass plot) WFDS simulations.

Fig. 11 provides a final illustrative example of the use of the level set model and its development and testing via a physics-based model such as WFDS. This figure shows the result of applying WFDS and the level set models to an area occupied by a community in southern California. This community was burned in the 2007 southern California wildfires and, as mentioned above, is the subject of an ongoing case study (Maranghides and Mell 2010). As a first step in assessing the performance of the simple level set model to this situation of interest, the entire landscape (2 km x 2 km) was covered in grass. Note that the community is on a hill, with a large valley to the north and two smaller drainages on the west and east (see Fig. 4b for wind vectors without a fire present). Santa Ana wind conditions (20 m/s from the northeast) were simulated. Both the head- and flank- fire spread rates used for input to the level set model were obtained from the WFDS simulation. The level set model assumes a constant wind direction from the northeast and used rules from the McArthur Forest Fire Danger Meter (MkV 2010) for the spread rate dependence on slope. Overall, the leading head and southeastern flank locations were well predicted by the level set method. The western flank was not as well predicted. While more testing and evaluation is needed, the most likely cause of this, based on examination of the WFDS results, is the lack of fire induced winds in the level set model. The western flank fire, in WFDS, significantly redirected the ambient winds toward the fireline, resulting in a faster spread rate.

Fig. 11: Simulation of firespread over a 2 km x 2 km region with complex terrain encompassing a southern California community. The terrain was obtained from LiDAR data. For simplicity, and as a first step in model testing, the entire domain is covered in grass (image showing the roads, structures, and vegetation is used for ease of reference when comparing the figures). The WFDS (level set) simulations required 41 million (2000) grid cells; 16 (1) processors; and were 400 times slower (5 times faster) than real time.

Summary and conclusions

An approach for using a complex, physics-based WFDS model to develop and assess a simple model level set model was presented. For simple scenarios with flat ground, constant wind speed and direction and simple fuel (grass), the level set model shows promise. Simulation results on relatively small domains were used to build simple models applicable to larger scale simulations. This has implications on field studies also: measurements from smaller stand-scale fires, which are more logistically and fiscally feasible, can potentially be used to develop models for, and improve our understanding of, landscape-scale fire behavior. The simple level set model can be easily and efficiently applied to more complex scenarios. Further testing of the simple model, over a range of environmental conditions (varying fuels, terrain, and winds) is underway.

Acknowledgements

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Predictive Services: Current and Future Directions in Decision Support

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Abstract:
The Predictive Services program integrates fire weather, climate, fuels, fire danger, and resource information to provide decision support for enhancing a proactive approach to fire management. This paper will highlight current and future Predictive Services products and services listed below.

Current:
- Day 1 and day 2 graphical weather forecasts.
- 7-day fire potential outlooks by Predictive Services Area (PSAs).
- Monthly/seasonal outlooks based on mainly subjective fire potential analysis.
- Fire severity funding decision support.
- Fuels and fire behavior advisories.
- Situation, incident and resource information.
- Geospatial web portal combining Predictive Services data with other sources.
- National Fuel Moisture Database.
- Podcasts and internet briefings.

Coming Soon:
- Improvements to the geospatial web portal with enhance user capability.
- Interactive display of the 7-day outlook product.
- 7 day fire potential outlooks utilizing a high-resolution gridded approach.
- Monthly/seasonal outlooks incorporating new objective (statistical and dynamic) tools.
- Improved dry-lightning forecasts.
- Preparedness Level and resource need forecasts.
- Most products available in GIS data layers.
- Redesigned Sit-209 reporting system.

Future:
- Incorporating live fuel moisture and greenness data into outlook products.
- 8-14 day fire potential outlooks.
- One-stop shop web portal for fire environment information, including weather, fire potential, smoke, fuels, fire danger, etc.
- New social network dissemination including products designed for mobile phones, Twitter, etc.

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Starfire: Decision support for strategic integration of wildland fuels and unplanned ignitions

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Abstract:
Addressing the 2009 Guidance for Implementation of Federal Wildland Fire Management Policy for managing unplanned ignitions is increasingly important. To the support evolving wildland fire policy, the STARFire analysis is designed to assess the risks and benefits of managing unplanned ignitions at the landscape scale. By using a probabilistic framework, the system addresses the expected benefits and risks of unplanned ignitions. Using the same inputs, the system also assesses fuel treatment optimization and smoke management considerations. By operating at the landscape level and incorporating local land management values, STARFire helps to achieve land management objectives and to relate risk reduction and ecosystem benefits. Managers can analyze fuels treatments and strategies for managing unplanned ignitions separately, or the interactions between them. It provides a visual display of the short and long-term tradeoffs between undesirable fire impacts and beneficial fire effects by identifying the combined effects of fuels treatment optimization and wildland fires. STARFire is adaptable to the needs of programs with different objectives and concerns. The geospatially rendered results are provided through web services and available to a wide range of applications. Initial results from six diverse landscapes indicate that the analysis may have wider applicability beyond national park units.

Additional keywords: modeling, wildland fire, prescribed fire, fuels treatment, strategic planning, trade-off analysis, fire management planning, smoke impact analysis

Introduction

The primary purpose of STARFire is to help decision makers quantitatively evaluate risk and benefit relative to local resource and social values when developing strategic multi-year plans for managing fire. It includes functionality to assess net benefit relative to management of unplanned ignitions (wildfires), it displays priority areas for fuel treatments based on local values including risk reduction, and it displays a smoke impact analysis.

The project was initiated in response to a finding that a common barrier to management of wildfires for multiple objectives consistent with evolving wildland fire policy (Wildland Fire Leadership Council 2009) in National Park Service (NPS) units was risk aversion by decision-makers. The risk aversion is in part due to a lack of balanced analysis articulating the risk along with the potential short and long term benefits that might be obtained from alternative management strategies. The analysis was developed to provide managers a sound and objective assessment in the hope of managing and mitigating risk aversion. The system was developed and tested on six federal land management units, primarily national parks[1]. The STARFire system is expected to be most useful in areas with complex wildland fire programs where decisions regarding unplanned ignitions are not obviously either full suppression or monitoring from afar. In such areas, STARFire will help sort out the relative benefits and risks of fires and help managers understand the cumulative impacts of wildfire responses and fuels treatments on long-term land management objectives.

The STARFire analysis results are displayed in a set of geospatial map layers that are a quantitative expression of the short and long-term tradeoffs between potential fire benefits and fire impacts under different management strategies. In addition to assessing strategies for management of unplanned ignitions, STARFire analyzes potential fuels treatments and their effect, separately or as they interact with wildfire strategies. The analysis is adaptable to the needs of field units having different fire management objectives, fire regimes and resource concerns.

Analysis outputs are spatial and designed to integrate with the Wildland Fire Decision Support System (WFDSS) process. Geospatial outputs are interactive and available through a web browser map interface or in various formats for use in third party applications such as ArcMap and Google Earth.

The analysis is intended to be conducted during the annual pre-season planning cycle, or as needed for strategic planning efforts such as the development of a new fire management plan. The results may be applied at various phases of the fire management planning process including;

1. Strategic multi-year planning
    - Developing and assessing the outcomes of various fuels and wildfire strategies for development of Fire Management Plans, and support of related National Environmental Protection Act (NEPA) analysis
2. Strategic annual planning
    - Identifying high priority areas to evaluate for fuels projects, as well as anticipate response strategies for unplanned ignitions in the upcoming fire season
3. Tactical decision support
    - Provide outputs that are intended to be used as part of the overall decision-making process when considering the management of a particular ignition. The outputs may be used stand-alone, or in conjunction with the WFDSS process.

Description of the analysis

The analysis utilizes a common set of inputs that are variously processed and used by three primary analytic modules to produce results relative to; net benefit of unplanned ignitions, fuel treatment optimization and smoke impacts (Fig. 1). All analytic components can project results through time, and certain assumptions may be modified to assess different strategic planning

[1] Prototype areas include; Sequoia & Kings Canyon National Parks, Yellowstone National Park, Rocky Mountain National Park, Big Cypress National Park, Great Smoky Mountains National Park, Grand Canyon National Park, and the Kaibab National Forest.

alternatives (e.g. primary wind direction, desired number of acres per year in fuel treatments, etc.).

The primary inputs include data that characterize the landscape and current conditions, and data to represent land management objectives including stewardship responsibilities derived from local land and fire management plans. Land management objectives include identification and assessment of local resources that can be affected by fire. The assessment incorporates values associated with ecosystem condition that can be improved by fire, the value of fire effects on fire sensitive habitat, and values associated with the protection of the urban interface and other developments. A structured elicitation process is used to obtain the value o protecting and improving the identified resources, and their relative importance (Rideout *et al*. 2008).

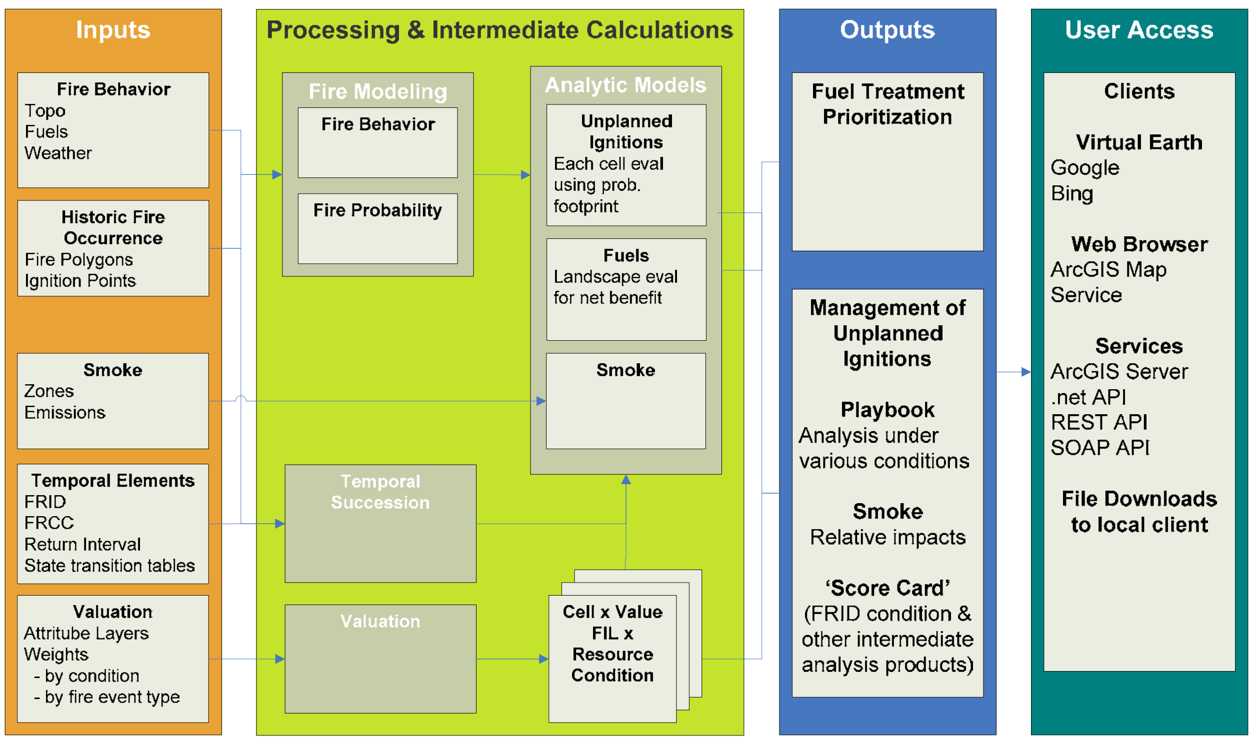


Figure 1. STARFire analysis overview

STARFire includes three integrated analytic models: one manages unplanned ignitions, one performs fuels treatment optimization (Wei *et al* 2008) and one estimates potential smoke impacts. In the first two models, fire behavior information is gathered and processed to establish a probabilistic platform (one for fuels and one for unplanned ignitions). This information is combined with the fire effects and valuation information. The combined information is intensively analyzed and applied to a sequence of complex mathematical models that generate the final results for wildfire net benefit and fuels treatment optimization. The results are then processed to provide user-friendly interactive maps that are accessible over the web.

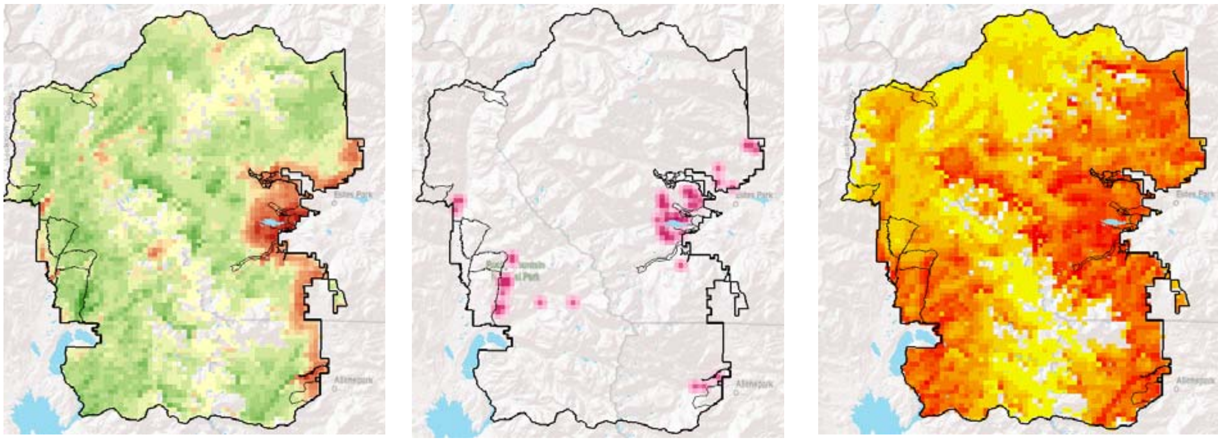
The unplanned ignition model analyzes beneficial and detrimental effects of fires that might occur at any location on the planning unit. Based upon location, fire intensity, and values, STARFire generates an interactive and scalable landscape map of the expected net benefits of fire at any location on the landscape. The maps use an intuitive color scheme of red, yellow and green so users can quickly visualize the benefits and risks of potential fires. A temporal assessment is enabled by aging the fuels and the ecosystem condition. As fuel models and ecosystem condition are aged, a map representing future conditions can be produced to quickly assess temporal tradeoffs. Comparison of current and future projections helps planners and managers visualize the potential impacts of alternative strategies. For example, aggressive suppression today may mean increased risk and issues for tomorrow's landscapes and managers as the ecosystem degrades and fuels accumulate.

In the fuel treatment optimization, the model searches the entire planning unit to identify the most beneficial locations for locating fuel treatments. To identify these locations the model assesses the potential for hazardous fuel reduction as well as enhancing resource conditions (benefits). By combining these objectives, the model suggests the best locations considering both objectives. The area of the landscape (number of cells) suggested as priority treatment areas displayed by the model starts low and increases, providing the planner with a sequence of increasing options for potential fuel treatment locations. By starting from a low number of cells selected and expanding to a large number, managers can quickly see how the model expands potential treatment locations. The fuel treatment locations identified by STARFire show potential areas for further analysis and consideration. The STARFire analysis does not provide tactical information such as how to treat identified areas (e.g. mechanical vs. prescribed fire) or provide a precise prescription for the treatment (e.g. thin, limb, pile burn, etc.).

By visually integrating the fuels treatment optimization maps with the fire net benefit maps, fire managers can plan for complementary integration of the two program elements. On some planning units, good locations for fuels treatments may differ from the best locations for managing unplanned ignitions. For example, burning in the proximity of developments is often best left to implementation of fuel treatments as opposed to treating through the use of unplanned ignitions. This complementary arrangement between the two program elements is evident at Rocky Mountain National Park as shown in Fig. 2. Each panel is oriented north to south. Here the relative benefits of unplanned ignitions are displayed in Panel A where the green areas indicate estimated positive effects and the red areas indicate risk. In contrast, Panel B shows fuel treatment optimization results. The pink areas have been assessed by STARFire to be promising locations for fuel treatment projects. Note the complementarities between Panels A and B as viewed from a landscape perspective.

A subsequent analysis could be conducted that would assume achievement of the identified fuels program. That analysis would reflect changes in the risk to resource values as well as reduced risk posed by unplanned ignitions.

Panel C shows the potential for smoke emission impacts, with red areas indicating high potential for impact and yellow areas indicating low potential impact. The red areas tend to be located near development and in valleys where smoke can be trapped or be entrained in down slope winds at night. Higher and more remote locations are often closer to yellow indicating less potential for impact. Areas without color are rock, ice or other non-burnable surfaces having no potential to produce smoke impacts. The smoke impact analysis provides managers an instantly available and quick read before tactical implementation decisions are analyzed, and can also be used to assess long term changes in potential impact by comparing pre- and post-fuels treatment scenarios.



Panel A: Unplanned ignitions. Panel B: Fuel treatment. Panel C: Smoke impact.

Figure 2. Examples of key STARFire results.

Conclusions:

The STARFire analysis fills a unique niche in fire management planning. It shows promise in providing information useful to decision makers on relative risks and benefits of implementing different fire management strategies over time. The ability to visualize the degree to which strategic and tactical fire management decisions mitigate risks and enhance resource benefits is expected to reduce risk aversion by managers and the public when considering the full range of management actions allowed under national fire policy. By helping land managers articulate local management values and objectives relative to wildland fire, and associating those values with potential sources of risk as well as beneficial effects over time, managers have a powerful tool to aid in making, communicating, and defending fire management decisions.

An additional strength of the model is that it incorporates large amounts of resource data along with capturing expert fire behavior knowledge and valuation information in a comprehensive framework. This framework allows for continuity of knowledge and understanding across time and through changes in local staff. This capability helps preserve and perpetuate a consistent and knowledge-based decision context for land management units. All of the information is available to managers through web access in an interactive framework to promote local analysis and communication within the planning unit, with the public, and across ownerships.

Additional work is needed to refine elements of the analytics, and to further articulate the technical and business process.

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Improving Decision Support in 2010 - Accomplishments and Lessons Learned from the National Fire Decision Support Center

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Abstract:
The National Fire Decision Support Center (NFDSC), a collaborative effort between Fire and Aviation Management and Research and Development, is tasked with providing state-of-the-art wildland fire decision support to interagency fire managers. The NFDSC is comprised of five components: Fire Economics Research, Fire Spread Research, Fire and Aviation Management, Human Factors and Risk Management Research Development and Applications (RD&A), and the Wildland Fire Management RD&A. The Wildland Fire Management RD&A portion of the NFDSC consists of specialists that provide timely decision analyses in support of large wildland fires in the areas of fire behavior, economic analysis, and management response capability.

The NFDSC provides real-time decision support to fire managers seven days a week through a variety of on-site and virtual mechanisms. Fire season 2010 is the first season the NFDSC will be operational; decision support is provided with fire behavior and economic assessment tools within the Wildland Fire Decision Support System (WFDSS), the decision support and documentation system used by federal fire managers. The analyses and output from these tools provide direct information for fire managers in making strategic and timely decisions. As needed and requested NFDSC staff can provide input and advice regarding WFDSS tool analysis into strategic planning and decisions. Presentation information will include operational procedures, accomplishments, and lessons learned regarding improving the decision support making process from the NFDSC perspective for fire season 2010 demonstrated through summary statics and/or specific fire case studies.

Proceedings of 3rd Fire Behavior and Fuels Conference, October 25-29, 2010, Spokane, Washington, USA
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The Interagency Fuels Treatment Decision Support System (IFT-DSS): Simulating Fire Behavior and Fire Effects to Support Fuels Treatment Decisions.

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Abstract:
The Software Tools and Systems Study was initiated by the Joint Fire Science Program and the National Interagency Fuels Coordination Group in March 2007 to address the proliferation of software systems in the fire and fuels treatment domain. In 2008, the Interagency Fuels Treatment Decision Support System (IFT-DSS) software framework was designed to organize and manage the many software systems and data used for fuels treatment planning and to make these tools available to fuels treatment planners through a single user-friendly web-based system. In 2009 a Proof-of-Concept system intended to illustrate potential IFT-DSS functionality was designed and released in early 2010. In this presentation, we discuss the current progress of the IFT-DSS. We discuss what fire behavior and fire effects models have been included in the system to data and how each of the models are intended to be used within the system to support fuels treatment decisions. We provide case studies that illustrate possible field applications of the system. Using these case studies, we show how the IFT-DSS can be used to simulate potential fire behavior and fire effects before and after simulated fuels treatments.

Using the Large Fire Simulator System to Map Wildland Fire Potential for the Conterminous United States

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Abstract:
This project mapped wildland fire potential (WFP) for the conterminous United States by using the large fire simulation system developed for Fire Program Analysis (FPA) System. The large fire simulation system, referred to here as LFSim, consists of modules for weather generation, fire occurrence, fire suppression, and fire growth modeling. Weather was generated with daily, seasonal, and spatial variation from numerous weather stations around the United States that contain records for 1 to 3 decades. Large fire occurrence probabilities were calculated by logistic regression based on historical data. Fire suppression is represented by a statistical model based on historic large fire records from 2000-2005. Fire growth was calculated using a minimum travel time algorithm. Outputs from LFSim include a burn probability and a conditional probability of flame lengths for six classes (0-2, 2-4, 4-6, 6-8, 8-12, and greater than 12 feet) at a 270 square meter cell size for the conterminous United States (CONUS). From this data we calculated a wildland fire potential (WFP) for CONUS by using simple map algebra. First we grouped flame lengths into three classes based on the fire behavior characteristic chart (0-4, 4-8, and greater than 8 feet) by spatially summing the individual flame length rasters into the appropriate group. Next we multiplied each group of conditional flame length probabilities by the burn probability, which created an absolute burn probability for each flame length group. Next each flame length group was weighted based on resistance to suppression by assuming each level of a flame length group is twice as difficult to control as the one below. Lastly, we adjusted for the high frequency of grass fires observed in the LFSim outputs by including a resistance to control weight based on line production weights for initial control by hand crews. In creating the final WPF, we smoothed the edge effect between adjacent fire planning units (FPUs), which was created by running LFSim by FPUs with different weather stations, by running a zonal averaging model based on ecoregion sub-sections and fire behavior fuel models. In this paper we will describe this methodology, as well as the resulting CONUS WFP map in detail, as well as discussing lessons learned from working with LFSim outputs.

A Practitioner's View of the Past Present and Future

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Extended Abstract:

The past provides perspective on where we came from in this profession. Staying grounded to the past is a way of staying in touch with innovation and the challenges pioneers and mentors went through to get us where we are today. Experiencing the past in non-traditional ways or simply making a trip to experience the real lay of the land provides us insight in to who we are. It can be as simple as holding that Babe Ruth autographed baseball the same way "the Babe" held it when he signed it, to walking through Mann Gulch and experiencing the same terrain, weather, and level of fatigue at the same time of day that the historic tragedy occurred. The past provides insight to the times and challenges before our time. It's a way to understand as well as honor our predecessors.

The present, particularly at this conference, demonstrates how the profession has expanded and the high level of intellect involved. The increase in digital and electronic research and gaming is also evident by the proportion of electronic research compared to field projects. It's important to stay in touch with the hands on side of the profession. Political influence is apparent in the use of politically correct terminology, and this exemplifies the influences established in the past. Where we are heading today is influenced more by the perceptions of current politics than by needs in the field. The use of computerization and political involvement will continue to distance how we get field projects done if it cannot meet the challenges of "staying connected" to what we all think is professional reality.

I would never pretend to know what direction we need to take. The current one is right or the need to change is apparent. Neither assumption is close to being right. What I know is, constraining intelligence is definitely the wrong thing to do. However I will suggest, the concept imparted to me by my employers is worthy of consideration. Tribal elders have a position of reverence in today's American Indian culture. Not to preserve the past so much, as to provide that connection between their ancestors and the present. Their wisdom is in preserving their traditional beliefs in a modern world, and they provide the means to interpret what is happening now and how it may affect their way of life. Their past does not involve ownership of the land. Theirs was a belief that from the land you made your way and provided for your family, but treated it and left it as good as or better than you received it. You did not own it; consequently your responsibility is to take care of it for the next generation.

It is in this way a value based profession helps move us through our portion of time, with the understanding that we guide our actions with professional ethics while allowing our thoughts to innovate ways to meet the challenges not yet encountered.

Introducing the *Canopy Fuel Stratum Characteristics Calculator*

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Abstract. The regression equations developed by M.G. Cruz, M.E. Alexander and R.H. Wakimoto (2003. *International Journal of Wildland Fire* **12**, 39-50.) for estimating the canopy base height, bulk density and fuel load in ponderosa pine, lodgepole pine, Douglas-fir and mixed conifer fuel types based on three stand characteristics (average height, basal area and stand density) have now been programmed into an excel spreadsheet.

Additional keywords: canopy base height, canopy bulk density, canopy fuel load, crown fire, basal area, stand density, stand height.

Introduction

Canopy fuel stratum characteristics determine to a large extent the behavior of crown fires. By linking an extensive forest stand database with foliage dry weight allometric equations. Cruz *et al.* (2003) were able to develop regression equations for estimating canopy base height (CBH), canopy fuel load (CFL), and canopy bulk density (CBD) that are compatible with Van Wagner's (1977) models of crown fire initiation and propagation. Three inputs are required: average stand height, basal area and stand density. Equations are available for four broad coniferous forest fuel types commonly found in western North America (i.e. ponderosa pine, lodgepole pine, Douglas-fir, and mixed conifer). The purpose of this paper is to describe a software application of the Cruz *et al.* (2003) equations, called the *Canopy Fuel Stratum Characteristics Calculator* (Fig. 1).

Overview of software

The main features of the *Canopy Fuel Stratum Characteristics Calculator* are:

- Given three user inputs (i.e. stand area basal area, average stand height and stand density), CBH, CFL and CBD are automatically calculated for one of the four fuel types.
- Provides for both SI or metric and English unit inputs/outputs (Figs. 2 and 3).
- Cautionary 'pop-up' messages (Fig. 4) for input values that exceed a maximum reliable value or variable range (Table 1).

A copy of the *Canopy Fuel Stratum Characteristics Calculator* software is readily available for downloading from the FRAMES website (**http://frames.nbii.gov/cfis**).

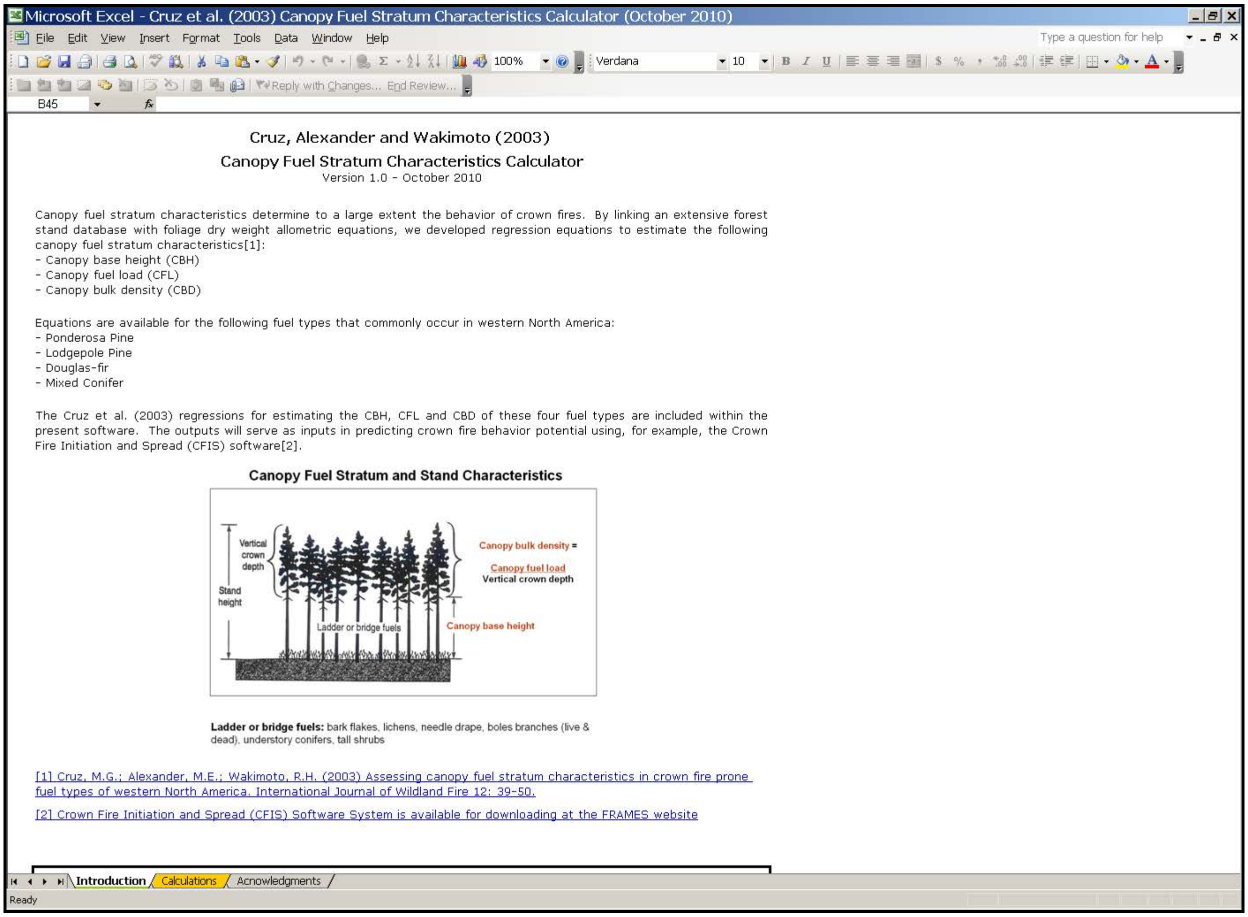

Fig. 1. Screen of the *Canopy Fuel Stratum Characteristics Calculator* tab.

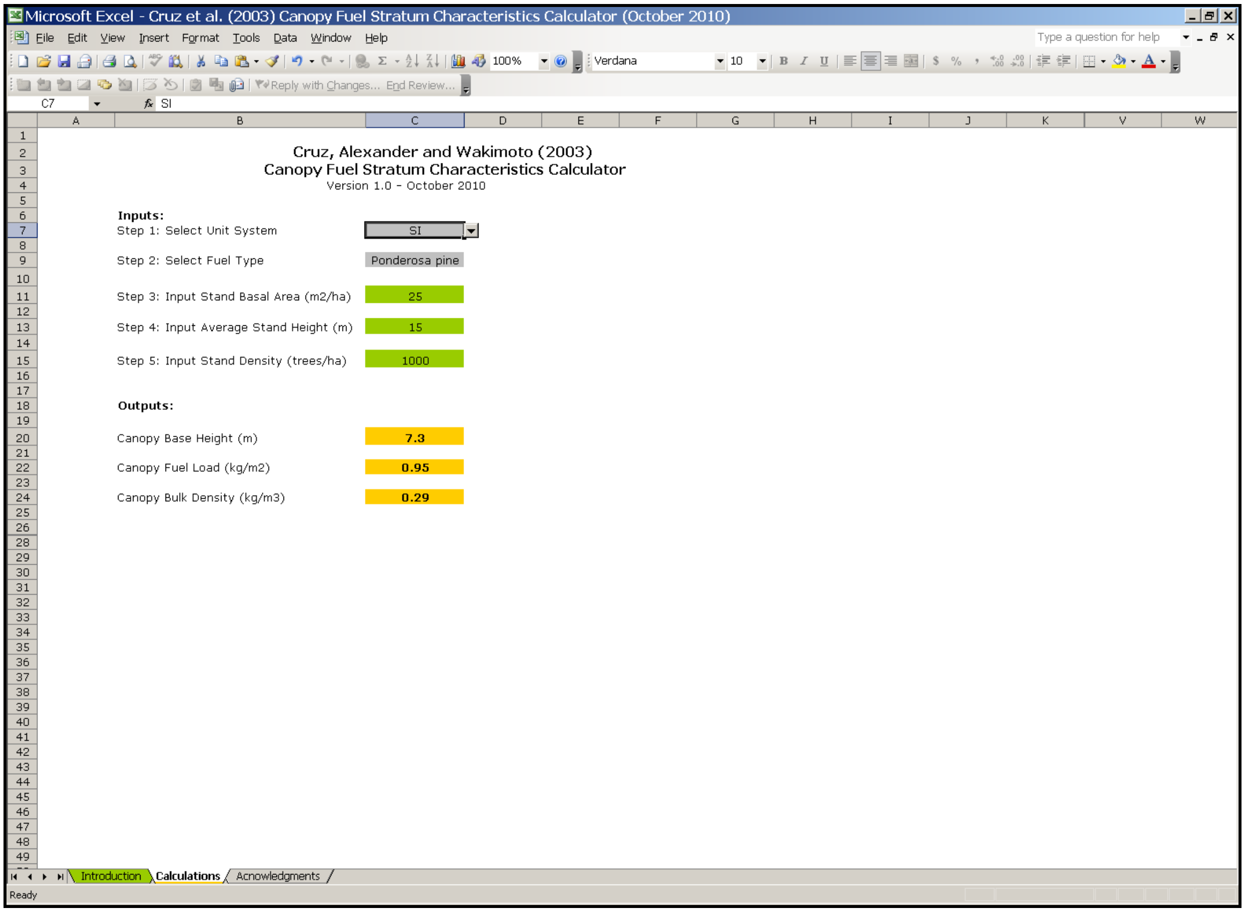

Fig. 2. Screen of the *Canopy Fuel Stratum Characteristics Calculator* SI unit calculation tab.

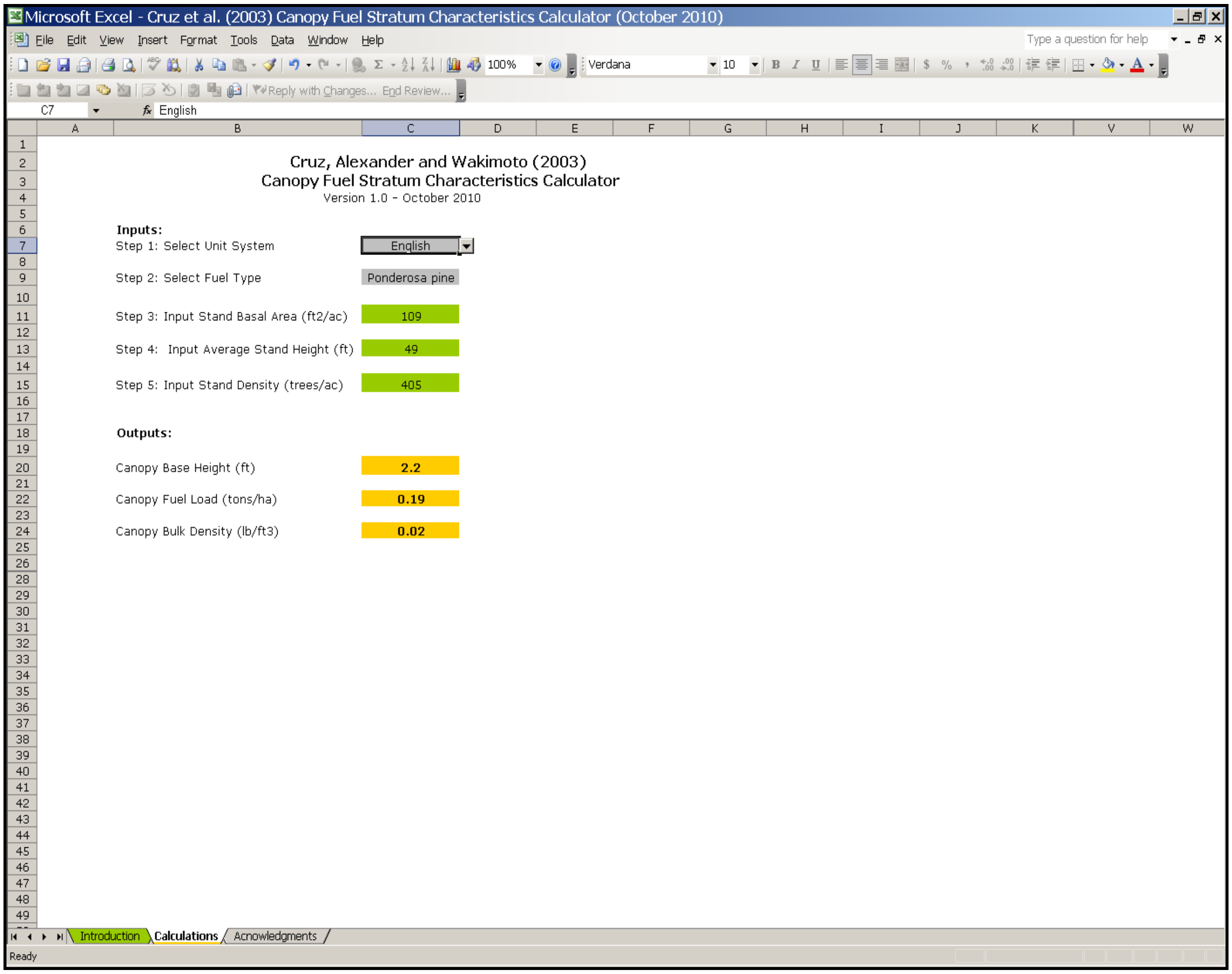

Fig. 3. Screen of the *Canopy Fuel Stratum Characteristics Calculator* English unit calculation tab.

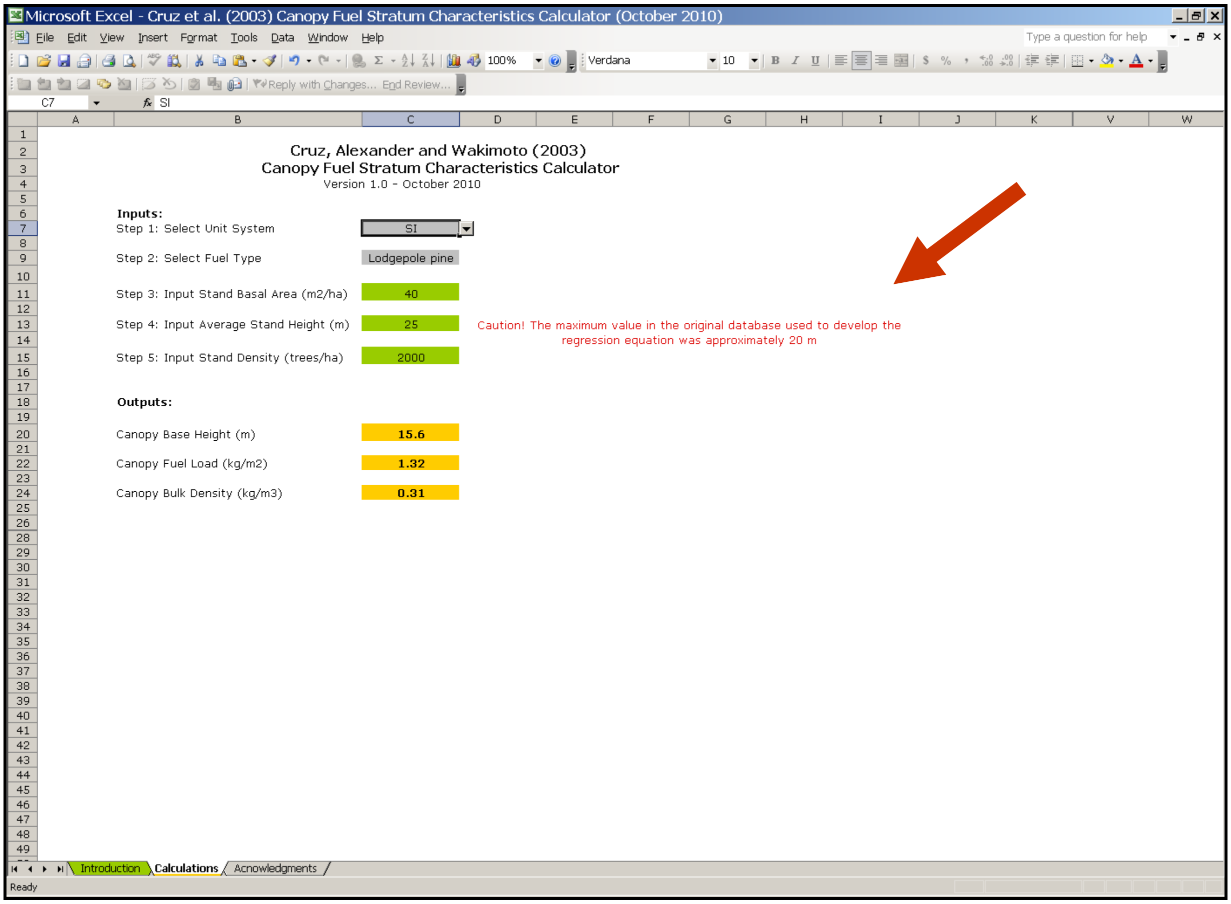

Fig. 4. Screen of the *Canopy Fuel Stratum Characteristic Calculator* cautionary note example.

Table 1. Maximum reliable values and/or reliable range of the three stand inputs used in the *Canopy Fuel Stratum Characteristics Calculator*

Conifer fuel type	Basal area $m^2\ ha^{-1}$	Basal area $ft^2\ acre^{-1}$	Stand height m	Stand height ft	Stand density trees ha^{-1}	Stand density trees $acre^{-1}$
Ponderosa pine	40	175	1-20	3-65	3000	1200
Lodgepole pine	50	220	3-20	10-65	4000	1600
Douglas-fir	55	240	2-25	7-80	3000	1200
Mixed conifer	70	300	3-25	10-80	4000	1600

Feedback received todate

The *Canopy Fuel Stratum Characteristics Calculator* was informally tested by a group of undergraduate students at the University of Idaho, Moscow, in April 2010 as part of a fire management course exercise. According to their instructor, Chad Hoffman, 'The class really liked the calculator. They thought it was easy to use and very straight forward … Several of the students decided to recommend this approach in the fuels inventory plan they are developing'.

Recent developments of note

The Cruz *et al.* (2003) regressions for estimating canopy fuel metrics were recently evaluated for their performance. The results as reported on by Cruz and Alexander (2011) were very encouraging. The evaluation consisted of comparing observed and predicted values for two different data sets. The first test involved a simulation of two low thinning regimes (i.e. 25 and 50% basal area reduction) based on a random selection of stand data used in the original Cruz *et al*. (2003) study, and was undertaken in direct response to a perceived shortcoming of the CBH regressions models (Cruz *et al.* 2010). The second test involved a direct comparison against independently collected data for ponderosa pine in the Black Hills of South Dakota by Keyser and Smith (2010).

Acknowledgement

This paper is a contribution of Joint Fire Science Program Project JFSP 09-S-03-1.

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Towards a crown fire synthesis: what would you like to know and what might you be able to contribute?

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Abstract. Members of the project team associated with the Joint Fire Science Program (JFSP) project JFSP-09-S-03-1 entitled 'Crown Fire Behavior Characteristics and Prediction in Conifer Forests: A State of Knowledge Synthesis' are actively seeking help and input from members of the wildland fire community in the form of photo documentation of crown fires and suggestions on the material content of the final written product.

Additional keywords: crown fire behavior, crown fire initiation, crown fire propagation, crown fire rate of spread, crowning.

Introduction

In 2010, the Joint Fire Science Program (JFSP) elected to support a project to undertake a state of knowledge synthesis on the subject of crown fire behavior characteristics and prediction in conifer forests. The project is expected to be completed by October 2012. The purpose of this paper is to provide a summary of background information on the project and at the same time make a formal request of the wildland fire community for their input and assistance.

Background information

The focus of JFSP Project 09-S-03-1 is on synthesizing the currently available information on crown fire behavior related to conifer forests (e.g. onset of crowning, type of crown fire and associated spread rate and fireline intensity) in relation to the wildland fire environment (i.e. fuels, weather and topography). Information on crown fire behavior is available from several scientific peer-review journals, including the seminal articles by Van Wagner (1977, 1993) on crown fire theory and Stocks (1987, 1989) on fire behavior in immature and mature jack pine stands in the *Canadian Journal of Forest Research* as well as the special issue on the International Crown Fire Modelling Experiment (Butler *et al.* 2004*a*, 2004*b*; Stocks *et al.* 2004; Taylor *et al.* 2004) plus articles on recently developed and tested models for predicting passive and active crown fire rates of spread (Cruz *et al.* 2005; Alexander and Cruz 2006). Additional articles dealing with crown fire behavior can be found in *Forest Science* (Cruz et al. 2004), *International Journal of Wildland Fire* (Cruz *et al.* 2003*c*, 2006*a*, 2006*b*; Cruz and Alexander 2010), *Forestry Chronicle* (Cruz *et al.* 2003*b*), and *Australian Forestry* (Cruz *et al.* 2008).

Links to a lot of this scientific material on crown fire behavior can be found at the FRAMES website (http://frames.nbii.gov/). Pertinent information will also be garnered from other written sources including conference proceedings papers (e.g. Alexander 1988; Agee 1996; Cruz *et al.* 2002, 2003*a*, 2006*c*; Alexander *et al.* 2006) and agency publications (e.g. Rothermel 1991; Peterson *et al.* 2005; Cruz and Plucinski 2007; Cronan and Jandt 2008) which typically have undergone at least an 'in-house' review. Other information on crown fire behavior is available – much of this has already been located and summarized in theses by members of the project team (Alexander 1998; Cruz 1999, 2004).

Data and information, including video footage (Fig. 1), obtained during wildfire monitoring and documentation by the fire behavior assessment team of the USDA Forest Service's Adaptive Management Enterprise Services Team (Henson 2005; Vaillant and Fites-Kaufman 2009) will also be examined (http://www.fs.fed.us/adaptivemanagement/).

Fig. 1. Time series photos from a fire-proofed video camera taken during the Black Mountain II Fire in Montana in August 2003. Photos courtesy of USDA Forest Service, Adaptive Management Services Enterprise Team.

While the focus is on North American forests, the synthesis is intended to be global in nature and is intended for multiple audiences ranging from the general public to college students to fire and land managers to university professors and other researchers. It's envisioned that publication of the synthesis will be patterned after the popular Australian book on grass fires by Cheney and Sullivan (2008), accompanied by a multimedia DVD featuring video imagery and other supporting documentation, and that a special issue of *Fire Management Today* devoted to crown fire behavior will serve to highlight the main conclusions and findings contained in the book.

We need your help and input

In addition to summarizing the existing scientific and technical literature on crown fires, project members are also seeking assistance from individuals in the form of field observations of crown fires and related experiences as well as still pictures (Fig. 2) and video footage. Of course proper credit will given to those are able to contribute photos and imagery.

Fig. 2. A free-burning active crown fire spreading through a lodgepole pine stand (stand height ~20 m) in the boreal forest region of central Alberta in August 1981. Head fire rate of spread and fireline intensity exceeded 15 m min^{-1} and 10 000 kW m^{-1}, respectively. Note that the 'wall of flame' extends well above the top of the tree canopy. Photo by M.E. Alexander.

Finally, we are interested in hearing from you -- the 'end user' -- as to your opinions on the subject of crown fires and any specific questions and/or research needs/knowledge gaps that you would like to see addressed in this crown fire synthesis project. This input could take the form of a simple question. For example, several years ago, Sando *et al.* (1970) posed the simple question: 'What fuel-weather combinations are required to produce a propagating crown fire in northern flatwood forests'? As well, in a fire ecology survey of land managers and environmental scientists in western North America conducted in the early 70s, several questions were raised that dealt with a number of aspects of crown fire potential (from Taylor *et al.* 1975):

Will fire in a thinned stand tend to stay on the ground as opposed to crowning? What are the effects of various spacings? What spacing inhibits spread of [crown] fire?

Crown fires are quite a threat in the ponderosa pine of the Black Hills. Extreme burning conditions may cause crowning any time of the day or night. Based on slope, what tree spacing would allow full stocking and yet be most desirable for separating tree crowns to preclude crown fire ignition?

How many tons/acre of fuel are required to support a crown fire in ponderosa pine and in mixed conifer forest in the Southwest?

What stand and crown density is required to carry a fire in standing pinon-juniper stands?

We would also appreciate your input in identifying and describing potential fire and fuel management applications of the proposed crown fire synthesis. In short, we want our work to be relevant!

Please feel free to contact any member of the project team regarding information, comments, thoughts or ideas. Note that we have created a 'public neighborhood' entitled 'JFSP Crown Fire Synthesis Project' at *MyFireCommunity.net* developed by the Wildland Fire Lessons Learned Center (http://www.myfirecommunity.net/Neighborhood.aspx?ID=816) in order to facilitate the soliciting process.

For the latest developments

In order to keep up todate on the progress of the crown fire synthesis project, periodically visit the project website (http://www.fs.fed.us/wwetac/projects/alexander.html). Publications and other products will be posted there and on the JFSP website (http://www.firescience.gov/) under Project ID 09-S-03-1.

Acknowledgement

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Large scale fire whirls: Can their formation be predicted?

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Abstract
Large scale fire whirls have not traditionally been recognized as a frequent phenomenon on wildland fires. However, there are anecdotal data suggesting that they can and do occur with some regularity. This paper presents a brief summary of this information and an analysis of the causal factors leading to their formation.

Additional keywords: Fire behavior, Fire intensity

Introduction

Large fire whirls have not been widely recognized as major contributors to wildland fire risk. However, recent evidence seems to indicate otherwise. An analysis of fire behavior that occurred on the Indians Fire in June of 2008 suggests that such fire behavior is more common than previously believed.

The Indians Fire reportedly started Sunday June 08, 2008 at about 12:35 pm in the Arroyo Seco drainage near the Escondido campground on the Los Padres National Forest. At this time the Arroyo Seco RAWS was reporting a temperature of 89 F with relative humidity (RH) at 11 % and east northeast winds at 5 mph gusting to 10 mph.

On the morning of Monday June 9th, the fire was estimated to be 400 acres. The fire was burning in steep inaccessible terrain. A high temperature of 102 F was recorded with 5% RH during the afternoon. Winds were east northeast at 3 to 5 mph with gusts to 13 mph. Relative humidity in the valley floor reached 40 % during the night with lows around 6 to 10 % during the day.

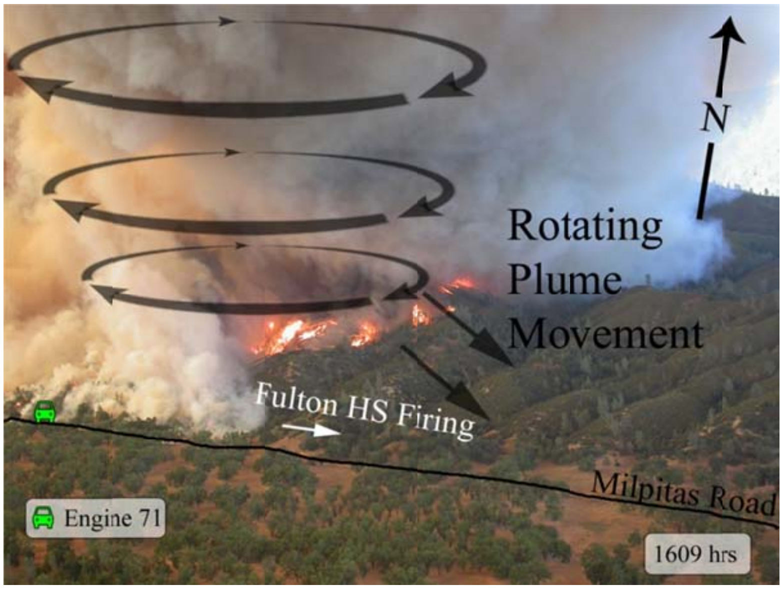
By 0600 hours on June 10th the fire had burned roughly 1100 acres. Fire growth was minimal the previous night. There was not much smoke visible from the fire that morning, and fire behavior was characterized as quiet. Between 2 pm and 5 pm June 10th, the fire activity increased significantly due to the very warm temperatures (95 F) and dry conditions (~5 % RH). A dry cold front was forecast to pass through the region during the night, with strongest winds located north of the fire area. Gusty north winds were to develop behind the cold front with warm and dry conditions forecast to persist for at least another 24 hours. No fire behavior forecast was developed.

By the evening of June 10th, the northern edge of the fire had moved to higher terrain (between 3000 and 4000 feet ASL) and was burning in dense mature chaparral fuels. At 2100 hours on June 10th Red Flag Warnings went into effect across the Bay Area Hills well to the north of the fire for strong north winds and low humidity. There were no Red Flag Warnings in effect over the Indians Fire area, but the conditions were forecast to become drier and windier. The air mass near the ground was very dry and consequently lower elevation relative humidity that night remained near or below 10 % at the Fort Hunter Ligget RAWS. Due to very poor humidity recovery, the fire burned actively all night.

By the morning of June 11th, the day of the entrapment, the fire had burned over 5000 acres. The IAP weather forecast called for north to northeast winds 8 to 18 mph at the ridges becoming north 5 to 10 mph in the afternoon and north 10 mph in the valleys becoming upslope and up canyon at 3 to 7 mph in the afternoon. Forecast fire behavior was also similar with an emphasis on the potential for moderate fire behavior on the south and eastern perimeters that would test containment lines. It was noted in the IAP that firefighters should expect spotting and sustained runs. Temperatures warmed quickly into the 90's at lower elevations (2000 ft. or lower) and RH's dropped to single digits (~5 %) by early afternoon. Ridgetop winds remained from the northeast about 5 to 15 mph, while lower slopes and valleys had lighter, diurnal terrain winds. Fuels along the Milpitas road consisted primarily of light dead grasses in the oak savanna. In the morning, fire behavior in the grass fuels was low, with limited success in a firing operation focused on expanding a safety zone. Around noon another firing operation was attempted. This time fire intensity matched forecast levels, burning actively in the fine grassy fuels driven north by diurnal winds and the ground level winds induced by the main fire further north. By 1400 hours, firefighters observed increased fire intensity as indicated by increased potential for lofting and ignition of new spot fires outside the containment lines.

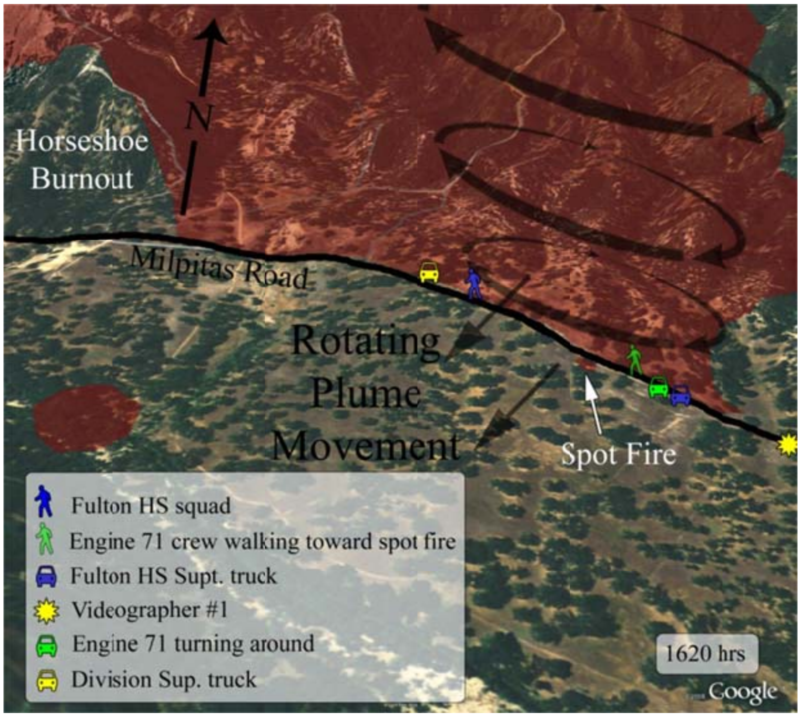
The main fire was now moving east, flanking across the chaparral slopes and making runs up hill to the north of Milpitas Road. The plan was to burn out along the road, heading east and keeping up with the main fire. Photographs of fire behavior in the chaparral on the steep slopes show 20-40 ft tall flames. Post fire inspection indicates intense, nearly complete combustion of all vegetation smaller than ¾ inch in diameter. Large diameter dead fuels were totally burned to white ash. Fire intensity from the burnout near the road in the grass fuels was much lower, with 1-3 ft flame lengths. Although not as intense, the fire spread quickly through the grass fuels toward the main fire.

The firing operation moved from the west to the east and at approximately 1530 hours the smoke plume from the main fire on the slopes north of the road had begun to slowly rotate. By 1557 a large, intense, vertically-oriented, rotating smoke plume was clearly visible above the slopes north of the burnout operation. From video footage, wind speeds in the rotating plume are estimated at 50+ mph (see fig. 1). We speculate that the vertical motion was enhanced by this rotation and was due to



the combination of intense heat released from the chaparral fuels on the slopes and the highly dissected terrain. Photographs indicate that by approximately 1600 the rotating plume was approximately 1000 feet in diameter at its base. The intense rotation would last for over 30 minutes. Video and camera images indicate that this rotating plume was part of the smoke column above the eastern portion of the main fire north of the firing operations being conducted along Milpitas Road (see Fig. 2). Witnesses state that the rotating column appeared to move east, parallel to the firing operation and road. Firefighters at the eastern endpoint of the firing operation had been watching and photographing the large rotating fire plume. Some firefighters stated that they had observed large “fire whirls like that on several occasions”, and did not perceive it to be any real threat to safety.

Also at 1621, the crew of Engine-71 had been assigned to hold the fire along Milpitas Road. At the time they saw a spot fire adjacent to the road only 320 feet west of their location. It was only about 5 ft X 5 ft in size. Three members of the engine crew walked west on the road toward the spot fire while the other two turned the engine around. Once the engine was heading in the correct direction, one of the crew members joined the other three on foot and the driver began to drive the engine toward the spot fire (see fig. 3). Soon after, winds suddenly increased near the crew and engine. The edge of the rotating vertical plume had moved over them and the road. Additional spot fires ignited near the road. The 4 crewmembers on foot were enveloped in strong winds (estimated to be 60-70mph), dense smoke, blowing embers and debris, flames blowing horizontally across the road, and highly variable wind direction and speed. Flame length in the grass is undetermined but flame height was reported to be “knee high” igniting any combustible surface fuels. Firefighters describe a “sheet of flame” over the ground. The spot fire located across the San Antonio River was drawn across the flats toward the main fire. Subsequent photos show active fire underneath the oaks, many of which sustained significant wind damage. After moving onto the flat valley floor the indraft inside the vertical rotating plume scoured any loose material on the ground including pebbles and ash, leaving broad areas of only hard-packed earth. Once the edge crossed the road the rotating plume soon dissipated and fire behavior decreased markedly.



Tornadic events generated by large fires can be extremely dangerous, and apparently occur more often than is generally realized. A brief look into the scientific literature and discussions with veteran firefighters indicate several examples. In 2007 a large fire whirl on the Fletcher Fire in Oregon damaged large trees. Many photos are available clearly showing a tornado-like structure that separates from the main column and moves at least a few hundred yards from the fire. The 2007 Neola Fire in eastern Utah produced similar vegetation damage and also tore the roof off of a nearby structure; three civilians were killed in what appears to have been a tornadic-event similar to that observed on the Indians Fire. The 2002 Missionary Ridge Fire has video documentation of a large rotating vertical plume during which winds were strong enough to overturn vehicles and damage the roof of a building in the area. A 1977 wildland fire in Japan seriously injured firefighters when a rotating plume formed on the lee wind side of a mountain. The 1871 Peshtigo, Wisconsin fire that killed up to 2,500 people was reported to contain a rotating plume that lifted a house off its foundations. In 1926, petroleum tanks near San Luis Obispo, CA ignited and burned intensely for days, generating many large rotating vertical plumes. One whirl was strong enough to lift a cottage located 1,000 yards from the tanks and move it 150 feet. The two occupants of the structure were killed. Evidence exists describing a larger rotating fire plume that occurred during a city fire in downtown Tokyo following an earthquake in 1923 that moved out of the city over a barren area where residents had gone for safety. This event ultimately killed an estimated 38,000 citizens within 20 minutes. Both the Hamburg, Germany and Hiroshima, Japan bombings during World War II also reportedly produced large, intense, damaging rotating plumes that appeared and behaved like tornados.

The main ingredients necessary for rotating vertical plumes of a large scale are a source of vorticity (rotation) and intense heat. Vortices may come from flow channeling from variable terrain/drainage orientation, vorticity induced in the wake of a hill or ridge, or horizontally oriented vorticity present (due to shear near the ground) in the ambient atmosphere that gets tilted to the vertical by the heat source. In all cases of large rotating plumes, an intense heat source is necessary to concentrate the vorticity. In the case of the Indians Fire, the drought had led to extremely dry live fuels and probably a buildup of dead fuels in the chaparral fuel types resulting in a highly flammable condition. The unstable atmospheric conditions promoted vertical transport in the plume. The variable terrain contributed to both enhanced combustion and channeling/blocking of inflow to the plume base. The channeling/blocking of the inflow may have been the initial source of rotation at the plume base. However, once the rotation was initiated the heat source concentrated the vorticity by stretching the plume whirl in the vertical direction, reducing its diameter. This reduction in diameter forced the rotation to increase in speed to conserve angular momentum (just like a figure skater spins faster when her arms are held close to her body). This concentrating mechanism allowed the whirl to obtain high wind speeds and explains the dramatic increase in winds proximal to the plume base. The rotation also significantly reduces the diffusion of energy (both kinetic and thermal) from the rotating plume to its surroundings. The result was a rotating tornado like structure that was able to exist and move across terrain for some distance away from its heat source before dissipating.

Four Types

Four general types of large fire whirls have been identified: 1) plume shedding, 2) L-shaped heat source in cross flow, 3) ambient vertical vorticity, and 4) lee side of hill or mountain.

The Neola fire and possibly the Indians fire fire-whirls are examples of the plume shedding phenomenon. Vortices shed off a main fire front due to shear from the ambient wind. The whirl forms on the lee wind side of the plume. It separates from the plume and advects in the downwind direction. It is very similar to Von Karman vortex shedding behind an obstruction in a flow. Wind in the whirl can be strong enough to cause damage to trees, structures, vehicles, etc. The whirl may stay intact for several minutes and travel for distances of possibly 1 mile. The fire whirls's ability to stay intact even though most of its vortex stretching mechanism (buoyancy) is lost is probably due to the strong reduction in turbulent diffusion of the core. Examples of this type of whirl have been reported by many authors (Church *et al.* 1980; Dessens 1962; Hissong 1926; Pirsko *et al.* 1965; Soma and Saito 1988; Soma and Saito 1991)

The second type or L-shaped heat source in cross flow is easily demonstrated in the laboratory. The whirl is generated by the cross flow interacting with the blocking effect of the corner of an L-shaped heat source. The great Kanto Earthquake fire in Tokyo Japan is an example of this type of fire whirl (Soma and Saito 1991). The whirl forms on the interior of the "L". This is also demonstrated at times from flow over randomly oriented heat sources (see fig. 4). If the orientation of the heat sources is such that a shear is formed then it is possible that a fire whirl will form over some area of the heat sources.

Fig. 4--Image of fire whirl generated by flow over randomly oriented heat sources.

The third type or ambient vertical vorticity is more associated with cold front passage (see fig. 5). It is caused by interaction between the vorticity that is generated by general flow field being rotated to the vertical and then developing into a fire whirl. It is generally associated with flat terrain, or terrain that has features that generate significant shear.

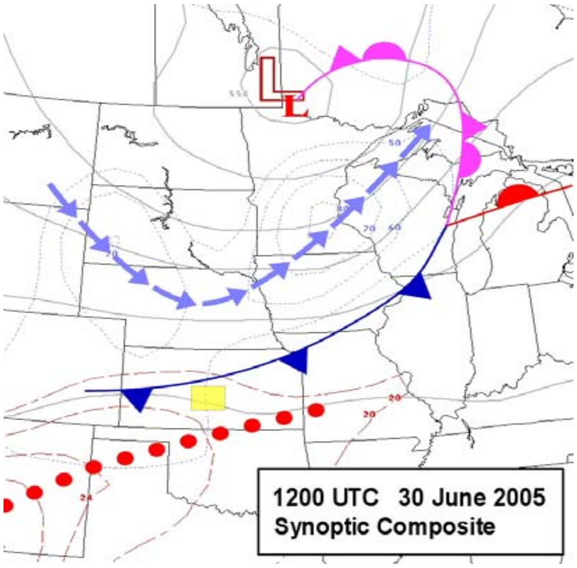


Fig. 5--Vorticity associated with cold front passage has been shown to generate large fire whirls.

The fourth type is generally formed by interactions between a fire located on the lee side of a ridge (see fig. 6). Vorticity generated in the wake of the mountain contributes to the formation of a fire whirl (Countryman 1971).

Common Factors

All four types of large fire whirls can be defined by four common factors: 1) a large heat source. The energy needed to form a fire whirl is significant and requires a large heat source. 2) Unstable atmosphere: For the most part, fire whirls form most easily when the atmosphere is unstable. Instability enhances that opportunity for vortex stretching and fire whirl formation. 3) Strong source of vorticity: all fire whirls require that significant vorticity be present in the flow. However, there are substantial sources of vorticity in most fires such as terrain features or multiple fire locations. 4) Low to moderate ambient wind: while some cases have been documented, in general, large rotating plumes do not develop in strong ambient winds.

Summary

To summarize, the Indians fire demonstrated the scale and danger associated with large rotating fire plumes. A review of the technical literature indicates that such plumes are not unusual given the appropriate set of environmental conditions. When the conditions are present, large rotating plumes can be generated that exhibit many of the characteristics of tornados, including high speed winds. In general it appears that such tornadic flows are very possible in large fires and can persist for 10-40 minutes and in some cases move almost independently of the fire. The added danger is that they can carry burning material with them, spreading the fire outside its normal boundaries. The best defense seems to be having lookouts at both close and long range that can provide up-to-the-minute information for fire crews working in the area. Clearly, when large fire whirls are observed, firefighters should note their presence to others in the area and consider modifying tactics.

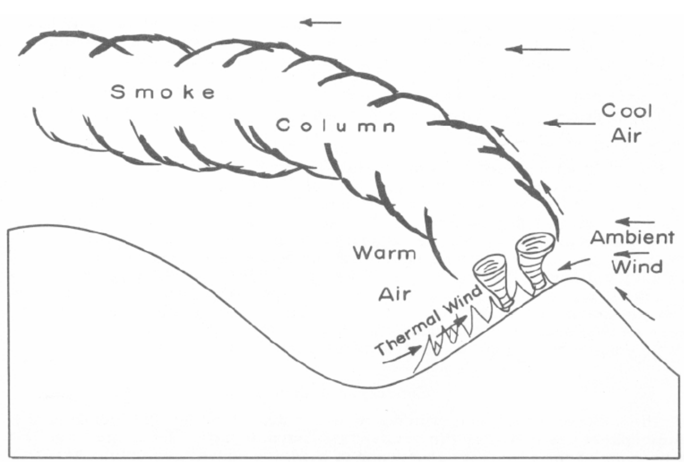


Fig. 6--Flow around and over a terrain obstruction has been shown to generate fire whirls on the lee side (Countryman 1971).

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Initialization of high resolution surface wind simulations using NWS gridded data

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Abstract
WindNinja is a standalone computer model designed to provide the user with simulations of surface wind flow. It is deterministic and steady state. It is currently being modified to allow the user to initialize the flow calculation using National Digital Forecast Database. It essentially allows the user to downscale the coarse scale simulations from meso-scale models to finer resolution.

Additional keywords: Wind modeling

Introduction

Wind can be the dominant environmental variable affecting wildland fire intensity and spread. When fire is burning in mountainous terrain winds can vary widely in speed and direction over scales of 3 to 200 ft. The result is rapid changes in fire intensity at small scales that can have significant influences on fire growth at larger scales. Fire analysts and managers have not had access to detailed wind speed and direction forecasts at the required level of detail. However, the advance of computer hardware capabilities, relative availability of GIS databases (elevation) and new advances in numerical solutions to the system of equations governing wind flow have led to the development of new tools capable of simulating surface wind flow.

Discussion

Two general types of models exist: diagnostic and prognostic. Diagnostic models predict the wind field at one point in time, and are sometimes called steady-state models, they do not look forward in time. They are useful for situations requiring fast simulations, with limited computing resources and casual users such as disaster response applications. Prognostic models step forward in time. Most models used for weather forecasts are prognostic.

Diagnostic models fall into three categories according to the amount of physics incorporated. The simplest category models are based only on conservation of mass, termed here mass-consistent models (Geai 1987; Montero *et al.* 1998; Moussiopoulos and Flassak 1986; Ross 1990; Sherman 1978; Stone *et al.* 1984). The second diagnostic group solves a linearized momentum equation (Mason and King 1985; Mortensen *et al.* 1993; Oberheu and Mutch 1975; Walmsley *et al.* 1986). Computation times are similar to the mass-consistent models; but non-linear momentum effects occurring in steep terrain are not handled well (Lopes 2003). The third type of diagnostic model considers conservation of mass and momentum with some form of turbulence closure (Alm and Nygaard 1995; Apsley and Castro 1997; Castro *et al.* 2003; Kim *et al.* 2000; Lopes 2003; Maurizi *et al.* 1998; Raithby and Stubley 1987; Uchida and Ohya 1999; Undheim *et al.* 2006) and even conservation of energy (Montavon 1998). In many of these models a k-epsilon turbulence closure using the RNG variant (Yakhot and Orszag 1986) is used (Jones and Rosenfeld 1972). Simulations using the RNG k-epsilon turbulence model have been shown to handle non-linear flow effects such as recirculation better than mass-consistent models (Lopes 2003). Simulations take from a few minutes to a few hours on personal computers.

Transient, or prognostic models, include equations for the physics relevant to weather prediction such as conservation of mass, momentum, energy, moisture and radiant transfer. Because of the added physics, prognostic model forecasts require significant computing resources, have complex initial and boundary conditions, and require highly trained specialists to run them.

Some of the most widely used prognostic weather models in the United States are the Weather Research and Forecasting (WRF) model, the NCAR/Penn State Mesoscale Model 5 (MM5), and the Global Forecast System (GFS). The US National Centers for Environmental Prediction (NCEP) run operational forecasts down to 12 km resolution. Other non operational models are commonly run down to 4 km resolution. At these resolutions, many important local terrain influenced flow effects cannot be captured (Atkinson 1995; Kim *et al.* 2000).

In an effort to include the physics of prognostic models in the high resolution of simpler diagnostic models a recently developed wind model of type 1 was modified to incorporate output from prognostic models to initialize the flow field in the diagnostic calculation. This model is called WindNinja and is available from the US Forest Service Missoula Fire Science Laboratory.

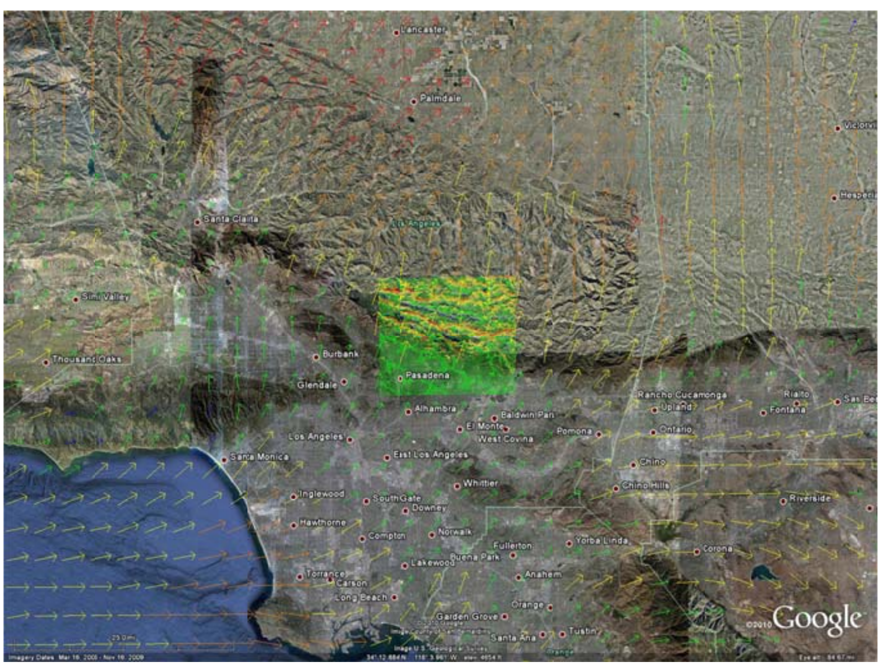

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Fig. 1 presents a WindNinja grid on a broader simulation grid from a prognostic model. The horizontal resolution of the prognostic model is so large that local terrain scale features are not incorporated in the flow.

Fig. 2 presents a zoomed in image of the prognostic model output data grid. As shown, wind direction and speed are shown for relatively large terrain areas. Fig. 3 shows the same region but with the WindNinja output grid imposed. Local terrain features such as drainages, ridges and other terrain features seem to be more accurately presented.

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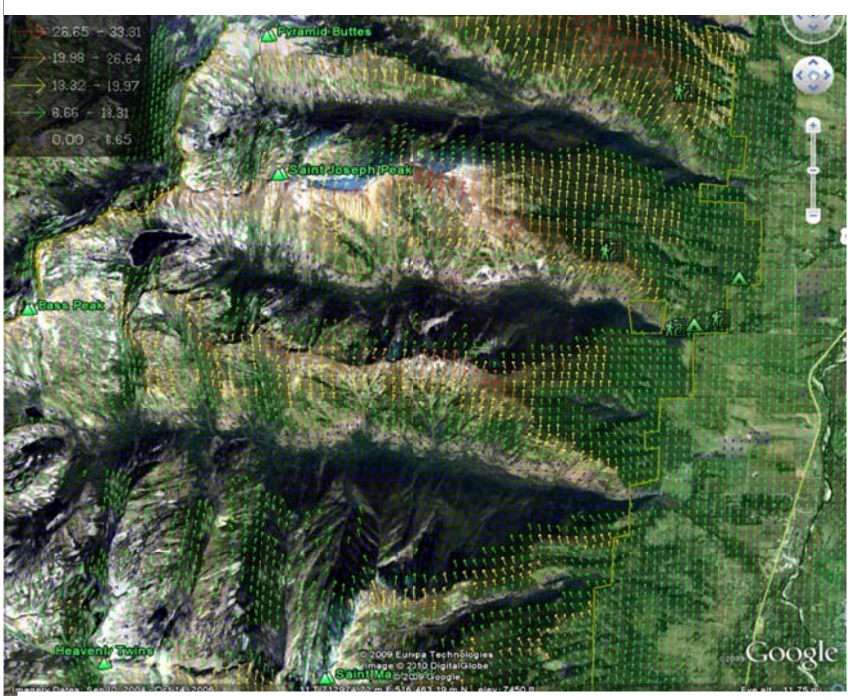

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The process is relatively straight forward. Several coarse scale weather models are run by NOAA National Centers for Environmental Prediction. These models range from 5km surface grids (NDFD) to 80km volume grids. These models can provide data from a point in time out to 3-7 days for a geospatial subset. WindNinja locates the data spatially and retrieves 3 days of data (this can change). WindNinja retrieves: Wind Speed and Direction, Temperature, Cloud Cover, and Geopotential Height if available.

If the coarse scale model is a surface model, such as NDFD, WindNinja initializes the surface with those data and initializes the rest of the volume as it would without coarse scale weather data, using a logarithmic profile. If the prognostic model output is volumetric, WindNinja interpolates those data to the internal volume mesh for the entire domain. Typically, the coarse scale weather model data is every 3-6 hours, 3 hours for the first 2-3 days, then every 6 hours after. WindNinja reads in the forecast, initializes the domain depending on the spatial dimensions, and does a run for each time step in the forecast.

Conclusions

A high resolution surface wind model has been modified to utilize data from a prognostic weather model at relatively coarse scale to initialize the calculation. A version of the model has been run using this option. Work continues on a GUI and final release version for distribution to wildland fire managers. This capability is unique in that it provides a physics based method for downscaling relatively coarse scale prognostic model data to 100-200m resolution. A release of this capability in the WindNinja software tool is expected in early 2011.

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In-situ characterization of wildland fire behavior

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Abstract
A system consisting of two enclosures has been developed to characterize wildand fire behavior: The first enclosure is a sensor/data logger combination that measures and records convective/radiant energy released by the fire. The second is a digital video camera housed in a fire proof enclosure that records visual images of fire behavior. Together this system provides a robust relatively inexpensive, system for characterizing wildland fire behavior.

Additional keywords: Fire behavior, fire documentation, fire instrumentation

Introduction

Computer models that are used for day-to-day fire management are largely empirical (Rothermel 1972); examples include BEHAVE(Andrews 1986), Farsite (Finney 1998). Wildland fire researchers have recognized the benefit of insitu measurements of fire intensity and behavior as one critical component of efforts to develop improved fire decision support models. Actual measurements of fire intensity benefit wildland fire behavior research and modeling by providing data for evaluating and developing fire models. Past measurements consisted primarily of observations of rate of spread, gas temperatures and fuel consumption and have been both field based (Barrows 1951; Cheney *et al.* 1993; Fons 1946) and laboratory based (Catchpole *et al.* 1998; Fons 1946; Rothermel 1972) . Such studies provided useful data and observations; however with the advent of modern numerical computers, the complexity of wildland fire models has increased (Call and Albini 1997; Linn *et al.* 2002; Mell *et al.* 2007). New mathematical models include additional physics which led to the need for additional measurements, particularly of the basic heat and chemical processes occurring in fire. This need has been addressed through both field (Alexander 1990; Hiers *et al.* 2009; Stocks *et al.* 2004) and laboratory experiments (Catchpole *et al.* 1998)

However quantitative measurements of energy and mass transport in wildland fire have been relatively sparse. The reasons are likely related to the risks and hazards to humans and equipment associated with wildland fires as well as the high degree of uncertainty in the weather and fuel conditions. Additionally, only recently has the technology become readily available at a cost that allows scientists to capture the desired measurements over the range of possible conditions. Some studies have been published that focus on relating fire intensity to emissions (Ward and Radke 1993), others on statistical modeling of fire behavior (Stocks *et al.* 1989).

Based on experience from an array of field experiments (Butler *et al.* 2004; Putnam and Butler 2004; Stocks *et al.* 2004) a field deployable, fire resistant, programmable sensor array mounted in a fire resistant enclosure and coupled with a video imaging system has been developed. This system reduces the safety risks to research team members and improves utility and reliability of the instruments. The development of this technology occurred over a significant amount of time involving multiple designs and tests. The sensor system has been coupled with a digital video system. The video system includes a programmable trigger linked to the fire sensors that allows the system to automatically initiate data and video recording when a fire is sensed (Jimenez *et al.* 2007).

In the following paragraphs we describe the system and some of the typical measurements provided by it.

Discussion

Two enclosures comprise the system. The primary sensor package is termed the Fire Behavior Flux Package (FBP). It measures 27 cm by 15 cm by 18 cm and in its current configuration weighs approximately 5.3 kg (fig. 1). Various enclosure materials have been used from mild steel, stainless steel and aluminum, the latest design consists of 3.7mm thick aluminum welded at the seams. A 12 volt 2.2Ah sealed lead acid battery or 8 AA dry cells provide power to the logger. A separate 8 AA dry cell battery array provides power for the flow sensors. Wiring and circuit diagrams can be found at www.firelab.org

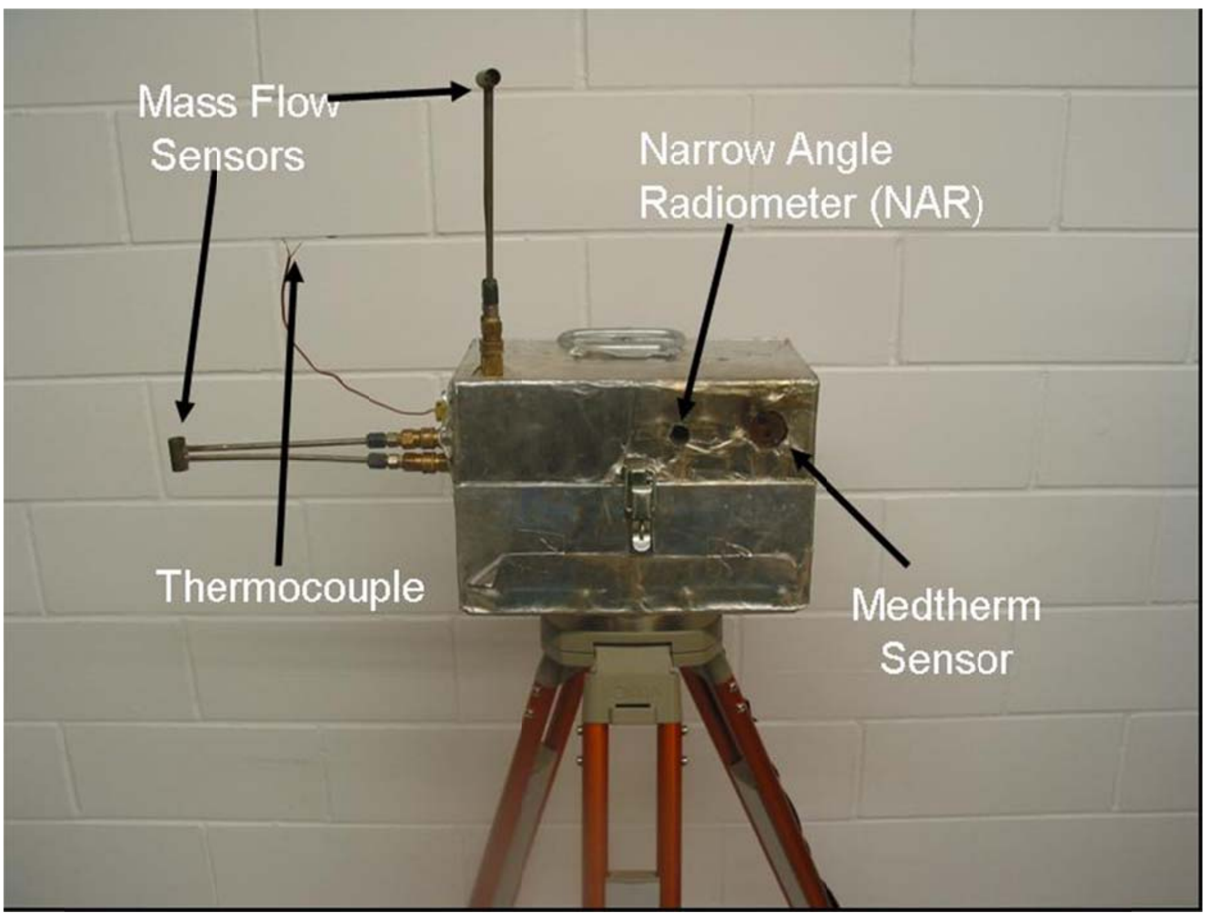

Fig. 1--Photograph of Fire Behavior Package.

The dataloggers used are Campbell Scientific® model CR1000. The dataloggers are capable of logging over one million samples, providing 20 hours of continuous data logging at 1hz. This logger is user-programmable and accepts a wide range of analog and digital inputs and outputs. It is thermally stable and has been relatively insensitive to damage incurred in shipping and handling. Alternative and lower cost dataloggers are available but generally do not have all of the features found in the aforementioned. Currently, all FBP's incorporate a Medtherm® Dual Sensor Heat Flux sensor (Model 64-20T) that provide incident total and radiant energy flux, a type K fine wire thermocouple (nominally 0.13 mm diameter wire) for measuring gas temperature, a custom designed narrow angle radiometer (Butler 1993) to characterize flame emissive power, and two pressure based flow sensors (McCaffrey and Heskestad 1976) to characterize air flow. Table 1 provides details about individual sensors and their engineering specifications.

Table 1. Insitu Fire Behavior Package (FBP) Specifications

Narrow Angle Radiometer	
Sensor	20-40 element thermopile
Spectral Band of Sensor	0.15 – 7.0 µm with sapphire window
Field of View	~4.5º controlled by aperture in sensor housing
Transient Response	Time constant of sensor nominally 30msec
Units of Measurement	Calibrated to provide emissive power of volume in FOV in $kW\text{-}m^{-2}$
Total Energy Sensor	Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer
Sensor	Schmidt-Boelter Thermopile
Spectral Band of Sensor	All incident thermal energy
Field of View	~130º controlled by aperture in sensor housing
Transient Response	< 290msec
Units of Measurement	Total heat flux incident on sensor face in $kW\text{-}m^{-2}$
Hemispherical Radiometer	Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer
Sensor	Schmidt-Boelter Thermopile (Medtherm Inc)
Spectral Band of Sensor	0.15 – 7.0 µm with sapphire window
Field of View	~130º controlled by window aperture
Transient Response	< 290msec
Units of Measurement	Radiant energy incident on sensor face in $kW\text{-}m^{-2}$
Air Temperature	
Sensor	Type K bare wire butt welded thermocouple, new, shiny, connected to 27ga lead wire
Wire Diameter	0.13mm
Bead Diameter	~0.16-0.20mm
Units of Measurement	Degrees Celsius
Air Mass Flow	
Sensor	SDXL005D4 temperature compensated differential pressure sensor
Pressure Range	0-5 in H_2O
Sensor Design	Pressure sensor is coupled to custom designed bidirectional probe with ±60º directional sensitivity.
Units of Measurement	Calibrated to convert dynamic pressure to velocity in $m\text{-}s^{-1}$ assuming incompressible flow
Sensor Housing Dimensions	150× 180 × 270 (mm)
Housing Weight	7.7 kg
Insulation Material	Cotronics Corp® 2.5cm thick ceramic blanket
Tripod Mount	½ inch female NCT fitting permantly mounted to base of enclosure.
Power Requirements	12V DC
Power Supply	Rechargeable Internal Battery
Data Logging	Campbell Scientific Model CR1000
Sampling Frequency	Variable but generally set at 1 Hz
File Format	ASCII

The second part of the system is a fire proof enclosure housing a video camera and is termed the In-situ Video Camera (IVC). The IVC measures 10 cm by 18 cm by 19 cm and is constructed of 1.6 mm aluminum with a weight of approximately 1.8 kg (fig. 2). The front of the IVC has two circular windows nominally 45 and 20 mm in diameter. A double lens configuration of high temperature pyrex glass and a second lens of hot mirror coated glass (Edmund Optics) is mounted in the ports. This multi-layer dielectric coating reflects harmful infrared radiation (heat), while allowing visible light to pass through. The system is designed to be turned on manually or can be set to trigger and record through a wireless link to the FBP data loggers (Jimenez *et al.* 2007). The system allows users to trigger the recording mechanism of the camcorder remotely by using its own unique internal computer source code. Once the FBP and IVC boxes are deployed the trigger system is armed from readily accessible switches in the respective enclosures.

Fig. 2--Insitu Video Camera package.

Both the FBP and IVC are designed to be mounted tripods. The preferred tripods consist of wall galvanized 2.5 cm diameter mild steel pipe with one extendable leg to facilitate deployment on slopes. Once mounted on the tripods a layer of 2.5 cm thick ceramic blanket enclosed in a single layer of fiberglass reinforced aluminum foil is wrapped around the boxes to provide further thermal protection.

Estimated material and construction costs for the FBP enclosures is $500 USD per box plus cost of data loggers, and sensors $700 USD per box plus cost of cameras for the IVC.

Typically each FBP is coupled with an IVC for simultaneous recording of video and in-situ measurements allowing researchers to better evaluate fire behavior measurements relative to flame size and local spread rate.

The packages are typically deployed so that the sensors are directed towards the oncoming fire front. The FBP is oriented to “look” at the expected fire approach direction, while the IVC is positioned to image both the FBP and approaching fire front (fig. 3). Once the FBP and IVC’s are mounted on tripods, they are powered up. The FBP’s have LED’s to indicate that the logger is indeed running, the IVC’s also have an LED to indicate that they are running and have entered “sleep” mode when they are being used with the remote automatic trigger system.

Fig.3--Insitu Video Camera mounted on tripod in wildland fire.

Other data typically recorded include the GPS location of each box, including reference orientation (compass direction), height above the ground, and any other local vegetation, or environment information deemed relevant.

Fig. 4 presents typical heat flux measurements from the total and radiant sensors. The sensors are calibrated to provide total incident energy flux and total radiant incident flux. In theory the convective heat flux at the sensor face would be the difference between the two sensors. The flux on the sensor face may not necessarily represent that incident on a nearby vegetation component. Surface incident energy flux is highly dependent on the properties of the surface itself. The sensors come from the factory calibrated against a high temperature source that emits the bulk of its energy in the near infrared. This source does not represent the spectral energy source produced by a typical wildland fire. The thermal transmission of the window on the radiometer has specific spectral properties. Thus the energy transmitted to the sensor in the calibration environment is not the same as that transmitted in the fire environment. Without additional calibration using a spectrally broad source, all that can be deduced from the radiometer data is that they represent the energy that would be incident on the face of the sensor

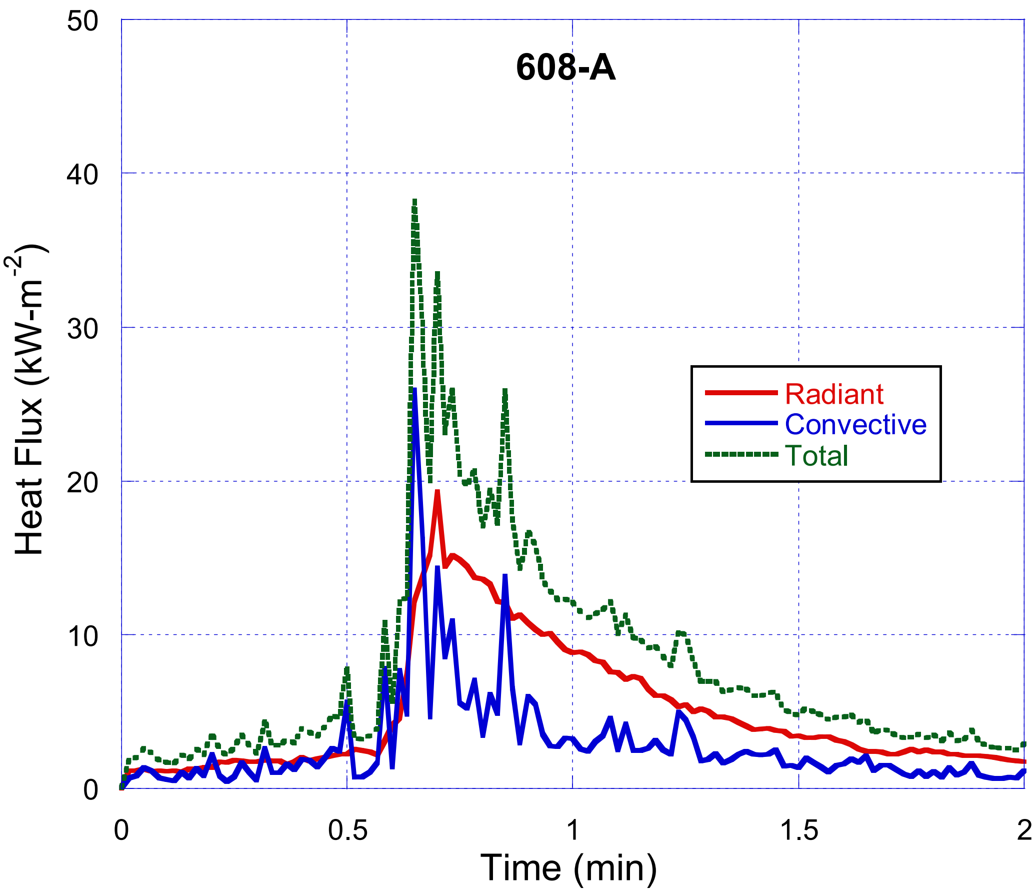

Fig. 4—Heat flux data from the FBP system.

if the source were similar to the calibration source. It is recommended that the radiometers be calibrated using a blackbody source over the expected range of energy flux to minimize error due to the spectral differences between the manufacturer calibration and that of a typical wildland fire source. However, ultimately, unless one uses a correction term determined from a known source (Frankman *et al.* 2010), uncertainty exists in the radiation measurement.

Type K fine wire thermocouples are used to measure air temperature (fig. 5). The use of new (shiny therefore low emissivity), small diameter (reduces radiant energy absorption), thermocouples can decrease measurement uncertainty (Ballantyne and Moss 1977; Satymurthy *et al.* 1979; Shaddix 1998). It is estimated that the measurements collected insitu using the 0.13mm diameter thermocouples specified above are subject to a measurement uncertainty of nominally ±50K but measurement uncertainty can be much larger depending on the temperature of the gas, the surroundings and the radiative properties of the local environment. For small or thin flames the uncertainty can be hundreds of degrees depending on the condition and size of the thermocouple (Pitts *et al.* 1999).

Fig. 5 presents typical flow measurements using differential pressure sensors (McCaffrey and Heskestad 1976). These sensors have been used extensively in laboratory experiments to characterize the flow field in and around flames generated by woody fuels (Anderson *et al.*

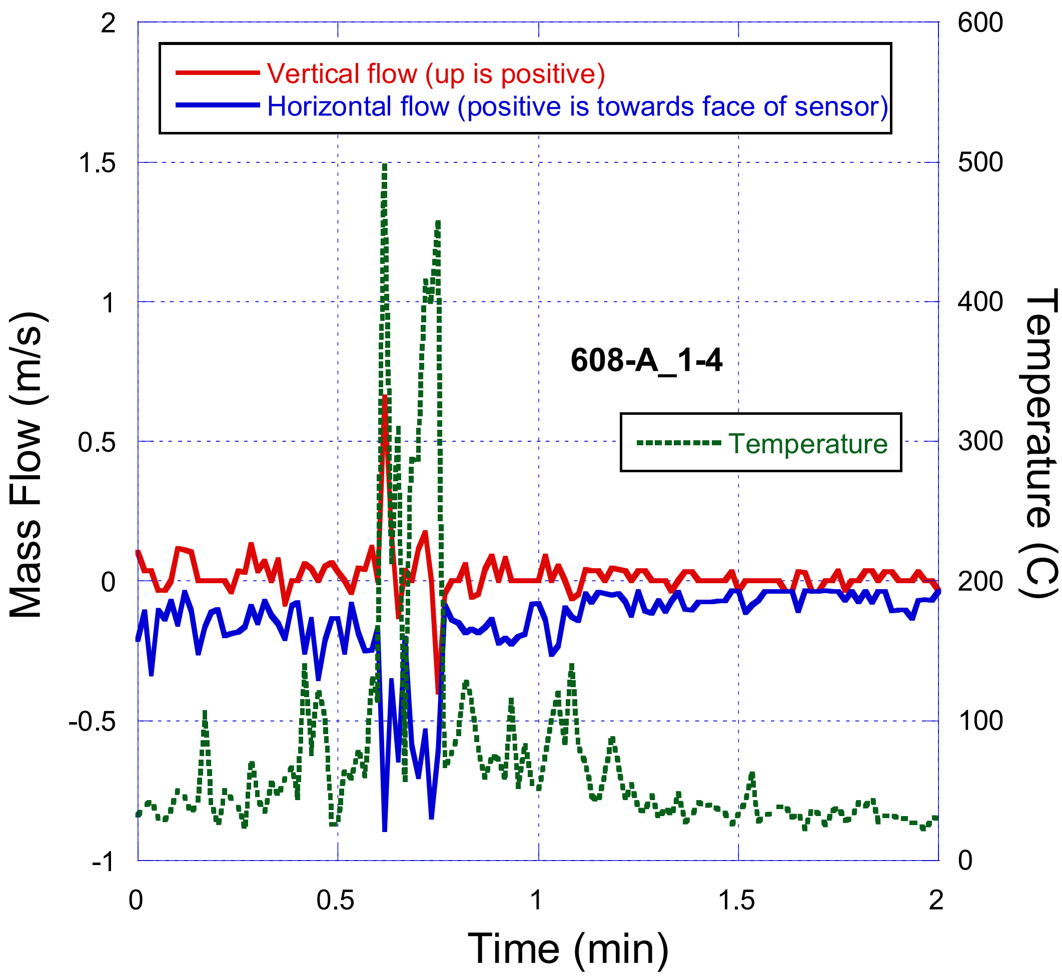

Fig. 5—Flow and temperature data from the FBP system.

2010). They are designed to capture the general horizontal or vertical flow given a nominally ±30 degree acceptance angle. The sensors are calibrated by comparison to a known sensor in a controlled flow. Because these sensors are based on pressure differences between the dynamic and static ports they are sensitive to changes in gas density as would occur due to temperature variations. Therefore the flow measurements require an air temperature measurement for determination of density. Additionally no correction is made for changes in the relative humidity of the air flow. Given the uncertainty associated with the air temperature measurement, it is estimated that the flow measurement uncertainty is approximately ±30% and may be larger.

In practice these measurement systems should be deployed with careful measurements of pre and post fire vegetation consumption. One of the challenges associated with characterizing physical processes in fire is the spatial heterogeneity introduced by variations in vegetation, terrain and weather. The sensors described here sense energy and mass transport at a very small scale relative to that of wildland fires. Consequently, another challenge is how to interpret data from these systems over the broad spatial scales characteristic of wildland fire. One approach is to deploy enough sensors to collect a statistically representative distribution. Alternatively, ground based sensors can be used to evaluate and correct remotely sensed data that represent spatial scales. Measurement success depends on a number of factors, including equipment reliability and weather. The automatic trigger option has increased the success of research efforts to quantify fire behavior; however, even in ideal conditions a realistic success rate of 50-80% is likely.

Conclusions

The FBP and IVC from a relatively low cost, light weight, ruggedized, portable, and programmable sensor system designed to provide measurements of energy and mass transport in wildland fires. The designs are flexible and can be adapted to fit other sensors and data loggers. When a fire is sensed, the fire behavior sensor package begins logging data and sends a wireless signal to activate the video package. This system can be constructed from readily available materials using basic tools and techniques. It seems that the use of sensors like those described here is the only practical solution to gathering quantitative information about energy and mass transport in wildland fires, at least in the near term.

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Validation of smoke plume rise models using ground based lidar

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Abstract
Biomass fires can significantly degrade regional air quality. Plume rise height is one of the critical factors determining the impact of fire emissions on air quality. Plume rise models are used to prescribe the vertical distribution of fire emissions which are critical input for smoke dispersion and air quality models. The poor state of model evaluation is due in large part to a lack of appropriate observational datasets. We have initiated a research project to address this critical observation gap. A ground-based, mobile elastic scanning lidar (**li**ght **d**etection **a**nd **r**anging) instrument and data-processing methodology have been developed at the Missoula Fire Science Laboratory to study the three-dimensional plume dynamics and the optical properties of smoke particles over large prescribed fires and wildfires. The lidar measurements are being used to validate several plume rise models, including the Briggs equations which are used in VSMOKE and other smoke management tools. We present the validation results and provide recommendations regarding application of the models to wildland fire.

Introduction
Tightening standards governing air quality have increased the pressure on land management agencies to address the air quality impact of wildland fire use and prescribed burning. Land management agencies need rigorously tested, accurate models to quantify the contribution of fire emissions to air pollution and visibility impairment.

Accurately describing and predicting smoke plumes and subsequent smoke transport is a major uncertainty in determining the impact of fire emissions on air quality. While many smoke plume models exist, few smoke plume observational datasets are available to properly validate these models and quantitatively assess their uncertainties, biases, and application limits.

We have initiated a research project to acquire the data needed for evaluation of plume rise and smoke dispersion models. The project deploys a ground based, mobile lidar and an airborne instrument package to investigate smoke plume dynamics, smoke aerosol distribution and chemical composition in and around active wildfires and large prescribed fires. Multiple wildland fires have been investigated over a two year period to measure plume rise and smoke transport over a wide range of meteorological, fire activity, fuel, and terrain conditions.

We have developed a new lidar data processing technique based on the concept of the Atmospheric Heterogeneity Height Indicator (AHHI) that enables the automatic determination of plume heights and the processing of large volumes of data (Kovalev *et al.* 2010).

Instrumentation
Lidar
Lidar measurements were made using a mobile, Q switched Nd:YAG scanning elastic lidar operating at wavelengths 1064 nm and 355 nm with 98 mJ and 45 mJ energy, respectively. The receiver section of the lidar consists of a 10 in. UV enhanced Schmidt-Cassegrain telescope with two detectors – a cooled, IR enhanced, avalanche photodiode for detection of the 1064 nm signal

and a photomultiplier tube for detection of the 355 nm signal. The lidar scan range is 0° - 180° in azimuth and 0° - 90° in elevation.

Aircraft
The Forest Service Region 1 Cessna 206 was equipped with a Radiance Research M903 single wavelength nephelometer, a LICOR LI-6262 CO2/H2O analyzer and a grab bag system for gas collection and later Gas Chromatograph analysis. Mass concentration of the particles with an aerodynamic diameter < 2.5 micron (an EPA criteria pollutant, PM2.5), is derived from the nephelometer scattering results using the calibration equation $C_{PM2.5} = 0.2148\ (\pm 0.0092)\ \mu g\ m^{-2}$ x $B_{scat}\ m^{-1}$. The calibration was derived by sampling smoke in the lab and then correlating the integrated scattering of the nephelometer with the particulate weights collected on co-located filter samples.

Lidar data processing

The normalized intercept function
In principle, lidar can easily detect the boundary between different atmospheric layers and discriminate the regions of smoke and clear atmosphere. However, the identification of the exact boundary location of smoke layers and plumes where the dispersion processes create a continuous transition zone between the heterogeneous areas and clear air presents a significant challenge. The smoke plume density, its concentrations, the level of heterogeneity and the smoke dispersion are extremely variable and depend heavily on the distance of the smoke plume from the fire source.

The absence of unique criteria for determining the boundary between the smoke plume and clear-air areas when it is poorly defined is the principal issue of any range-resolved remote sensing technique. No standard definition of such a boundary exists. When determining the boundary, the most common approach is to use some relative, rather than absolute characteristic. For example, one can select the boundary location as the area where the examined parameter of the interest, e.g., the square-range-corrected lidar signal, decreases from a maximum value down to a fixed, user-defined level. However, there is no way to establish a standard value for this level which would be acceptable for all cases.

An improved data processing methodology has been developed for the use of vertical lidar scans in areas of smoke plumes for extracting information about the plume heights and their spatial and temporal changes. The initial transformation of the lidar signal is as follows.

The recorded lidar signal, $P_\Sigma(r)$ is the sum of the range-dependent backscatter signal, $P(r)$ at the range r and the range-independent offset, B, the background component of the lidar signal and the electronic offset,

$$P_\Sigma(r) = P(r) + B\,. \qquad (1)$$

This signal is transformed in the auxiliary function $Y(x)$, defined as,

$$Y(x) = P_\Sigma(x)x = [P(x) + B]x\,, \qquad (2)$$

where $x = r^2$ is the new independent variable. The sliding derivative of this function, dY/dx, is calculated and the intercept point of each local slope fit of the function with the vertical axis is found and normalized. The intercept function versus x is found as,

$$Y_0(x) = Y(x) - \frac{dY}{dx}x\,. \tag{3}$$

The retrieval technique that is used here for processing the measurement data of both scanning and one-directional lidar is based on determining the so-called normalized intercept function (Kovalev *et al.* 2009). The normalized intercept function is defined as,

$$Y_{0,norm}(x) = \frac{Y_0(x)}{x + \Delta}\,, \tag{4}$$

where Δ is a user-defined positive non-zero constant whose value can range from 0.02 - 0.05 of the maximum value of the variable x over the selected range.

For the scanning lidar, the absolute value of the normalized function under the slope direction φ is calculated as a function of height, $h = r \sin \varphi$, giving

$$.\ (h,\varphi) = \ Y_{,} \qquad (h,\varphi)\ . \tag{5}$$

Determining the maximal height of a smoke plume using the AHHI

The concept of the Atmospheric Heterogeneity Height Indicator (AHHI), used in this measurement methodology, has been introduced in the study by Kovalev *et al.* (2009). The AHHI is a histogram showing the number of heterogeneity events determined for consecutive height intervals. It defines the heights where the heterogeneity events were fixed and the number of events observed at those heights. The AHHI enables large volumes of lidar data to be analyzed providing an accurate time series profile of smoke-plume heights.

Fig. 1 shows graphically the principal behind the AHHI. The basic principal behind this new lidar-data processing method is the same as for any other method used to determine atmospheric heterogeneity - to identify ranges where increased gradients in the backscatter signal exist. This new method, though, does not require initial separation of the background component, B, in the recorded lidar signal [Eq. (1)]. In order to determine smoke layer and plume heights and to monitor their changes over time, the lidar signal transformation described in Kovalev *et al.* (2010) is utilized.

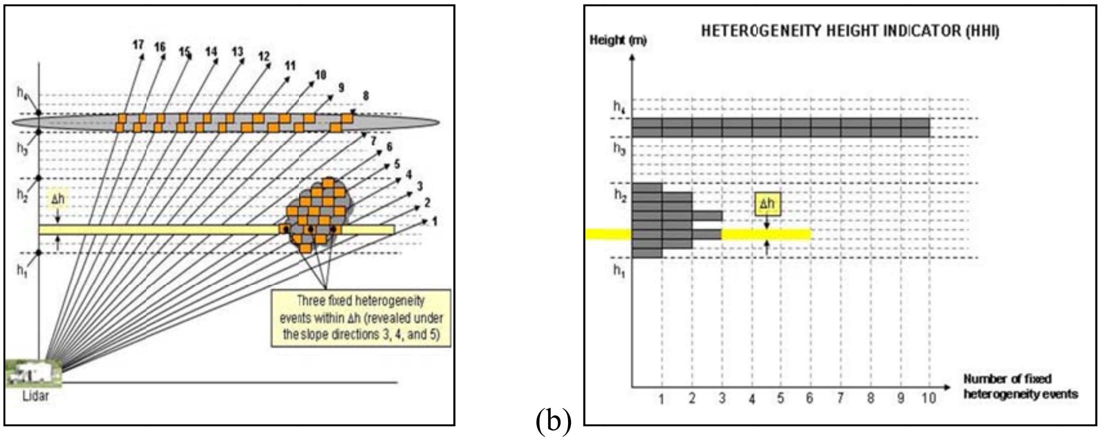

Fig. 1. (a) Principle of determining the locations with increased backscatter gradient in the atmospheric lidar signals. The thin lines show the scanned slope directions, and the filled rectangles are the areas with increased backscatter. (b)The Atmospheric Heterogeneity Height Indicator (AHHI), a histogram which shows a number of heterogeneity events defined by scanning lidar at the consecutive height intervals.

Using Eq. (5), the function $F_i(h, \varphi)$ is determined for each slope direction φ and the maximum function, F_{max}, for the above set of functions is found. The local heterogeneity event is considered as being true at the locations where the function $F_i(h, \varphi)$ reaches some user established threshold, χ, relative to F_{max} (Kovalev *et al.* 2009). Using such a histogram, one can determine the location and the maximal height of the region with the increased heterogeneity that corresponds to the selected χ. The smoke-plume maximum height is defined as the height where the plume presence can be discriminated from noise in the lidar data. In the example of the experimental data presented in Fig. 2, the AHHI identifies the maximal height of the plume at 2700 m.

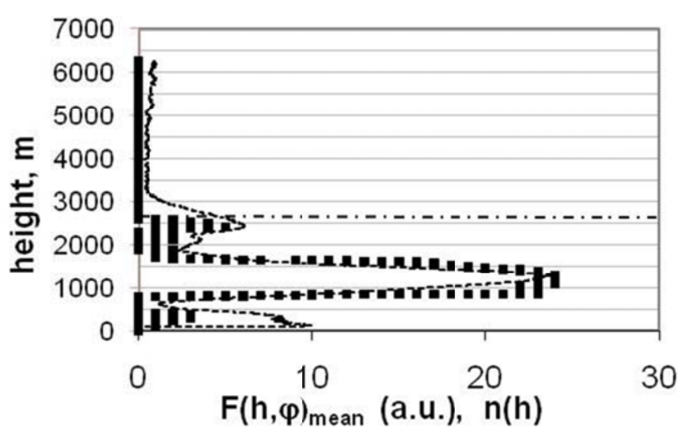

Fig. 2. Plot of the AHHI (the filled squares) overlaid with the mean normalized intercept function (the dotted curve) showing three regions of polluted air from ground level to 3000 m, a region of polluted air from ground level to 700 m and regions of smoke from 700 m to 1900 m and from 2000 m to 3000 m. The AHHI identifies the height of the upper boundary of the smoke plume at 2700 m, indicated by the horizontal dashed line.

Plume rise models

Seven plume rise models comprising three categories are investigated, two Briggs equation based models, three empirical models and a one dimensional time dependent entrainment model.

FEPS (Anderson et al., 2004) and VSMOKE (Lavdas 1996) use modified Briggs equation based plume rise models. These computer programs use atmospheric stability and buoyancy flux values to choose between multiple built in models. Because the atmosphere stability was neutral to unstable on August 27, 2009 and the buoyancy flux was greater than 51.602, the Briggs equation used by FEPS and VSMOKE to determine plume rise on that day is,

$$H = \frac{38.7F^{3/5}}{W} \tag{6}$$

where H is the plume rise in meters, F is the buoyancy flux and W is the transport wind velocity in ms^{-1} (Anderson *et al.* 2004; Lavdas 1996).

FEPS and the Harrison and Hardy models (H_H 1992 and H_H 2002) use empirical plume rise models based on inputs of fire energy release rate (Harrison and Hardy 1992; Hardy 2010). FEPS uses fuel consumption rate as a surrogate for energy release rate while the fire energy release rate is directly input into the Harrison and Hardy models. FEPS determines the minimum and maximum plume rise in meters using the empirical models,

$$H_{min} = 4000 - \left[\frac{4000}{e^1}\, e^{\left(1-\frac{A}{400}\right)}\right] \tag{7}$$

$$H_{max} = 8000 - \left[\frac{8000}{e^1}\quad {}^{\left(1-\frac{A}{400}\right)}\right] \tag{8}$$

where A is the fuel consumption rate in acres per hour. The Harrison and Hardy empirical models give the maximum plume rise in km using,

$$H = 1.54\sqrt{Q} - 0.276 \tag{9}$$

$$H = 1403Q^{\cdot} \tag{10}$$

where Q is the fire heat release in GigaWatts.

PLUMP is a one-dimensional, time-dependent, entrainment model that neglects the effects of wind and uses input soundings of pressure, temperature and dew point along with either fuel loading or energy release rate to predict plume rise (Latham 1994).

Kootenai Creek case study

We investigated the smoke plume characteristics of the Kootenai Creek Fire in the Bitterroot Valley, Montana, USA over several days during July and August of 2009. Between mid-July and early September, the fire burned 2,000 ha of conifer forest.

Fig. 3 shows the schematic of the method used to obtain lidar transects of the plume. For the Kootenai Creek study the lidar vertical scan corresponding to 130° azimuth is used for comparison with the modeled plume rise. The 130° azimuth scan transects the plume approximately 12 km from the fire and 2 km downwind of where the aircraft sampled the plume.

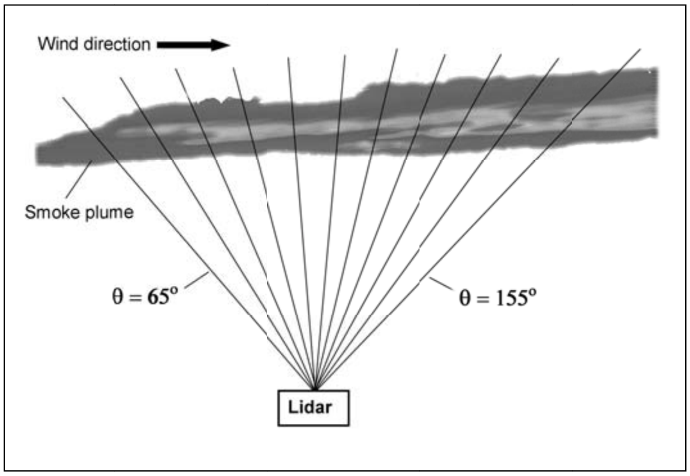

Fig. 3. Schematic of data collection with the vertically scanning lidar during the Kootenai Creek fire in Montana during July and August 2009. The thin lines show the scanned azimuthal directions. (The sector 45° - 65°, which overlaps the wildfire site, is not shown).

Fig. 4 shows a time series of smoke plume profiles obtained from the Kootenai Creek Fire on August 27, 2009 between the hours of 14:30 and 17:00. These profiles were constructed from vertical lidar scans taken of the smoke plume at the lidar's 130° azimuth and show relative smoke-concentration variations. Overlaid on the smoke plume profiles are the AHHI histograms and the AHHI determined plume height.

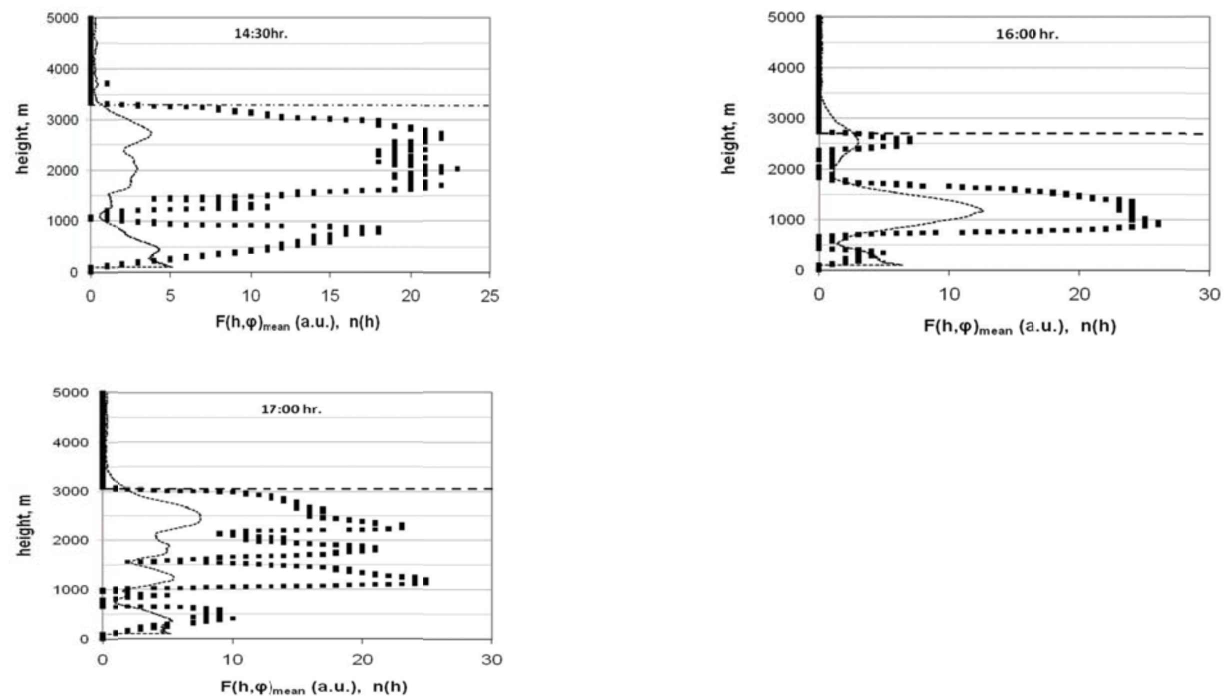

Fig. 4. Lidar vertical scan time series showing the mean normalized intercept function (thin sold line) of the smoke plume overlaid with the AHHI histogram (the filled squares). The horizontal dashed line indicates the AHHI determined smoke plume height.

Fig. 5 and 6 show aerosol (PM2.5) mass concentrations measured during aircraft penetrations of the smoke plume approximately 10 km downwind of the active fire at approximately 16:00 on August 27, 2009. Fig. 5 shows a vertical profile of the aerosol mass concentration when the aircraft made a spiraling decent into the downwind plume. The upper smoke plume boundary can be clearly seen at ≈2790 m AGL.

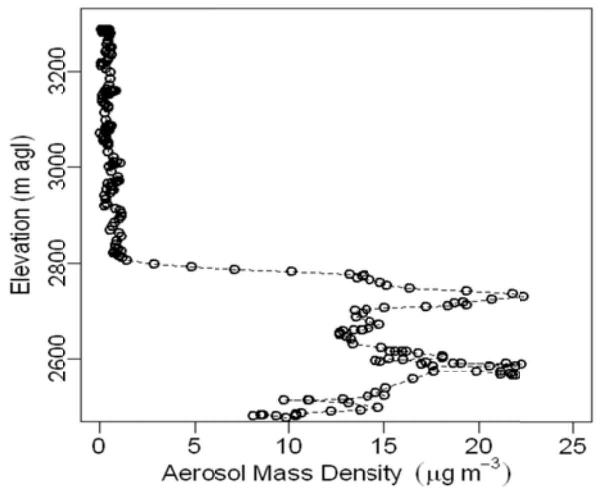

Fig. 5. Vertical profile of aerosol mass concentration measured ≈10 km downwind of the Kootenai Creek Fire. The vertical profile identifies the top of the smoke plume located ≈2790 m AGL.

Comparing the Fig. 4, 16:00 lidar vertical scan with the vertical profile in Fig. 5, the AHHI determined plume height agrees well with the aircraft measured plume height at 2790 m. Fig. 6 shows the aerosol mass concentration of the plume at 1900 m AGL and 2500 m AGL, measured when the aircraft flew two transects of the plume approximately 30 km in length and perpendicular to the transport wind direction. Comparing the Fig. 4, 16:00 lidar vertical scan

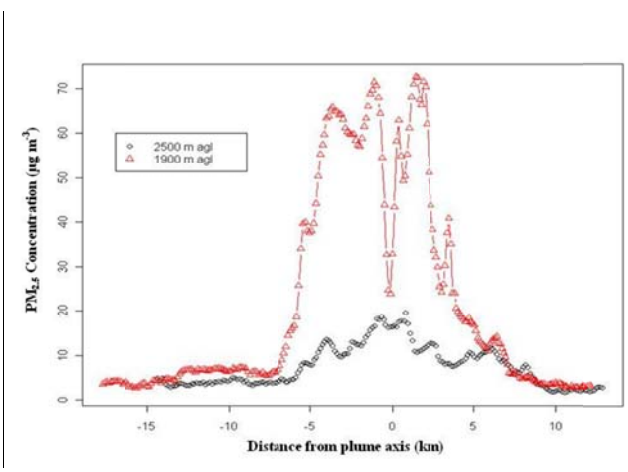

Fig. 6. Airborne measurements of aerosol concentration downwind of the Kootenai Creek fire on august 27, 2009. The aircraft flight path consisted of two 30 km segments, oriented perpendicular to the transport winds (i.e. the direction of the plume's flow and located ≈10 km downwind of the active fire.

with the Fig. 6 aircraft horizontal transects, the lidar backscatter profile tracks the corresponding aerosol mass concentrations measured by the airborne instruments.

Fig. 7 compares the plume rise models' predicted plume heights with the lidar measured heights at the Kootenai Creek Fire during the period from 12:30 to 17:00 on August 27, 2009. In all cases the plume rise models underreported the plume height determined by the AHHI algorithm.

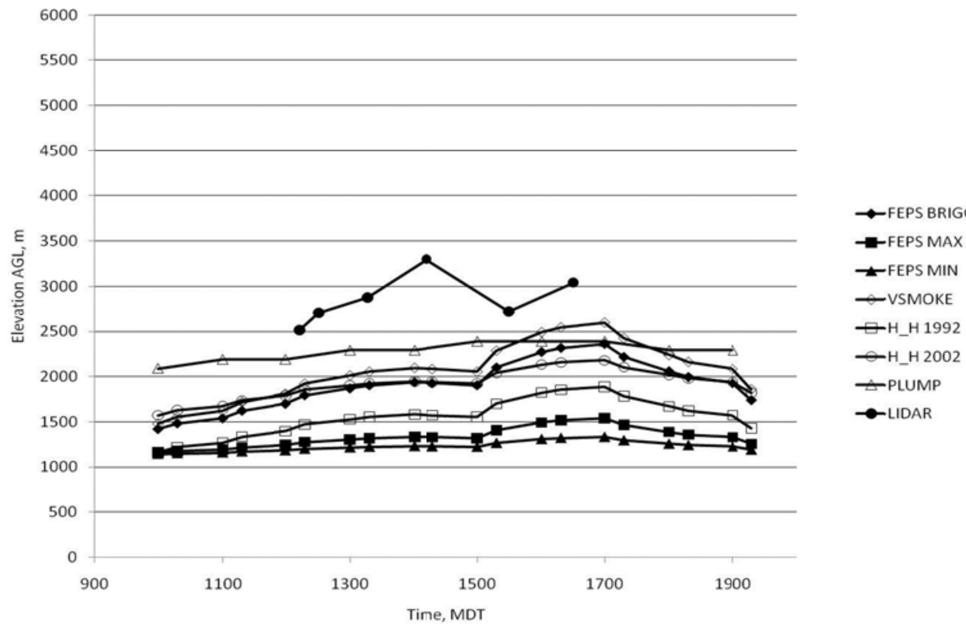

Fig. 7. Comparison of modeled smoke plume heights with heights determined by the lidar AHHI algorithm at the Kootenai Creek Fire on August 27, 2009.

The Briggs equation based models produced similar plume height predictions with the maximum difference of 239 m occurring at 17:00; the variations in the predictions of the two models is due to the manner in which they handle the transport winds, the transport winds on August 27, 2009 were approximately 4 ms^{-1} and this is the value used by the VSMOKE model, FEPS sets the transport wind minimum at 5 ms^{-1} and used that value, consequently the plume rise prediction of FEPS is lower than that of VSMOKE.

The maximum difference between the empirical plume rise models was 847 m and occurred at 17:00. The H_H 2002 model most closely agreed with the Briggs based models, underreporting the VSMOKE model by 420 m at 17:00.

In general, the PLUMP model performed better than the other models.

Comparison of the plume profiles in Fig. 4 with the predicted plume heights shown in Fig. 7 indicates that, although the predicted plume heights underreport the maximum smoke plume boundaries measured by the lidar, the predicted plume heights lie at approximately the same height as the lidar maximum backscatter and at presumably the maximum particulate concentrations in the plume.

Summary

To acquire the data needed for evaluation of plume rise and smoke dispersion models, a research project has been initiated. The project deploys a ground based, mobile lidar and an airborne instrument package to investigate smoke plume dynamics, aerosol distribution, and chemical composition in smoke-polluted atmospheres.

The new lidar AHHI algorithm was developed, which successfully detects the maximal smoke plume boundary and automates the process of smoke plume boundary detection, enabling the ready processing of large volumes of data from many prescribed and wild fires.

The AHHI algorithm and the airborne instruments agree on the maximal smoke plume height of the Kootenai Creek Fire at 16:00 on August 27, 2009. The lidar measured smoke plume profiles are in good agreement with the profiles of the PM2.5 concentrations measured by the airborne instruments.

All plume rise models investigated underreported the AHHI determined smoke plume height for the Kootenai Creek Fire on August 27, 2009. The PLUMP model predicted heights were generally closer to the AHHI determined heights than all other models. FEPS and VSMOKE use Briggs equation based models and predicted heights close to those of the PLUMP model. FEPS and VSMOKE compared closely with each other, the difference resulting from the manner in which the two programs deal with transport wind, FEPS having a set minimum wind speed while VSMOKE does not. The H_H 2002 empirical model performed as well as the FEPS Briggs equation based model, all of the empirical models significantly underreported the measured maximum plume height.

While the plume rise models underreported the AHHI determined maximal smoke plume height, their predicted heights appear to correlate with the maximum particulate concentration heights detected by the lidar and measured by the airborne instruments.

Acknowledgements

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Climate change and fire regimes in the Sierra de Manantlán, México

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Abstract
Fire has been attributed as one of the most influential factors in vegetation community and succession in the Sierra de Manantlán Biosphere Reserve in Jalisco and Colima, México. A mosaic of low, mixed and high severity fire regimes characterizes the landscape with ecosystems ranging from mesophyllous mountain forest to higher elevation pine and oak forest. Research needs to be done to ascertain the fire regime(s) and historical range of variability in the biosphere reserve in order to facilitate scientifically informed land and fire management plans.

Additional keywords: Fire regimes, historical range of variability, pine, oak,

Introduction

Since 1987, the Sierra de Manantlán in Jalisco and Colima, México, has been a UNESCO MAB Biosphere Reserve. Located in the northwestern region of the Sierra Madre del Sur (Fig. 1) and running along the Pacific Coast, the reserve contains the largest area of protected tropical dry forest in México and the largest protected area of mesophyllous mountain forest (cloud forest) on México's Pacific slope (Cuevas-Guzmán *et al*. 1994). Vegetation within its 139,600 hectares ranges from tropical dry and subdeciduous forest to oak, pine, fir and mixed forest types and supports one of the highest levels of biodiversity in the world with 3,460 plant and animal species (Jardel *et al.* 2003). *Zea diploperennis*, a rare wild maize of significant cultural and scientific importance, grows in the reserve and requires a frequent, low-severity fire regime to maintain open pine-oak stands (Jardel *et al*. 2004). *Selasphorus rufus* (rufus hummingbird), an important migratory bird to México, the United States and Canada, also relies on these open areas of the reserve for its wintering ground. However, many species, such as the threatened jaguar, rely on the dense cloud forest that is susceptible to complete destruction in high-severity fires (Jardel, *et al.* 2004). Fire is common in the biosphere reserve and has been attributed as one of the most influential factors in vegetation communities and succession. Ignitions are primarily from agricultural burning and other anthropogenic sources, although lightning is responsible for a small percentage. Preliminary studies put the mean fire return interval between 5 and 14 years, and the fire regimes over the landscape range from frequent (<25 years) low severity surface fires to infrequent (50-100 years) stand replacing fires (Jardel *et al.* 2003).

Fig. 1. Location of the Sierra de Manantlán biosphere reserve. From Jardel *et al*. (2003).

Climate change has the potential to have a severe effect on the ecosystem's function by decreasing soil and foliar moisture, increasing fuels and flammability and increasing mortality of flora and fauna by fire. Results may be loss of habitat and biodiversity, additional releases of carbon into the atmosphere and reduced absorption of greenhouse gases. In addition, the reserve protects the upper portions of three watersheds that provide critical water supplies to over 400,000 people (Jardel *et al.* 2004). Within the reserve are several thousand indigenous inhabitants who participate in decisions about management related to their communal and ejido lands and are directly impacted by wildfire and ecosystem alterations. Fire regimes in México and the reserve are not well understood, and research is needed before scientifically informed management plans can be designed to adaptively protect the area in the face of climate change while providing quality of life for a historically marginalized community. While ecological effects of fire regimes have been studied in the reserve, there has been no research to establish the historical range of variability of fire regimes, the impact of climate change on the historical range of variability or to examine adaptive management plans.

Objectives

To determine the historical range of variability (HRV) in the Sierra de Manantlán, to ascertain the effects of climate change on fire regimes and to propose strategies to return the landscape to a trajectory compatible for purposes of ecological conservation, protection of biodiversity and preservation of cultural integrity.

Hypotheses

1. The historical range of variation of fire regime prior to 1987 was statistically different from the present range of variation of fire regime.
2. The main contributing factors to changes in fire regime in the Sierra de Manantlán biosphere reserve, México, are climate, fire suppression (fuels accumulation) and timing of anthropogenic burning.
3. Dendrochronological records will show that increases in wildfire occurrence and severity correspond with years of higher temperature and lower precipitation.

Methods

We collected 120 cores during the first field season and the process of mounting, sanding and analyzing those samples to create a master chronology for crossdating tree rings is underway. We also GPS-located fire-scarred trees, snags and stumps. In the second field season we will sample live and dead trees with fire scars in order to crossdate years with fire. We will conduct a rigorous forest inventory of vegetation, fuels and age-structure using the standards in the U.S. Forest Service's Fuels Characteristics Classification System (FCCS) Field Sampling Guide. This will allow accurate prediction of fire behavior and the ability to use the Forest Service's FCCS software to design potential silvicultural treatments to reduce fire hazard. We will analyze climate data using superposed epoch analysis to determine whether the master chronology patterns are correlated with climate, and if so, we will be able to project future fire behavior based on existing climate projections using statistical time-to-event analysis. We will collaborate with research scientists and students from the University of Guadalajara, the reserve managers, and members of the ejidos and indigenous communities to author proposed restoration and land-use management plans.

Reconstruction of the historical range of variability of fire regimes will be the basis for developing the land and fire management plans. This will include recommendations for fire management on a landscape scale with reintroduction of fire by the use of prescribed fire in some areas, fire exclusion in others, silvicultural treatments (thinning, pruning, scattering and removal of fuels) to accelerate a return to a resilient forest with a fire regime within the historical range of variability.

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Effects of landscape-level fuel treatments on carbon emissions and storage over a 50 yr time cycle

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Abstract
We investigated how multiple fuel treatment types, organized in varying spatial arrangements, and at increasing proportions of a mixed-conifer forest in the Klamath Mountains of northern California (~20,000 ha) variably affect carbon sequestration and emissions over a 50 year time period. Preliminary analysis of three fuel treatment scenarios (fire only, mechanical only, and fire + mechanical) and an untreated landscape indicates that treating large areas with prescribed fire may increase carbon emissions in the short term but may be off-set by an increase in long term carbon storage.

Introduction

Fuel reduction projects are a common and proven means for protecting wildland-urban interface (WUI) communities and forest resources in the western US (Stratton 2004; Murphy 2007; Schmidt *et al*. 2008). However, removing vegetation from a landscape to reduce fire danger poses a possible conflict: vegetation stores close to half of the carbon on a landscape (Boerner 2008). By removing vegetation, fuel treatments can alter carbon sequestration and emissions at a given location (Dicus 2009, Dicus *et al*. 2009), a topic of growing concern in the fire management community.

The Eddy Gulch Late Successional Reserve (LSR) on the Salmon River and Scott River Ranger Districts of Klamath National Forest, in northwest California, is a large landscape consisting of mixed-conifer forests that provides potential habitat for spotted owls and borders multiple WUI communities. Like many regions in the western U.S. with understory and mixed-severity fire regimes, fire exclusion in the LSR have resulted in an increase in surface and canopy fuel loading and continuity, increasing fire danger to local communities and critical habitat. Increased fire danger is the impetus for many landscape level fuel reduction programs (Keane *et al*. 2002; Stephens and Ruth, 2005). The Forest Service has proposed such a fuel treatment project for the LSR, providing a location to test how landscape level fuel treatment alternatives influence potential carbon emissions from wildfires and carbon storage over a long term cycle. This manuscript provides preliminary results for how three alternative fuel treatment strategies impact these aspects of the LSR.

Study Site and Methods

The study site is the Eddy Gulch LSR of the Klamath National Forest in northwest California (123 4.72 W 41 1554 N). Vegetation consists largely of a multi-layered, multi-aged forest dominated by Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) in association with Pacific madrone (Arbutus *menziesii*), white fir (Abies concolor), and others.

Initial landscape vegetation data came from the forest inventory and analysis data for the Klamath National Forest. This initial vegetation was altered to represent three fuel treatment alternatives (Fig. 1) using the Forest Vegetation Simulator (FVS) within the ArcFuels (Ager *et al* 2010) workstation for ArcMap v. 9.3 (ESRI 2009). Alternative-1 is the complete treatment design proposed by the Forest Service for the Eddy Gulch LSR: it includes fuel reduction zones (FRZ's) that utilize mechanical treatments and prescribed fire, prescribed fire units, and mechanical treatments. Alternative-2 includes only areas designated for FRZ and mechanical treatments. Alternative-3 includes the portion of the initial design designated for prescribed fire.

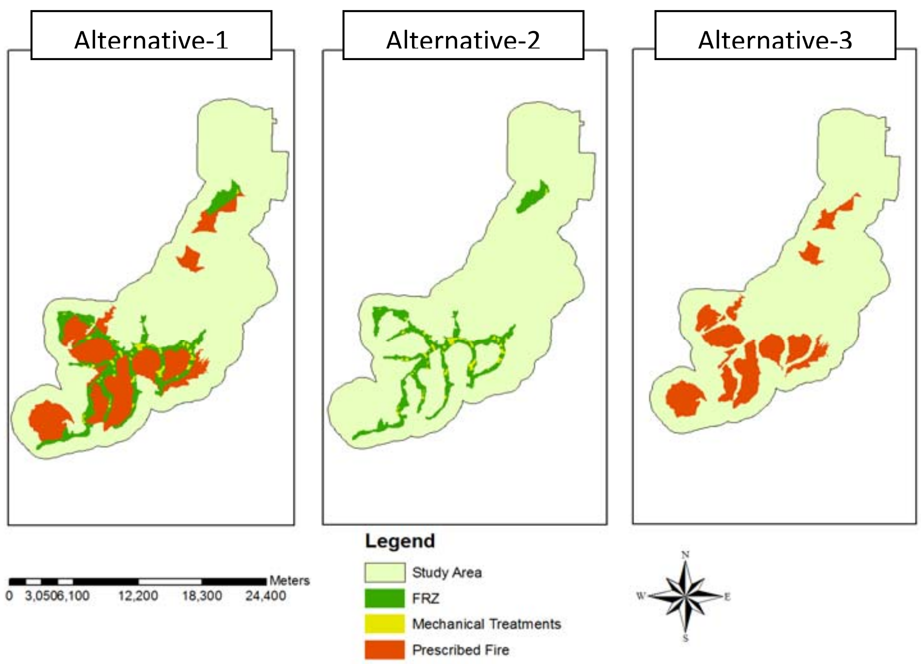

Fig. 1. Treatment alternatives within the Eddy Gulch LSR.

Each alternative was subsequently modeled for 50 years using the Fire and Fuels extension (FFE) within FVS (Reinhardt and Crookston 2003). Included in each FVS-FFE scenario was a wildfire simulated across the entire study area using 97th percentile weather conditions, 5 years after treatment implementation. An untreated landscape was also modeled for 50 years in FVS-FFE with the wildfire in year 5 for comparison to the treatment alternatives. The wildfire simulations provided potential carbon emissions for the entire landscape, not the potential spread or size of a wildfire as it moved across the study area. This is because FVS is non-spatial and fire behavior in any given stand is not influenced by the fire behavior in adjacent stands. In order to maintain consistency across all alternatives the wildfire was assumed to burn across the entire landscape, representing a worst case scenario for carbon emissions.

At the end of the 50 year cycle FVS-FFE generated a carbon report for each alternative and the untreated landscape. The carbon report contained yearly tons/acre values for emissions from fire (prescribed fire and wildfire) in years where fire occurred (year 1 for prescribed fire stands and year 5 for the entire landscape) and carbon storage. These tons/acre values were multiplied by the area of the study site to determine total values for tons of carbon lost via smoke emissions and total tons of carbon stored on the landscape in year 50.

Results and Discussion

Our results point to a contradiction: the treatment scenario with the largest standing stock of carbon 50 years post treatment (Alternative-1) is also the treatment strategy that lost the most carbon when prescribed fire and potential wildfire emissions were accounted for. However, increases in carbon storage appeared sufficient to off-set the higher emissions over the 50 simulation, meaning that the net change in carbon for Alternative-1 compared to no-treatment was positive (Fig. 2). A positive net change was also present in Alternative-3, but not as large as Alternative-1. Alternative-2 did not show this positive trend; the net change from no-treatment was negative.

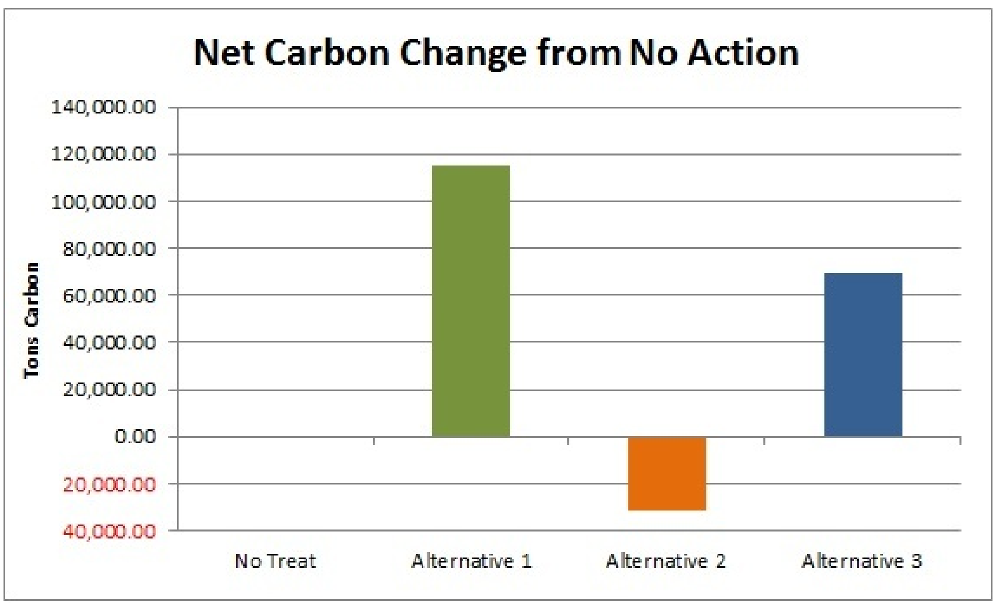

Fig. 2. Net C change derived from comparing carbon emissions and storage for each scenario to no-treatment and summing the values.

The increase in storage and emissions may stem from the same cause. Alternative-1 and Alternative-2 both had larger emissions than alternatives with smaller or no prescribed fire treatments. Simultaneously, the areas of prescribed fire treatment produced large areas resilient to catastrophic wildfire, allowing for the retention of more large trees when a wildfire was modeled. Because vegetation is a large pool of carbon (Boerner 2008), the alternative that created the largest area resilient to fire also retained the largest amount of carbon. Alternative-1 combines large prescribed fire units with mechanical units, creating the largest area resilient to catastrophic wildfire, resulting in this alternative having a slightly larger positive change in carbon than seen in Alternative-3.

Alternative-2 has small prescribed fire events as part of the FRZ units resulting in slightly larger carbon emissions than the no-treatment alternative. The area treated in this alternative is small compared to alternatives 1 and 3, resulting in much less area becoming resilient to high-severity wildfire. As a result, this alternative lost large amounts of carbon when the wildfire was simulated. The combination of prescribed fire emissions and large vegetation losses due to wildfire resulted in this alternative having a negative net change in carbon when compared to no-treatment.

Under the no-treatment scenario there were no emissions from prescribed fire so the emissions under this alternative are lower than any of the three other alternatives. However, because there are no fuel reductions, this alternative had no area resilient to wildfire, resulting in the largest loss of carbon during the wildfire in Year-5 of the simulation. The growth over the reaming 45 years was not enough to off-set the large amount of carbon lost in the form of vegetation during the wildfire event.

This work represents a worst case scenario in which the entire landscape experiences a wildfire even after fuel treatments. It is expected that the reduction in fire behavior and spread resulting from fuel treatments would realistically provide an even larger increase in carbon storage than was modeled here due to less area experiencing high intensity fire and larger areas retaining the large trees that account for much of the carbon storage.

Acknowledgements

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Tools, courses, and learning pathways offered by the National Interagency Fuels, Fire, and Vegetation Technology Transfer

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Abstract:
Technological advances in the area of fuel and wildland fire management have created a need for effective decision support tools and technology training. The National Interagency Fuels Committee and LANDFIRE have chartered a team to develop science-based learning tools for assessment of fire and fuels and to provide online training and technology transfer to help managers implement fuels, fire, and vegetation assessment technology for fire risk mitigation and ecosystem restoration. The team is called the National Interagency Fuels, Fire, and Vegetation Technology Transfer (NIFTT). NIFTT has developed and maintains several GIS tools and associated user resources. In addition, NIFTT offers online courses that facilitate the implementation of these tools as well as courses focusing on topics related to the assessment of fuels, fire, and vegetation in forests and rangelands. NIFTT has also developed "Learning Pathways" to assist independent learning, which provide easy-access to related learning materials in an order designed for optimal learning efficiency. Lastly, NIFTT hosts a website (www.niftt.gov) and helpdesk (helpdesk@niftt.gov) where users can access additional information and direct comments and questions.

Additional keywords: GIS, online resources, independent learning, LANDFIRE

Introduction

Fire exclusion in the 1900's altered wildland fuel characteristics, vegetation structure, landscape patterns, and fire regimes, leading to uncharacteristic behavior, severity, frequency, and size of wildland fires (Covington *et al.* 1994; Rollins *et al.* 2001; Hann *et al.* 2003; Rollins 2009). The introduction of invasive species in native plant communities has altered fire behavior and fire regimes (Dewey *et al.* 1995), and the wildland-urban interface has become a focal area for human-environment conflict, including wildland fire (Radeloff *et al.* 2005). Since the mid-1980s, an increase in large wildfire frequency, longer fire duration, and a longer wildfire season have been observed, associated with increased spring and summer temperatures and an earlier spring snowmelt in the western U.S. (Westerling *et al.* 2006; Rollins 2009). These changes in wildland fire characteristics and associated costs for fire suppression have inspired scientists and managers to learn about the role of fire in ecosystems, and wildland fire management is currently transitioning towards strategies in which fire suppression is balanced with approaches to re-introduce wildland fire into ecosystems (Gollberg *et al.* 2001). Recent recommendations for future wildland fire management, summarized by Gollberg *et al.* (2001), emphasize the need to: 1) Focus on wildland fire management tools that are grounded in ecological research and principles; 2) Develop a national approach to the mapping of fuels and to the integration of spatial technology, geographic information systems (GIS), and remote sensing; 3) Improve technology development, transfer, and communication between developers and users; and 4) Engage in training that incorporates the latest developments in remote sensing, GIS, communication technologies, and information management. At the same time, natural resource management is shifting towards managing ecological systems and individual species at the landscape-scale rather than focusing on small-scale projects (Forbis *et al.* 2007). The National Interagency Fuels, Fire, and Vegetation Technology Transfer (NIFTT), formed in 2005, addresses many of these identified needs and future directions in wildland fire management.

NIFTT's mission is to assist federal, state, and private land managers in the development and implementation of effective fuels, fire, and vegetation assessment technology for addressing risks related to severe fire behavior, fire effects, and departed ecosystems. NIFTT operates under the Rocky Mountain Research Station (RMRS) Wildland Fire Management RD&A and is sponsored by the U.S. Forest Service and the Department of Interior (DOI). NIFTT partners with the University of Idaho's Fire Research And Management Exchange System (FRAMES), The Nature Conservancy (TNC), and the RMRS Fire Modeling Institute (FMI). To date, NIFTT has developed a number of computer-based tools and six online courses focusing on technology transfer relating to stand- and landscape-scale assessments of fuels, fire and vegetation dynamics. NIFTT also contributes to fire and fuels education by hosting educational material for the National Wildfire Coordinating Group (NWCG). NIFTT's tools and courses have been well received by natural resource managers, and over 1700 students have registered for the online courses. Students registering for NIFTT courses come from a variety of sectors, but most are affiliated with the USDA Forest Service and the Department of Interior (DOI). In 2010, 32% and 35% of the registering students were affiliated with the USDA Forest Service and DOI, respectively, while the remaining 33% of the students came from the private, state, and university sectors. In addition to online course delivery, NIFTT offers in-person workshops on topics relating to the analysis of fuels and fuels treatments at stand and landscape scales.

NIFTT's technology transfer products are designed to use the spatial data developed by LANDFIRE (www.landfire.gov), but spatial datasets developed via other methods can also be made compatible and used with NIFTT tools. LANDFIRE produces a comprehensive suite of over 20 spatial data layers across the United States. Specific data layers include: biophysical settings, existing vegetation type, canopy cover and height, environmental site potential, fire behavior fuel models, fire regime class, and fire effects fuel model layers. LANDFIRE data development methods are described in detail by Rollins (2009) and Reeves *et al.* (2009). Existing vegetation and wildland fuel layers are being updated through the 'LANDFIRE Refresh' (www.landfire.gov) to maintain the currency of data sets. Changes resulting from recent (1999-2008) natural disturbances and management activities are included in the LANDFIRE Refresh maps, and Refresh corrects discrepancies that were detected after the original LANDFIRE National maps were completed.

NIFTT tools

NIFTT tools (Fig. 1) are designed to help users learn how to access, edit, and analyze input data to assess fire behavior, fire effects, and ecological departure. All tools are compatible with ArcGIS software (ESRI 2009) versions 9.0 – 9.3 and are continuously updated to be compatible with new versions of ArcGIS and new Windows platforms (e.g., Windows 7).

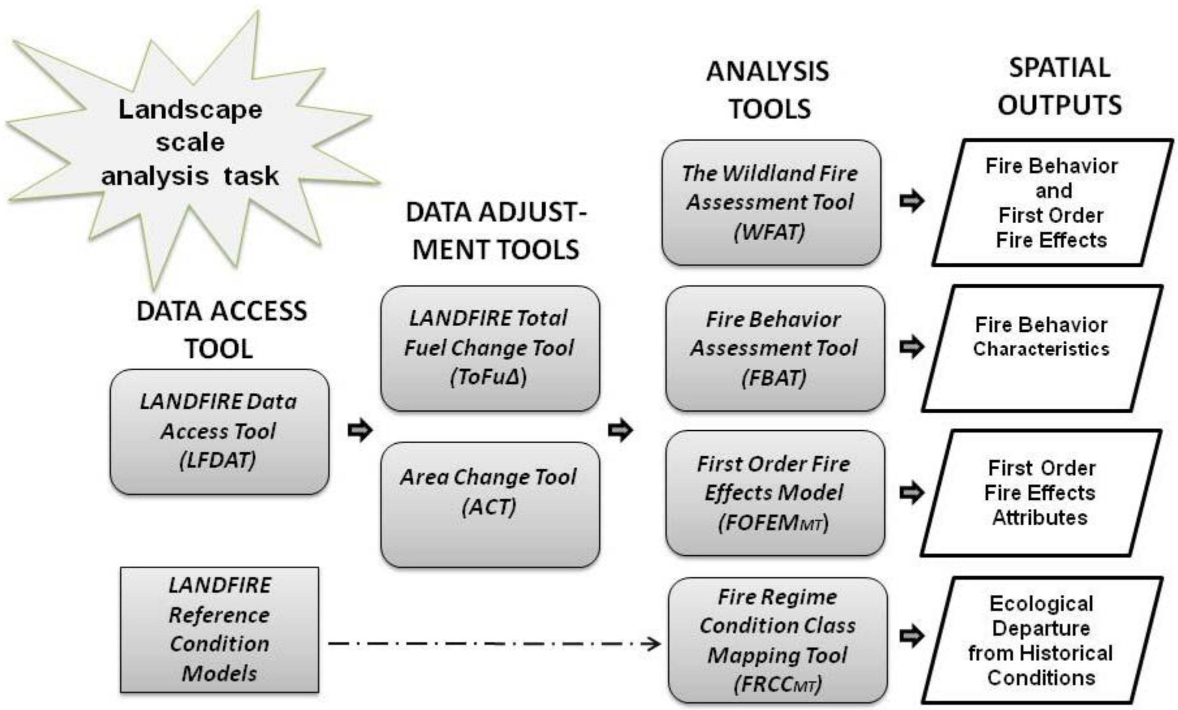

Fig. 1. An overview of NIFTT's GIS tools.

Landscape-scale analysis requires spatial data inputs. LANDFIRE provides a number of base data layers, such as biophysical setting and existing vegetation type, cover, and height. The LANDFIRE Data Access Tool allows the user to download LANDFIRE data directly into ArcMap. The Area Change Tool is designed to update LANDFIRE data to reflect changes resulting from natural disturbance or management activities. Surface and canopy fuels can be updated in the LANDFIRE Total Fuel Change Tool. The updated data layers can be processed in the Wildland Fire Assessment Tool, Fire Behavior Assessment Tool, or First Order Fire Effects Model Mapping Tool to produce spatial outputs of fire behavior characteristics and first order fire effects. The current distribution of vegetation structural classes can be compared to historical conditions, and ecological departure can be calculated across the landscape using the Fire Regime Condition Class Mapping Tool.

The LANDFIRE Data Access Tool (LFDAT; Toney *et al.* 2009) allows users to download LANDFIRE spatial data directly from ArcMap via a custom made LFDAT toolbar. Specifically, the user can define the download area by simply drawing the boundary of the desired extent in ArcMap, select desired LANDFRIE layers, and then downloaded data for that specific area directly into ArcMap. The tool automates the processing of downloaded zip files by unzipping and merging data into seamless raster formats ready for spatial analysis. LFDAT helps the user to automatically project LANDFIRE data to a desired map projection. NIFTT recommends that all users periodically consult the LANDFIRE website (www.landfire.gov) or the LANDFIRE Data Distribution Site (http://landfire.cr.usgs.gov/viewer/) for data updates.

Even though LANDFIRE data are updated via LANDFIRE Refresh, local events such as recent wildland fires, hurricanes, or insect infestations may not yet be included in the data. Accurate analysis requires that these changes be reflected in the GIS data layers. The Area Change Tool (ACT; Hutter *et al.* 2009) is an ArcMap toolbar that can help users update LANDFIRE layers (or other GIS data) to reflect recent changes caused by natural or human-induced disturbance events. ACT streamlines the editing of raster data layers and allows the user to edit multiple raster layers simultaneously. For example, the user can enter a recent fire perimeter into ArcMap and use the ACT toolbar to update the vegetation characteristics for several raster data sets within the fire perimeter. Typically, a fire alters canopy bulk density, canopy base height, canopy cover, canopy height, existing vegetation type, fire behavior fuel model, fire effects fuel model, and succession class. The LANDFIRE Total Fuel Change Tool (ToFuΔ; Smail and Martin *et al.* 2010) is specifically designed to allow users to update LANDFIRE fuel data directly in ArcMap. Fire and fuel managers and scientists can use ToFuΔ to develop rule sets for updating fuel data based on the existing vegetation type, existing vegetation cover, existing vegetation height, and biophysical setting – which are GIS layers available from LANDFIRE. Fuel characteristics can be updated for both surface and crown fuels. Through ToFuΔ, users can: 1) calculate area and percent existing vegetation type changed per fuel rule, 2) compare surface and crown fire behavior characteristics and interpret the transition for passive crown fire initiation, 3) create and graph custom fuel models, and 4) create distribution graphs to show vegetation structure and quantity.

NIFTT provides several spatial analysis tools focusing on the analysis of fire behavior, fire effects, and ecological departure. The Wildland Fire Assessment Tool (WFAT)[1] combines two previously developed NIFTT tools: the Fire Behavior Assessment Tool (FBAT; Hamilton *et al.* 2007) and the First Order Fire Effects Model Mapping Tool (FOFEMMT; Hamilton *et al.* 2009)**.** WFAT allows the user to spatially model wildland fire behavior and first order fire effects. The tool provides an interface between ArcMap, FlamMap (Finney 2006), and the First Order Fire Effects Model (FOFEM; Reinhardt *et al.* 1997), combining their strengths into a spatial fire effects analysis tool in a GIS. NIFTT recommends that users have a good understanding of fire behavior, fire effects, and fuel model concepts as well as experience using non-spatial systems such as BehavePlus, NEXUS, and FOFEM before attempting to use WFAT. WFAT requires spatial inputs of fuel models, canopy characteristics, and topographic and weather data, similar to those required by FARSITE (Finney 1998) and FlamMap (Finney 2006). A FARSITE Landscape

[1]*Hamilton D, Jones J (In preparation) Wildland Fire Assessment Tool (WFAT) for ArcGIS 9.2-9.3 (version 2.2.0). National Interagency Fuels, Fire, and Vegetation Technology Transfer. Available on-line at www.niftt.gov.

(LCP) File can also serve as input to WFAT. Fire behavior outputs include flame length, rate of spread, fireline intensity, fuel moisture, and fire type. Fire effects outputs include post-fire or consumed fuel loadings, emissions, soil heating, and tree mortality.

Altogether, over 50 spatial output layers can be generated by WFAT, although it is highly recommended to limit the number of outputs to those relevant to the proposed analysis question. WFAT can help fire and fuel managers locate potential fuel treatment units, develop a prescription for those units, and evaluate the effects of proposed treatment on potential fire behavior and fire effects. WFAT saves fire managers the time and effort of converting data between multiple formats for use in ArcMap and FlamMap and gives managers the option of using downloadable data from the LANDFIRE Data Distribution Site (http://landfire.cr.usgs.gov/viewer/) as their GIS input layers.

Fire Regime Condition Class (FRCC) assesses vegetation and fire regime departure in relation to historical vegetation and fire regimes based on concepts published by Hann and Bunnell (2001), Hardy *et al.* (2001), and Schmidt *et al.* (2002). Departure from historical conditions can cause change to key ecosystem components, such as vegetation characteristics (species composition, structural stage, stand age, canopy cover, and landscape pattern), fuel composition, fire frequency, fire severity, and burning patterns. Examples of other associated disturbances include insect- and disease-induced mortality, livestock and wildlife grazing, and drought. Causes of ecological departure that are initiated by human activities include (but are not limited to) fire suppression, timber harvesting, livestock grazing, introduction and establishment of exotic plant species, and introduced insects and disease (Schmidt *et al.* 2002). Fire Regime Condition Class (FRCC) is an interagency standardized tool for determining the degree of departure from reference condition vegetation and fire regimes. At the national forest and BLM district levels, FRCC is a metric that can be used for prioritizing watershed-scale management activities. FRCC is a required component of Fire Management Plans and can provide decision support regarding how to implement fire-use events for restoring desirable fire regimes. LANDFIRE data layers, adjusted to represent the analysis area, serve as the input data to the Fire Regime Condition Class Mapping Tool (FRCCMT; Hutter *et al.* 2008) and include layers of biophysical settings (BpS), current succession class (S-class), and the landscape reporting unit (commonly drainage basins or hydrologic units). FRCCMT computes the amount of each succession class within the individual biophysical settings and compares this current distribution to the historical reference condition. The output maps depict departure from historical conditions at three levels: S-class, BpS strata, and landscape unit. The departure categories consist of classes 1 through 3, where class 1 depicts areas that are the least departed from historical conditions and class 3 represents the most departed. Currently, FRCCMT accounts only for vegetation composition departure; however, an updated version of FRCCMT that also accounts for fire regime departure is in development. Lastly, the Fire Regime Condition Class Software Application (FRCCSA; Hamilton and Hann 2010) is a non-spatial application for deriving and graphing FRCC. A summary of NIFTT tools and their applications can be found in Fig. 2.

NIFTT Tools	Function and Application
LANDFIRE Data Access Tool (LFDAT)	▪ Downloads LANDFIRE layers directly into ArcMap for a customized extent ▪ Map projection is specified by the user ▪ Automates the attachment of attributes and metadata
Area Change Tool (ACT)	▪ Facilitates editing and combining Arc Grids ▪ Multiple Arc Grids can be edited simultaneously to maintain logical relationships ▪ Arc Grids can be refined/updated to better reflect local conditions
LANDFIRE Total Fuel Change Tool (ToFuΔ)	▪ Facilitates editing LANDFIRE rulesets to create customized surface and canopy fuel layers for local applications ▪ Useful for validating spatial fire behavior outputs ▪ Helps with routine and recurring database management operations
Wildland Fire Assessment Tool (WFAT) *Combines the tools FBAT and FOFEM$_{MT}$*	▪ Integrates ArcGIS, FlamMap, and FOFEM ➢ FlamMap estimates fire behavior (e.g., flame length, spread rate, etc.) ➢ FOFEM estimates fire effects (e.g., soil heating, tree mortality, smoke, etc.) ▪ Useful for prioritizing, designing, & evaluating fuel treatment projects ▪ Outputs can be used for deriving "risk" metrics
Fire Regime Condition Class Software Application (FRCC$_{SA}$)	▪ Non-spatial derivation of departure metrics (e.g., FRCC) ▪ Provides tabular and graphic summaries ▪ Provides an efficient means to enter, edit, and store data
Fire Regime Condition Class Mapping Tool (FRCC$_{MT}$)	▪ Spatial derivation of departure metrics (e.g., FRCC) ▪ Capable of assessing multi-million acre landscapes ▪ Provides tabular summaries

Figure 2. A summary of currently available NIFTT tools and their applications.

Online training

NIFTT provides technology transfer to managers and scientists via online courses. Six NIFTT online courses are currently available (Fig. 3), and several new courses are in development; all courses can be accessed through www.niftt.gov. Students can register for and take NIFTT online courses at their convenience. The courses are structured for self-learning, with components such as narrated slide presentations, readings describing important concepts, tutorials, hands-on exercises, self-tests with immediate feedback, and course evaluations. Most NIFTT courses take approximately 3-4 hours to complete; however, some of the more in-depth courses require additional time. The LANDFIRE Concepts, Data, and Methods course reviews fundamental ecological concepts relevant to LANDFIRE, describes the LANDFIRE Program and data resources, and provides instruction regarding how to access and use LANDFIRE data on the job. In the Fire Regime Condition Class course, fundamental FRCC concepts are introduced, and students learn how to estimate FRCC using the Standard Landscape Worksheet Method – a non-spatial field-based approach. Applications of FRCC are demonstrated for a variety of ecosystems, and students are led through hands-on exercises that show how to diagnose FRCC for an example assessment landscape of the student's choosing. Policy and law implications are also discussed. Students completing the course receive FRCC certification.

The course Introduction to the Fuel Characteristic Classification System (FCCS) gives background on the Fuel Characteristic Classification System (Sandberg *et al.* 2001) and provides instruction on how to download, install, and use the FCCS software. Students learn real-world applications of FCCS, including the mapping of fuelbeds, the development and mapping of custom fuelbeds, and the use of fuelbeds for fire hazard analysis. Exercises walk students through the process of selecting a default fuelbed and help them customize the fuelbed. The Introduction to the 40 Fire Behavior Fuel Models course provides an overview to the Scott and Burgan 40 fire behavior fuel models (Scott and Burgan 2005), demonstrates the resources available for learning about the models, and guides students through model selection. Using Fire Behavior Nomographs to Estimate Fire Behavior Characteristics describes the history and use of nomographs for estimating fire behavior, explains the new fire behavior nomograph format (Scott 2007), illustrates the use of a wind vectoring charts, and describes the use of the new nomographs format for estimating spread rate and flame length for head fires, flanking, and backing fires. The course GIS Tools for Fuels, Fire, & Vegetation Management Using LANDFIRE Data introduces the GIS tools for fire, fuels, and vegetation management described above in the NIFTT Tools section. The course currently includes tool lessons on the First Order Fire Effects Model Mapping Tool (FOFEMMT), the Fire Regime Condition Class Mapping Tool (FRCCMT), and the Area Change Tool (ACT). Additional tool lessons, including WFAT, are currently in development. Lessons include tutorials and hands-on exercises, and students learn interpretation of tool outputs as well as tool applications in day-to-day management.

Course	Objectives
LANDFIRE: Concepts, Data, & Methods	▪ Introduces the LANDFIRE Project and data products ▪ Increases understanding of data derivation to assist in appropriate application
Fire Regime Condition Class	▪ Introduces the concepts and derivation of FRCC ▪ Applications of FRCC in a variety of ecosystems ▪ Policy and law implications
Fuel Characteristic Classification System (FCCS)	▪ Introduces the concepts and structure of the FCCS ▪ Teaches how to install and use the FCCS software ▪ Teaches how FCCS can be applied in the real-world
40 Fire Behavior Fuel Models	▪ Provides an overview of the Scott & Burgan fuel models ▪ Describes the process for selecting the appropriate fuel model
Using Fire Behavior Nomographs to Estimate Fire Behavior Characteristics	▪ Describes the history and use of nomographs for estimating fire behavior ▪ Describes the new nomograph format and associated resources
GIS Tools for Fuels, Fire, & Vegetation Management using LANDFIRE Data	▪ Introduces GIS tools that can be used for downloading, editing, & assessing LANDFIRE data ▪ Familiarizes participants with the purpose and function of NIFTT tools

Fig. 3. A summary of currently available NIFTT online courses and course objectives.

Learning pathways

NIFTT has developed "Learning Pathways" designed to provide guidance to individuals interested in learning specific areas of study. These pathways – available at www.niftt.gov – provide a compilation of materials organized in an order designed for optimal learning efficiency. Learning pathways currently available include Fire Behavior, Fire Effects, and Fire Regimes, and pathways for Spatial Analyses, Vegetation Dynamics, and Integration are in development. The Fire Behavior Pathway includes relevant courses, tutorials, and guides for use in fire behavior-related planning, treatment implementation, and monitoring. The Fire Effects Pathway provides a compilation of courses, tutorials, and guides that will help natural resource professionals better understand fire effects concepts and learn about the latest tools available for planning, treatment implementation, and monitoring. The Fire Regimes Pathway provides information necessary to understand the concepts of natural fire regimes, historical range of variability, biophysical settings, and fire regime condition class. Students learn how to access and download spatial data and how to run the FRCC Mapping Tool and interpret results.

Website and helpdesk

Access to NIFTT tools and associated resources, online course registration, learning pathways, and additional information are available at www.niftt.gov. Comments and questions can be directed to NIFTT via helpdesk@niftt.gov.

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Fire characteristics charts for fire behavior and U.S. fire danger rating

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Abstract
The fire characteristics chart is a graphical method of presenting U.S. National Fire Danger Rating indices or primary surface or crown fire behavior characteristics. A desktop computer application has been developed to produce fire characteristics charts in a format suitable for inclusion in reports and presentations. Many options include change of scales, colors, labels, and legend. The fire danger fire characteristics chart displays the relationship among SC, ERC, and BI by plotting the three values as a single point. A chart can be used to compare years, months, weather stations, and fuel models. Indices calculated by FireFamilyPlus can be imported into the fire characteristics chart program. Surface and crown fire behavior charts are separate because a different flame length model is used for each. Plotted values can be observed rate of spread and flame length or calculated values from a program such as the BehavePlus fire modeling system. The charts can aid fire model understanding by comparing, for example, the effect of a change in fuel model or wind speed on fire behavior. Other applications include fire documentation, prescribed fire plans, and briefings.

Additional keywords: Energy Release Component, Spread Component, Burning Index, rate of spread, fireline intensity, flame length, heat per unit area, computer program

Introduction

The fire characteristics chart is a graphical method for presenting either U.S. National Fire Danger Rating System (NFDRS) indices (Spread Component [SC], Energy Release Component [ERC], and Burning Index [BI]) or primary surface and crown fire behavior characteristics rate of spread (ROS), flame length (FL), and heat per unit area (HPUA).

Fire behavior fire characteristics charts are useful as a communication aid for displaying the character of a fire based on spread and intensity values that are either calculated or observed. The fire danger chart illustrates the relationship among indices that are often considered separately.

The surface fire behavior and the fire danger fire characteristics charts were presented by Andrews and Rothermel (1982). Rothermel (1991) developed a fire characteristics chart for crown fire. Those charts were designed primarily for plotting by hand. While some aspects of fire characteristics charts are available in computerized systems such as BehavePlus, FARSITE, and Nexus, a general purpose application has not been available.

A desktop computer program has been developed to produce fire characteristics charts in a format suitable for inclusion in reports and presentations. The fire behavior application is documented in (Andrews, Heinsch *et al.* in press). A similar publication for fire danger rating will also be available. Those papers include operating instructions and example applications as well as the mathematical modeling foundation. This paper provides an overview with examples.

The fire characteristics chart program does not include calculation of fire danger indices or fire behavior values, but rather displays values obtained elsewhere. Fire danger indices produced by FireFamilyPlus can be imported directly into the fire characteristics chart program. Fire behavior values can be calculated using a program such as the BehavePlus fire modeling system (Andrews 2007), or observed fire behavior values can be plotted.

The program offers options that allow formatting to suit the application at hand. A user can, for example, change axis scales, use multiple colors, and add point labels and legends. While we use English units in these examples, metric units are available in the program.

The fire characteristics chart program and associated documentation can be found in the BehavePlus section of http://www.FireModels.org.

Fire danger fire characteristics chart

The U.S. National Fire Danger Rating System is used for pre-fire management applications such as fire prevention and suppression readiness. NFDRS is comprised of components and indices based on seasonal fire weather data. A fire danger rating fire characteristics chart can be used to compare indices from multiple years, months, weather stations, or fuel models.

The fire danger chart displays the relationship among SC, ERC, and BI by plotting the three values as a single point. The chart is possible because BI is derived from SC and ERC according to the following relationship:

$$.. = \left[\frac{ERC \times SC}{0.091}\right]^{\cdot} \qquad (1)$$

SC, based on the spread rate model, is strongly impacted by wind speed, and can vary greatly from day-to-day. ERC, on the other hand, is based on the model for heat per unit area with weighting on the heavy fuels and does not include the influence of wind. ERC is driven by fuel moisture, particularly 1000-h fuel moisture (if heavy dead fuels are present in the selected fuel model), providing a seasonal look at fire danger. BI, which is derived from the flame length model, is a combination of the two components, combining the underlying seasonal trend of ERC with the daily fluctuations in SC. The fire characteristics chart can be used for comparing indices.

Among the applications of the NFDRS fire characteristics chart is communication and comparison of the level of fire danger. Andrews and Rothermel (1982), presented the example of a hypothetical briefing to describe the general fire season to an audience that included those not familiar with NFDRS. We have updated their chart as shown in Fig. 1. They wrote:

The fire danger of most of the west side of the region is low as indicated by point A, although there are a couple of districts that may cause problems (point B). Point C refers to the fire danger on the east side of the region. If we have another week of dry weather, the situation on the east side could become critical (point D).

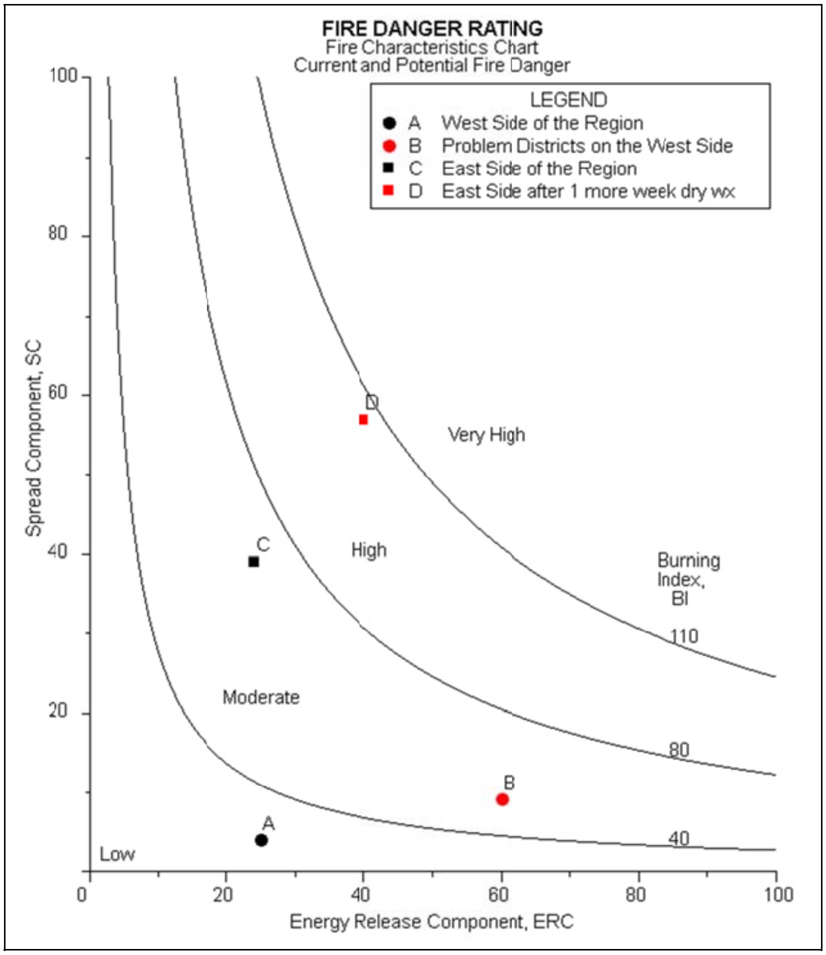

Fig. 1. An NFDRS fire characteristics chart that might accompany the hypothetical briefing outlined in the text (based on Andrews and Rothermel 1982).

The original fire characteristics concept was developed for a few points to be plotted on paper by hand. The program we describe here allows for hundreds of points to be plotted, using files imported directly from FireFamilyPlus. In the following examples, weather data for Remote Automated Weather Stations (RAWS) were obtained from the Fire and Aviation Management Web Applications website (http://fam.nwcg.gov/fam-web/). FireFamilyPlus version 4.1 was used to calculate indices. The **Weather > Season Reports > Daily Listing** function was used to export SC and ERC. BI is calculated by the fire characteristics chart application using equation 1. Relevant fire data from the U.S. Forest Service and National Park Service were also obtained from the Fire and Aviation Management Web Applications website. These data were imported into FireFamilyPlus, associated with the appropriate RAWS, and summarized.

Fire characteristics charts can be used to explore the relationship between fire activity and NFDRS indices. The indices on the discovery date of the largest nine fires (>1,000 acres) on the Nine Mile Ranger District (MT) from 1980-2009 were compared with NFDRS values from the Ninemile RAWS station for all days during that time period. The resulting graph (Fig. 2) indicates a relationship between large fires and high ERC values. Eight of the nine fires were reported on a day with ERC > 60.

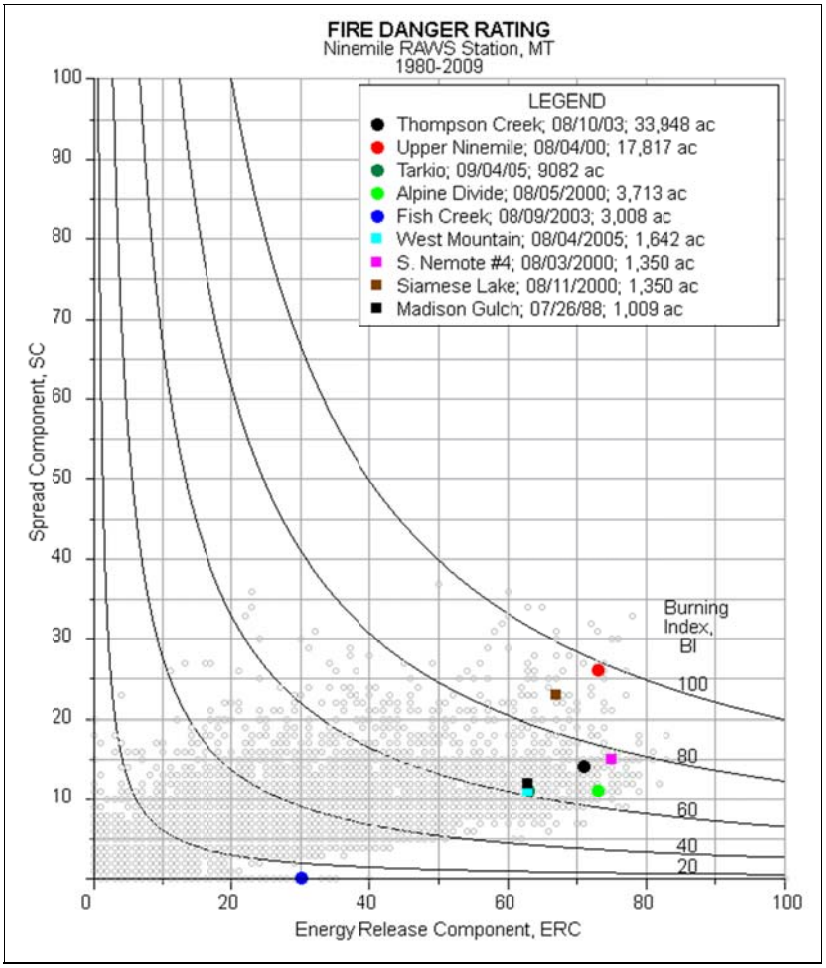

Fig. 2. Indices from the Ninemile RAWS (1980-2009) and discovery day indices for the nine largest fires on the Nine Mile District.

Seasonal plots of NFDRS indices can be supported by an associated fire characteristics chart. Fig. 3 demonstrates the fire season for the Missoula RAWS (MT) in 2000. Data from FireFamilyPlus were separated into two-month periods and imported into the chart program. Each file can be identified using a specific icon/color combination in the Fire Characteristics Chart program. Seasonal traces of SC, ERC, and BI were generated using other software to use corresponding colors. During 2000 the highest ERC values were found during July and August, months that are often the height of the fire season for the area. High values of SC in March and April are associated with the higher winds that typically occur during that time.

Fuel model selection has a great impact on fire danger indices. As described by Heinsch and others (2009) fuel models G and H are quite similar in the way that they reflect the fire season, although the magnitude of index values is quite different. Fuel model L, on the other hand, is comprised solely of fine fuel, resulting in indices that behave quite differently. In Fig. 4 NFDRS indices for Conroe, TX, were calculated for Fuel models G, H, and L, all using the same weather data. Fuel model G provides much more information about fire danger at Conroe as demonstrated in the wider range of values. Overlap between models G and H demonstrates their similarity. Fuel model L shows the high SC and low ERC values typical of grass fuel models.

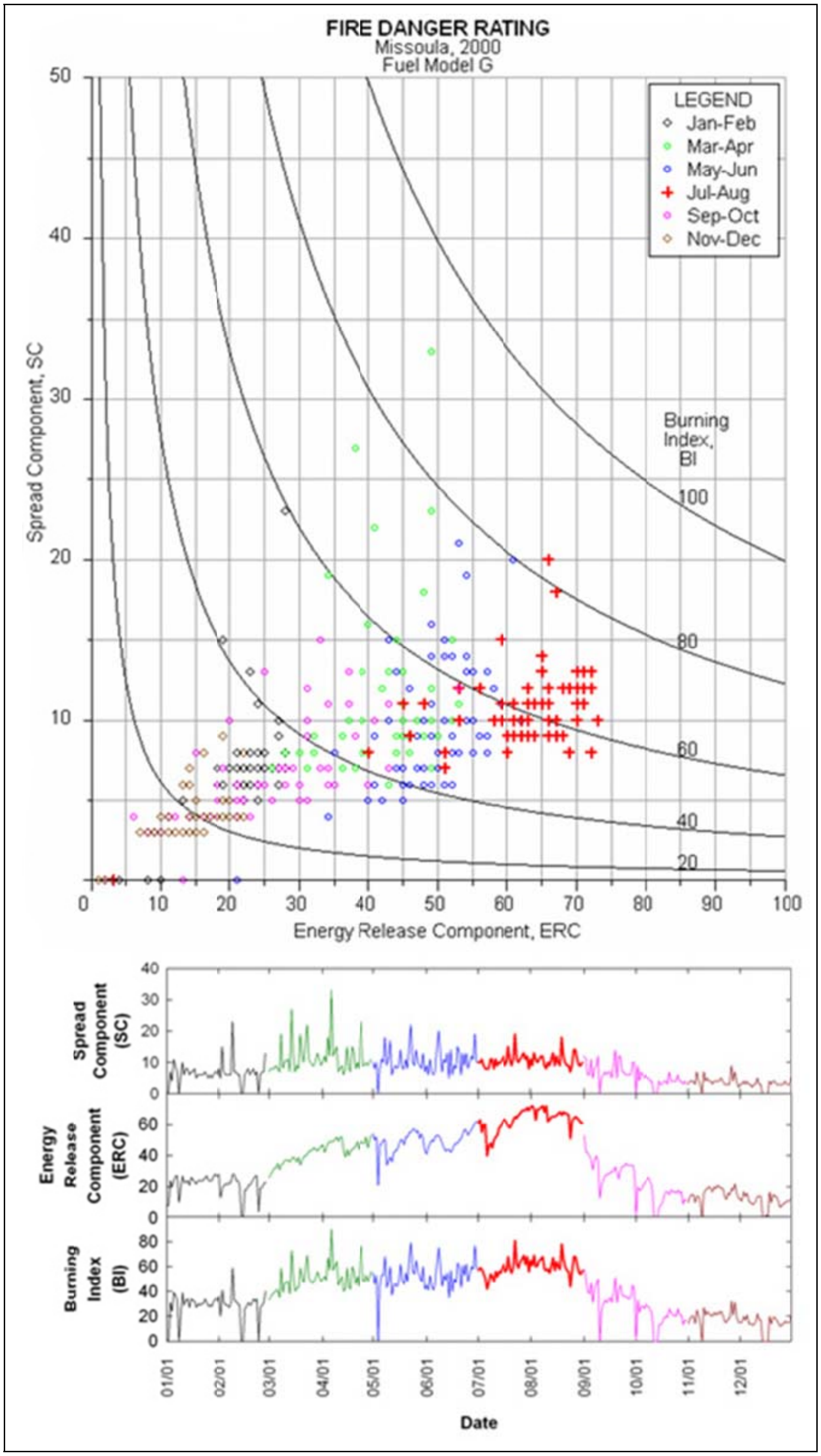

Fig. 3. Fire characteristics chart and corresponding seasonal traces for Missoula, MT, 2000.

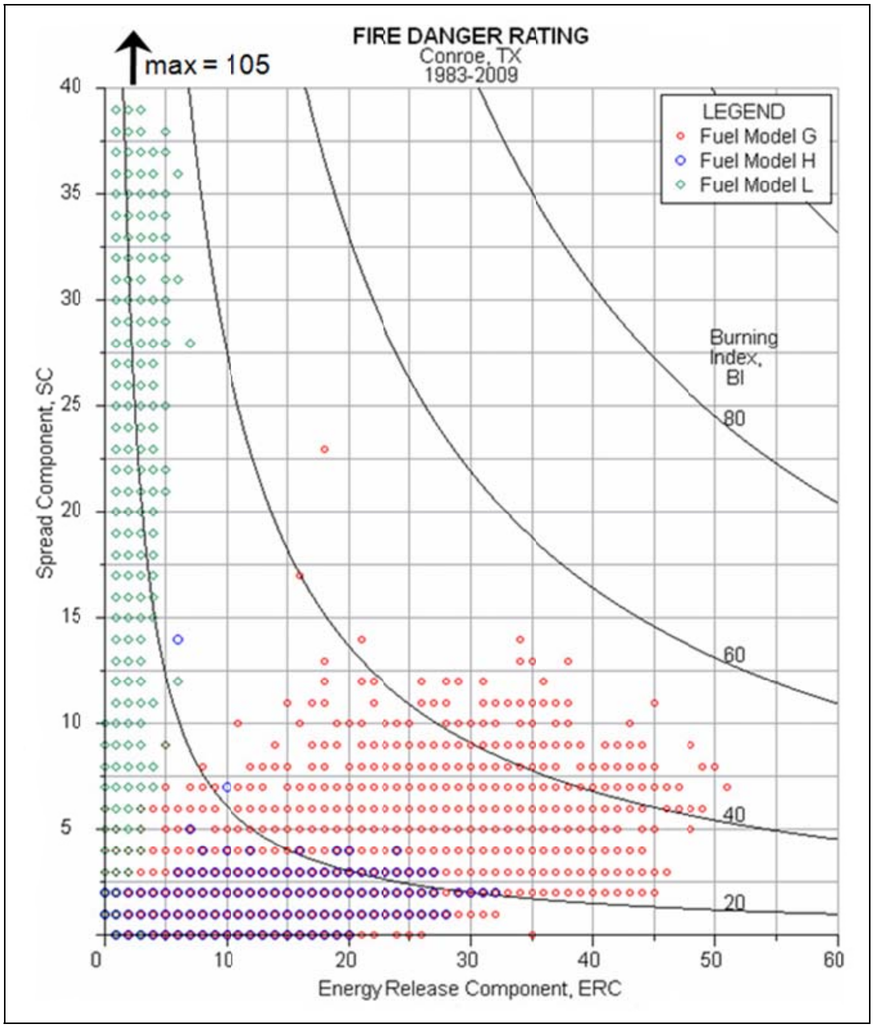

Fig. 4. Comparison of indices for fuel models G, H, and L calculated for the Conroe, TX, RAWS.

Comparison of interannual variability is an important application of fire danger rating. At the Mammoth, WY, RAWS in Yellowstone National Park (Fig. 5), data for July through August, 1988 (a very dry year; red) and 1991 (a relatively wet year; blue) are compared. Similar data from 1965-2009 (grey) are also plotted. The difference in fire danger for the two years becomes apparent through the difference in ERC. The large fires of 1988 were associated with higher values of ERC on the day they were reported (ERC > 80).

Proper use of fire danger rating indices is based on a climatological analysis. The fire characteristics chart can supplement the seasonal plots, percentile analysis, and relationship to fire activity available in FireFamilyPlus.

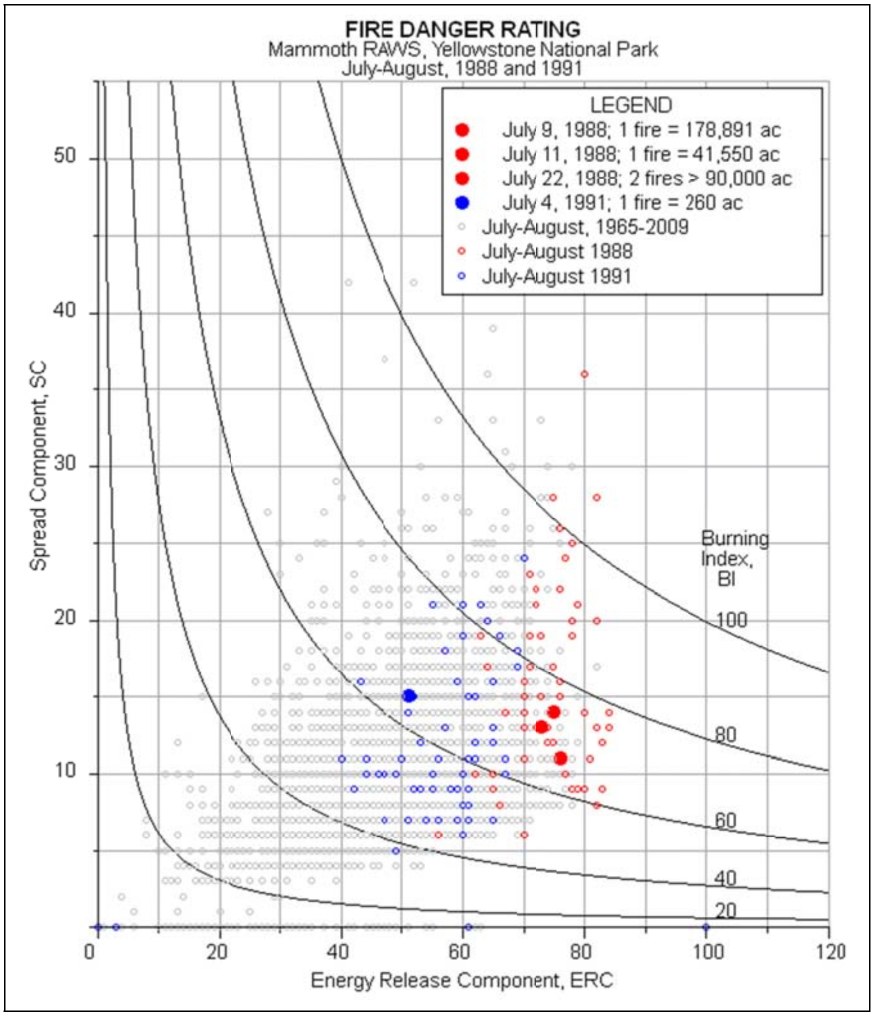

Fig. 5. Interannual variability is demonstrated at Mammoth, WY, for a very dry year (1988) and a fairly wet year (1991) compared to 1965-2009 indices.

Fire behavior fire characteristics charts

Fire behavior fire characteristics charts illustrate the relationship among primary fire behavior values—rate of spread (ROS), flame length (FL), and heat per unit area (HPUA). Two values, one of which must be ROS, are entered. The user can then input either FL or HPUA—the program will calculate the third value. These values can be either observed values or calculated using other software. For observed fire behavior a user will often input ROS and FL; HPUA will be calculated. Calculated fire behavior values were generated for the following examples using BehavePlus version 5.0. The following examples (and others) are given in more detail in Andrews and others (in press).

A fire characteristics chart can aid fire model understanding by comparing, for example, the effect of a change in fuel model or wind speed on fire behavior. Other applications include fire documentation, prescribed fire plans, and briefings.

Byram's (1959) fireline intensity model forms the basis of the fire behavior charts. Separate charts are used for surface and crown fire behavior charts because a different flame length model is used for each. Byram's (1959) flame length equation, based on fireline intensity, is used for the surface fire chart.

$$F_B = 0.45\ {}_{B}^{\cdot} \tag{2}$$

where F_B is Byram's flame length (ft) and I_B is Byram's fireline intensity (Btu/ft/s).

The crown fire chart uses Thomas' (1963) flame length model.

$$F_T = 0.2\ {}_{B}^{2/3} \tag{3}$$

where F_T is Thomas' flame length (ft) and I_B is Byram's fireline intensity (Btu/ft/s).

The difference between the two flame length models is significant as shown in Fig. 6. Fireline intensity of 4000 Btu/ft/s is associated with surface fire flame length of 20 ft and crown fire flame length of 50 ft. For simplification, the curves on the fire behavior charts are labeled with flame length, not fireline intensity.

Flame length and fireline intensity are related to the heat felt by a person standing next to the flames. Table 1 is an interpretation in terms of suppression capabilities (National Wildfire Coordinating Group 2006; Rothermel 1983). Icons are available for the surface fire behavior chart and can be removed from the chart when the flame length curves no longer reflect the specific values for which they apply. Because crown fire exceeds all suppression activities, there are no icons on the crown fire behavior chart.

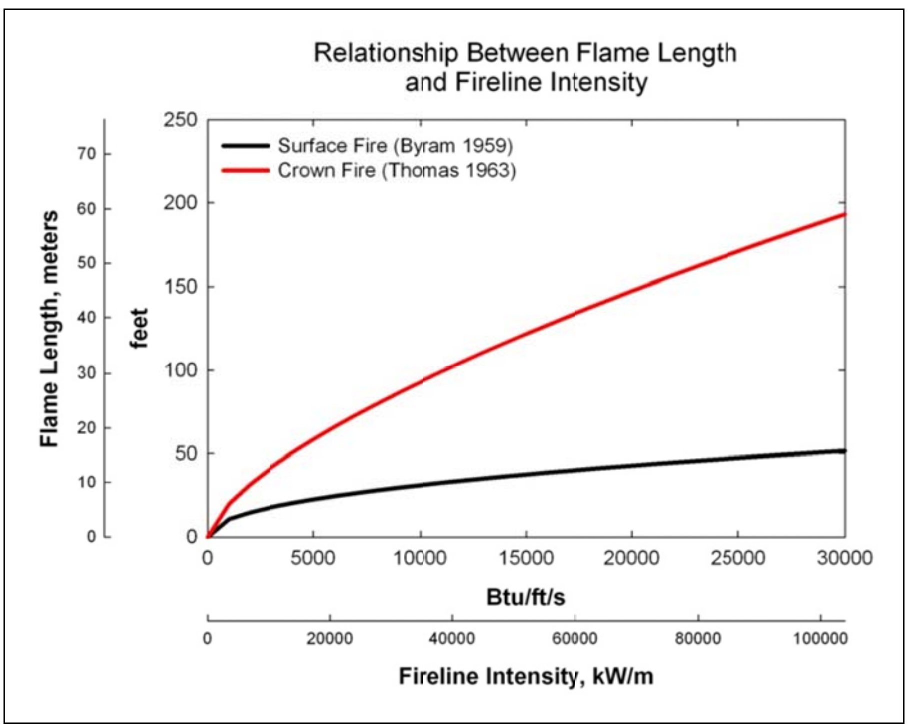

Fig. 6. Differences between Byram's and Thomas' flame length models are apparent as fireline intensity increases.

Table 1--Relationship of surface fire flame length and fireline intensity to suppression interpretations (Rothermel 1983).

Flame Length		Fireline Intensity			Interpretation
ft	m	Btu/ft/s	kJ/m/s		
< 4	< 1.2	< 100	<350		• Fires can generally be attacked at the head or flanks by persons using hand tools. • Hand line should hold the fire.
4 – 8	1.2 – 2.4	100 – 500	350 - 1700		• Fires are too intense for direct attack on the head by persons using hand tools. • Hand line cannot be relied on to hold the fire. • Equipment such as dozers, pumpers, and retardant aircraft can be effective.
8 – 11	2.4 – 3.4	500 – 1000	1700 - 3500		• Fires may present serious control problems -- torching out, crowning, and spotting. • Control efforts at the fire head will probably be ineffective
> 11	> 3.4	> 1000	> 3500		• Crowning, spotting, and major fire runs are probable. • Control efforts at head of fire are ineffective.

As an example of the value of the surface fire characteristics chart in displaying relationships, consider the effect of fuel model on calculated fire behavior. Fig. 7 demonstrates the differences for four fuel models (1, 4, 8, 10; Anderson 1982) with other conditions held constant: dead fuel moisture 5%, live fuel moisture 100%, midflame wind speed 7 mi/h, and slope 10%.

While the flame length is roughly the same for fuel models 1 and 10, the character of the two fires is very different. The fire in fuel model 1 (short grass) is fast spreading with a low heat per unit area, while the fire in fuel model 10 (timber litter and understory) is slow spreading with a high heat per unit area. A fire in fuel model 8 (short needle litter) has both a low spread rate and low heat per unit area. At the other extreme, fire in fuel model 4 (chaparral) is very fast spreading with high intensity.

Plotted points are circled for emphasis (added to our chart using other software) and might also serve as a reminder of the inherent variability of wildland fire and the limitations of fire modeling, including the fire models, fuel description, and/or model inputs.

Rothermel's (1972) surface fire spread model is based on the assumption that the fire is steady-state and burning under uniform conditions. While this might be appropriate for modeling the behavior of potential spot fires outside the unit, fire behavior on prescribed burns is often controlled by ignition pattern (Wade and Lunsford 1989). Such behavior can be illustrated on fire characteristics charts as described by Rothermel (1984). The chart can be included in prescribed fire burn plans to show the relationship between model results based on ambient weather and planned fire behavior affected by ignition pattern.

Fig. 8 shows calculated steady-state behavior based on the forecast zero wind speed as well as behavior that would result from 8 to 10 mi/h winds. The planned range of fire behavior, with induced winds of 8 to 10 mi/h is indicated on the chart by the large red oval. Flame length curves were changed from the default values on Table 1 and icons were removed from the chart.

In the final example application, observed crown fire behavior from the Sundance Fire (northern Idaho, 1967) is plotted on a crown fire behavior characteristics chart (Fig.9). Observed rates of spread and calculated fireline intensity were taken from Anderson (1968). Flame length values were calculated using Thomas' (1963) flame length model. This fire burned through mixed conifers, driven by winds of up to 45 mi/h, reaching spread rates of 6 mi/h. A prolonged dry spell, persistent high temperatures, sustained winds, and an uncontrolled 4-mi fire front led to a sustained major crown fire run on September 1, 1967 from 1400 to 2300 hours. During that 9 hour period, the fire traveled 16 miles, burning more than 50,000 acres. The sharp increase in ROS between 1900 and 2000 hours and the rapid decline by 2100 show the diurnal variability in fire behavior, even during a sustained major run.

Summary

The Fire Characteristics Chart program is useful for interpretation of fire behavior values or fire danger rating indices. Charts can effectively be used for communication in briefings, presentations, and reports. While features of the program may eventually be integrated into comprehensive systems, it is now a supplement to BehavePlus and FireFamilyPlus.

Dead fuel mois 5%, Live mois 100%, Midflame wind 7 mi/h, Slope 10%

Fuel Model	ROS (max) ch/h	Heat per Unit Area Btu/ft2	Fireline Intensity Btu/ft/s	Flame Length ft
1	196.6	92	333	6.5
10	14.1	1330	344	6.6
8	3.5	200	13	1.5
4	125.9	2712	6262	25.1

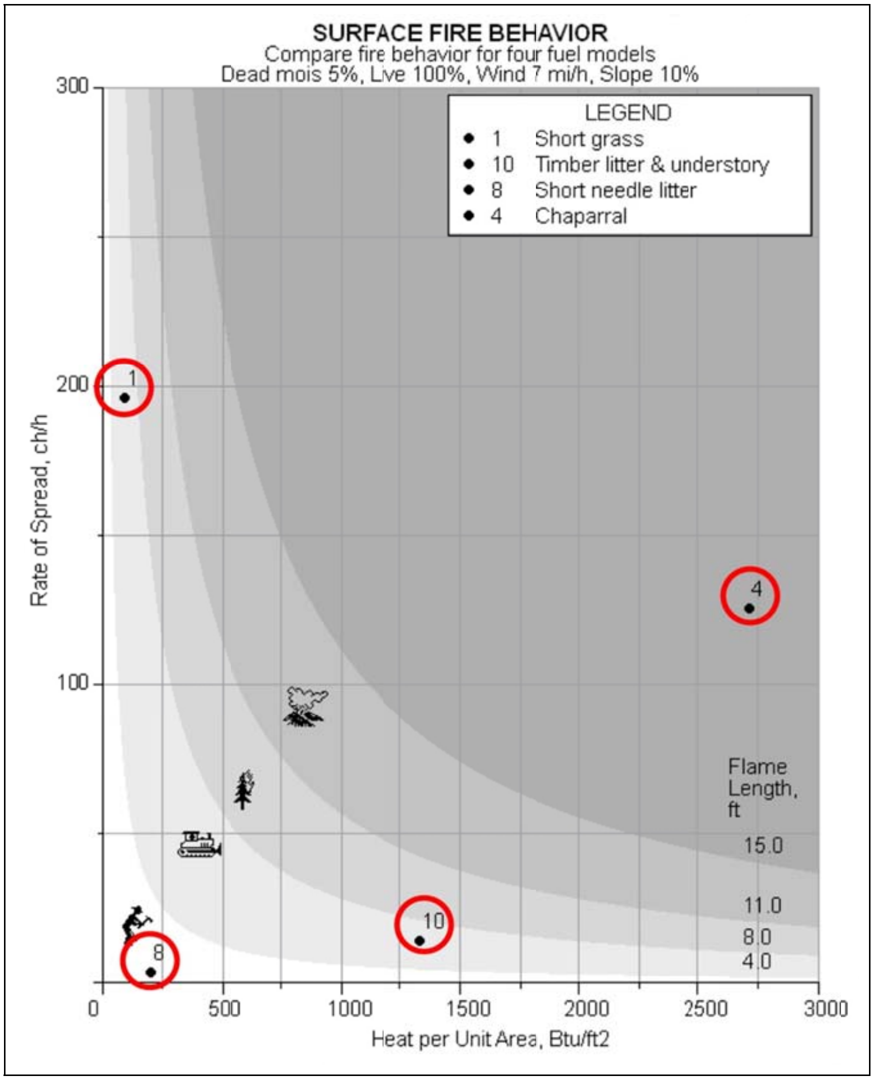

Fig. 7. Outputs from BehavePlus are plotted on the fire characteristics chart to illustrate the effect of fuel model.

Fuel model 5, Dead mois 6%, Live mois 90%, Zero slope

Midflame Wind Speed mi/h	ROS (max) ch/h	Heat per Unit Area Btu/ft2	Fireline Intensity Btu/ft/s	Flame Length ft
0	1.2	656	15	1.6
8	50.1	656	602	8.5
10	67.9	656	816	9.8

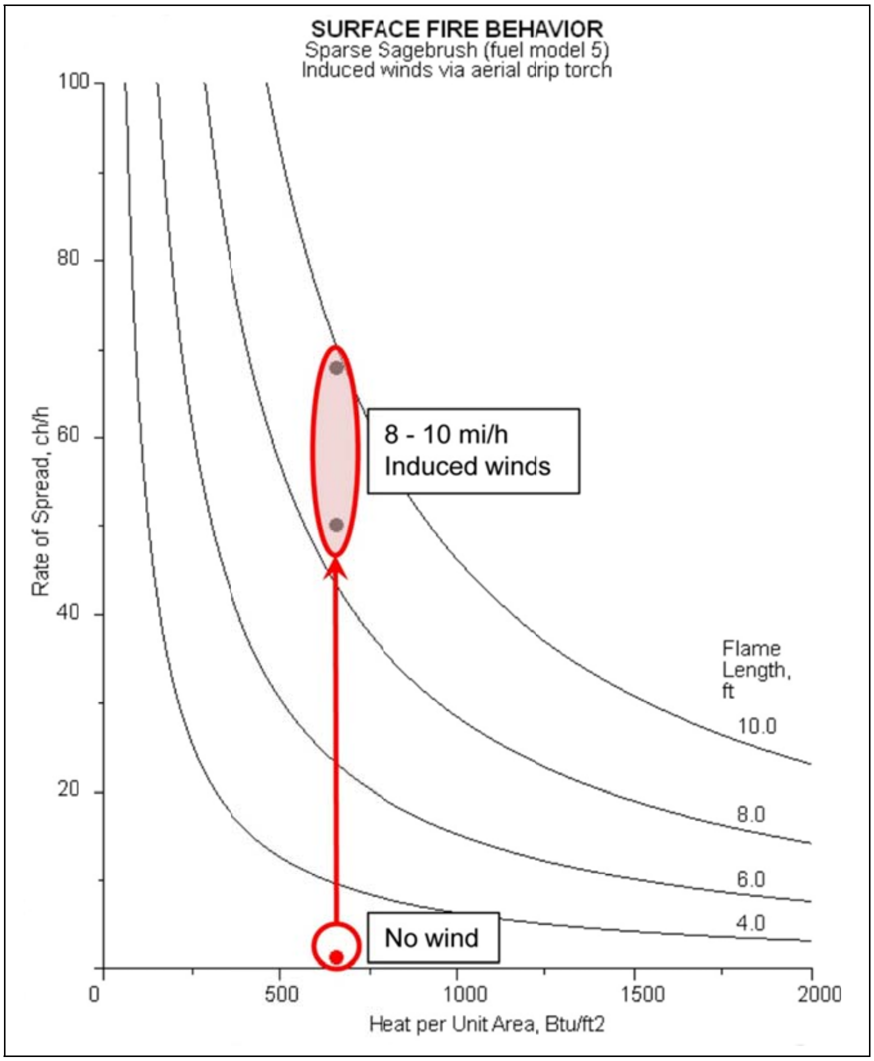

Fig. 8. Effect of induced wind on sagebrush fire characteristics (based on Rothermel 1984).

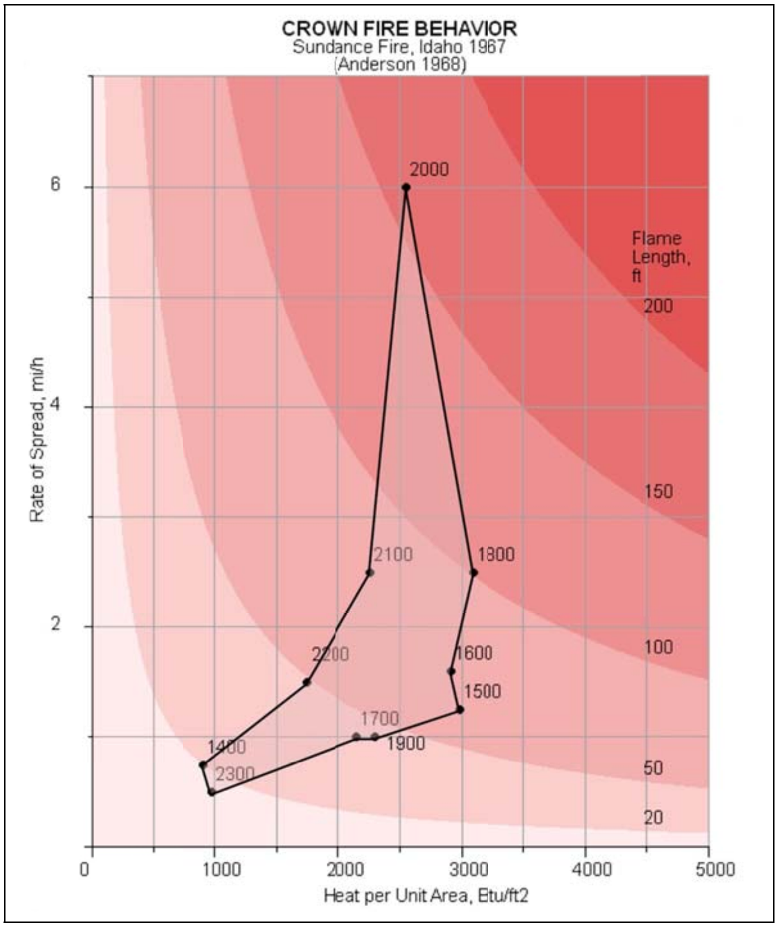

Fig. 9. Envelope of observed behavior for the Sundance Fire by time of day for September 1, 1967.

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Advanced fire products from the AMS-Wildfire airborne sensor

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Abstract
Aircraft observations of active fires offer a combination of spatial coverage and timely delivery of data that cannot be obtained with other platforms. Traditional aircraft observations of active fires have been obtained with simple infrared cameras, which are used to generate imagery from which an operator can extract a map of a fireline. Adjustable-gain infrared camera systems do not produce data useful for quantitative analysis. A new generation of aircraft imagers is now coming online, led by the AMS-Wildfire instrument developed by the NASA Airborne Science Program, and matured by the NASA / U.S. Forest Service-funded Wildfire Research and Applications Partnership (WRAP) project (NASA-Ames Research Center, California). This instrument offers advanced capabilities for fire monitoring, including fully-resolved isotherms, with a spatial resolution of 10-20 meters and a temperature resolution of 1-2°K; automated active burning detection and mapping; estimation of fire intensity through radiative power output; and estimation of burn severity behind the fire front. All of these products can be delivered either direct from the aircraft data telemetry communications downlink (via SatCom) or with a latency of less than an hour from a ground station. This presentation describes some of these products and their potential uses for wildfire response applications.

Additional keywords: aircraft fire mapping, thermal multispectral imagery, burning, sensor

Introduction

Data collected from aircraft have been an integral part of wildfire response and research for the last several decades. The workhorse instruments of wildfire response have been, for the most part, thermal-infrared sensors with adjustable gain settings used for detection and mapping of the hottest part of the fire, the flaming front. Orbital platform sensors such as Landsat Thematic Mapper (TM) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) provide a multispectral observation of fires, which have been used in the research community to extract detailed information on fuel condition, fire behavior, and fire severity. Orbital platform instruments offer the benefits of fully calibrated data for quantitative applications, and also offer a wider range of spectral bands; however, they lack the flexibility of airborne instruments for targeted observations, and therefore are hard to use for responding to active fire events.

The AMS-Wildfire sensor combines a multispectral, well-calibrated sensor with spectral channels (bands) ranging from near-UV to thermal-infrared, deployable on a variety of aircraft systems. The AMS-Wildfire processing system includes a near-real-time calibration and data processing suite that delivers raw data and derived fire products to wildfire responders on the ground while the aircraft is still flying. The goal of AMS-Wildfire is to bring the quantitative products that can be made with well-calibrated, multispectral data to wildfire responders via a flexible, airborne platform, and significantly improve the time lapse between acquisition and actionable data delivery to personnel on the ground.

1. The AMS-Wildfire sensor

The AMS-Wildfire sensor is an airborne multispectral imaging line scanner capable of semi-autonomous operations on both manned and unmanned aircraft (Fig. 1). The sensor is a modified Daedalus AADS-1268 scanning system with adjustable Instantaneous Field of View (IFOV) resolutions of 1.25 milliradian and 2.5 milliradian, with an angular field of view of 43° or 86°, respectively. Spatial resolution is variable, dependent on the sensor operational altitude. The system is configured with sixteen spectral channels ranging from the visible through short-wave-, mid-, and thermal-infrared (VIS-IR-MIR, TIR) wavelengths (Table 1). There are 16 active video channels and two 'housekeeping' channels, for total of 18 channels of data stored on the sensor disk. The maximum scan speeds are 33 revolutions-per-second (rps) for the 2.5mrad IFOV and 16 rps for the 1.25mrad IFOV. These are dictated by the speed limitations of the A-to-D converters (they have to run twice as fast for 1.25mrad pixel sampling.) These speeds are all at 1X over-sampling, but spectral over-sampling can be enabled, allowing more measurement observations over a given ground spot, by reducing scan speeds. The TIR channels simulate those found on the proposed Visible/Infrared Imager/Radiometer Suite (VIIRS) instrument, scheduled for orbital operations aboard the National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellite series. These two TIR channels replace the original AADS-1268 channels 11 and 12, which were wide-band (8.5-14μm) low- and high-gain TIR channels. The thermal-infrared (TIR) channels have been calibrated for accurate temperature discrimination with laboratory thermal targets capable of measurements between 0-850K. To increase the temperature range of measurements available in the MIR and TIR channels (bands 9-12), four duplicative channels (bands 13-16) were configured with the same spectral band-pass filter ranges, but at a different (lower) gain setting.

The AMS-Wildfire system employs a 16-bit analog-to-digital (A/D) converter to transform the individual band spectral measurements (by pixel) to digital numbers (DNs). The sensor collects 716 pixel samples in the cross-track direction, and continuous line collection in the along-track direction (flight direction). The sensor has been flown on manned and unmanned (UAV) platforms at altitudes ranging fro(5,000 feet) Mean Sea Level (MSL) to 19,817 meters (65,000 feet) MSL. Operations at varying altitudes and sampling at different scan speed rates (dependent on required 'oversampling' of ground features required), allows the flexibility of the sensor to map Earth surface phenomenon with a nominal pixel ground footprint of 3-meter to 50-meter (across-track dimension) spatial resolution.

Configuration for the Western States Wildfire Mission

For the Western States Wildfire Missions in 2006-2009 (see Table 2), the sensor was configured with the first 12 bands as shown in Table 1. The visible and near-infrared bands (1-10) used a linear calibration based on bench measurements with a calibration light source. The infrared bands (11 and 12) used two onboard blackbodies, at ambient and 303K, which were each

Table 1. Spectral-band wavelength specifications for the AMS-Wildfire sensor. The entries identified with (*) are redundant channels with different gain settings, used to improve the dynamic range detectable by the sensor. Campaigns before 2010 did not have these channels.

Band	Wavelength (μm)
1	0.42 - 0.45
2	0.45 - 0.52 (TM1)
3	0.52 – 0.60 (TM2)
4	0.60 – 0.62
5	0.63 – 0.69 (TM3)
6	0.69 – 0.75
7	0.75 – 0.90 (TM4)
8	0.91 – 1.05
9	1.55 – 1.75 (TM5) (high gain)
10	2.08 – 2.35 (TM7) (high gain)
11	3.60 – 3.79 (VIIRS M12) (high gain)
12	10.26 – 11.26 (VIIRS M15) (high gain)
13*	1.55 – 1.75 (TM5) (low gain)
14*	2.08 – 2.35 (TM7) (low gain)
15*	3.60 – 3.79 (VIIRS M12) (low gain)
16*	10.26 – 11.26 (VIIRS M15) (low gain)

scanned once per line by the thermal channels. This method provides the calibrated data some measure of stability against variations in voltage in the sensor electronics.

Modifications to sensor configuration for 2010 fire mapping campaigns

During the development of the NASA King Air B200 aircraft to supplement the Ikhana UAS and support AMS sensor missions in 2010, some modifications were made to the sensor system. As shown in Table 1, the infrared and thermal bands of the sensor were duplicated and each assigned a high-gain and low-gain channel. This dual-gain configuration is expected to improve radiometric resolution of infrared observations, and to eliminate saturation issues observed using the previous configuration (12 channels) over very hot fires. Additionally, sensor control on the B200 King-Air aircraft will continue with the instrument engineer operating the system remotely through a satellite communications link with the aircraft / sensor. That platform configuration was readied in November 2010.

Data delivery from AMS-Wildfire

The Level 1B product delivered from AMS-Wildfire is calibrated, geo-located, ortho-rectified, and matched with digital elevation model (DEM) data from the Shuttle Radar Topography Mission (SRTM) 30-meter elevation dataset. This product includes calibrated at-sensor radiances. Routines are available to calculate thermal brightness temperatures and surface reflectances from these data. In addition to the Level 1 product, the AMS-Wildfire data are used to generate a series of advanced products, which are described below.

Table 2. Major flight campaigns for the AMS-Wildfire sensor.The date ranges, number of flight (hours), and general geographic area are shown for AMS-Wildfire aircraft campaigns from the last 5 years. Dates for 2010 campaigns are approximate. More detail on specific flights is available online at: http://airbornescience.nasa.gov/instrument/instruments.html#AMS.

MISSION ID	YEAR	AIRCRAFT	FLIGHTS	HOURS	FIRES FLOWN
WSFM 2006	2006	Altair	4	68	Mono Lake Prescribed Fire, Esperanza Fire (CA)
WSFM 2007	2007	Ikhana	12	89	Zaca(CA), Tar(CA), Colby(CA), Babcock(CA), Jackrabbit(CA), Trapper Ridge(ID), Castle Rock(ID), W H Fire(MT), Columbine(WY), Hardscrabble(WY), Granite Creek(WY), Butler(CA), North(CA), Fairmont(CA), Grouse(CA), Lick(CA), Bald(CA), Moonlight(CA), GW Fire(OR), Big Basin(OR), Domke Lake(WA), South Omak(WA), Zaca(CA), BAER on Butler, Lick, Moonlight fires(CA), So. Cal. Fires: Harris, McCoy, Witch, Poomacha, Horno/Ammo, Slide, Grass Valley, Buckweed, Ranch, Magic, Santiago, Rice (all flown 3-5 times in 4 days of flights)
WSFM 2008	2008	Ikhana	4	21	All CA fires: Piute, Clover, Silver, North Mountain, American River, Cub Complex, Canyon Complex, Basin, Gap, Cascadel, Hidden, post-burn assessmen on Piute fire,
WSFM 2009	2009	Ikhana	2	11	Post-burn assessment on Piute and Station fires (CA)
TOTALS			22	189	60

The AMS sensor product data and imagery have been provided in a variety of geo-enabled formats, including GeoTIFF formats and Keyhole Markup Language (KML) formats. The KML formats are native to the Google Earth freeware application, and therefore allow an inexpensive, simplified client for visualizing the AMS data in a 3D rendering. Other standard Open Geospatial Consortium (OGC) product formats are produced allowing an enhanced browser-based viewing of the AMS wildfire products to be displayed on a user-selectable base-map layer such as Yahoo, Google Maps, OpenStreetMap, and Microsoft Bing. With the high spatial resolution of the data, and the ability to create near-real-time false-color composite imagery or generate standard vegetation indices, the AMS-Wildfire data provide a wealth of information for predicting movement and spread of fires.

2. Applications of AMS-Wildfire data

Uses for operational wildfire response

Effective wildfire response requires a large body of information about both the fire and the landscape surrounding it. AMS-Wildfire data and derived products can help meet these information needs with data that are timely, quantitative, and packaged for easy integration into other wildfire management tools.

Active fire information

In addition to the location and extent of the flaming front that can be obtained from a thermal infrared imager, AMS-Wildfire can provide quantitative thermal measurements of the area of active burning. Multispectral data from AMS-Wildfire makes it possible to retrieve the size and temperature of an active fire, even when the pixels contain unburned or previously burned areas (Dozier 1981). The thermal data from AMS-Wildfire can be used to directly estimate the radiative energy output of a fire (the 'Fire Radiative Power' (FRP)), which has been shown to relate quantitatively to the rate of fuel consumption (Wooster *et al.* 2005). This information is an important input needed to estimate the amount of smoke produced by a fire. In addition, AMS-Wildfire has excellent sensitivity to smoldering or otherwise low-intensity fires, thanks to the large dynamic range of the infrared channels, allowing an unsaturated estimate of various burning-stage temperature variations. The AMS-Wildfire sensor represents an upgrade over other airborne sensing systems in precision, accuracy, and dynamic range; it improves on current satellite sensors in terms of timeliness and high spatial resolution of its data. Fig. 2 shows an example from the Witch fire in southern California in October 2007, illustrating how AMS-Wildfire data can be used to extract information about the area of active burning which can be used as quantitative input to models of fire behavior and emissions.

Information on areas previously burned

Fire severity information is important input for a range of planning processes related to wildfire response both during and after the fire. During the fire, severity information can be used to:

- evaluate the re-ignition potential of areas the fire has passed through
- check the accuracy of fuel flammability information
- provide an easy and accurate map of areas the fire has passed through.

After the fire is extinguished, fire severity information is an important input for Burned Area Emergency Response (BAER), used to evaluate erosion hazards and prioritize landscape rehabilitation plans. Fire severity information from AMS can be used in the same ways or in conjunction with data from the Monitoring Trends in Burn Severity project, which uses Landsat data. Fig. 2 illustrates retrieval of burn severity from AMS-Wildfire data using the Normalized Burn Ratio (NBR), which is not quantitative but gives an estimate of the relative severity of different areas within a burn, as well as a means to compare severity among burns imaged by AMS-Wildfire (Epting *et al.* 2005).

Landscape context of burns

Response to wildfires requires information about the surrounding unburned landscapes to understand fire behavior and estimate potential risks such as erosion or landslide potential. The AMS-Wildfire suite includes a range of information useful for this purpose, all integrated into a single instrument footprint. The elevation data included with the products can be used to calculate slope and aspect, and to visualize the data in 3 dimensions (see Data Delivery, above). Information from visible and near-infrared channels can be combined to derive information on vegetation density and condition (Tucker and Sellers 1986).

Uses for fire science

In addition to applications for immediate wildfire response, the AMS-Wildfire is also a resource for scientific experiments aimed at understanding fire behavior, as well as characterizing other fire observing systems. The ability of the sensor to deliver quantitative thermal measurements provides an important means to test hypotheses about fire growth and severity. It also makes AMS-Wildfire a valuable tool for evaluating the data from other sensors with fire detection capability, such as MODIS, GOES, or the forthcoming NPOESS VIIRS system. Two critical AMS thermal fire-discrimination channels (channels 11 and 12, and 15 and 16), are duplicative of the spectral bandpass regions of the planned VIIRS system, and provide a pre-launch airborne assessment tool of expected data capabilities supporting wildfire observations. Detection algorithms using those channels will be critical to evaluating the efficiency of VIIRS TIR acquisitions for fire / hot target discrimination.

3. Next steps

Upcoming flight campaigns

A series of manned and unmanned platform wildfire observations with the AMS are planned for 2011 and beyond to support both fire science mensuration and disaster incident management teams on emergency events. The WRAP team is configuring the sensor for operations on two Beechcraft B200 King-Air platforms; one operated by NASA and the other operated by the U.S. Forest Service. Operations on the manned platforms will allow an improved capability to respond faster to wildfire events and preclude the need for advanced notification to the Federal Aviation Administration (FAA) as was the case for UAS operations. The sensor is being configured to allow sensor engineering / payload operations to be performed on the ground, through a SatCom data telemetry link. This will remove the operator from the aircraft, allowing an improved safety margin and also allowing a greater fuel weight capacity to extend mission durations. Operations on a U.S.F.S. aircraft will additionally allow a greater number of wildfire conditions to be sampled over a given fire season, since the platform / sensor will be performing 'operational' missions supporting fire response needs.

Applications under development
The WRAP team and associated scientists are developing further critical wildfire-related on-board-processed data products for evaluation and adaptation by the community. These products include both pre- and post-fire spectral products as inputs to assess burn severity in a given ecosystem through delivery of autonomously-generated Normalized Burn Ratio Difference (DNBR) data sets. Additional data sets and algorithm development, supporting wildfire management needs, are also under evaluation and implementation.

4. Acknowledgements

The authors acknowledge the support of the National Aeronautics and Space Administration (NASA) through grants NNX09AT09G and REASoN-0109-0172 and ARRA grant No. NNX09AW28A awarded to support this work. We are also grateful for the support of: S. Buechel (BAERI), S. Wegener (BAERI), D. Sullivan. Myers (UCSC), T. Hildum (UCSC), R. Dominguez (UCSC) who supported AMS mission operations with algorithm development, modeling, and data provision. We also would like to acknowledge the wildfire management community members who engaged us in defining observation criteria and metrics that allowed us to help improve their wildfire / disaster mitigation capabilities.

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Keeping Up With the Changing Landscape in Wildland Fuels (ToFuΔ a Practical Tool for Fire and Fuel Managers)

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Abstract
LANDFIRE fuels data were developed from national scale existing vegetation type (EVT), existing vegetation cover (EVC), existing vegetation height (EVH), and biophysical setting (BpS). From the original LANDFIRE National Fuels Layers (LF 1.0.0), local input from fire and fuels specialist from across the country was sought for input into the national database to calibrate the fuel characteristics on a more mid level scale. The Total Fuel Change Tool (ToFuΔ) was developed from this calibration process to quickly produce maps where local experts could view their proposed fuel characteristics changes. Because vegetation, and thus fuel is in constant change, the need exists for a systematic method to reflect those changes spatially to accurately assess the fire behavior that could occur from site to site.

ToFuΔ works through an MS Access database to produce geospatial layers in Arc Map based on rule sets devised by the user which principally take into account the EVT, EVC, EVH, and BpS from LANDFIRE grid data. There are also options within ToFuΔ to add discrete variables in grid format through the wildcard option, or to subdivide specific areas for different fuel characteristic assignments, with the BpS grid.

The size of the area chosen for assessment is defined by the user through the Management Unit (MU) determination; then refinements of the fuel characteristics within the MU are made through rule sets made up of EVT, EVC, EVH, BpS, and any wildcard that might be used. The most common output, once the user determined changes have been made to the fuel characteristics, is the creation of revised spatial grids for use in fire behavior analysis or planning endeavors.

Additional keywords: LANDFIRE, fuel characteristics assignments, existing vegetation type, existing vegetation cover, existing vegetation height, biophysical setting.

Introduction

LANDFIRE (2010) is a National scale project whose primary mission is to spatially describe the fuel characteristics of vegetation types in 30m dimensions continuously throughout the conterminous United States, Alaska, and Hawaii. Due to production time frames, uses for National level analysis, and available ground-based information, the first National LANDFIRE Map (LF 1.0.0) lacks local application in many fuel characteristics assignments (fire seasons 2007, 2008, 2009 after action reviews). Some of the major advantages of LANDFIRE data are its format, which is compatible with fire behavior processors like FARSITE (Finney 2008), and its capability to describe fuels continuously across ownership boundaries. With easily accessible data available from LANDFIRE in the format needed for use in fire behavior processors, fire and fuel specialists will be able to modify the coarse fuels data to more accurately reflect regional and local conditions.

ToFuΔ was developed by LANDFIRE for fuel characteristics editing and includes many comprehensive methods to accomplish refinements in fuel data for large and small landscapes. The routines based in ToFuΔ are set to the LANDFIRE classification system. Manipulation of data within those classifications is standard, but local information can be either re-classed to fit or brought into ToFuΔ for editing by other means.

As mentioned, LANDFIRE data is organized for fuel identification by EVT, EVC, EVH, and BpS by 30 meter pixels. The EVT depicts the vegetation life-form in terms of grass, shrub, or tree and describes the species which exist in particular vegetation systems. The EVT is identified by a number, name, and description which were developed by Nature Serve (http://www.natureserve.org/getData/vegData/nsDescriptions.pdf). The EVC is coded by number within the LANDFIRE classification system to indicate the life-form and the cover in ten percent increments. The EVH is coded by number within the LANDFIRE classification system to indicate lifeform and average height of the dominant vegetation in metric breakpoints. See ToFuΔ User Guide 3.1 (Tirmenstein *et al*. 2010) for a complete description.

ToFuΔ focuses on this triplet along with the biophysical setting to allow the user to edit surface and canopy fuel attributes dependent on life-form, vegetation type, and structure of the vegetation based on cover and height.

ToFuΔ installs with the default rule-sets and fuel assignments that exist for each map zone in LF 1.0.0. This gives the user a starting point to either accept the assignment or refine it to fit the situation on their site of interest. Analysis tabs are embedded in the Tool to help guide the user in determining the fuel model, or to design custom models as needed. The outputs from ToFuΔ are edited fuels and ancillary grids clipped to the size of the user-defined management unit and are ready for fire behavior processors.

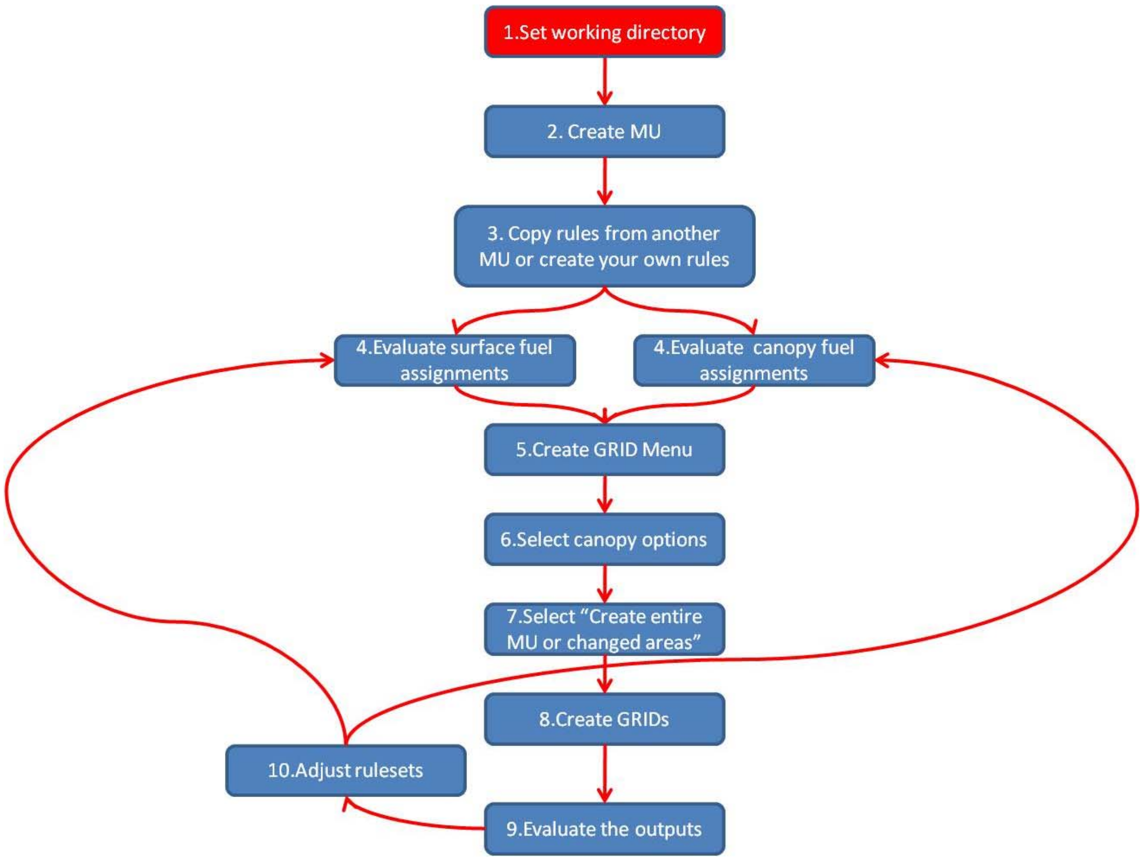
Applications

The ToFuΔ Tool was introduced and made available for distribution at the 3rd Fire Behavior and Fuels Conference (this conference) with an instructional session and poster display. The poster depicted a case study of a field application of the fuel characteristics editing capabilities of ToFuΔ.

The Bridger-Teton National Forest enlisted a specialist to revise the LANDFIRE national map fuels attributes to reflect specific conditions on their forest. Canopy characteristics (cover, height, canopy base height, and canopy bulk density), and surface fuel models were reviewed and edited by vegetation type. Recent disturbances were added in the form of changed surface fuel model and canopy attributes. The poster exhibited one such area, encompassed by the Green Knoll Fire, which had been classed by LF 1.0.0 as primarily a grass shrub (GS2) and timber understory (TU5) surface fuel model that was changed to a less active burning timber litter model (TL3) to reflect the recent fire activity.

Process

The following figures and text provide an overview on the use and capabilities of ToFuΔ.



1. Set Working Directory

Creating a filing system using good organization is an important first step. Create a new directory and project folder, if one does not already exist, with default LANDFIRE rule-sets or by importing to your new project folder from an existing project. A project folder stores a Microsoft Office Access database (MDB) and three folders: Input, Output and Management Unit (MU).

2. Create Management Unit (MU)

The Management Unit (MU) serves as the basic building block for changing fuel characteristics in a particular area. The extent of the MU is defined by the user and can be designated by drawing a bounding rectangle, or determined by the largest overlapping extent, the intersection of the required input grid layers. As new MUs are created, they will consist of a combined grid of the four mandatory grid layers from the LANDFIRE dataset and any optional grid layers the user inputs. They will reside in the MU folder. Four separate LANDFIRE datasets are required to build an MU and run ToFuΔ: Existing Vegetation Type (EVT), Existing Vegetation Cover (EVC), Existing Vegetation Height (EVH), and Biophysical Settings (BpS). All of these data layers are easily accessible from http://landfire.gov on the distribution site, and must be downloaded from the LF 1.0.0 or other LANDFIRE sources. Ancillary grids of slope, aspect, and elevation can also be downloaded and put into the combination, so they too are clipped to the extent of the MU and ready to be incorporated into the fire behavior processor as inputs.

For development and processing within the LANDFIRE Project, map zones were used as the standard area for analysis. The default dataset was processed by LANDFIRE map zone and consequently, rule sets for fuel characteristics that are within the default were calibrated and set at that extent. The grid layers EVT, EVC, EVH, and BpS (all set to the extent of each LANDFIRE map zone) were combined for processing.

Any other grid data that may have an effect on the fuel type within an EVT may also be used in the wildcard slot. For instance elevation may be used to differentiate lowland fuel models as opposed to upland areas in the same EVT. Management actions, proposed NEPA alternatives, historical fire data, aspect, or slope can be included as wildcard data to help clarify the fuel rule-sets.

3. Copy rules from another MU or create your own rules

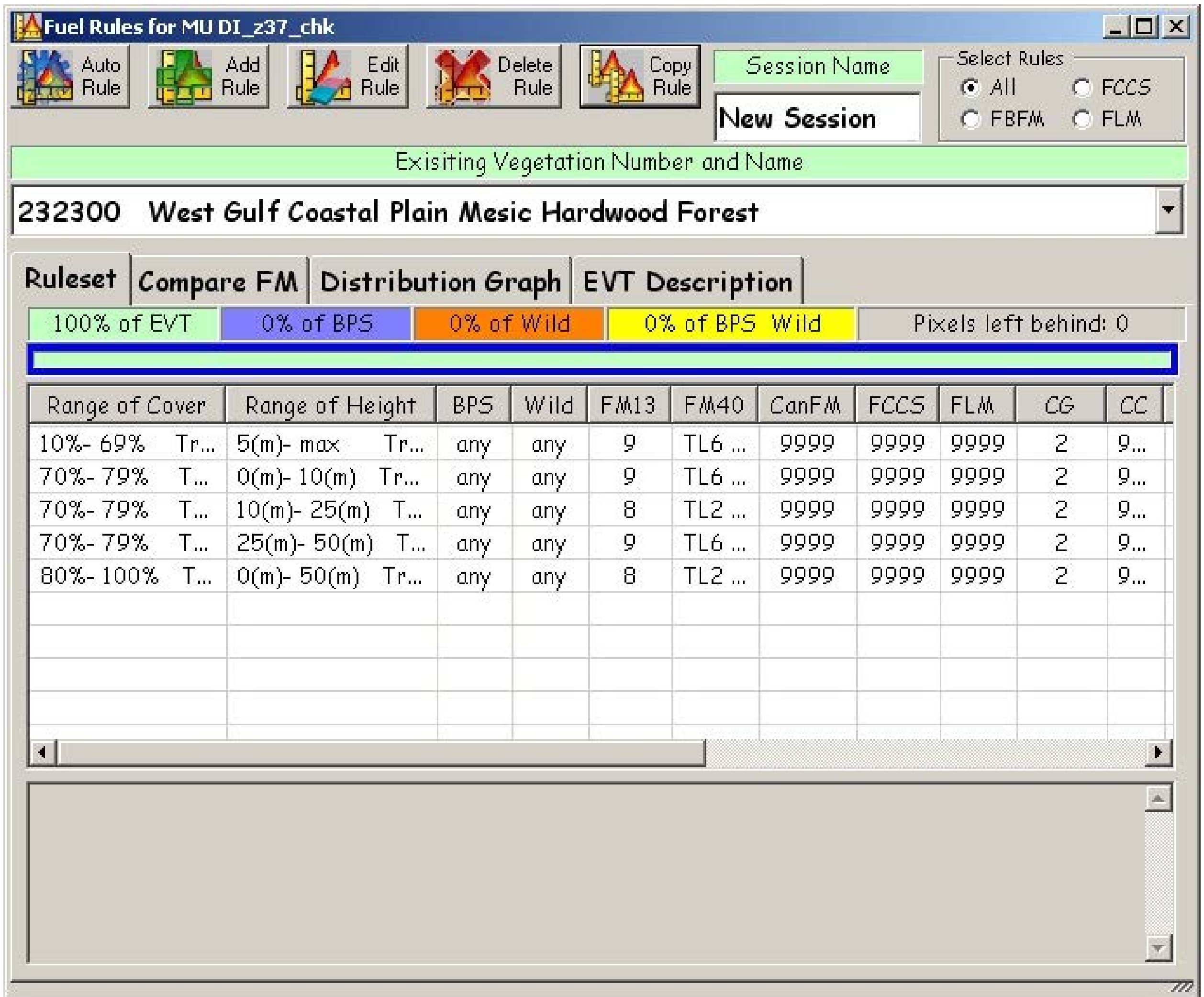
Select the MU you want to work with. Open the Fuel Rules interface to start working with the rule-sets. ToFuΔ users will spend most of their time working with this screen. Rule sets used to modify surface and canopy fuels are accessed here. If this is a new MU you can copy the rules from the default dataset for the surface fuel models. These rule-sets were developed by the LANDFIRE fuels team in conjunction with calibration meetings with local fuel experts. There is also the option to create your own rules if the defaults don't fit your area of interest. The Copy Rule input option gives the typical user a good starting point.

4. Evaluate surface fuel Assignments and canopy fuel assignments

There is a wealth of information within the rule sets as developed. Many users work with the FUEL Rules screen just to ensure that they understand the existing default rule sets before opting to make any modifications. The user should have good documentation and adequate reasons before making any changes to these rule sets. For additional information on calibration exercises and fuel model determination, see: www.landfire.gov

Once you have determined that the rule sets within the default dataset will suffice, or you have decided to make an MU with a revised set of rules, or to modify the existing rule set in the default data, you can begin to work with ToFu Delta's Rule-sset screen. From here, edits can be made to the copied rule sets and additional rules including BpS segmentations can be added. The Add Rule option can be used when there are no available rules to edit. The Add Rule option may be appropriate if rules exist and EVTs have been added but EVTs are populated by '9999' indicating 'no data', or when rule sets are split into new cover and height rules and there are no existing applicable rules to edit. Use the Edit Rule selection if rules exist but modifications are desired, such as when there is a need to adjust canopy cover or canopy height. The Auto Rule option creates Fuel Rules from existing surface fuel model layers. For this option to work, the surface fuel model layer must be included when creating the management unit. The Delete Rule option can delete rules that you no longer want (such as those that may conflict with other rule sets you have added).

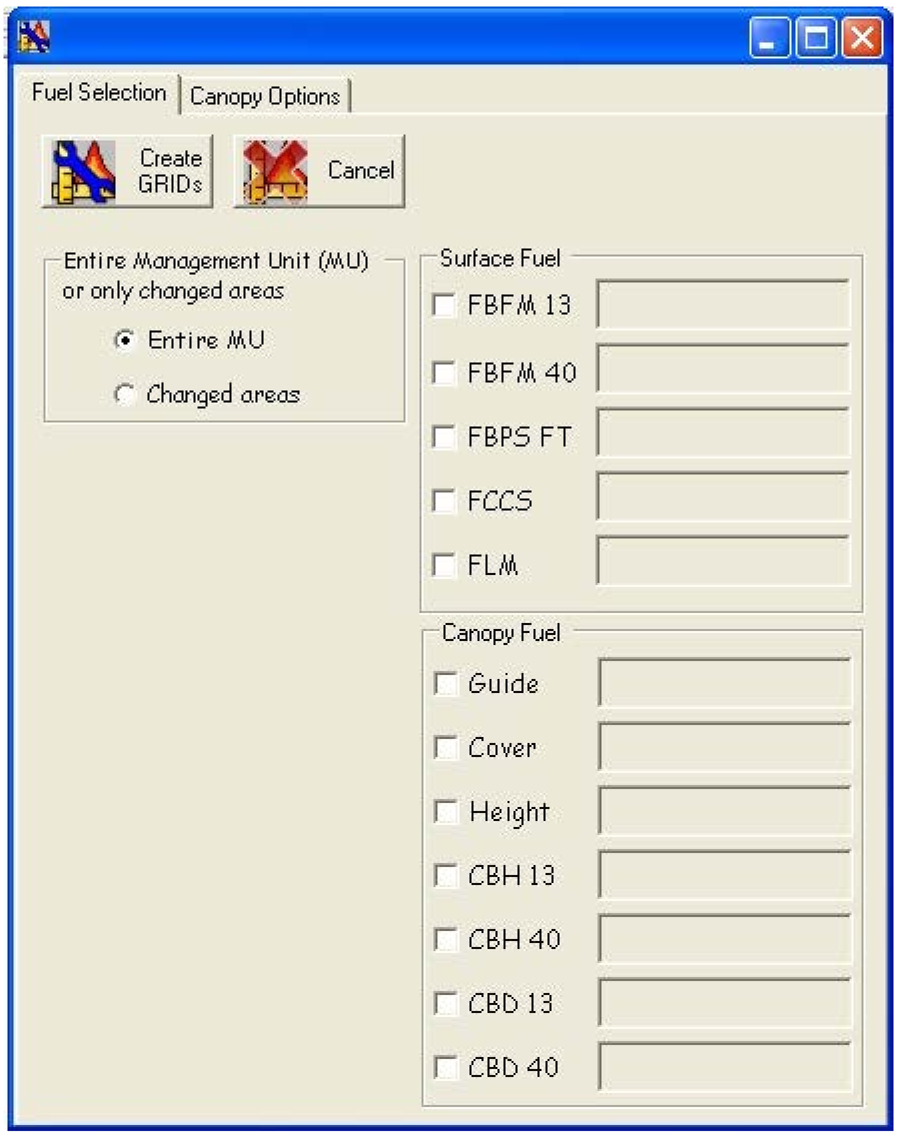
You can add or edit existing notes in the bottom section of the Fuel Rules page by double-clicking inside of that screen.



5. Create GRID Menu

Fuel characteristics can be edited or modified based on logical decisions determined by cover, height, vegetation and biophysical settings and incorporated into Fire Behavior Fuel Models. Once the fuel rules are added, deleted, or adjusted, you are ready to create the new layers.

Select FUEL GRIDs on the ToFuΔ toolbar drop-down menu. Use the Fuel Selection tab to create new fuel layers. Select the layers you want included by checking the boxes to the left of the grid. Name the layers to be created in the box to the right of the selection.



6. *Select Canopy Options*

If you altered any canopy parameters, click the Canopy Options tab and make the appropriate selections.

7. *Select 'Create entire MU or changed areas'*

Use the radio buttons in the upper left corner to specify if you would like these changes applied to the entire MU or Changed areas only (Options are 'Entire MU' or 'Changed areas'). Entire

MU creates new GRIDs of the full extent of the MU. The Changed areas option creates new GRIDs of just the areas that were altered for the last, 'Entire MU' created.

The Canopy Options tab allows you to make changes to the canopy layers by adding a coefficient to multiply by, or by using rules that are not '9999' in the rule sets, to overwrite the predicted value.
Check 'Also use rule values that are not 9999' and/or change all of the values by checking the 'Multiply by' box and entering desired values.

8. Create GRIDs

When finished with both Fuel Selection and Canopy Options tabs, make sure the Fuel Selection page is open, and click the Create GRIDs button at the upper left.

Errors in grid creation are usually due to mistakes with naming conventions or from using the same name. If any pixels are left behind a message will appear telling you that EVT has missing pixels and asking you if you would like to continue.

9. Evaluate the outputs and adjust the rules

There are many tools to help evaluate the rules and make any needed adjustments. The EVT Description page provides a summary of the concepts behind the vegetation type determination. It provides a geographical range as well as information on scale, soil, climate, and species. This page can help with determination of cover and height by breakpoints for the Fuel Rules. Follow the steps listed below to work with this page. Click on the EVT Description tab to open the page. Use the Existing Vegetation Number and Name drop-down menu to view a specific description of the EVT you specified.

The Distribution Graph tab opens a graph that shows the distribution of acres of classified cover and height by lifeform that exist in the grid data for the entire EVT or by BpS or Wildcard (if a wildcard is used in the MU grid).You can use the Distribution Graph page to view the height of the vegetation by cover and the numbers of acres present in the selected EVT within the defined MU.

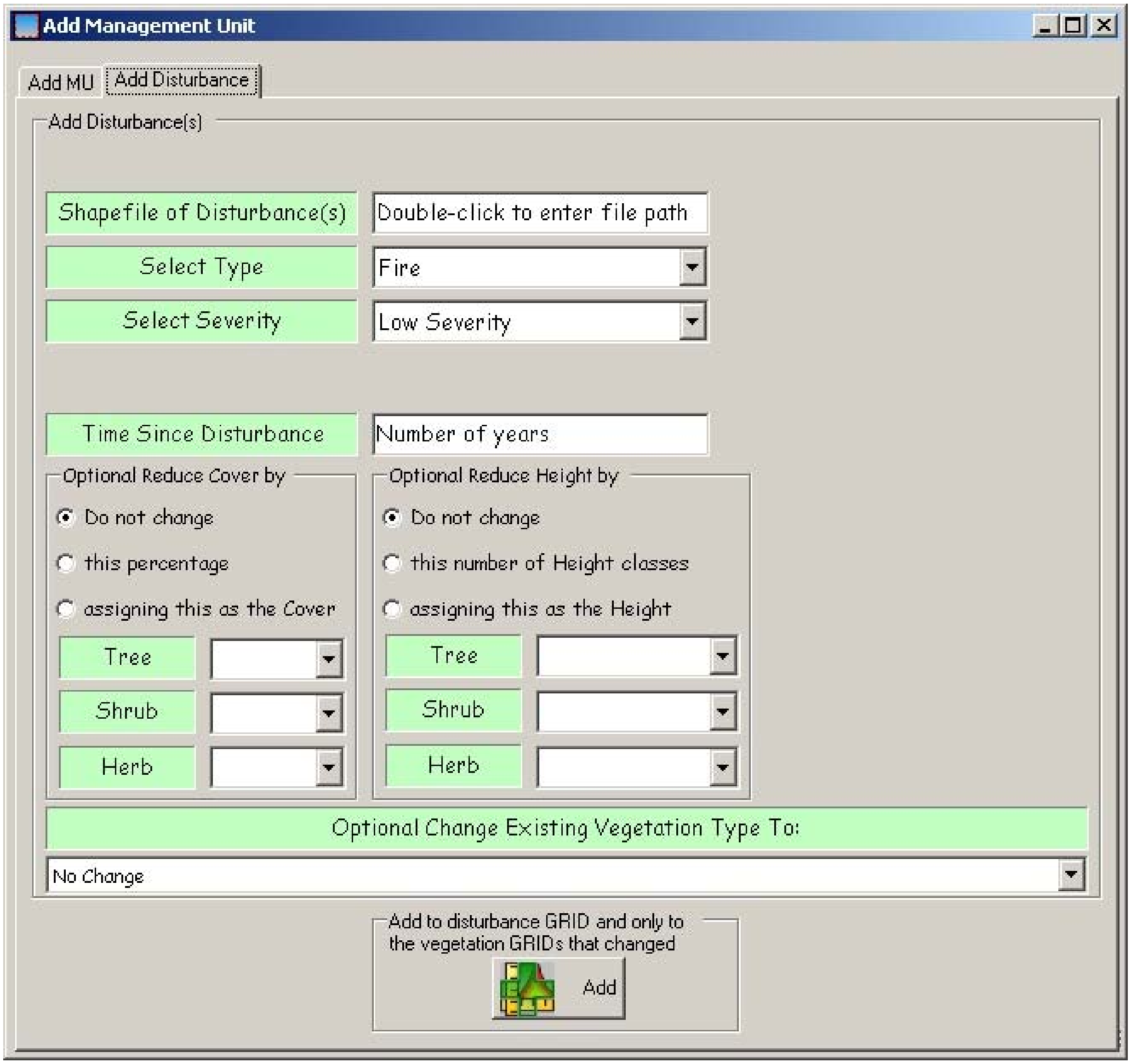
The Compare FM page graphically illustrates fire behavior traits such as Rate of Spread (ROS) and Flame Length (FL) for surface fuel models in the FBFM 13 and FBFM 40 systems at various fuel moisture regimes, wind speeds and slope. A graphic display of CBH range that would initiate crown fire behavior at various fuel moisture regimes, wind speeds, and slope is also included. Use radio buttons to select desired ROS or FL, percent Dead Moisture, and percent Live Moisture. Use drop-down menus to enter percent slope and desired fuel models for comparison. These options are very useful in determining FBFM 13, FBFM 40 and CBH for the fuel characteristics assignment displayed on the rule sets from the Ruleset sheet.

Fuel grid colors of your choice can be applied to Fire Behavior Fuel Models (FBFM 13) and (FBFM 40) as well as to the Canadian Fire Behavior Prediction System Fuel Types (FBPS). To apply fuel grid colors, click FUEL Color on ToFuΔ's drop-down menu.

10. Adjust Rulesets

Identify rulesets to change and make fuel adjustments. Go back to, 'Evaluate surface fuel Assignments and canopy fuel assignments' to work through the process multiple times until you are satisfied with your fuel layers.

Additional functionality of including disturbance data and altering existing vegetation data was added to an updated version that will be available soon.



Concluding Remarks:
The ability to have accurately assessed fuels for fire behavior projects in treatment planning and effectiveness, incident management, and NEPA analysis is now readily accessible with ToFuΔ. The edited fuels products developed in ToFuΔ are Arc Grids clipped to the MU ready for conversion and use in the fire behavior models. As fuels change across the users landscape, edits can be made to the fuel attributes in the LANDFIRE layers to keep them current. In the next version of ToFuΔ, disturbances, such as fire, mechanical treatments, wind damage, and insect and disease will be available as inputs by intensity level and by time since disturbance. This will allow updates to fuel attributes through a wide range of effects by applying disturbance data, or adjustments may be made from fuel attribute changes due to succession. The versatility of

ToFuΔ will allow local specialist the ability to reduce the scale of products, such as LANDFIRE, to the local project level with a user accuracy to fit multiple situations. ToFuΔ software, complete User Guide (Tirmenstein *et al.*2010), Tutorial (Kreilick 2010) and Help Utility are located at http://fire.org/nifft .

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Recreating historical fire return intervals and stand origin maps to capture historical fire regime conditions

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Abstract
Fire regime modeling was used to address an important issue with fire history data gaps, specifically with regards to the spatial extent of historical fires, which over time are obliterated by subsequent natural and anthropogenic disturbances. Using empirical data, thousands of years of simulated fire distributions under homogeneous fire regime characteristics were run, with the purpose of determining the historical spatial variation of Mean-Fire-Return-Intervals (MFRI) and mean age-class distributions. The simulation approach was an excellent tool for identifying dissimilarities between fire cycle, MFRI and weighted mean age values. It was also found that despite simulating homogeneous fire regimes, cumulative age-class distributions do show inflections, or a change in the slope. In the past, these inflections have been interpreted as changes in fire regimes, but the modeling approach demonstrated that this is not the case. The rates of burning do not remain constant and are associated with the natural range of variation, and pools of fire refugia in rugged landscapes. This exercise showed that we need to use caution with the interpretation of fire history data. Further, historical fire regime simulations were shown to be a key element in measuring departure from current conditions and a good planning tool for forest managers.

Additional keywords: mountains, foothills, fire cycle, age-class distributions

Introduction

Documenting historical fire regimes and, mapping the extent of historical burns, can be a challenging task due to the lack of historical records and/or fire history field data. The latter of which, is very resource intensive to collect over broadscale landscapes. As a result, field sampling is often limited to a handful of watersheds selected for their ability to exemplify a fire regime. While this process further enhances our comprehension of fire pattern dynamics, historical fire frequencies and Mean-Fire-Return-Intervals (MFRI) specific to a region, forest fire and timber managers can be left with significantly large areas with no spatial information on historical fire occurrences.

The management of forest fuels, via prescribed burning or mechanical means, require an understanding of historical conditions in order to assess fire regime and fuels departure as per the Fire Regime Condition Classification (FRCC) process (www.frcc.gov). Fire regime simulation modelling, in conjunction with fire history data representative of the area, was found to be a practical tool that provides spatial variations in fire frequencies, fire intervals and age-class distributions. A separate outcome of this computerized process was the ability to compare fire cycle values to MFRI and weighted mean forest age values, in order to evaluate discrepancies. Under a homogenous fire regime, these three parameters were thought to be interchangeable (Johnson and Van Wagner 1985; Johnson and Gutsell 1994; Van Wagner *et al.* 2006).

Fire regime modelling using STANDOR

STANDOR is a landscape disturbance model that uses documented fire frequency statistics endemic to the study area in order to emulate its long term fire distribution patterns. The model disperses fires over the landscape in a non-random fashion, based on the spatial distribution of causal factors of ignition. STANDOR was designed by the author and written by Ugo Feunekes from REMSOFT INC, New Brunswick, Canada. The technicalities of the model were published by Rogeau *et al.* (1996), and have only been slightly modified since. To summarize, STANDOR grows fires using formulas from the Canadian Forest Fire Behaviour Prediction System (Forestry Canada 1992) to calculate the rate of fire spread based on a combination of these elements: Fire Behaviour Prediction (FBP) fuel type, slope from a DEM, wind speed, FFMC (Fine Fuel Moisture Code) and BUI (Build-Up Index). The model makes use of a large fire weather data set from local and regional weather stations. To simulate a fire regime, additional GIS layers such as spatial probabilities of ignitions, spatial probabilities of burning that vary with topographic locations or fuel type, and fire weather zones, are used as inputs to dictate ignition patterns, fire spread patterns and which fire weather data set to use. A range of fire frequency values is also a required input along with the lapse time between fire occurrences (Table 1).

Historical fire frequencies are evaluated from fire history data collection and interpolated for those watersheds that do not have empirical data. For regions of Canada that have recently been populated (late 1800's - early 1900's), the total number of full and partial stand replacing historical fires can be estimated by using the 1:40,000 aerial photography dating from 1948-1952[1].

Table 1. Input GIS layers and data requirements to simulate a fire regime, and output maps and data sets provided by STANDOR.

Inputs	Outputs
- Digital Elevation Model map - Fire Behaviour Prediction (FBP) fuel map - Probability of ignition map - Probability of burning map (varies between spring/fall and summer seasons) - Fire weather zone map - local and regional fire weather data, last 20 to 25 years - simulation length: 1000 years - number of iterations: 10 - age-classes: 10 years - start date of green (leaf-out) period - fire frequency range by decade	- Fire frequency map - Mean-Fire-Return-Interval (MFRI) map - Stand origin map - age-class distribution - burn area from each simulated fire, which can be used to calculate a fire cycle (FC)

[1]Most of Canada was flown between 1948 and 1952 and this aerial imagery data set offers a temporal benchmark from which comparisons can be set.

Running thousands of years of fire simulations provide tendencies in fire distribution and burning patterns, which are reflected in the MFRI and age-class map outputs. It was found that running 10 iterations of 1000 years of fire simulations produced the desired range of fire cycles typical of those fire regimes that have a mean fire cycle that is less than 300 years. For regions dominated with very long fire intervals, a simulation period of at least 2000 years would be more adequate. The use of a computerized fire regime simulation model has the advantage of keeping track of all fire sizes before being overlapped or completely obliterated by more recent fires. This fire size database allows the interpreter to sum up these values to determine the fire cycles, which in turn can be compared to the MFRIs and mean forest ages.

Case study

STANDOR was applied to Forest Management Unit R11, which is managed by the forest officers of the Clearwater District of Alberta Sustainable Resource Development. The 521,900 ha (5,219 km^2) region rests against the east boundary of Banff National Park and south-east boundary of Jasper National Park. R11 lies approximately between the Brazeau River to the north and the Panther River to the south. Its western portion is mainly composed of the main ranges of the Rocky Mountains and is part of the Rocky Mountain Natural Region, while the eastern fringe falls in the Foothills Natural Region (Fig. 1). Elevations range from 850m to 3560m and the forest is largely composed of lodgepole pine (*Pinus contorta* Dougl. Ex Loud. var *latifolia* Engelm.) at valley bottoms and on warmer aspects, and of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) at higher elevations. White spruce (*Picea glauca* (Moench) Voss) and trembling aspen (*Populus tremuloides* Michx.) trees are also common at lower elevations in the Foothills Region. Six fire regime regions, described in Table 2, were identified within R11 based on the combination of these elements: topographic characteristics (rock bound watersheds with discontinuous fuel cover vs broad fuel continuity among adjacent watersheds) and, probabilities of ignition (amount of lightning strikes and lightning fire ignitions, intensity and distribution of historical landscape human use).

It is important to stress that prior to setting the simulation parameters, a large amount of data was collected and analysed to document fire regime parameters (cause, size, seasonality, cycle, MFRIs, intensity, severity, spatial probabilities of ignition) under the current fire suppression conditions and under a pre-suppression / pre-settlement era. In relation to this entire research project, a three volume, 275 page technical report was submitted to the Government of Alberta (Rogeau 2009, 2010*a*, 2010*b*). This paper specifically targets the simulation component and what can be learned from these outputs.

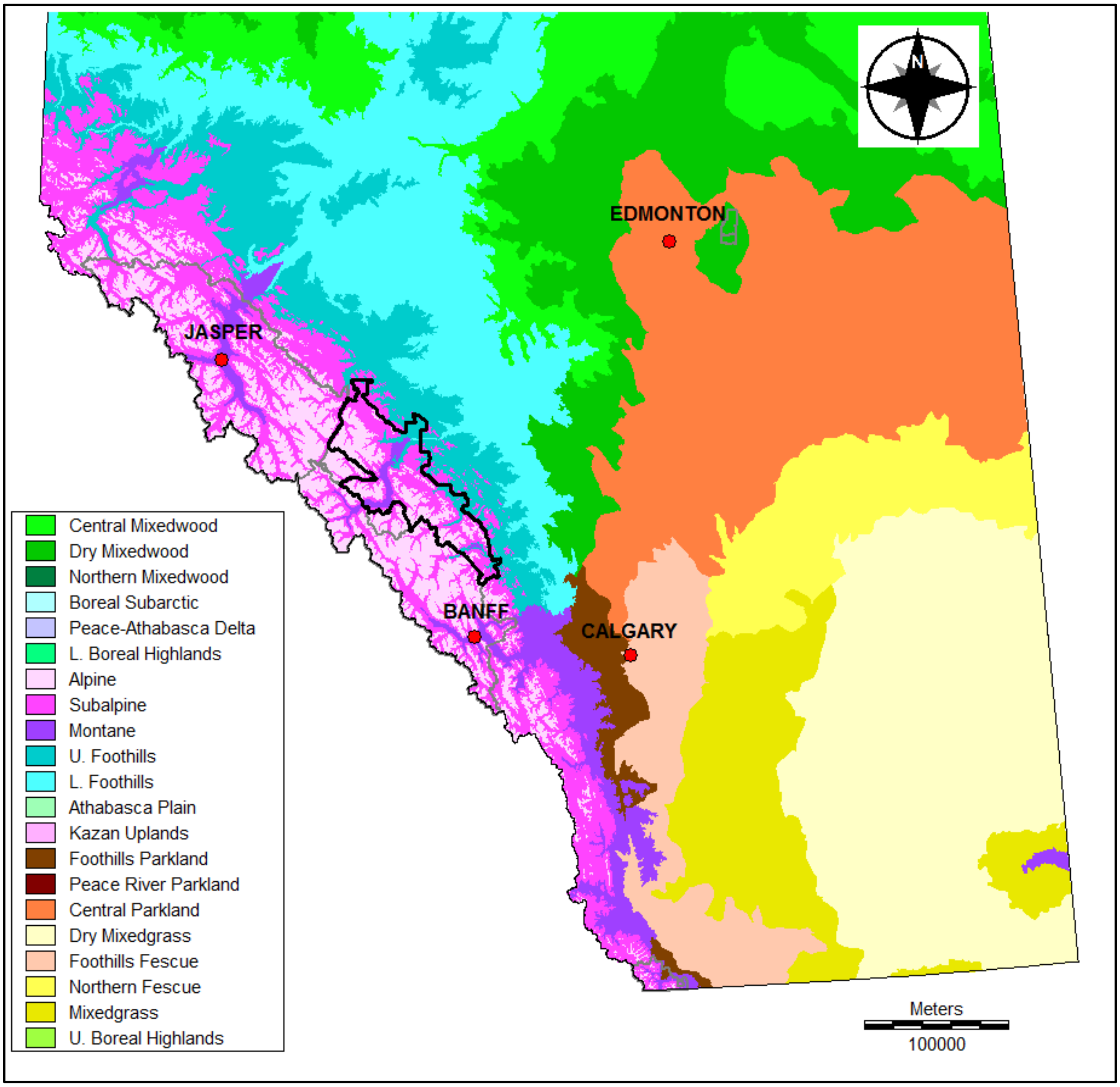


Fig. 1. Black outline shows the location of the study area: Provincial Forest Management Unit R11, Alberta.

Table 2. Description of the historical fire regime for six regions of Forest Management Unit R11. The average fire frequency by decade is provided, from which a range was determined. It is the fire frequency range that served as inputs in the fire regime model.

Fire Regime Regions	Historical Fire Frequency by Decade
Blackstone – Wapiabi Immediately to the east of an alpine setting (Brazeau-Coral Region), these valleys are only partially bound by rocks at their headwaters and by the Bighorn Range to the east. These contiguous valleys have an uninterrupted forest cover and are more likely to see larger size fires. Historical fire frequency was relatively low and almost non-existent after 1850. This region lies in the lightning strike shadow and sees few lightning fire ignitions (Wierzchowski *et al.* 2002).	0 = 4.28 fires Range: 1 - 7 fires Vegetated area: 42,372 ha
Brazeau – Coral This fire regime region encompasses watersheds that are bound by rocky ridges. This alpine setting contains narrow valleys that run in a perpendicular fashion to the major Brazeau Valley. As a result, the average fire size is small. Very few lightning fires are recorded, and with the exception of the Brazeau, human access is difficult. Its fire regime is dominated by stand replacing fires occurring at intervals often greater than 100 years.	0 = 3.76 fires Range: 1 - 7 fires Vegetated area: 27,305 ha
North-Saskatchewan Valley This region includes one broad valley at low elevations and its immediate tributaries. This valley has a tradition of human use and is affected today by a primary, paved access road. It is subjected to high winds and more clement weather. The large tracts of continuous fuel favour larger size fires. Fires occur more frequently, but with a fire severity that is lower.	0 = 9.5 fires Range: 6 - 14 fires Vegetated area: 63,814 ha
North Ram – Ram Headwaters of most watersheds are in an alpine setting and bound by rocky ridges, whereas the lower portions of these watersheds see large tracts of continuous forest cover. These variations in fuel continuity and valley sizes contribute to a wider range in fire sizes. Risk of lightning fire ignitions is low, human access is restricted and fire weather is not conducive to frequent burning.	0 = 5.64 fires Range: 2 - 10 fires Vegetated area: 60,760 ha
Foothills All watersheds drain directly into the Foothills subregion. Risk of lighting fire ignitions is greater, has a tradition of human land use and, has large tracts of continuous forest cover that are conducive to large size fires. Its historical fire frequency was greater, with short intervals between burning events, and the severity of fires was also lower.	0 = 5.64 fires Range: 2 - 10 fires Vegetated area: 41,867 ha

Clearwater - Red Deer This fire regime region is in an alpine setting where most tributaries off the main valleys are bound by rocks. While lightning fire ignitions is not frequent, both valleys have a history of traditional land use. Warm aspects and valley bottoms historically had more fires than the cooler aspects.	0 = 9.52 fires Range: 4 - 16 fires Vegetated area: 68,997 ha

Simulation outputs

At the end of each simulation run of 1000 years, two raster maps are created by STANDOR: a fire frequency count by pixel (1ha resolution was used) and a stand origin map (10-year age-classes). In turn, a MFRI map can be produced by dividing 1000 years by the fire frequency values. Despite the homogeneity in the fire regime modelled, it was observed that capturing a snapshot in time can provide very different age-class distributions and weighted mean stand origin ages. This is demonstrated in Fig. 2 that shows two map outputs following 1000 years of fire simulations. The natural range of variation in a fire regime can produce widely different stand age mosaics depending on the fire weather and fire frequency of the last few decades prior to the ‘snapshot’. This illustrates how using a stand origin map created from time-since-fire data can yield a skewed interpretation of the fire regime.

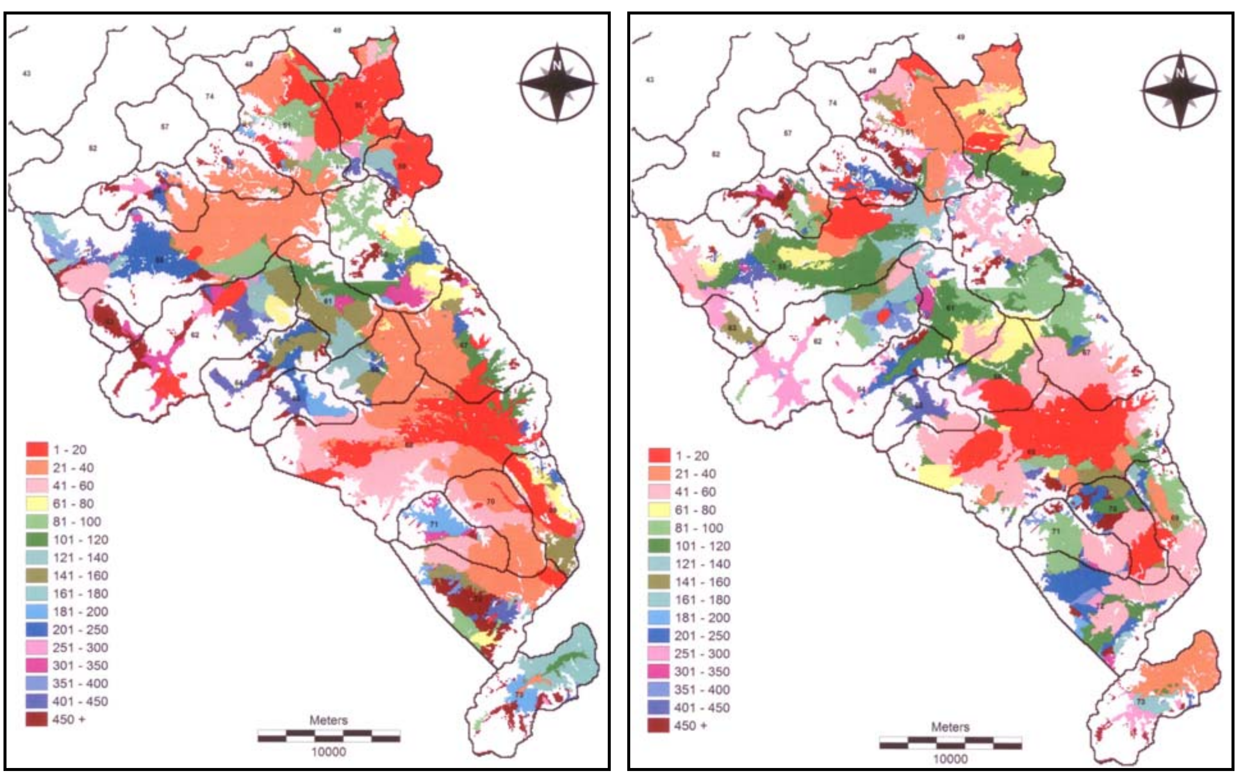
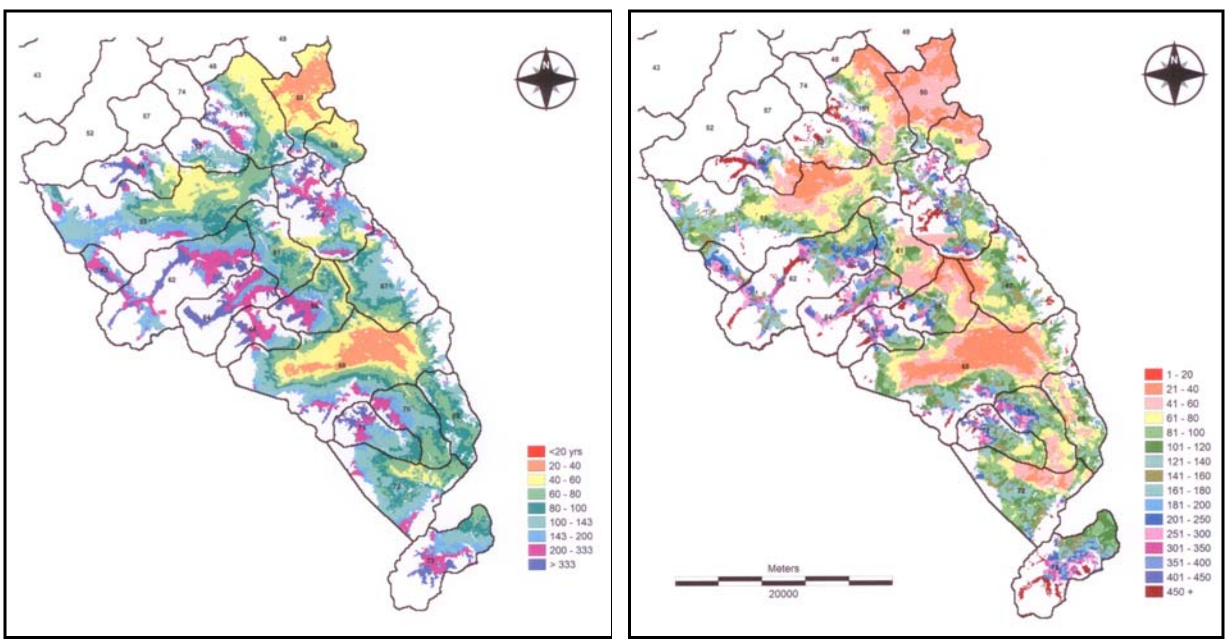


Fig. 2. Example of two stand origin maps created from two snapshots in time of a landscape under the same fire regime conditions.

Fig. 3a and 3b display the tendency results in MFRI and age-class distributions after averaging the ten simulations. The example provided is for the Clearwater-Red Deer Region, which is in the front range of the Canadian Rockies. As a general rule, the longest fire return intervals prevail at the headwaters, in narrow valleys and on cooler aspects. Similar tendencies were observed with the mean stand origin map where old-growth forests thrive in these fire refugia. At the other end of the spectrum, it was interesting to observe that areas with sustained MFRIs less than 60 years, will maintain large tracks of younger aged forests. For fire intervals ranging between 60 and 200 years, the outcome stand origin is very patchy, or fragmented, suggesting a wide variation in fire occurrences over time. In terms of fire and forest management, the spatial distribution of MFRIs and age-classes help delineate regions that have ecosystems that are most departed from their historical conditions. For instance, a region with 80 years of successful fire suppression would see a form of fire regime condition departure in all zones that have MFRIs that are less than 80 years, with the most severe departure for those zones that were subjected to a forest fire every 20 years or so. Further, the identification of fire refugia on the landscape also helps with forest planning as these areas can be preserved from broadscale harvesting and should also not be targeted for prescribed burning.



3a) 3b)

Fig. 3: a) Mean-Fire-Return-Interval map output; b) mean stand origin map output. Averaged from 10 map outputs. Clearwater-Red Deer region.

As introduced earlier, another aspect of the fire regime modelling approach was the ability to compare fire cycle values to weighted[2] mean MFRI values, and weighted mean forest ages. A fire cycle is defined as the number of years required to burn an area equal to the area of interest. During one cycle, some areas may burn more than once, while others may not burn at all (Canadian Interagency Forest Fire Centre 2003). Over the years, there have been several publications that discuss the calculation of fire cycles from Time-Since-Fire data obtained from a stand origin map, and how to interpret the temporal fluctuations in the age-class distributions (Johnson and Van Wagner 1985; Johnson and Gutsell 1994; Finney 1995; Reed *et al.* 1998; Van Wagner *et al.* 2006). One statement that prevailed was that everyone seemed to agree that in order to apply any of these statistical methods, the fire regime must be spatially homogeneous. Also, any temporal changes in the fire regime (i.e. changes in the fire cycle) is reflected by an inflection, or a change in the slope angle, in the age-class distribution.

A strong asset of the computerized fire regime modelling process was the ability to determine that despite maintaining a homogenous fire regime through time, cumulative age-class distributions did show inflections when plotted on a negative exponential scale (Fig. 4). The multiple iterations conducted revealed that these inflections occur at different points in time and are not consistent. Inflections are explained by a couple of elements. First, by the natural range of variation in the fire regime, which can be triggered by either a sharp increase in burning as a result of a severe drought period, or by little fire activity resulting from wetter than normal conditions. Second, the presence of significant amount of fire refugias that are maintained for hundreds of years due to their topographic location, most often create an inflection to produce a steeper slope in the cumulative age-class distribution around 250 to 300 years since the last fire. This is particularly obvious in the Clearwater-Red Deer and Brazeau Regions, located in a rugged portion of the Rocky Mountains, which have many rock bound watersheds. This phenomenon has been falsely interpreted by many (Johnson *et al.* 1990, Johnson and Larsen 1991 and Van Wagner *et al.* 2006) as a temporal change in the fire regime, coinciding with an increased rate of burning (i.e. a shorter fire cycle).

[2] A weighted mean is the sum of all unique values multiplied by their surface area.

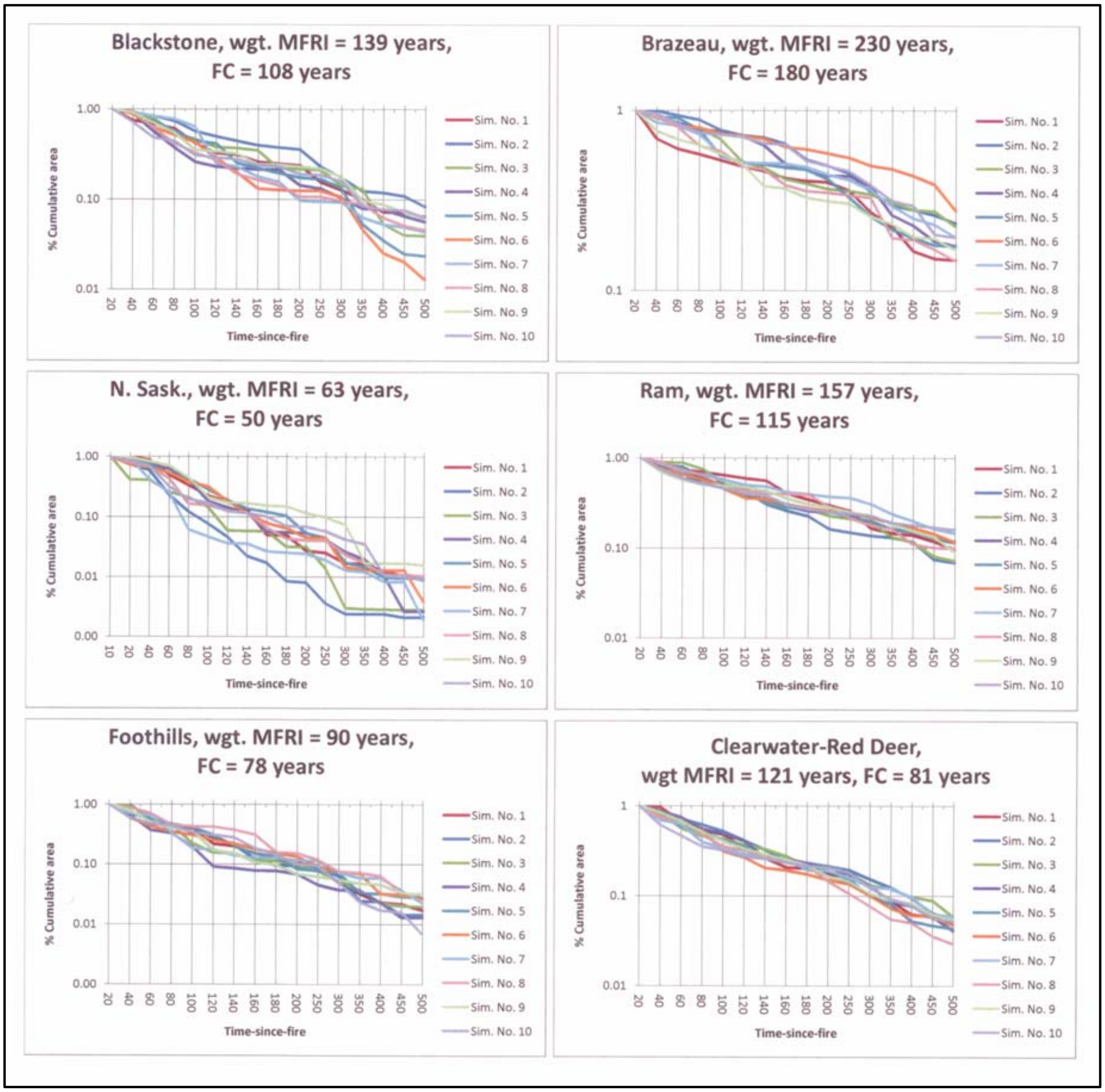


Fig. 4. Fluctuations in cumulated age-class distributions attributed to the natural range of variation of the fire regime, and pools of fire refugia found in rugged landscapes.

The modelling of six different types of fire regimes shed some light on the crucial need for the fuels, topography, fire weather and, probabilities of ignition to remain homogenous across the landscape for analysis purposes. It was found that fire cycle values, weighted MFRIs and weighted mean forest ages tend to converge when homogeneity criteria are respected. However, in rugged landscapes where fire refugias develop, such as many areas of the Canadian Rockies, we see a greater divergence in these values, notably when MFRIs vary significantly across the land. Table 3 presents the fire cycles, weighted MFRI and weighted mean age values that were calculated for each of the fire regimes modelled. It was found that the North-Saskatchewan Valley and Foothills regions, which have both continuous fuels and less variance in their topographic features, have fire cycle, weighted MFRI and weighted mean age values that are fairly similar with differences that are less than 20 years. For the other fire regime regions, which are found in rugged landscapes, fire cycle values cannot be a substitute for the weighted MFRI or weighted mean age due to their great divergence. In this respect, by definition a fire cycle provides us with an overall rate of burning value and does not capture the spatial variation that can occur within a landscape. A useful tool however, is the weighted mean age, which appears to capture quite well the weighted MFRIs. Seventy percent of the time, the weighted mean age will be within 10 years of the weighted MFRI and occasionally it can be as great as 30 years (data not presented). For the tendency MFRI and stand age maps (produced from averaging 10 maps), the weighted mean age can be within 12% of the weighted MFRI.

Table 3 Fire cycle (FC), Mean-Fire-Return-Interval (MFRI) and weighted (wgt) mean age values produced for six separate fire regime simulation outputs.

Fire regime statistics	Brazeau	Blackstone	N. Sask.	N. Ram	Foothills	Clearwater
Number of FC in 1000 yrs	49	88	196	82	123	119
Average FC	180	108	50	115	78	81
FC STD around the mean (FC range)	+/- 31yrs (149 to 211)	+/- 27yrs (81 to 135)	+/- 15yrs (35 to 65)	+/- 25yrs (90 to 140)	+/- 19yrs (59 to 97)	+/- 17yrs (64 to 97)
Minimum & Maximum FC	130 to 280	50 to 180	20 to 90	60 to 180	40 to 130	40 to 120
weighted MFRI	230	139	63	157	90	121
weighted mean age	217	123	63	168	98	119
FC - weighted MFRI	-50	-31	-13	-42	-12	-40
FC - weighted mean age	-37	-15	-13	-53	-20	-38
wgt MFRI - wgt mean age	13	16	0	-11	-8	2
percent accuracy (MFRI-age)	5.65	11.51	0.00	-7.01	-8.89	1.65

STD = standard deviation

Concluding remarks

We need to change the way time-since-fire data from fire origin maps are analysed. A single snapshot in time does not necessarily capture what should be the modal rate of burning and modal age-class distribution. Further, any variations in the slope of a cumulative age-class distribution does not automatically indicate a change in the fire regime. As the computer fire regime modelling demonstrated, it can 1) reflect a change in the rate of burning due to the natural variation in the fire regime and, 2) indicate the presence of pools of fire refugia that are able to escape burning for hundreds of years. These findings ascertain that time-since-fire distributions from mountain landscapes have been mis-interpreted for years and that they do not give much insight to the long-term fire regime. Weighted mean ages calculated from a variety of spatially explicit topographic features are more likely to provide information on historical MFRIs within a region of similar fire regime conditions.

Acknowledgements

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Georeferencing Historical Photos to Quantify Century-scale Changes in Forest Structure

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Abstract
Throughout western North America, past fire exclusion policies have had many detrimental ecological effects, including a fundamental restructuring of vegetation along the east slopes of the Alberta Rocky Mountains. As shown by a comprehensive systematic repeat photography survey, the Mountain Legacy Project, forested areas today are more prevalent, dense, and homogenous in structure and composition than they were at the start of the 20th century. It is hypothesized that these changes in structure and composition have elevated the probability of large, severe wildfire events, but these changes have not been quantified. This paper describes: A) the findings of a pilot project which was designed to georeference these historical photographs, and B) a proposed application of this method to quantitatively measure changes in landscape diversity and fuel structure on the east slopes of the Rocky Mountains of Alberta. With this information, land managers can gain an understanding of how the systems have changed over the past century. This will provide quantitative measures and targets that can be used for managing vegetation on a landscape scale. By fully exploring the potential of these photos using innovative techniques, we may be opening up an entirely new area of decision-support for land managers.

Introduction – An Altered Landscape

It has been observed from a variety of sources that the structure of the ecosystems along the North American Rocky Mountains has changed considerably over the past century. In addition to climate change, the most significant driver of this change is thought to be a fundamental disruption of the natural disturbance dynamics of the region caused by modern European settlement. This settlement brought fire suppression, fire exclusion, railway construction, land clearing, the removal of First Nations, and numerous other land use changes.

In Canada, these changes occurred in the mid to late 19th century, however, we are seeing how these changes, and specifically fire exclusion policies, have had many detrimental ecological effects throughout a much wider swathe of western North America. The vegetation on the landscape is more homogenous in structure and composition than it was at the beginning of the 20th century. These ecosystem level changes have been hypothesized to have caused:

1. Decreased landscape diversity and local biodiversity as a result of increased forest cover and homogenization of the landscape. Increased forest cover has come at the expense of

grasslands and alpine meadows, which are home to a majority of the endangered species of the region.

2. Increased susceptibility of forests to mountain pine beetle (due to massive increases in mature lodgepole pine cover throughout western North America.
3. Elevated probability of large, severe wildfire events. Fuel complexes are more continuous, and fires that would have burned at low to moderate severities through grasslands and open canopy forests are now more likely to burn as large crown fires.

These effects, coupled with the uncertainty of how climate change will affect these ecosystems into the future, leave this landscape vulnerable to disturbances well beyond its natural range of variability.

How have these ecosystems changed?

Land managers are actively managing this altered landscape in the hopes of restoring ecosystem resilience and diversity, and thus reducing the probability of catastrophic wildfire and mountain pine beetle disturbances (Alberta SRD, 2010). However, there is little quantitative information upon which to base management targets. An understanding of historic landscape structure and ecosystem dynamics would help set these targets, but current stand reconstruction techniques and fire regime analyses often lead to conflicting conclusions (Johnson et al, 1994) regarding the structure of the ecosystems from a century ago. Historical data would provide the most accurate information on how the landscape has been altered since European settlement and development.

The Mountain Legacy Project (MLP) provides us with an invaluable view of this past. These photographs confirm much of what other research has suggested. At the time of European settlement, there was a dramatically different landscape than today: total forest cover was less prevalent, alpine treeline was at lower elevation, glaciers were larger, there were fewer mature forest stands, and grassland and meadow cover were significantly greater. Rather than relying on stand reconstruction and other methods that infer what the historical landscape looked like, the MLP photos can be used to measure exactly what it looked like at a coarse vegetation scale.

The Mountain Legacy Project

The Mountain Legacy Project (Higgs et al, 2009) is the largest repeat photography project in the world. More than 140,000 images from the western Canadian mountain regions were taken by several surveyors from the late 19th to the early 20th centuries. These images were taken using large format cameras with 4” by 6” glass plate negatives, which reveal astonishing clarity. More than 4,000 of these images have been repeated by taking images from the exact locations as the originals, allowing researchers to examine historical landscape change (see Fig. 1). These repeated photographs are referred to as “paired images”. The Mountain Legacy Project is based at the University of Victoria under the leadership of Dr. Eric Higgs.

The detail in the original photos is very high. Coarse scale vegetation patterns are visible at significant distance from the camera station in most images. While the MLP images have been used frequently to qualitatively show landscape change, they have only been used infrequently to quantitatively assess these changes. These studies (Rhemtulla, 1999; Watt-Gremm, 2004) have been restricted to small landscapes due to the lack of a user friendly method that allows for spatial interpretation of the images.

Fig. 1: Paired images taken from Jumping Pound Summit Station 1 (Image 9-4), Wheeler Irrigation Survey. Top image taken between 1895-1897, bottom image from 2009 (Higgs). Image shows advancing treeline in foreground and background, and densification

Georeferencing images for quantitative analysis
In the pilot study (Stockdale et al, 2010), our objective was to identify an existing solution(s) for georeferencing land-based photographs and test its applicability to the MLP images. The freeware Corripio Application (Corripio, 2004) (Fig. 2), written on the IDL Platform has been successfully tested in similar studies. The process combines the image to be referenced with a

digital elevation model (DEM) and creates a georeferenced image that can be examined in a GIS program to create spatial data.

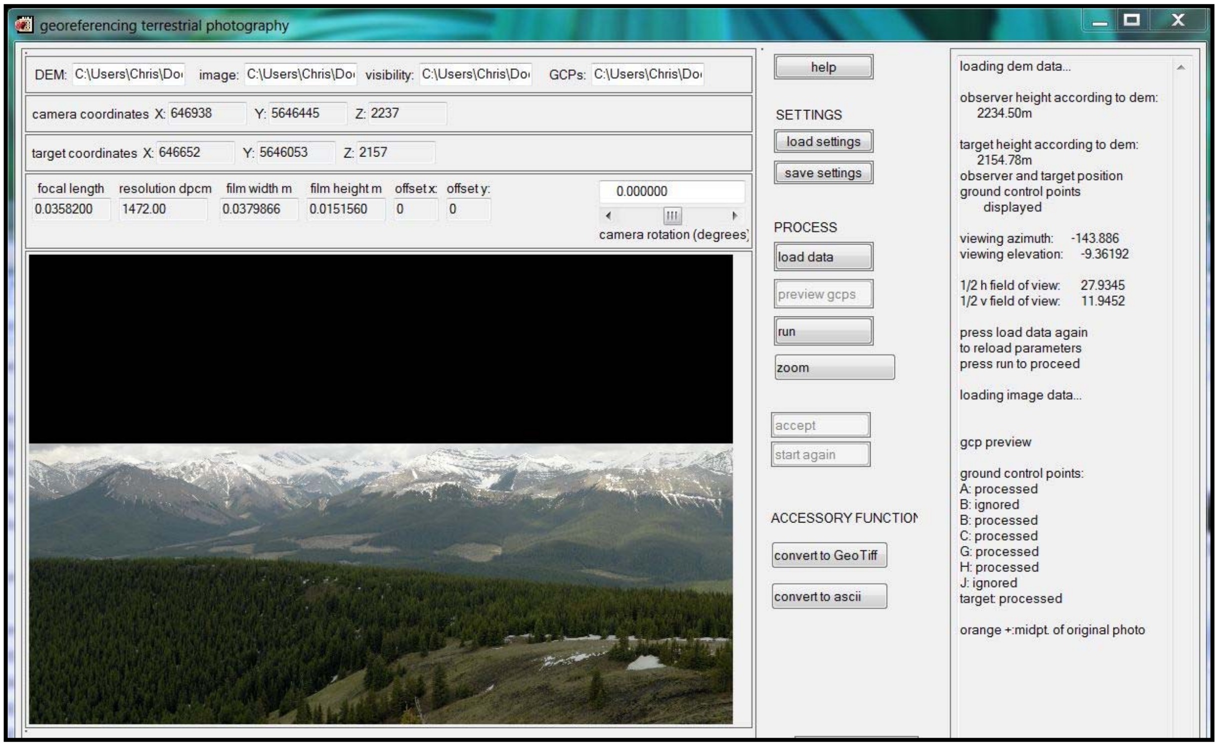

Fig. 2: Screen capture of the Corripio Application with Jumping Pound Summit Station Image 9-4 loaded for georeferencing.

The process requires two accurately located points: the point of view (camera coordinates), and the image centre point (ICP, or target coordinates). In order to evaluate the accuracy of the georeferencing process, the non-referenced retake photos and aerial orthophotos covering the same area were used. Distinctive features that were clearly visible in both the oblique and aerial orthophotos were located and the spatial location was marked on the photos. The distance between the oblique photo point and corresponding aerial orthophoto points were measured. In total, 33 reference points were chosen in six photographs from the Jumping Pound Summit and Moose Mountain Centre stations. The mean error in the distance between the Corripio Application referenced photo and its real-world location (as determined from the aerial orthophotos) was 37.7m (standard error = 4.9m, see Fig. 3). This error is directly proportional to the accuracy of the location of the ICP.

Relative distances and spatial extents within the images themselves were accurate. Polygons were drawn on both sets of photographs to determine if the area measured (and therefore relative distances between points) was accurate. Thirty polygons were drawn in the same six photos using cutblocks or meadows as distinct objects to measure. While sizes did not perfectly agree, they were never more than 20% in disagreement, and there was no directional bias leading to the conclusion that there was no significant difference in the sizes of cutblocks or meadows measured in the oblique versus aerial photographs.

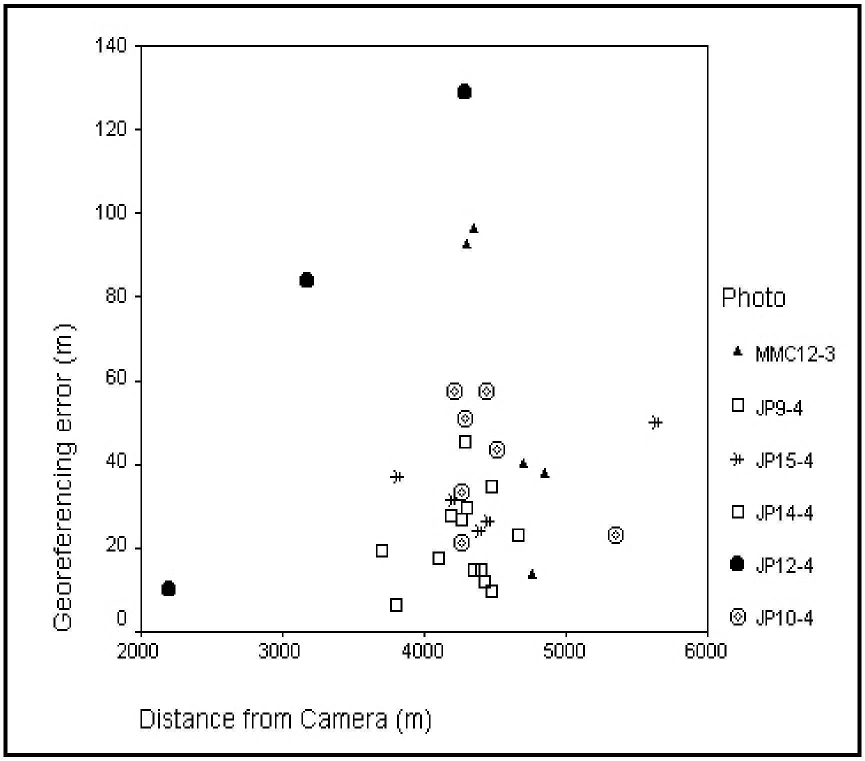

Fig. 3: Scatterplot showing georeferencing error relative to distance from the camera.

The referencing process degrades the images to the resolution of the input DEM, making subsequent interpretation impossible (see foreground of Fig. 4). We determined that interpretation of images prior to the georeferencing process is a better approach. While we have only finished initial testing of this concept, we have identified numerous improvements to the method to make the process more accurate. Most of the improvements require modification of images prior to processing. Higher resolution DEMs will make significant improvements too. The test images were georeferenced using a 10m DEM. Smaller sub-images could be processed on a 1m DEM (computer memory limits prevented this in the pilot study using whole images).

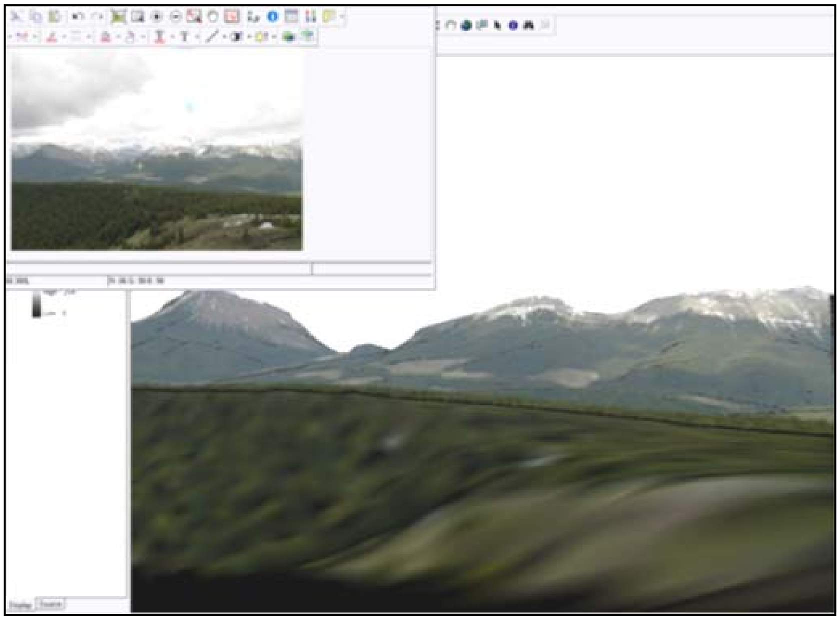

Fig. 4: Georeferenced image from Corripio Application showing loss of resolution of the image due to resampling to the scale of the DEM.

Why does understanding historical landscapes matter?
Forested areas are more prevalent, dense, and homogenous in structure and composition today than they were at the start of the 20th century. Coinciding, and quite possibly the result of this past-century shift in landscape condition is the epidemic scale arrival of the Mountain Pine Beetle (*Dendroctonus ponderosae*) in Alberta, and the potential for massive, and intense wildfires.

By georeferencing the MLP photos, we will be able to measure precisely how this landscape has changed, and what the consequences of that change have been over the past century, and may be for the future. The historical landscape condition has been examined by numerous methods, but all rely upon inference, often leading to conflicting conclusions (Johnson et al 1994). Meanwhile, management continues apace with the objectives of lowering risks from MPB and wildfire. With this information, it may be possible to restore ecosystems at the same time.

This work can provide quantitative targets for management to work towards, and test the hypotheses that the historical landscape was indeed more diverse, and less prone to fire and insects and disease.

Where does this go next?
The work outlined in this poster is the basis for a PhD project beginning in 2011, the objectives of which will be to:

1. Refine Geographic Information System (GIS) methods for classifying, georeferencing, and quantifying the landscape changes visible in the MLP photos using open-source GIS tools.
2. Measure changes in landscape diversity, vegetation structure, treeline migration, and forest encroachment on meadows and grasslands, and test hypotheses regarding the synecological processes driving these changes
3. Examine the effects of human land-use patterns (fire suppression, fire exclusion, settlement, transportation) on changes in landscape diversity, and
4. Use the historical landscape structure to model and measure changes in wildfire risk and mountain pine beetle susceptibility of the landscape.

Acknowledgments
Foothills Research Institute's Mountain Pine Beetle Ecology Program provided the funding for the search and test for methods of georeferencing oblique photos. The GIS work and initial testing of the Corripio Application was done by Katelyn Loukes and Oliver Clovis while taking their Advanced Diploma in GIS at the British Columbia Institute of Technology. The Mountain Legacy Project staff and students aided in data support. I thank Dr Eric Higgs for his ongoing support and Graham Watt for numerous discussions and tips.

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Mountain pine beetle affected fuels: Planning and fire behaviour implications

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Abstract
Using newly acquired vegetation resource inventory (VRI) data, Parks Canada has developed an up to date fuel map to be used as an input into the Canadian Forest Fire Danger Rating System's Fire Behaviour Prediction System (FBP). However, some fuel complexes found on the landscape do not correspond to the standard 16 fuel types within the FBP system. Furthermore, there are certain fuels that are dynamic in nature and that change rapidly over time. In Yoho and Kootenay National Parks, the mountain pine beetle is rapidly changing the nature of pine forests. We describe a method by which aerial red attack mountain pine beetle survey data is combined with the new fuel map to determine how the fuels landscape will change over time. We also examine how recent observations and research on fire behaviour in mountain pine beetle affected fuels are important considerations when managing fire and vegetation on the landscape.

Additional keywords: Fuel mapping, GIS, vegetation resource inventory, fuel types

Introduction

The mountain pine beetle is a native insect to North America that has killed millions of hectares of pine forest throughout Western North America. In British Columbia alone, over 16 million hectares have been affected to some degree during the current outbreak (Canadian Forest Service, 2010). Yoho (YNP) and Kootenay (KNP) National Parks are located in the Canadian Rocky Mountains along the boundaries of the Provinces of Alberta and British Columbia. While the MPB has now been found in all the mountain national parks, Yoho and Kootenay represent the most significantly affected areas. Both YNP and KNP have experienced populations of MPB multiple times over time, with significant increases in the 1970s, 1980s, and with the current outbreak beginning in the 1990s.

Typically MPB affected forests pass through four phases over time: 1) green attack phase when changes in foliage are not yet detectable; 2) red attack phase when foliage has changed to red/brown but are still retained; 3) grey attack phase when foliage has dropped from the tree but the stem remains upright; and 4) the dead and down phase when stems have dropped to the ground due to windthrow or decay (Fig. 1). When planning prescribed fires, wildfire containment areas, and fire guards for community protection, forest managers often need to project future fuel states. Although forest managers have been mapping the extent of MPB populations through annual aerial surveys, annual maps alone do not capture the dynamic nature of MPB affected forests. In order to proactively manage prescribed fire, wildfire and wildland urban interface issues on the landscape, managers must be able to easily visualize future forest fuel conditions.

By using annual aerial red attack survey data and recently acquired vegetation resource inventory data, we are working on developing an accurate and temporally dynamic map of MPB affected fuels in Yoho and Kootenay National Park. This tool will be highly useful in making landscape level fire and vegetation management decisions.

Fig. 1. (L-R) Red, Grey and Dead and Down phases of MPB affected fuels.

Several studies have examined changes in fuel following MPB attack and have shown that both fine fuels and coarse woody debris change significantly over time after MPB have impacted a stand. Page and Jenkins (2007a) showed that dead foliage slowly falls off trees over a period of approximately four to five years following MPB attack corresponding to the red attack phase. Once all needles have fallen to the ground, the remaining stems stay upright for another 9 to 14 years representing the grey phase, with 90% of MPB attacked trees down on the ground by 14 years following the initial green attack phase (Mitchell and Preisler 1998).

Given that the arrangement and amount of fuel changes following MPB, potential fire behaviour can also be predicted to change. Scholars have theorized about the affect of MPB on fire behaviour (Page and Jenkins 2007b; Jenkins *et al*. 2007) but have largely modeled predicted fire behaviour rather than measured observed fire behaviour and effects. Current research initiatives by Parks Canada seek to make direct observations of fire behaviour associated with these stands through detailed studies during prescribed fires in these fuel types.

Dynamic MPB fuel mapping, coupled with research projects in Yoho and Kootenay National Park, will provide managers with highly valuable information to manage fire and fuel on the landscape in MPB affected areas.

Methods

Dynamic MPB affected fuels mapping

Using annual red attack aerial survey data collected by the Canadian Forest Service, we created separate layers of red attack extents for each successive year from 2001 to present. Since earlier data was collected as point data and later years mapped as polygon data, both point and polygon data was merged into a single layer per year. All geoprocessing and map work was completed using ESRI ArcMap version 9.3.1 (ESRI, 2009).

Using thresholds established from literature (Mitchell and Preisler 1998; Page and Jenkins 2007a), a series of maps can be produced to show a progression of MPB affected fuel through time (Fig. 2). The 2020 snapshot is intended to show how stands might look 10 years from now. The criteria for the MPB stages show stands between five and 15 years (2006 through 2015) in ‘grey attack’ phase, and stands older than 15 years (2005 and older) as dead and down and shown in black. The year 2005 is shown in dark grey to allow a transition between ‘grey’ and 'dead and down'. Polygons have also been layered with oldest layers on top so they are not obscured by newer and larger red attack polygons.

Fig 2. Pair of maps showing present situation near Field, British Columbia (red attack) and 10 year projection of MPB affected fuels (2020 snapshot).

Fire behaviour in MPB affected fuels
Since there is limited empirical data on fire behaviour in MPB affected fuel, predicted fire behaviour in each phase of MPB attack must be estimated from existing literature. However at press time, Parks Canada had conducted one research project to measure fire behaviour in MPB affected fuels (Quinn 2010) and there are plans to continue such research during future prescribed fires in these areas. The following is a compilation of information from current research as well as anecdotal reports of fire behaviour in the various phases of MPB affected fuels.

Red Attack Phase
Lower foliar moisture content associated with the red attack phase generally increases the potential for passive crown fire development (Xanthopoulos and Wakimoto 1993). Anecdotal evidence from the 2003 wildfire season in British Columbia confirms that higher than expected fire behaviour was observed (Beck *et al*. 2005). Furthermore, the presence of dead aerial fuels increases the probability of surface fires developing into crown fires (Jenkins *et al*. 2008).

Grey Attack Phase

Anecdotal evidence from the 2010 wildfire season showed that with active, high intensity wildfire, the potential long range transport of fire brands from grey phase trees increased. Fireline observations also showed that as active crown fire approached standing dead fuel, fire intensity increased, possibly due to low fuel moisture in standing dead trees and infilling of understory by other coniferous species providing vertical continuity (R. Osiowy, personal communication). However, at least one other study indicates that the probability of active crown fire decreases during this phase due to a decrease crown bulk density (Simard *et al*. in press). However, this study examines probability of torching and crown fire and not overall head fire intensity which may still indicate more severe fire behaviour in intermediate grey/dead and down areas due to the large quantities of standing dead timber, increased surface fuel, solar penetration and wind speeds(Jenkins *et al.* 2008).

Dead and Down Phase (Quinn 2010)

The Mitchell Ridge prescribed fire in Kootenay National Park presented an excellent opportunity to examine fire behaviour in dead and down MPB affected fuel. The burn unit fell within an area of southern KNP that had experienced over 20 years of dynamic MPB activity resulting in a fuel type atypical to the 16 standard Canadian Forest Fire Behaviour Prediction System (FBP) modeled types.

Three one hectare study plots were located within the burn unit and readily accessible by helicopter for pre and post burn fuel and fire effects measurements. The three plots represent unattacked mature lodgepole pine, MPB affected fuel greater than 15 years following attack (down dead), and MPB affected fuel less than two years following attack (red attack).

At each plot data regarding rate of spread, duff consumption, large fuel consumption, and change in stand structure were gathered. In addition, pre- and post- fire photographs were taken, and in-stand video cameras were installed.

Observed fire behaviour on the day of ignition showed that MPB affected forests greater than 15 years following initial colonization had high fuel loads and significantly increased fuel consumption and head fire total intensity than predicted by the FBP system using the most appropriate standard fuel type M3 – mixedwood boreal with 60% dead balsam fir (Table 1). Data showed that high fuel consumption and high fire intensities may have implications for severity and impacts on revegetation and soil properties. Given that fuel moisture contents during summer wildfire seasons are significantly lower than those reported in the spring prescribed fire, this particular phase of MPB affected fuels could pose significant operational and ecological ramifications for land managers.

Table 1. Observed fire behaviour in MPB affected fuels (>15 years post attack) during the Mitchell Prescribed fire compared to C3 (Mature Lodgepole pine) and M3 (Mixed wood with 60% dead balsam fir) (from Quinn 2010)

Predicted		
C3	Fire Type(head) ROS[A] (m/min) Consumption[B] Intensity[C] (kW/m, estimate)	*Surface* *4.1* *1.1* *1300*
M3	Fire Type(head) ROS(m/min) Consumption Intensity (kW/m, estimate)	*Continuous crown* *27.4* *1.9* *22,408*
Observed		
Mitchell	Fire Type(head) ROS(m/min) Consumption[D] Intensity (kW/m, estimate)	*Continuous crown* *27.6* *4.9(11.1 kg.m^{2} initial) = 45% reduction* *38,787(L≥10m)*

[A]ROS indicates head fire rate of spread
[B]Consumption indcates surface fuel consumption
[C]Intensity indicates head fire total intensity
[D]Only large fules are reflected in Mitchell observed consumption

Practical Implications

As the area affected by MPB increases over time, changes in fire behaviour potential and fuel loading must be considered when making landscape level fire and vegetation management decisions. Park managers can use dynamic fuel mapping to forecast changes in fuels within a particular area of interest and predict fire behaviour. Combining both dynamic MPB affected fuel mapping with new and emerging information on the associated fire behaviour, park managers can also have extremely useful tools in planning community fire guards. Current fire guards may be adequate for present conditions, however with potential increases in fire intensity or spotting distances, fire guards may need to be adapted as the nature of fire hazard changes.

Management decisions which consider the shifting spatial arrangement of fuel on the landscape will be more realistic in terms of meeting objectives, ensuring maximum effectiveness over time and preparedness for possible diversions from predicted fire behaviour based on current conditions.

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Mountain Pine Beetle (*Dendroctonus ponderosae*) and Lodgepole pine (*Pinus contorta*) in south-central Oregon: Fuel dynamics and consequences for fire behavior through time

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Abstract
Recently, mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) has caused extensive lodgepole pine (*Pinus contorta* Dougl. ex. Loud) mortality in the western North America. This extensive mortality raises questions about the potential for catastrophic wildfire. Although there is a major concern about fire behavior following widespread tree mortality caused by MPB, previous research has provided inconclusive evidence concerning the influence on temporal and spatial aspects of fuels and potential fire behavior. In lodgepole pine dominated forests of south-central Oregon, we hypothesize that following MPB epidemics several stages will occur in which surface, ladder, and crown fuels will change and alter the risk and severity of wildfire. Initially, an increase in potential for large crown fires may occur due to remaining dead needles in the canopy, although fire severity may not increase. As needles fall off dead trees and before trees begin to fall, crown fire potential is reduced. When dead standing trees and branches begin to fall, and regeneration of understory shrubs and trees initiate, surface fire severity will increase. The magnitude of change in both fire risk and severity will be dependent on forest composition and tree regeneration. We address this hypothesis by combining field measurements and modeling efforts.

Additional keywords: mountain pine beetle, lodgepole pine, fuels, fire risk, fire severity

Introduction
Bark beetles (Coleoptera: Curculionidae, Subfamily Scolytinae) are important mortality agents in North America (Raffa *et al*. 2008, Negron *et al*. 2008). These insects have caused mortality over millions of acres during the past 20 years. Recently, the mountain pine beetle (*Dendroctonus ponderosae*) (MPB) has caused extensive lodgepole pine mortality in the western US, especially in Colorado, Wyoming, Montana, Idaho, Washington and Oregon. This extensive mortality from bark beetles, especially the MPB, has raised questions about the potential for catastrophic fire following widespread mortality (Fire Science Brief, Issue 11, August 2008, Romme *et al*. 2006). Although there is a major concern about fire behavior following widespread tree mortality caused by bark beetles, recent literature reviews and research have suggested that there is a lack of specific data concerning how MPB-caused mortality influences temporal and spatial aspects of fuels and potential fire behavior (Romme *et al*. 2006; Negron *et al*. 2008; Jenkins *et al*. 2008; Simard *et al*. 2008). In addition, evidence from recent research has created uncertainty around changes in fire risk and severity following MPB epidemics (e.g., Turner *et al*. 1999; Lynch *et al*.

2006; Page & Jenkins 2007; Simard *et al*. 2011). This lack of data seriously limits the ability of fire managers to determine when and if fuels treatments will be effective.

We hypothesize that following MPB epidemics, several stages will occur in which surface, ladder, and crown fuels will change and alter the risk and severity of wildfire. One to two years following epidemics dead needles remain on trees (the red and brown phase) while many other fuels categories will remain unchanged. This may increase potential for large stand-replacing fires, although fire severity may not increase. As needles fall off dead trees and before trees begin to fall (gray stage), crown fire potential is reduced, and simulated fires will progress similarly to undisturbed forest. When dead standing trees and branches begin to fall, and regeneration of understory shrubs and trees initiate, ground fire severity will be highest because of an abundance of fine and large fuels. Specifically for the lodgepole pine forests of south central Oregon, on the Deschutes and Fremont-Winema National Forests, we will address the following objectives; 1) quantify ground, surface, ladder, and crown fuels over time following epidemics of mountain pine beetle (MPB) in lodgepole pine forests of south-central Oregon, and 2) understand the effects of temporal fuel dynamics on fire behavior.

Methods

Using a chronosequence approach (retrospective) based on aerial detection survey of MPB (Fig. 1), we will sample lodgepole-dominated stands on the Deschutes and Fremont-Winema National Forests in south-central Oregon (Fig. 2) with different times since MPB epidemic (2-30 years). To quantify forest structure and the associated fuels complex, the plot design in Fig. 3 will be used. Each plot consists of a central 250 m^2 (8.92 m radius) circular plot in which standing live and dead trees and aerial fuels will be measured. Canopy cover will be estimated for the plot. Diameter at breast height (1.37 m) and total tree height will be measured for both live and dead trees. Tree condition (vigor), canopy position (dominant, co-dominant, intermediate, suppressed), canopy base height, and crown lengths (Scott and Reinhardt 2001) will be taken for live trees, and with total available crown fuel load will be used to calculate crown bulk density (Keane *et al.* 1998). Each individual live tree will also be assessed for *Arceuthobium americana* (Nutt ex. Engelm.) and given a dwarf mistletoe rating (Hawksworth 1977). Standing fuel volume and available crown fuel loads will be calculated using allometric equations from BIOPAK (Means 1994). A subset of live and dead trees will be cored to determine stand age as well as growth release dates which will provide the precise timing of MPB outbreak.

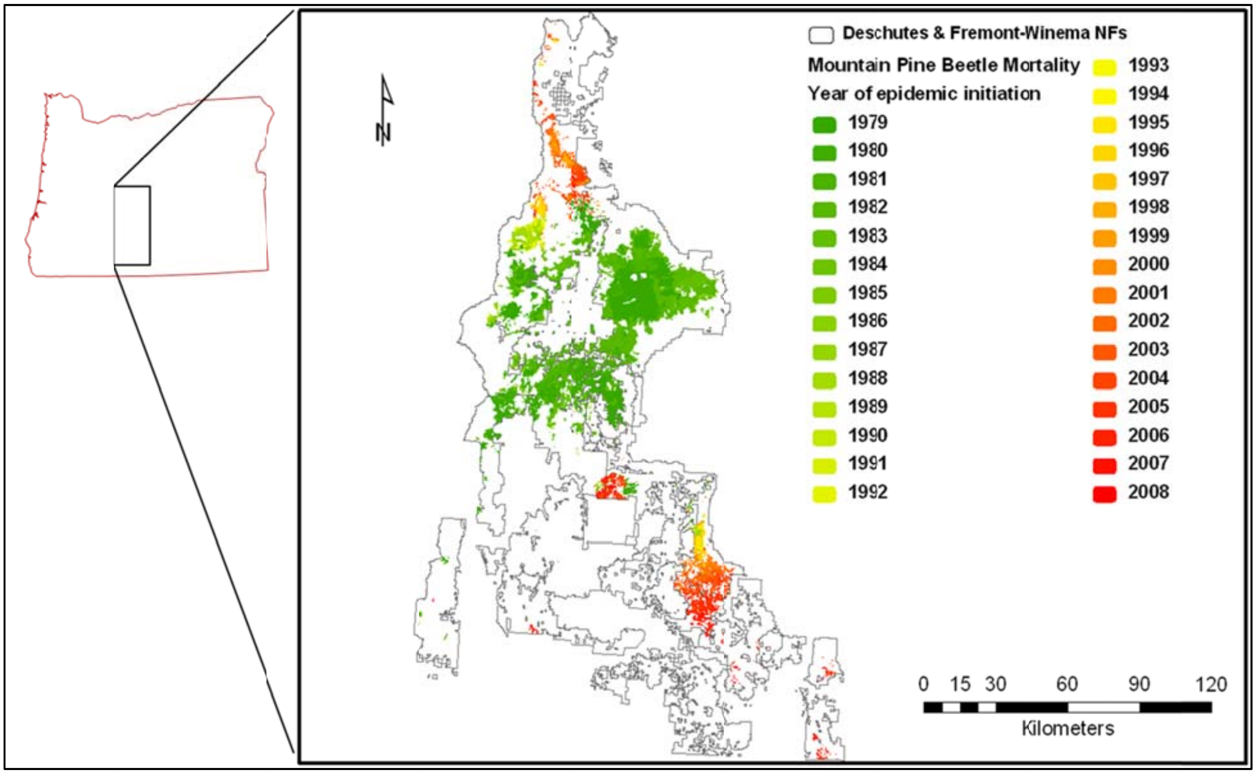

Fig. 1. Chronosequence of mountain pine beetle epidemic initiation across the Deschutes and Fremont-Winema National Forests, OR. Developed from aerial survey cumulative mortality data.

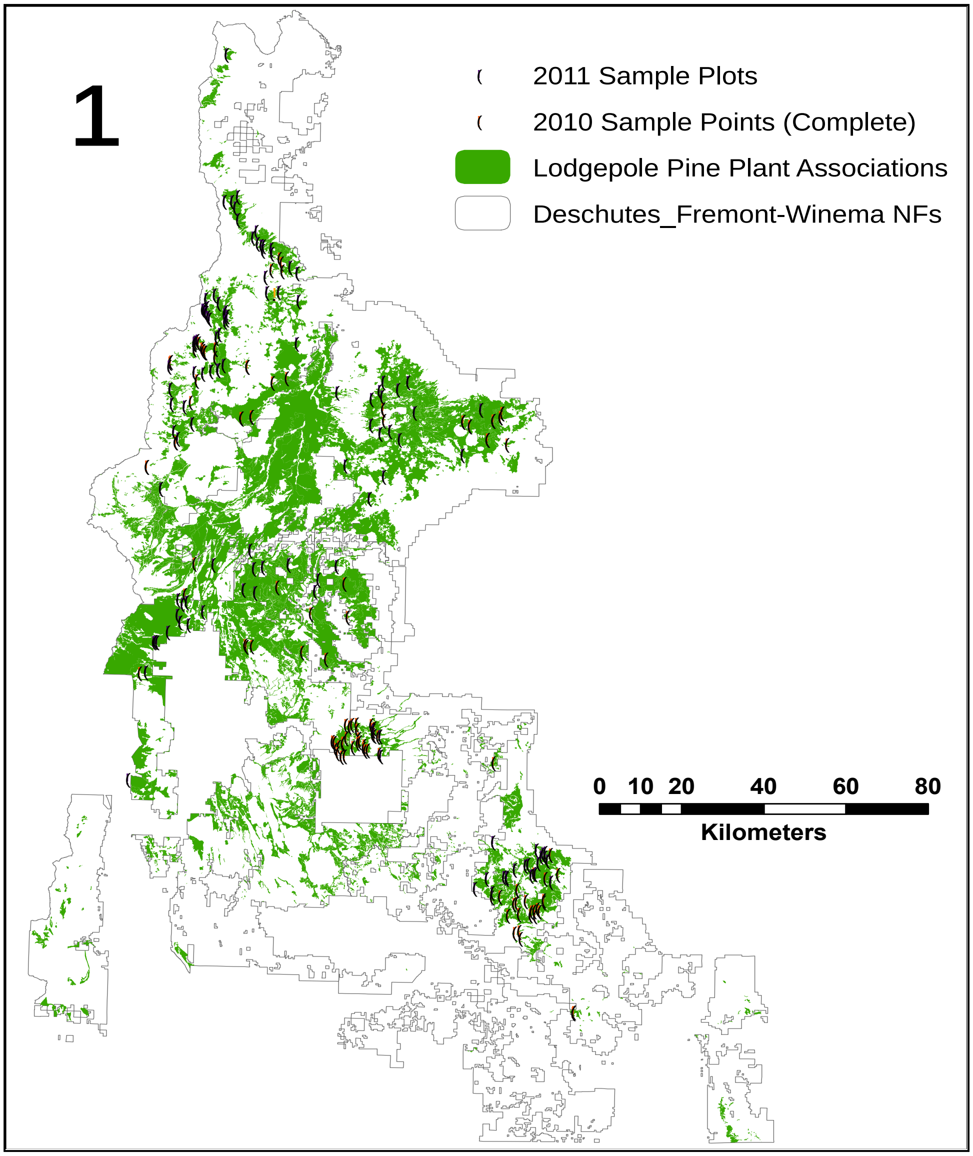

Fig. 2. Spatial Distribution of sample points within lodgepole pine plant associations across the Deschutes and Fremont-Winema National Forests, OR**.**

Surface and ground fuels will be quantified using 25 m length line intercept transects (Brown *et al.* 1982). At least 4 transects will be established, and supplemental transects will be installed if necessary to adequately capture fuel pieces. Litter, duff and high particle intercept depth will be measured at 10 and 25 m along each transect. The 1-h (0-0.64 cm), 10-h (0.65-2.54cm), 100-h (2.55-7.62cm), and 1,000-h (< 7.62 cm) timelag fuels will be measured along each transect in the following manner. The number of 1-h fuels will be recorded from 0-5 m along each transect, the number of 10-h fuels from 0-7.5 m along each transect, 100-h fuels from 0-10 m along each transect, and the number of 1,000-h fuels will be recorded along the entire 25 m transect length. 1,000-h fuels will also be given a decay class between 1 and 5 (Harmon *et al.* 1985).

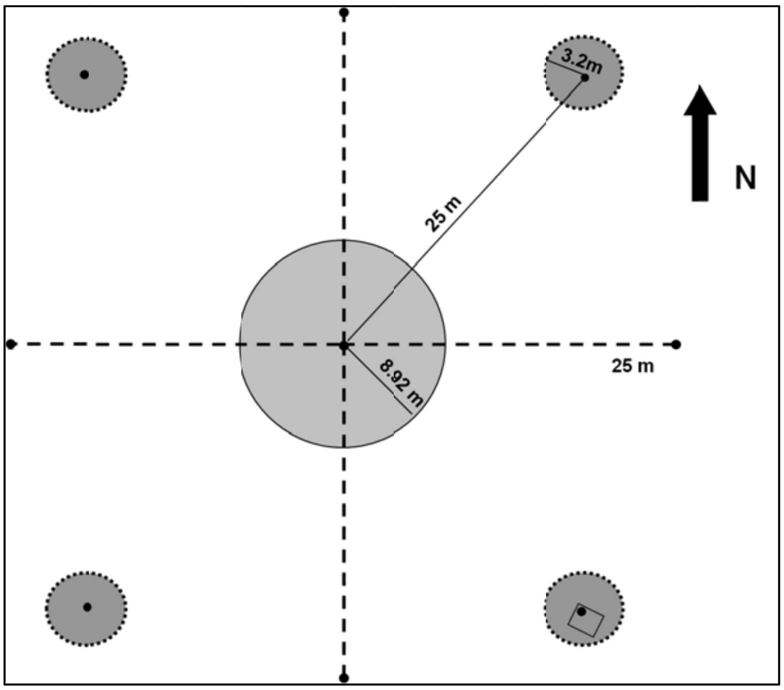

Fig. 3. Sample plot schematic indicating spatial layout of subplot and transect measurement points.

A total of four, 2 m radius circular micro-plots will be placed 15 m from plot center at 45º from the fuels transects. These micro-plots will be used to estimate tree regeneration, total cover of live and dead herbaceous vegetation and shrubs, average live and dead shrub and herbaceous height, and a tally of shrub stems by size class and species similar to (Brown 1976). Tree regeneration will include any tree < 1.37 m in height and will be quantified by tallies of stems by species and size class, and total height.

To model and estimate the change in potential fire behavior over time following MPB epidemics, we will use both standard (Anderson 1982; Scott and Burgan 2005) and, if necessary, custom fuels models from our collected data. Surface and crown fire behavior will be modeled using *BehavePlus v 4.0.0* (Andrews *et al.* 2008) and FlamMap. FlamMap will be used to demonstrate the potential fire behavior across a landscape and show how the potential varies spatially and temporally as the MPB progresses. Minimum travel time in FlamMap will be used to determine burn probability and show potential fire movement across the landscape and how these vary as the MPB progresses. Using weather station data from the region, several weather scenarios will be used to capture the range in possible fuel moistures and fire weather conditions. If a high degree of variability exists within any given fuel type within a specified time since

MPB outbreak, a sensitivity analysis will be performed that applies this variability in multiple modeling runs.

Conclusions

The results from this research will give managers on the Fremont-Winema and Deschutes National Forests invaluable information to manage past, current, and future MPB epidemics and wildfires. Custom fuel models and both stand and landscape patterns of fire behavior will provide the tools needed to move forward with fuels reduction treatments, and restoration projects aimed at developing landscapes more resilient to future fire and insect disturbances. In addition, results from this research will add to the growing body of work examining the interactions of multiple disturbances.

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Sensitivity analysis and application of WRF-Fire

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Abstract
When numerical weather prediction models capable of simulating atmospheric dynamics are coupled with fire behavior models, the resultant modeling system is a tool that could allow for better understanding of prescribed fires. The Weather Research and Forecasting (WRF) model and its fire behavior physics module WRF-Fire connect the fire and atmosphere through exchanges of atmospheric winds into the fire behavior component, which models the spread of a wildland fire in that time step and returns sensible and latent heat flux perturbations into the atmospheric dynamics. We present a sensitivity analysis of this model under an ideal burning scenario in which parameters relevant to prescribed fires are tested, such as ignition parameters and atmospheric stability. The sensitivity of simulated fire behavior to these parameters is presented.

Additional keywords: numerical weather prediction model, coupled atmosphere-fire model, fire behavior, prescribed fire, fire model, Weather Research and Forecasting model, fire ignition, atmospheric stability effects on fire behavior

Introduction

Though much has been written about the environmental conditions affecting wildland fire behavior, largely relating fuel, terrain slope, and wind conditions to steady state fire rate of spread, some issues take on greater significance in the execution of prescribed fires. In the desire to keep fire behavior within a defined range of behavior, factors that could amplify or suppress fire behavior or lead to different outcomes in given atmospheric conditions are particularly important. Here, we examine the effect of atmospheric temperature stratification and ignition scenarios on the outcome of simulated small-scale prescribed fires.

A fundamental aspect of wildland fire behavior training and education involves teaching consideration for the effect of the fireǿs atmospheric environment on fire behavior. Although primary variables, such as the near surface wind in the vicinity of the fire, are crucial, vertical profiles/derivatives of other fields, such as the rate at which the atmospheric temperature decreases with height (known as the ǿlapse rate of temperatureǿ) are also of primary importance. The ambient lapse rate affects the dynamics of the warm convection column over the fire. A dry adiabatic lapse rate, common in well-mixed atmospheric boundary layers, is one in which a lifted parcel of unsaturated air in the plume expands and cools at the lower pressure of the higher elevation and finds itself at the same temperature of the ambient air, thus experiencing no buoyancy force causing it to rise or fall (neutral stability). Variations from this lapse rate towards a lapse rate that decreases slower (a stable lapse rate) or faster (an unstable lapse rate) with height either decelerate or accelerate, respectively, the vertical motions in the updraft, with corresponding damping or enhancing effects on fire behavior. Fire training materials and textbooks incorporate this material alerting students to watch for indicators of unstable lapse rates as a heads up for increases in fire activity (Schroeder and Buck 1970; Luke and McArthur 1977; Pyne *et al*. 1996).

Moreover, it is known that fires evolve differently under different ignition scenarios and ignition techniques themselves can be used to modify intensity. Fire behavior differences can be compared without having to venture into the real world, but one should remember that the accuracy with which an ignition pattern is simulated will affect the modeled fire behavior evolution later in time.

Our simulations use WRF-FIRE, a coupled wildland fire-atmosphere physics module within the Weather Research and Forecasting Model that allows explicit treatment of the effects of fire on atmospheric dynamics and feedback to fire behavior. We conducted a sensitivity analysis of atmospheric stability and ignition radius to determine what changes in these initial conditions have on the overall fire/atmosphere behavior.

Model description

WRF-FIRE is a coupled wildland fire-atmosphere physics module within the Weather Research and Forecasting (WRF) Model that allows explicit treatment of the effects of fire on atmospheric dynamics and feedback to fire behavior, thus the simulated fire can ‘create its own weather’.

Atmospheric model component

The Advanced Research WRF model (Skamarock *et al*. 2008) is a fully compressible and nonhydrostatic numerical weather prediction model designed to be a flexible, state of the art tool that is portable and computationally efficient on a wide variety of platforms. It has two-way nesting and can accommodate multiple embedded nests. Its vertical coordinate is a terrain-following hydrostatic pressure coordinate. It is able to simulate a wide range of atmospheric motions and can do two types of simulations – those with an idealized initialization and those utilizing real data. WRF is in the public domain and freely available for community use (http://www.wrf-model.org).

Wildland fire behavior component

WRF-Fire is an added physics option in WRF, available v. 3.2 and later, that allows users to simulate the growth of a wildland fire. The fire behavior is two-way coupled to the atmospheric dynamics components of WRF. The winds from the lowest levels of WRF are passed to the fire module where they are used, in combination with terrain slope and fuel characteristics, to calculate a surface fire rate of spread. In each time step, the fire line (the interface between burning and non-burning fuel) is advanced, igniting fresh fuel while previously ignited areas consume more fuel. This consumption is partitioned into sensible (temperature) and latent (water vapor) heat fluxes, which are returned as source terms to the atmospheric dynamics components of WRF where they are distributed vertically through an empirically estimated extinction depth, altering the atmospheric state.

Because such models are representing wildland fire physics at scales smaller than the grid size, the wildland fire component contains parameterizations and semi-empirical relationships. At the surface, each atmospheric grid cell is further divided into two-dimensional fuel cells with fuel physical characteristics and fuel loads specified by the user, the default categorization being the 13 standard fuel models (Anderson 1982). An algorithm relates fire properties such as rate of spread to local wind, terrain slope, and fuel characteristics through the semi-empirical Rothermel (1972) surface-fire rate of spread algorithm. Fire spread rates are calculated locally along the fire front as a function of fuels, wind speed and direction from the atmospheric model (which includes the effects of the fire), and terrain slope. The interface is tracked using the level set method numerical technique (Sethian 1999), which was applied to wildland fire front propagation in Mallet *et al*. 2009; Rehm *et al*. 2009. Another algorithm calculates the post-frontal heat release rate (Albini 1994) which characterizes how the fire consumes fuels of different sizes with time after ignition, distinguishing between rapidly consumed grasses and slowly burned logs. A simple radiation treatment distributes the sensible and latent heat and smoke into the lowest atmospheric grid levels. The e-folding height over which the heat is distributed is specified by the user ï typically 10 m for grass fires and 50 m for crown fires, based on analysis of fire observations (Coen *et al*. 2004; Clements *et al*. 2007).

Experiment design

An idealized base case was used in which there were no terrain features. The fuel used for these simulations was tall grass (Andersonõs Fuel Model 3). The fuel was uniform in moisture content (0.08%) and the fuel loading was spatially homogeneous. The ignition was assumed to be a line. The domain was 6.0km long, 2.46km deep, and 3.5km tall. The grid resolution for the atmospheric model was 30m and the fuel cell resolution for the fire was 3m (Fig 1).

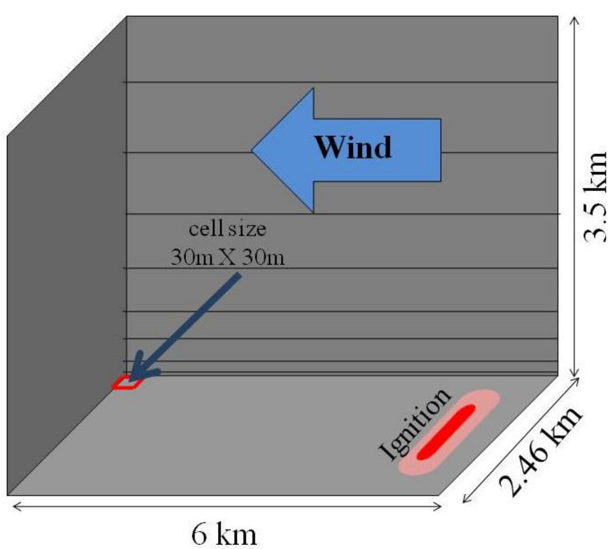

Fig. 1 Initial surface wind direction denoted by the blue arrow remained constant. Wind speeds aloft and the vertical wind profile were varied in magnitude and proportion**.** The light pink and red ovals labeled óignitionô denote the same line fire with two different ignition radii.

Wind direction through the full height of the domain was easterly (no y-component). The length of the fire line was 1km and was assumed to ignite instantaneously. Ignition took place one minute after simulation began. The heat of ignition was $1.3 \times 10^6 W/m^2$. Our sensitivity analysis involves perturbation of the following parameters:

Atmospheric static stability experiments

Changes to atmospheric stability were investigated by introducing neutral and stable vertical wind speed profiles. The profiles for these two cases (Fig 2) were calculated using a power law relationship with the constant *m* set to 0.20 and 0.50 for neutral and stable conditions respectively (Equation 1).

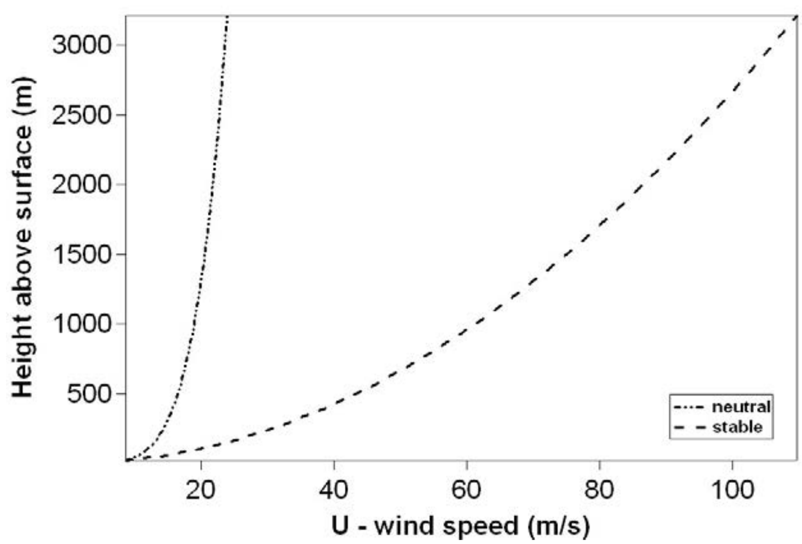

Fig. 2 The above wind speed vertical profiles are calculated using a power law relationship to define neutral and stable atmospheric boundary layer conditions. The coefficients used for these are 0.20 and 0.50, respectively.

Equation 1. $$U = U_0 \left(\frac{z}{z_0} \right)^m$$

The above initial wind profiles were used in this analysis to gauge how differences in winds aloft may influence plume rise and Rate of Spread (ROS) of the flaming front. The initial surface wind speed for both cases was set to 8m/s. The ignition radius for the ignited line was 90m. Temperature profiles were not modified to reflect the stability conditions.

Ignition radius experiments

The ignition radius for WRF-Fire is the distance away from the declared ignition line in x and y directions. A neutral vertical wind speed profile was assumed and three different ignition radii (35, 60, and 90m) were investigated for their effect on ROS.

Results

Effect of atmospheric static stability

Water vapor mixing ratio is used as a proxy for the location of the buoyant plume produced during combustion. We have found that plume rise is definitely influenced by the level of atmospheric stability. The neutral wind speed profile has plumes reaching ~1.18km while the stable wind speed profile shows no discernable rise (Fig 3).

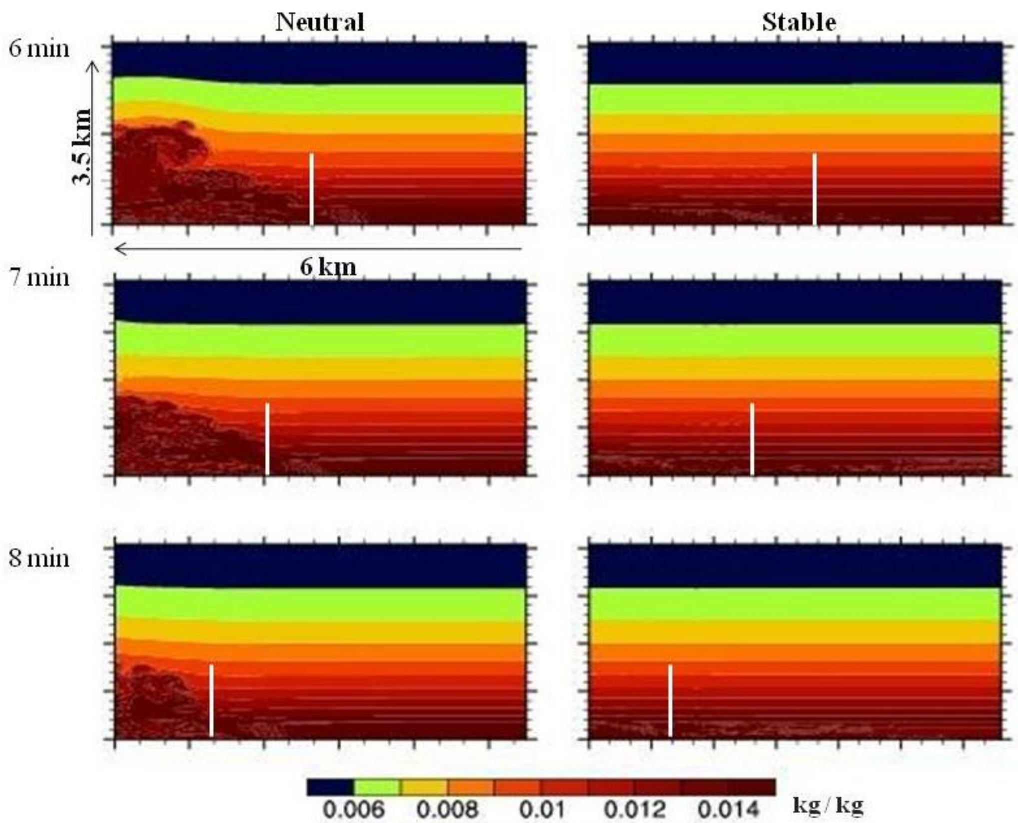

Fig. 3 Water vapor mixing ratio (kg/kg) is used as a proxy for plume rise. The white lines denote the front of the heading fire in the middle of the domain as it spread from right to left. The rows from top to bottom are 6, 7, and 8 minutes after ignition respectively. The columns from left to right are for Neutral and Stable vertical wind profiles respectively.

Also of interest, ROS does not appear to be influenced significantly however; further work will need to be done in order to verify this.

Effect of ignition radius

The potential effect of ignition radius is quantified using ROS. The location of the flaming front at y=1.25km at t=8min is used as an indicator of ROS (Fig 4).

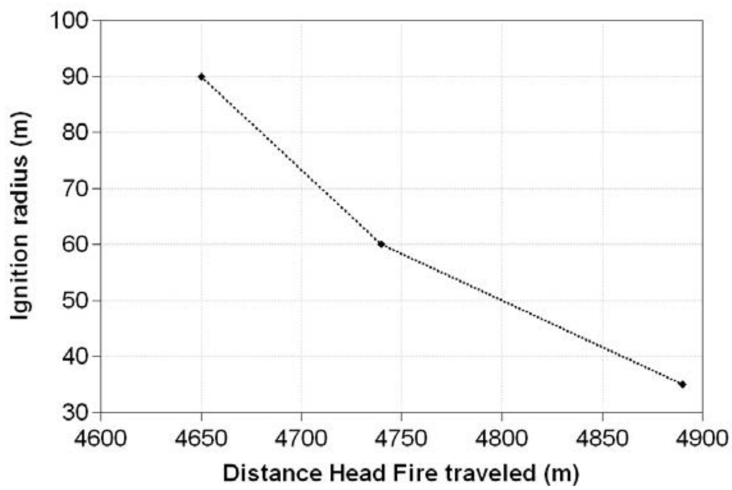

Fig. 4 The distance the heading fire traveled was calculated from the location of the peak latent heat flux 8 minutes after ignition. The distance was taken at the west-east domain centerline.

It appears that there is an inverse relationship between ignition radius and ROS of the flaming front. Furthermore, the largest difference in distance traveled for the three scenarios is 240m.

Discussion

Changes to vertical wind speed profiles affect the shape and plume rise height of the hot buoyant air; however they do not appear to affect ROS. Work is underway to modify potential temperature profiles as well. Changes in ignition radius affect the ROS. Furthermore, the ignition radius appears to be inversely related to ROS. Work is underway to look at differences in ROS for longer time intervals.

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Do polyethylene plastic covers affect smoke emissions from debris piles?

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Abstract
Shrubs and small diameter trees exist in the understories of many western forests. They are important from an ecological perspective; however, this vegetation also presents a potential hazard as 'ladder fuels' or as a heat source to damage the overstory during prescribed burns. Cutting and piling of this material to burn under safe conditions is a common silvicultural practice. To improve ignition success of the piled debris, polyethylene plastic is often used to cover a portion of the pile. While burning of piled forest debris is an acceptable practice in southern California from an air quality perspective, inclusion of plastic in the piles changes these debris piles to rubbish piles which should not be burned. A review of available literature (Wrobel and Reinhardt 2003) suggested that emissions resulting from burning piles with polyethylene plastic would be similar to emissions from debris piles without polyethylene sheeting. The literature review was based on bench-scale tests of polyethylene pyrolysis and combustion.

With support from the four National Forests in southern California, we conducted a laboratory experiment to determine if the presence of polyethylene plastic in a pile of burning wood changed the smoke emissions. Debris piles in southern California contain wood and foliage from common forest trees such as sugar (*Pinus lambertiana* Douglas), Jeffrey (*P. jeffreyi* Balf.), and ponderosa (*P. ponderosa* C. Lawson var. *ponderosa*) pines, white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr. var. *lowiana* (Gord. & Glend.) Lemmon), incense cedar (*Calocedrus decurrens* (Torr.) Florin), and California black oak (*Quercus kelloggii* Newberry) and shrubs such as ceanothus (*Ceanothus* spp.) and manzanita (*Arctostaphylos* spp.) in addition to forest floor material and dirt. The inner portion of the pile is covered with a polyethylene sheet and more forest debris piled on top. In the present study, manzanita wood was used to represent the debris pile in order to control the effects of fuel bed composition. The mass of polyethylene plastic incorporated into the pile was 0.0, 0.5 and 5.0 % of the wood mass—a range representative of field conditions. The plastic was mixed throughout the fuel bed (Fig. 1). A small quantity of alcohol was used to ignite the pile. Ductwork was used to sample the smoke produced by the lab pile (Fig. 2). Several different instruments were used to measure NOx, CO, CO2, SO2, polycyclic and light hydrocarbons, carbonyls, particulate matter (5 to 560 nm), and elemental and organic carbon. Due to the shifting nature of the smoke plume, we observed high variability in the measurements. However, the presence of polyethylene with the manzanita wood did not alter the emissions composition when compared to emissions from the wood alone

supporting the findings of Wrobel and Reinhardt (2003).

Additional keywords: hazard reduction, fuel treatment, LDPE

Fig. 1. Mixtures of clear polyethylene plastic (LDPE) and manzanita wood used to simulate debris piles containing 0.5% and 5.0% LDPE by mass.

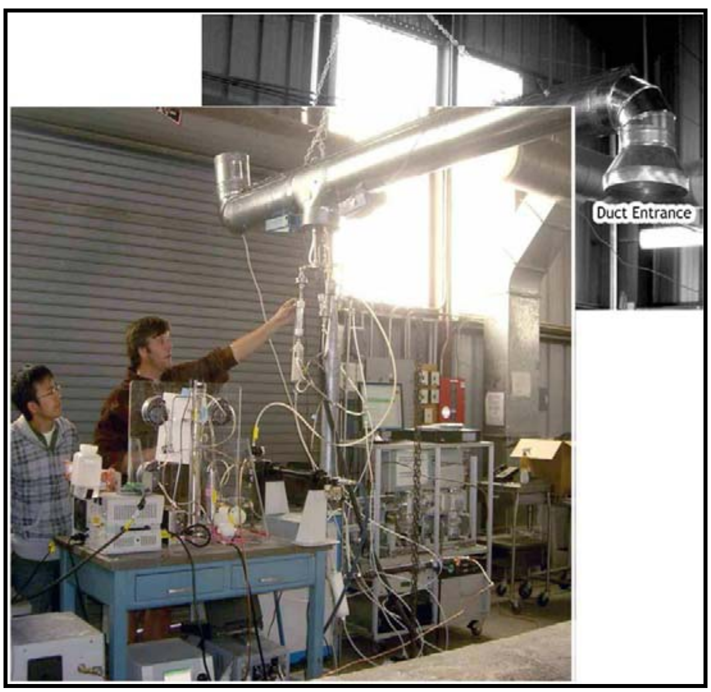

Fig. 2. Experimental setup used to sample smoke produced by the burning of clear polyethylene plastic (LDPE) and manzanita wood.

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Development of new fuels and emissions data for maritime chaparral and Madrean oak woodland fuel types

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Abstract
The use of prescribed burning on Department of Defense (DoD) lands is subject to the same air quality constraints as other federal, state, and local lands. Information on fuel loading and smoke emissions developed on DoD lands is applicable to similar fuel types on other land holdings. A large study currently in progress is measuring fuel loadings at three DoD installations in California and Arizona for comparison with published fuel loadings for chaparral and oak woodland fuel types. Important fuel types from Vandenberg AFB and Ft. Hunter-Liggett in California and Ft. Huachuca have been sampled. The California fuel types include maritime chaparral, coastal sage scrub, California sagebrush, manzanita, ceanothus, and chamise/scrub oak (Table 1). The fuel types at Ft. Huachuca include oak savannah and oak woodland and masticated mesquite. Fuel loading of the fuel types associated with prescribed burns is being compared to published fuel loadings. Samples of these fuel types were collected and burned in a series of laboratory experiments at the Missoula Fire Sciences Laboratory. Initial results from the lab burns have produced emission factors for particulate and gaseous emissions (Hosseini *et al.* 2010, Burling *et al.* 2010). Several results for the laboratory experiments were presented. The fuel loadings of the fuel beds were generally much higher than published fuel loadings and fuel loadings measured in the field (Table 2). Generally > 90% of the dry fuel beds were consumed; however, consumption of the fuel beds which were vertically oriented to mimic actual field fuel arrangement was poor (< 60%). Burling *et al.* (2010) reported laboratory emission factors for 19 gases. Nitrous acid (HONO) was observed in all laboratory fires and may be a significant source of the oxidant OH in a smoke plume. Oxygenated volatile organic compounds comprised the majority of the large amounts of non-methane compounds measured in the lab. Elevated levels of SO_2 and HCl were detected during flaming combustion. Correlations between fire-integrated Modified Combustion Efficiency (MCE) and emission factors for the gases were developed. Hosseini *et al* (2010) presented information from two instruments that measured particle size distribution in real-time from 0.007-0.520 µm and 0.5-20 µm. These instruments cover the EPA standards for particles – PM2.5 covers particles < 2.5 µm and PM10 covers the range 2.5-10 µm. Geometric mean diameter of particles from the chaparral fuels (0.045 µm) was larger than for the Madrean oak fuels (0.029 µm). Instantaneous MCE was used to evaluate particle size distribution changes over time. Geometric mean diameter increased during flaming combustion

and gradually decreased during mixed and smoldering phases. Two prescribed burns in maritime chaparral at Vandenberg AFB and one burn in an oak woodland/savannah at Ft. Huachuca were sampled using ground and aircraft-based instruments. Aircraft sampling of the chaparral fire enabled the measurement of emissions as they aged in the plume over a four-hour time frame up to 50 km downwind. The plume measurements confirmed the presence of HONO.

Additional keywords: NMOC, OVOC, elemental carbon, organic carbon, smoke, prescribed burning

Table 1. Important fuel types identified by Department of Defense personnel that were burned in a series of laboratory fires at the Missoula Fire Sciences Lab in February 2009.

Location	Fuel type	Species[1]
Ft. Hunter-Liggett	Chamise, scrub oak	chamise (*Adenostoma fasciculatum),* scrub oak *(Quercus berberidifolia)*
	Ceanothus	chaparral whitethorn (*Ceanothus leucodermis*)
Vandenberg AFB	Maritime chaparral	Santa Barbara ceanothus (*Ceanothus impressus* var. *impressus),* sedgeleaf buckbrush (*Ceanothus cuneatus* var. *fascicularis)*, black sage (*Salvia mellifera)*
	Coastal sage scrub	*Salvia mellifera*, California goldenbush (*Ericameria ericoides),* California sagebrush (*Artemisia californica)*
	California sagebrush	*Artemisia californica, Ericameria ericoides*
	Manzanita	shagbark manzanita (*Arctostaphylos rudis),* La Purissima manzanita (*Arctostaphylos purissima)*
Ft. Huachuca	Madrean oak savanna	Emory oak (*Quercus emoryi),* Lehmann lovegrass (*Eragrostis lehmanniana)*
	Madrean ak woodland	*Quercus emoryi,* pointleaf manzanita (*Arctostaphylos pungens)*
	Masticated mesquite	velvet mesquite (*Prosopis velutina),* desertbroom (*Baccharis sarothroides)*

1. Plant nomenclature from USDA, NRCS (2010).

Table 2. Fuel loadings associated with laboratory and field smoke measurement experiments (tons/acre).

Fuel type	Measured		Estimated	
	Lab	Field	Dynamic model[1]	Photo series[2]
Chamise, scrub oak	21.8	8.5	12.6	10.0-11.5
Ceanothus	16.2			20.5-22.1
Maritime chaparral	20.0	7.1	30.9	
Coastal sage scrub	16.0	5.8	30.9	6.5-9.3
California sagebrush	17.1			6.5-9.3
Manzanita	20.3	8.0	30.9	
Madrean oak savanna	19.5			3.5
Madrean oak woodland	14.3			6.9

1. Rothermel and Philpot (1973). Assumed 40 year-old chamise chaparral for chamise/scrub oak fuel type; broadleaf chaparral for all other chaparral fuel types.
2. Ottmar *et al*. 2000, 2007.

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Electric Relay Pumping

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Abstract:
A hose based system is proposed that can move water over long distances by using electric booster pumps to perform relay pumping. The system has features that can be used to contain prescribed fires.

Additional keywords: prescribed fire, fire control, fire suppression

Introduction

A relay pumping hose lay typically uses internal combustion engines to power the spatially distributed booster pumps. However, it is possible to use electric booster pumps if electric power wires are attached to the hoses along the length of the hose lay. If communication wires are also attached to the hoses, then the booster pumps can be monitored and controlled by a control network. Control networks are commonly used in intelligent irrigation systems.

System Description

A version of the proposed system is shown in Fig. 1. Each hose lay is 6 inch LDH, which can pump 400 gpm of water two miles to the next 50 HP electric pump on a pickup truck which can pump the water another two miles to the next pickup truck with pump. The hoses can be deployed from large towed reels. If smaller hoses are used, they can be deployed from small tractors or plows.

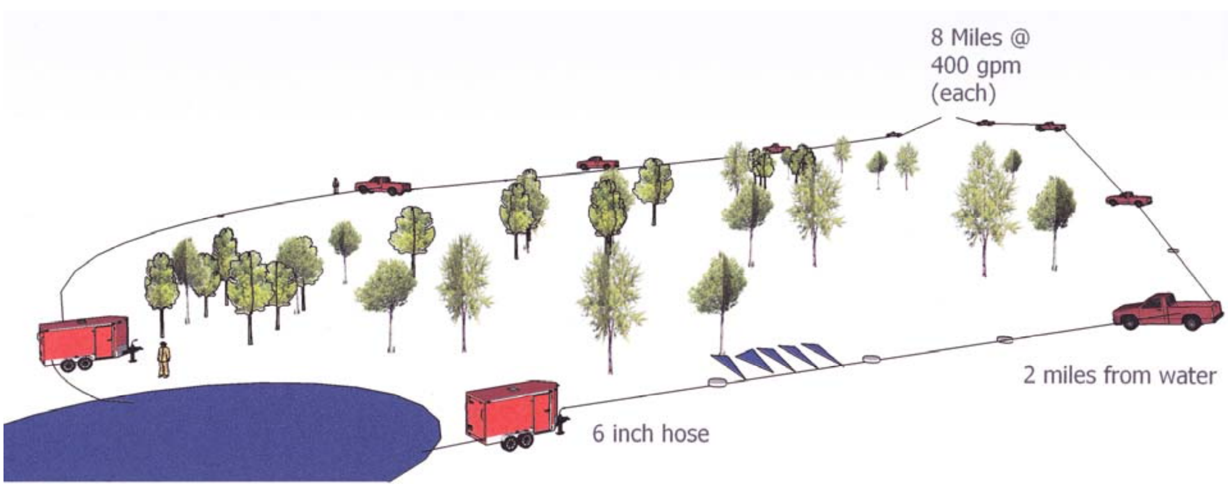

Fig. 1. Two separate hose lays encircling the burn unit, both originating at a pond. Each hose lay starts with a large electric generator trailer which also contains a 50 HP electric pump. The lower hose lay shows water being sprayed from one segment of the line.

By using four booster pumps, each hose lay can move the 400 gpm of water 8 miles with a rise of 190 feet. During hose deployment, at the end of each segment of hose, a decision must be made between adding a booster pump or adding another section of hose. A GPS unit is attached to the network in the hose, and the latitude, longitude and elevation of the location is sent to a computer at trailer. The computer then sends a PUMP or NO PUMP message to the firefighters. A cross-section of hose with attached wires is shown in Fig. 2.

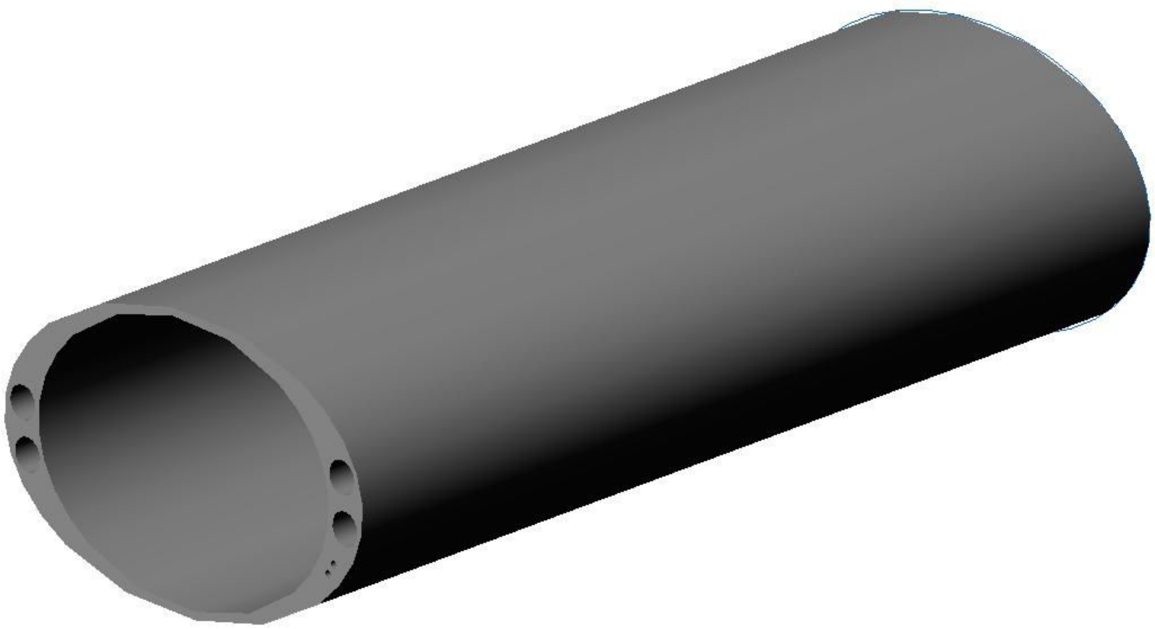

Fig. 2. Cross section of hose showing tunnels for attached wires.

Fig. 3 shows a proposed design for a hose coupler. The water connection is a Storz type.The large plates (shown in exploded view) are used to make the electrical connections between the hoses. The plates are used to separate the water from the electrical connections.

Fig. 3. Proposed hose coupler design

Fig. 4 shows a proposed hose configuration that has two chambers on the bottom for transporting water, and three chambers on the top for optionally spraying water.The outer layer of hose has been removed to show the internal details.

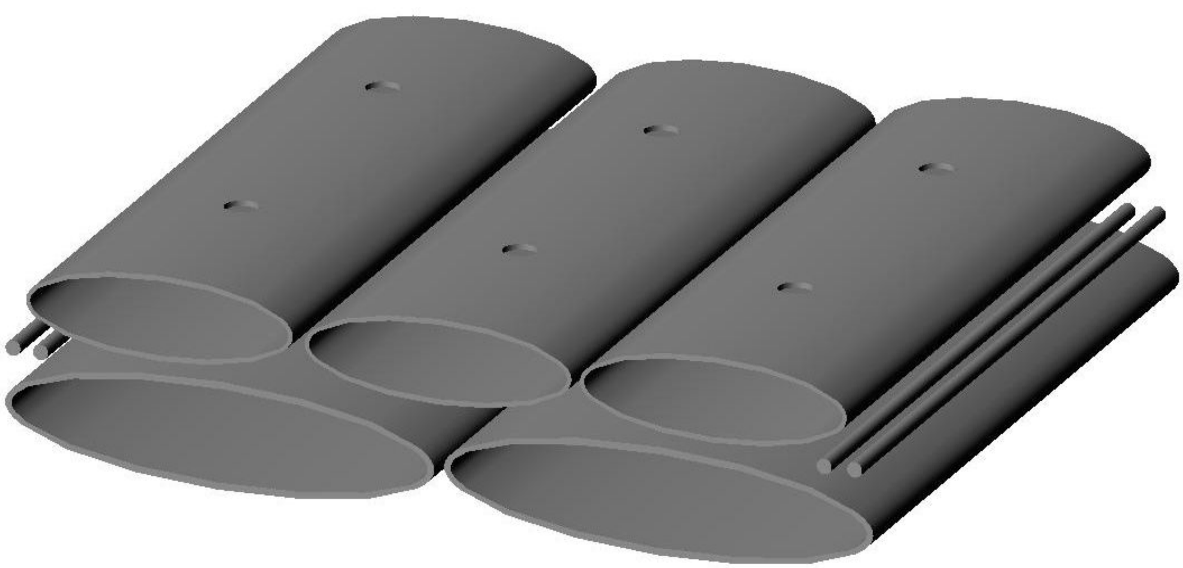

Fig. 4. Proposed hose configuration to both move and spray water.

The hose lays in Fig. 1 can be used to prevent escape of a prescribed fire ignited within the five mile perimeter defined by the two hose lays. .The decision to activate segments of the hose lay to to spray water is done by remote control. A more detailed discussion including deployment of a smaller hose with booster pumps via helicopter can be found at www.electric-fluid-pipeline.com.

This invention has been granted US Patent 7,819,345 and Australian Patent 2008-302-447.
It is patent pending in Canada.

The Coalition of Prescribed Fire Councils: Partnering to Promote Understanding of Prescribed Fire, and Address Management, Policy, and Regulatory Issues

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Abstract
Twenty-first century prescribed fire managers face new and increasingly complex challenges. Concerns about public safety and health, ecological stewardship, liability, public education, and air quality regulation create misapprehensions that constrain the use of prescribed fire as a management tool and that surpass the ability of any one agency or state to resolve. To more effectively address the issues of prescribed fire management and to better meet the challenges of managed fire in an increasingly development-focused landscape, a diverse group of public and private leaders formed the "Coalition of Prescribed Fire Councils" in 2008.

The overarching goal of the Coalition is to create one voice to assist fire practitioners, policymakers, regulators, and citizens with issues surrounding prescribed fire use. Its core mission is to promote the appropriate use of prescribed fire for enhancing public safety, managing resources, and sustaining environment quality. In addition, the Coalition encourages and facilitates the organization of prescribed fire councils in states that lack active councils. Partnering with the existing twenty-six councils' efforts, which represent twelve million acres of annual prescribed fire use, has created a forum to voice and address issues of national concern. The Coalition's work facilitates communication among interested parties in the field of prescribed fire, provides a focal point for sharing ideas and information, and creates opportunities for prescribed fire collaboration.

Additional Keywords: [insert text here]

Introduction

As a nation, we are not meeting today's fire needs and prescribed fire managers share the common responsibility to inform and educate the public about the benefits of prescribed fire. State prescribed fire councils address regional and local issues that protect landowner rights to burn, encourage the appropriate use of fire, and promote public understanding. The Coalition provides a forum for exchange and efficiency through partnering the various successful state and local prescribed fire councils, with the unique ability to work on both regional and national scales.

Background

Historically, the states have been responsible for wildland fire management. Some states, such as Florida, encouraged prescribed burning. Other states were and some still are suppression-oriented. Federal agencies have also used prescribed fire to a greater or lesser degree on their own property. For decades, this decentralized approach to prescribed fire seemed to meet most landowners' needs. But recently, regulators and various interests have challenged the ability of states, federal agencies, and private landowners to use prescribed fire. The laws of each state drive the response to fire.

Beginning in Florida, burners began to organize PFC's, nonprofit local groups meeting on a regular basis to exchange technical knowledge, share resources, and advocate for their interests. The PFC movement quickly spread beyond the Southeast, with new councils organizing across the nation. Now, with 30 Councils in 26 states and one International group (Fig.1), the PFC movement reaches out to more federal, state, and local groups than any other prescribed fire organization, leveraging over 12 million acres of land managed by prescribed fire. The CPFC was created to both serve as a resource for state-level councils and as a national interest group promoting the appropriate use of prescribed fire.

Current Activity

In August, 2010, the CPFC Governing Board formed the organization's first committee. The Communications Committee was charged with creating a communications strategy that would link prescribed fire councils, the Coalition and the professional natural resource community, strengthening existing connections with current internal audiences and creating general contacts with potential new members. This new communication 'pipeline' will link the largest group of prescribed fire stakeholders in American history. Timeline for implementation is January 2011.

Prescribed Fire Use in 21st Century…

Many leading conservationists have stated: ***"the future use of prescribed fire will be defined by the success or failure of the Coalition's efforts", stay tuned….***

For more information about the CPFC or how to develop a PFC in your state contact mark.melvin@prescribedfire.net

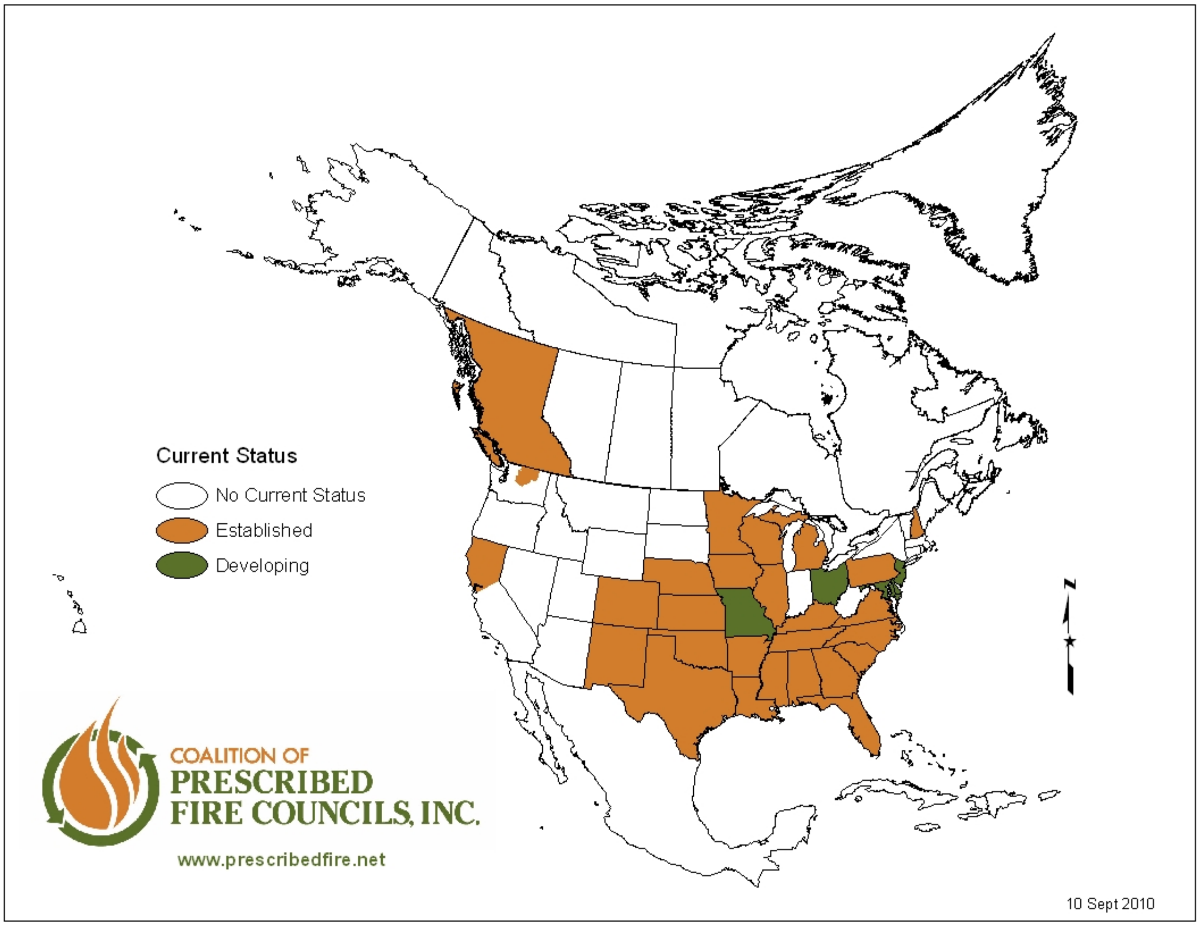

Fig.1 Map of North America showing states/ provinces with existing and developing prescribed fire councils.

A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure

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Extended abstract.
We simulated fuel reduction treatments on a 16,000 ha study area in Oregon, US, to examine tradeoffs between placing fuel treatments near residential structures within an urban interface, versus treating stands in the adjacent wildlands to meet forest health and ecological restoration goals. The treatment strategies were evaluated by simulating 10,000 wildfires with random ignition locations and calculating burn probabilities by 0.5 m flame length categories for each 30 m x 30 m pixel in the study area. The burn conditions for the wildfires were chosen to replicate severe fire events based on 97th percentile historic weather conditions. 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 (>53.3 cm) that are a key indicator of stand restoration objectives. Expected wildfire mortality for large trees was calculated by building flame length mortality functions using the Forest Vegetation Simulator, and subsequently applying these functions to the burn probability outputs. Results suggested that treatments on a relatively minor percentage of the landscape (10%) resulted in a roughly 70% reduction in the expected wildfire loss of large trees for the restoration scenario. Treating stands near residential structures resulted in a higher expected loss of large trees, but relatively lower burn probability and flame length within structure buffers. Substantial reduction in burn probability and flame length around structures was also observed in the restoration scenario where fuel treatments were located 5–10 km distant. These findings quantify off-site fuel treatment effects that are not analyzed in previous landscape fuel management studies. The study highlights tradeoffs between ecological management objectives on wildlands and the protection of residential structures in the urban interface. We also advance the application of quantitative risk analysis to the problem of wildfire threat assessment.

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Ager AA, Vaillant NM, Finney MA (2010) A comparison of landscape fuel treatment strategies to mitigate wildland fire risk in the urban interface and preserve old forest structure. *Forest Ecology and Management* **259**, 1556-1570.

Additional keywords: wildfire risk, wildland urban interface, burn probability, wildfire simulation models

Foliar moisture content and Smoke release characteristics of tree species on Mt. Halla, South Korea

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Additional keywords: Smoke production, carbon monoxide, carbon dioxide, forest fire, foliar moisture content

Extended abstract:
As the weather becomes drier, fire danger increases. The shape of any fires that occur not only depends upon the wind, but will also vary according to topography, vegetation present and its distribution. To predict the magnitude of danger, ignition, the heat of combustion, and the occurrence of smoke and combustion products should be considered. These factors directly affect the growth and spread of a forest fire, so an analysis of these combustion characteristics will help predict the rate at which fireline intensity increases.

The purpose of this study was to determine the moisture content and analyze the characteristics of smoke release and combustion products from the foliage of trees on Mt. Halla (the highest point in South Korea). Sixteen samples of live foliage were collected along two trails on Mt. Halla: one from Sungpanak to Backnokdam, the peak of Mt. Halla, which corresponds to the East slope of the mountain, the other from the peak to Kwanum Temple, which corresponds to the North slope of the mountain. We picked the East and North aspects because the other slopes were off limits to us.

The first group of samples was collected at an elevation between 750 and 850m along the Sungpanak to Backnokdam trail and was comprised of the following seven species: *Carpinustschonoskii, Daphniphyllum macropodum, Carpinus laxiflora, Prunus sargentii, Acer palmatum, Styrax japonica,* and *Acer pseudo-sieboldianum.* The second set of samples was collected between 850 and 1,950m elevation along the Sungpanak to Backnokdam trail, and was comprised of five species: *Prunus maximowiczii, Betula ermani var. communis, Abies koreana, Rhododendron mucronulatum Turcz. var. ciliatum Nakai,* and *Quercus mongolica.* The final set comprised four species that live at an elevation between 600 to 1950m along the Backnokdam to Kwanum Temple trail: *Pinus densiflora, Taxus cuspidate, Sasa borealis,* and *Quercus serrata.*

The moisture content of each sample was determined prior to testing its combustion characteristics.

In this study we used a smoke density chamber to measure total smoke release (TSR) and maximum smoke density (Max. Ds). Carbon monoxide (CO) and carbon dioxide ($CO_{2)}$ were measured to characterize combustion products. Heats of combustion of these foliage samples are reported in Park (2010).

Moisture content of the 16 live foliage samples ranged from 98~248%. Sasa borealis had the lowest moisture content of the species tested. On the East side of the mountain, *Betula ermani var. communis, Abies koreana, Carpinus laxiflora* had low moisture contents, 129% on average. *Daphniphyllum macropodum* registered the highest foliar moisture content (248%).

Total smoke released from sample set three (the trail from Backnokdam to Kwanum Temple) ranged from 222~441 m^2/m^2, the samples from the 2nd set (Sungpanak to Backnokdam trail [elevation 850 m~1,950 m]) released 166~341 m^2/m^2, and sample set one (Sungpanak to Backnokdam trail [(elevation 750 m~850 m]) released 127~495 m^2/m^2.

The highest total smoke release was from *Sasa borealis* in sample set three (Backnokdam to Kwanum Temple trail); *Abies koreana* released the most total smoke from set two species (Sungpanak to Backnokdam trail [elevation 850 m~1,950 m]) but less than that released from *Sasa borealis;* the highest release from set one (Sungpanak to Backnokdam trail [elevation750 m~850 m]) was from *Carpinus laxiflora* and this amount was lower than that from *Abies koreana*. *Carpinus laxiflora* yielded about 4 times as much smoke as that of *Daphniphyllum macropodum. Pinus densiflora, Abies koreana,* and *prunus sargentii* reached their maximum smoke density quickly, and also released lots of smoke at the beginning of combustion.

The highest mean release of CO per 50 g was 0.0755 kg/kg from *Taxus cuspidata;* next was *Pinus densiflora* (0.0697 kg/kg), third was *Abies koreana* which released 0.0637 kg/kg of CO, followed by *Betula ermani var. communis* with 0.063 kg/kg. The highest release of CO_2 was from *Carpinustschonoskii* at 1.15 kg/kg; next came *Quercus serrata* (1.12 kg/kg) and third was *Acer pseudo-sieboldianum* with 1.10 kg/kg.

Acknowledgment

This study was carried out with the support of 'Forest Science & Technology Projects (Project No. S210809L010130)' provided by Korea Forest Service.

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Validation and prediction of the Canadian fine fuel moisture code (FFMC) under future climate change in Kangwon province, Korea

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Abstract
The prediction of fire occurrence under future climate change will be very important to prevent future disasters. The causes of fire occurrence are complicated because they are related to both environmental factors (climate, tree species, topography, fuel moisture, etc.) and human factors. In this study, we predicted future forest fire occurrence using General Circulation Models (GCMs) and the Canadian Forest Fire Danger Rating System Fine Fuel Moisture Code (FFMC). The results will be helpful in developing forest management policy.

FFMC is a Canadian index that predicts fine-fuel moisture content, and is the major factor in determining ignition probability. The FFMC is computed using temperature, wind speed, relative humidity and rainfall. In this study, we compared fuel moisture changes under actual conditions with daily FFMC predictions over a 15year period in Kangwon province, Korea, thereby validating the FFMC in this province of Korea. The correlation coefficients between actual and daily calculated moisture contents from FFMC under various forest densities were very high (correlation coefficient was 0.595 in sparse density, 0.837 in normal density and 0.768 in dense density).

We also compared actual forest fire occurrence in Kyungsangbuk-Do, Korea with FFMC during 2007-2009. When FFMC was 82-90, the probability of forest fire occurrence was high as it is in Canada (The mean value was 83.533 with standard deviation 5.375). After validating FFMC for use in Korea, we calculated a future FFMC using a future climate condition from GCMs developed by the National Institute of Environmental Studies in Japan (NIES) using SRES (special report on emissions scenario) A1B. In this study, we used future daily average temperature and rainfall in Kangwon region, Korea based on GCMs to predict future FFMC in 2039, 2069 and 2099.

Predicted future FFMC differed from that under current conditions. Although fire occurrence remained high from December to April,, future FFMC was lower in May, October and November because of increased summer rainfall. The result was reduced probability of ignition compared to current conditions.

Because correlation between actual fuel moistures and those predicted by the Canadian FFMC was high, the Canadian FFMC can be used to predict fine-fuel moisture contents in deciduous forests of Kangwon province, Korea. Actual fire occurrence also increased as FFMC values increased, suggesting that the Canadian FFMC would be an accurate index to predict fire danger in Kangwon province. Using GCM's to predict future FFMC values showed that increased summer rainfall would reduce the probability of fire occurrence during May, October and November while the probability of ignition would increase December through April in spite of higher summer rainfall.

These results suggest use of Canadian FFMC would improve the Korean forest fire danger rating system, while the future forest fire analysis would help in development of a long-term forest fire prevention policy for this area.

Additional keywords: forest fire, fuel moisture, forest fire danger rating system, forest fire prediction

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Flame spread characteristics of tree species on Mt. Halla, South Korea

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Additional keywords: Flame spread, heat of combustion, ignition, forest fire

Abstract
The Korean Peninsula has a variety of climates, ranging from warm temperate to polar and a wide range in topography from sea-level to high elevation alpine regions that result in a diverse flora. When a forest fire occurs, it has a distinctive footprint that is dependent upon fuel type and shape, and differences in combustion characteristics such as ignition, smoke release, heat of combustion, and carbon oxide (CO, CO_2) products. To predict fire intensity and spread, the combustion characteristics of each species of tree as well as fire type and shape need to be determined. The study reported herein analyzed ignition time and the heat of combustion of the live foliage of tree species on Mt. Halla.

Sixteen samples of live foliage were collected at three locations along two trails on Mt. Halla: one from Sungpanak to Backnokdam, the peak of Mt Halla (the highest point in South Korea), which corresponds to the east slope of the mountain; the other from the peak to Kwanum Temple, which corresponds to the North slope of the mountain. We picked the East and North aspects because we were not allowed to enter the other slopes. Samples of seven species were collected at location 1 (elevation 750m~850m) along the trail from Sungpanak to Backnokdam including *Carpinustschonoskii, Daphniphyllum macropodum, Carpinus laxiflora, Prunus sargentii, Acer palmatum, Styrax japonica,* and *Acer pseudo-sieboldianum.* Five species were collected at location 2 (elevation 850m~1,950m) along the trail from Sungpanak to Backnokdam including *Prunus maximowiczii, Betula ermani var. communis, Abies koreana, Rhododendron mucronulatum Turcz. var. ciliatum Nakai,* and *Quercus mongolica.* Four species were collected along the trail from Backnokdam to Kwanum Temple (elevation 600m~1,950m) including *Pinus densiflora, Taxus cuspidate, Sasa borealis,* and *Quercus serrata.* Live foliar moisture content data and smoke release characteristics for species at the three locations can be found in Lee (2010).

We measured the flame ignition time using the ignition point tester. Results of the ignition tests showed that *Sasa borealis, Rhododendron mucronulatum Turcz. var. ciliatum Nakai,* and

Carpinustschonoskii had flame ignition. *Sasa borealis* having the lowest moisture content, ignited the fastest and had the longest flaming time.

A cone calorimeter was used to determine heat of combustion differences between samples. The heat of combustion for tree species from the Backnokdam to Kwanum Temple trail ranged between 30 to 51MJ/m^2. Heat of combustion for the samples from location 2 (elevation 850m~1,950m) along the Sungpanak to Backnokdam trail was 27~35MJ/m^2, and 18~38MJ/m^2 from location 1 (elevation 750m~850m) along the Sungpanak to Backnokdam trail. The species with the highest heat of combustion for each location were *Sasa borealis,Rhododendron mucronulatum Turcz. var. ciliatum Nakai,* and Carpinustschonoskii.

Based on these results, we can conclude that when a fire occurs, the foliage of *Sasa borealis, Rhododendron mucronulatum Turcz. var. ciliatum Nakai,* and *Carpinustschonoskii* has a higher probability of ignition than other tree species, and also owing to the heat of combustion of these three species, fireline intensity will increase rapidly, which in turn will result in a higher threat to humans and increase the difficulty of fire suppression.

Acknowledgment

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Modeling wildfire property risk in near real time

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Extended Abstract
Stochastic models are increasingly used to estimate potential losses from catastrophic perils such as hurricanes, tornadoes, and earthquakes. Stochastic and real time modeling of wildfires is an important tool for the insurance industry. This paper describes the development of a stochastic wildfire model that allows interested parties to estimate property loss - both in near real time as a fire occurs, and for an ensemble of 10000 scenario years of simulated fires.

Although highly accurate computational fire propagation algorithms have been developed, such deterministic simulation programs are unwieldy and too time consuming for simulating the large number of fires needed to build a stochastic model suitable for risk analysis. The computational effort for each individual fire is prohibitive. The challenges for the catastrophe modeler are to capture many plausible fire growth scenarios, using far fewer computational resources than those required by a full-fledged simulator, and to filter out the generated fires that are not in areas where property loss is likely. Although thousands of fires ignite in California each year, only about a couple dozen cause any significant property damage; and, of those, many fewer cause catastrophic losses. When such catastrophic fires do occur, they are almost invariably in or near the wildland urban interface (WUI). Assessing the risk of these extreme events – with losses for certain historical events in the billions of dollars, and for certain plausible modeled scenarios in the tens of billions - is of great interest to fire researchers, government, insurers, and reinsurers.

The outline of the paper is as follows: The paper begins with an overview of catastrophe modeling. This is followed by a detailed description of the parameters specific to wildfire, and how they are modeled: fire ignition location, frequency, and seasonality; the distribution of fire size; the regional distribution of wind speeds and directions; the geographic distribution of different kinds of vegetation, as well as their combustibility. The simulated propagation of wildfires will be discussed. The vulnerability and damageability of structures will be discussed. The relative vulnerability to fire of different kinds of roofing and siding materials will be introduced.

We then discuss modeling of loss due to wildfire in near real time. During fires, real time perimeter information is provided by various state and government agencies to the geomac.gov consortium. This data can be run through our model, along with details of insured property, to estimate losses. As the fire perimeter becomes more refined, the modeled loss estimates become more accurate. Using the three large Southern California fires of 2008 as a case study, we describe the real time loss modeling process.

Finally, we present observations and findings of our onsite post disaster surveys, and the validation of the real time perimeters. After the large fires in 2007 and 2008, we visited the burned areas. Our surveys focused on two main objectives: 1) validating our model's vulnerability functions, and 2) examining the reliability of the real time perimeter data. Results

of the surveys are presented, focusing on the validation of the reported 2008 fire perimeters.

More information on our project, along with several articles, can be found on our website at http://www.air-worldwide.com.

Additional keywords: Fire behavior; modeling; catastrophic risk analysis; wildland urban interface; loss estimation; structural vulnerability

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Compounding Disturbances and Their Impact on Subalpine Forest and Landscape Structure

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Abstract: Disturbances which overlap in space, and within a short time period, are likely to create impacts which cannot be predicted from knowledge of the disturbances individually, often termed "ecological surprises." Forest managers, researchers, and modelers need information on disturbance interactions and their long term consequences, however landscape-scale investigations are lacking, especially between disturbances common to western North American forests: Fire, wind, and logging. In 1997, a large windstorm impacted the subalpine Routt National Forest in Colorado, USA. From 1998 to 2001, salvage logging was conducted on the windthrow, and in 2002, a large fire consumed portions of the blowdown, logged areas, and the surrounding forests. Research indicates that areas which experienced both windthrow and burning have severely limited tree recruitment, whereas areas which experienced the disturbances individually (blowdown or fire) appear to be recovering strongly. Blowdown areas which were salvage logged prior to the fire appear to be recovering strongly as well. Thus the disturbance history of a given site appears to exert a strong control on post-fire recovery. There is potential for sites which experienced severe blowdown and severe fire to fail to recover to closed canopy forest, and persistent subalpine meadows may form as a result of the disturbance interaction. This has implications for future landscape composition, biodiversity, and carbon storage, and may inform future management decisions regarding disturbance management.

Retrospective Fire Modeling to Quantify the Hidden Consequences of Fire Suppression

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Abstract: Management actions to suppress lightning-ignited wildfires interfere with one of the most important natural processes of fire-dependent ecosystems. Even so, impacts of suppression are seldom evaluated and land managers do not have a consistent way to measure or monitor the effects of their suppression decisions. We developed a retrospective modeling approach using the fire growth simulation tool FARSITE to systematically evaluate the hidden consequences of suppression decisions. Environmental conditions that occurred at the time of the ignition were used in FARSITE to simulate where a fire would have spread and what effects would have resulted had it been allowed to burn. In an evaluation of cumulative suppression impacts for Yosemite and Sequoia-Kings Canyon National Parks, we used retrospective fire modeling in conjunction with Fire Return Interval Departure (FRID). FRID is a metric used by both parks to help measure progress toward restoration goals. We simulated the spread and effects of lightning ignitions that were suppressed between 1994 and 2004, used the results to estimate new FRID values, and used various fire behavior and effects metrics to evaluate other suppression impacts. Results reveal that the suppression decisions during these 11 years dramatically affected landscape conditions, and have missed opportunities to accrue managerial benefits. In another application of retrospective modeling, we are quantifying the monetary and non-monetary consequences of suppression decisions made in 2007 and 2008 and using this analysis as a learning tool for managers.

Assessing Fire Severity among Interacting Fires in Three Western U.S. Wilderness Areas

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Abstract: Wildfires are an important process in many ecosystems; they alter vegetation composition and density, maintain landscape heterogeneity, and consume fuel. In most areas of the U.S., however, fires are suppressed for political, economic, and/or social reasons. Recent research suggests that if fires are allowed to naturally burn, landscapes can become self-limiting or “fire resistant” over time. A few wilderness areas, because they are not actively managed and have, in recent decades, allowed natural fires to run their course, are ideal for studying the influence that prior fires can have on subsequent fires. We studied fire severity within three large wilderness areas in the western U.S. We analyzed a large number of recent (1984 – 2007) fires, examining the portion of each fire that overlapped a previous fire (i.e., it reburned) and the portion that did not overlap a previous fire. For each fire, we compared the fire severity of the reburned area to that of the area that did not reburn. Results show that in reburned areas, fire severity was generally less than areas that did not experience a reburn. While these results are not surprising, they add to the growing body of information regarding interactions among fires. Specifically, these results indicate that where a fire occurs, a subsequent fire will likely burn at a lower severity than if the initial fire had not occurred. This information provides land managers a longer timeframe at which to view the benefits and costs of an individual fire by providing quantitative information on the future reduction in fire severity. Land managers will find these results useful in assessing trade-offs in the decision of whether or not to suppress a wildfire. Future research will focus on the length of time that prior wildfires affect the severity of subsequent fires and how prior fires limit the spread/extent of subsequent fires.

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Climatic and Topographical Influences on Fire Regime Attributes in the Northern Cascade Range, Washington, USA

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Abstract: Recent studies have shown that warmer and dryer climatic conditions are positively correlated with increased large fire occurrence and increased annual area burned in the western United States. The influence of annual climate on smaller fires, and on burn severity, has largely been left unaddressed. This study examines the influence of annual climate and topography on the occurrence, size, severity, and spatial pattern of fires between 1984 and 2008 in the northern Cascade Range of Washington state, USA. Fire severity was quantified for 100 fires > 40 ha using Landsat Thematic Mapper data and a remotely sensed index of burn severity, the Relative differenced Normalized Burn Ratio (RdNBR). Increased understanding of whether local controls, such as topography, or individual climate variables, such as temperature and precipitation, have a stronger influence on fire regime attributes will provide a more nuanced basis for predicting the role fire may play under future climate.

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Wildland-urban Interface in Ontario, Canada

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Abstract: The area where homes or other structures meet with, or are dispersed within, wildland vegetation is known as the wildland-urban interface (WUI). Understanding forest fires in the WUI is crucially important due to potential impacts on land management, economics, ecological relationships, and human communities. The WUI will become increasingly important as more homes are built in WUI areas and as fire activity increases due to climate change. In the province of Ontario (Canada), there is a large human population along with vast amounts of burnable wildland fuels. Thousands of hectares burn annually in Ontario and increases in area burned are forecasted for the near future due to climate change. Despite the importance of the WUI, little is known about determining its location, extent, and how many homes are at risk. In this study, the WUI in Ontario was defined and quantified. Building location data from the Land Information Ontario (LIO) database along with fuel types from classified Landsat satellite images were used. The use of actual building locations (instead of population density over broad areas) allowed an accurate determination of the WUI, which no other study to date has been able to do. The location of the WUI across Ontario was mapped, showing areas where WUI conflicts may potentially occur; along with the characteristics of the WUI land area (e.g. land ownership, fuel types, fire management zones). These results will provide useful data for land and fire management, fire research, and urban planning. This study is a first step towards understanding fire in the WUI in Ontario and offers a necessary baseline to work from. Future work will include incorporating a measure of fire risk for each area in the WUI, expanding the spatial coverage, and predicting how future urban growth and changes in fire activity due to climate change will affect fires in the WUI.

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Mapping Wildland Fire Risk to Populated Areas across Scales: Two Methodologies for Representing Residentially Developed Lands

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Abstract: In recent years there has been an increase in the complexity of wildland fire management due to increasing exurban development into fire prone ecosystems. Alternative methods to identify the interaction of human development with wildland fire have emerged that vary based on the management problem that is being addressed. Analyses range from fine scale analyses with manually digitized individual structure location using high resolution aerial photography linked to wildland fire simulations of specific wildland fire conditions, to national assessments comprised of intersecting census block level housing data with national vegetation maps. In this poster we will demonstrate two methodologies that are emerging within Forest Service Research to further our understanding and ability to manage wildland fire risk to human development. These methods represent advances in both our ability to identify residential locations and improved representation of the wildland fire threat. At the individual event level the Rapid Assessment of Values at Risk (RAVAR) uses cadastral data to identify developed parcels threatened by wildland fire. Researchers from the Rocky Mountain Research Station and Federal Geographic Data Committee Cadastral Sub-Committee have acquired over 70 percent of the western US cadastral data for use in RAVAR. However, national level applications require consistent data. For national level risk assessment the authors have developed a dataset which reconciles population and the associated residential structures to create a nationally consistent residentially developed populated areas dataset. They interact this dataset with a large wildland fire simulation model that produces estimated likelihood of wildland fire to determine national risk to populated areas. These advances will aid fire managers by providing improved structure location information, as well as assisting in hazardous fuels reduction prioritization and federal budgetary allocation issues.

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From the Flames to the Frame: Communicating Messages of "Conflagration" and "Climate Change"

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Abstract
The publicly managed practice of fire management operates in the public "marketplace of ideas." After the 1910 fires, for instance, this public debate ranged from those who sought an increased federal control of fire management to those calling for the dissolution of the fledgling Forest Service. Today, forest and fire managers are charged to respond to a more widespread though dispersed crisis -- climate change and climate variability -- and critics ask, "What climate crisis?" While managers ask, "How do we manage a variability we can't yet specifically predict?" And as in any fire season, the public asks, "How will you save my house?"

A study of historic dissemination of framing messages identifies such labels as the "conflagration" and "big burn" of 1910 and the "Let it burn" fires of 1988. Interpretations of these historic fire dialogues inform our approaches today for framing a message that will engage fire professionals and the public in a critical dialogue regarding "climate-change" fires. Specific examples of contemporary fire messaging offer a checklist of communication elements, ranging from "fire resilience" to "global wildfire," that have resonated with the media and the public.

Fire Regimes in Mexico

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Abstract:

Mexico is a country with high species and ecosystem diversity, and where fire has become one of the top priorities in forest management policy. However, current management fire management practices are still centered in firefighting and fire suppression. To ensure that the ecological conditions that gave rise and maintain the high diversity of species in Mexico is maintained, it is important to incorporate information on the natural fire regimes in fire management programs. Here, we analyze information available on the main terrestrial ecosystems of Mexico to suggest what the likely fire regimes were for each one of them.

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A New Approach for Fire Risk Assessment in Wildland-urban Interfaces: A Case Study in the South of France

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Abstract: Each year, wildfires destroy about 500,000 ha of vegetation, especially in the five most affected countries in southern Europe (Portugal, Spain, France, Italy and Greece) of the Mediterranean region, and climate change scenarios indicate an increase in fire risk leading to increased fire frequency and extension of the fire season. Many large fires are linked to the huge land transformations that have taken place in this region in recent decades that have increased the risk of wildfires. On the one hand, agricultural fallows and orchards are slowly colonized by vegetation, while on the other hand, the forest is not sufficiently used, both of which result in increased accumulation of fuel. In addition, urbanization linked to forest extension involves new spatial configurations called “wildland-urban interfaces” (WUI). WUI are commonly defined as “areas where urban areas meet and interact with rural lands, wildland vegetation, forests” creating a new conjunction of housing and vegetation characteristics. A method was developed to characterize and map WUI at large scales and over large areas for wildland fire prevention in the South of France. Based on the combination of four types of residential housing configuration and three classes of vegetation structure, twelve interface types were classified. Spatial and statistical analysis was performed based on this WUI typology in order to build a total index of fire risk. The levels of fire risk were evaluated through the modelling of three indicators of fire risk and their combination: (i) “fire ignition density”, derived from the distribution of fire ignition points, (ii) “wildfire density”, derived from the distribution of wildfire area and (iii) “burned area ratio”, derived from the proportion of the burned area to the total study area. The values of the total index of fire risk varied depending on the WUI types but also on the natural, social or human environment. Improving our knowledge on risk levels in WUI will increase the efficiency of wildfire prevention through the suggestion of adapted preventive measures in terms of land management and fire management in WUI.

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Snag Fall, Coarse Wood Decomposition, and Fine Fuel Succession Following High-Severity Fire in Dry-mixed Conifer Forests of Oregon's Cascades

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Abstract: Reducing future fire severity is a proposed objective of salvage and reforestation operations following wildfire disturbance. Considerable debate continues over the ability of such management practices to achieve this objective given limited understanding of coarse woody detritus (CWD) dynamics, fuel bed alterations, and post-fire vegetative growth. The objective of this study was to estimate future fire severity by understanding the dynamics of CWD and fine surface fuel succession. A total of 6,275 snags in thirty 0.25-ha plots were sampled at seven different fire sites, covering a 24 year chronosequence following high-severity fire. Three cross-sections from sixty fire-killed *Pinus ponderosa* snags, sixty *Abies sp*. snags, and forty *Pinus ponderosa* logs were sampled to estimate decay rate constants for standing and downed CWD. A snag and CWD dynamics model was created to track the accumulation of surface CWD and its decay state across time. Custom fuel models were developed at points across time, incorporating CWD and post-fire vegetative fuels.

Legacy CWD was responsible for the largest total accumulation of surface fuel as snags break and fall, but primarily in 100- and 1000-hr fuel classes. Decomposition rates more than double as CWD transfers from standing to downed material reducing total CWD biomass by 30-40% in 24 years. Fine fuels are primarily derived from post-fire vegetation and steadily increase over the 24 year period. Herbaceous fuel loads peak within 2-4 years but decrease rapidly as *Ceonothus velutinus* and *Arctostaphylos patula* shrub cover exceeds 65% by year 5, steadily increasing in total biomass over 24 years. Spread rates and flame lengths in post-fire environments are primarily driven by fuels generated from new growth. In addition to the size of CWD, the dynamic processes of snag fall, breakage, and decomposition limit its influence on fire spread and flame length when reburning occurs. Soil heating and total heat release is exacerbated by combustion of CWD, but the severity of this effect is dependent on its decay state and combustion efficiency. Results of this study therefore suggest post-fire management decisions consider vegetation dynamics as well as dead wood dynamics to meet objectives.

Quantifying Fire Hazard after Blowdown in Southwestern Oregon

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Abstract: Severe windstorms, or 'blowdown' events, alter forest ecosystems by changing species composition, vertical and horizontal structure, and ecological processes, including subsequent ecological disturbances. In January of 2008, a severe windstorm, with wind gusts up to 145 kilometers per hour, blew down 2,800 ha of timber in the Butte Falls Resource Area (Medford Bureau of Land Management) in southwestern Oregon. Blowdown severity ranged from light (10% of the ground covered in blowdown) to severe (40-95% of the ground covered in blowdown), and occurred primarily in fire-prone mixed-conifer forest dominated by Douglas-fir. The fuelbed profiles created after windstorms can predispose forests to subsequent large-scale disturbances (stand replacing fire, insect and disease epidemics). In response to the blowdown event, salvage logging treatments followed by pile and burn surface fuel treatments are being conducted to recover value of commercially valuable time, to reduce fuel loads and fire hazard, and to reduce risk of insect infestation. We conducted a study to evaluate the effects of salvage logging and surface fuel treatments on fuelbed structure and potential fire behavior in the severe blowdown stands. To evaluate fire hazard, we measured fuelbed structure before salvage logging, after salvage logging, and after surface fuel treatments and analyzed associated fire hazard using the Fuel Characteristic Classification System. We expect results to indicate that salvage logging decreases coarse woody fuels, but increase fine woody fuels, thus potentially increasing fire hazard. However, we expect that subsequent surface fuel treatments reduced fire hazard.

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Variation in Flammability of North America Pine Species

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Abstract: *Pinus* species are an important component of fire-prone and fire-driven ecosystems throughout the northern hemisphere and their litter is a driver of surface, ground, and canopy fire behavior. In spite of the assumptions related to pine flammability, little data are available that quantify among species variation and no substantive work addresses the underlying mechanisms of these differences. We evaluated burning characteristics and physical leaf characteristics of pine species collected throughout North America. For each species, seven 15 g replicates were burned under controlled laboratory conditions. Average fuelbed height (cm), maximum flame height (cm), flaming duration (s), smoldering duration (s), and residual mass (g) were all recorded. At the time of each burn, moisture content of the litter was less than 3%. Leaf length, leaf thickness, and weight of fascicle were recorded for each pine species collected. Among species burned, *Pinus rigida*, *P. washoensis*, and *P. muricata* burned with greatest intensity, generating longer average maximum flame heights (mean = 85.6, 84.9, and 84.3 cm, respectively). *Pinus balfouriana*, *P. monophylla*, and *P. edulis* burned with the shortest average maximum flame heights (mean = 20.4, 28.1, and 40.0 cm, respectively). Preliminary analysis relating physical traits to flammability characteristics revealed that needle length was the best predictor of flame height, but only explained 45% of the variation in this metric. Needle length also predicted percentage of fuel combusted ($p<0.01$, $R^2=0.47$). Needle thickness was not related to flame height or percentage of fuel combusted. Pine physical measures explained little variation in burning characteristics, suggesting that chemical variability may play the dominant role in pine flammability.

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Assessing Fuel Loading in Longleaf Pine Forests for the BlueSky Framework

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Abstract: Fuel classification has evolved from a fire control planning focus to the beginning of predictive fire behavior modeling in the 1970s. Current fuel classification models have focused on the rate of spread, resistance to control, and the flame length of fires in surface fuels. Fire behavior is predicted by land managers with thirteen stylized fuel models (Rothermel, 1972; Albini, 1976). Decision support systems such as FARSITE and the National Fire Danger Rating system are based on the Rothermel's fire spread model and are the basis of predicting fire behavior today. Land managers recognize that these models are limited in their ability to predict extreme fire behavior, persistent fires, and fuel consumption. Some of the fuel information limitations are currently being addressed by the Fuel Characteristic Classification System (FCCS) research funded by the JFSP. But of the original 13 and the new standard fire behavior fuel models, few adequately characterize fuels given historical land management practices found at North Carolina sites. The availability of smoke trajectory and concentration models has increased the need for quantitative fuel field data. A line-intersect method developed by Brown (1974) has been widely adopted and is being used by the USDA Forest Service Forest Inventory and Analysis (FIA) program to quantify fuel-loading inputs. The FIA methods generally partition the forest ecosystem into pools for live trees, down deadwood, standing dead trees, understory vegetation, forest floor materials, and soil. We report on the characterization of fuels in longleaf pine forests in North Carolina and its application to smoke trajectory and concentration modeling utilizing the BlueSky framework.

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Deriving Conifer Needle and Branch Mass for Crown Fuel Modeling using Terrestrial Laser Scanning

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Abstract: Requirements for characterizing coniferous forests in the U.S. are changing in response to wildfire concerns, bio-energy needs, and climate change interests. At the same time, technology advancements are transforming how we measure forest properties. For example, Terrestrial Laser Scanning (TLS) is yielding promising results for measuring fundamental tree crown biomass parameters that historically have required costly destructive sampling and correspondingly small sample sizes. In this study, we use a near-infrared TLS to examine the effects of range and scan density on quantification of needle and branch mass. We systematically image conifer specimens at multiple ranges and point densities, then dry and weigh needles and branches of each. Comparisons of biomass with laser-derived reflection intensity and density suggest that the TLS can represent results obtained by destructive sampling. However, there are range dependencies that appear to be caused by variable target geometry, influencing the partitioning of crown fuels by size class. By understanding these range dependencies, we anticipate increasing the efficiency of biomass sampling for derivation of accurate crown fuel models using relatively large samples of trees.

Leaf Litter and Coarse Woody Debries Dynamics in Pinus Douglasiana Stands of Different Age after High and Low Severity Fires

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Abstract: Pine forests experience high fire occurrence in Mexico, and are the more intensively managed ecosystems for production, conservation and restoration. A quantitative description of fuel dynamics after low and high severity fires is critical to adequately manage these forests. Here, we describe fuel dynamics of the leaf litter-duff (LLD) and downed woody debries (DWD) in a chronosequence of sites with different ages since the last fire for low and high severity fires. Fuel loads for the LLD and DWD complex in the low severity fire chronosequence adjusted to a logarithmic model ($r^2 = 0.97$, $p < 0.001$), with loads increasing from 17 to 82 Mg/ha after 37 years from the last fire. In the high severity fire chronosequence, fuel loads decreased from 141 to 50 Mg/ha in the first 15 years, but then increased again to 81 Mg/ha after 25 years. Sites experiencing low severity fires accumulate considerable fuel loads after 10 years (> 64 Mg/ha), while sites experiencing high severity fires accumulate large fuel loads in the first 10 years, and then after 25 years.

Another Compelling Reason for Establishing National Sampling and Data Standards for the National Fuel Moisture Database

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Abstract: The National Fuel Moisture Database (NFMD), a web-based database and query system, evolved from a need to provide field-sampled live and dead fuel moisture information to the wildland fire organization – from fire danger and fire behavior specialists to fire managers and incident command staff. The data comes from comprehensive fuels management programs run by federal, state and local land management agencies across the United States. Because **in situ** fuel moisture information is an integral part of fire danger and fire behavior analysis and prediction, the NFMD has proved to be an invaluable tool in the management of wildland fire. Better fire danger and fire behavior predictions contribute to better preparedness and safety decisions and improve the response to wildland fire that can reduce land management costs.

When the NFMD went online in 2007, it was known that national, interagency standards for sampling protocols and data quality had to be established to ensure fire decision-makers were using consistent and reliable information. Since then, this requirement has expanded beyond operational necessity. The scientific community has found a role for the NFMD in research in such varied categories as satellite remote sensing of vegetation, soil moisture monitoring and fire prediction modeling. However, without a rigorous quality control program, these data cannot provide an accurate baseline for statistical analysis. Efforts are underway among the land agencies to establish interagency standards for collection of fuel samples (i.e., collection tools and receptacles), processing of samples (i.e., storage, scales for weighing, ovens for drying, etc.) and statistical analysis (i.e., sampling frequency, sample size, normalization, etc.). This work must include the academic and research communities to ensure a proper foundation is established that can aid the advance of fire science and improve wildland fire management.

A Comprehensive Guide to Fuels Management Practices for Ponderosa Pine / Mixed Conifer Forests

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Abstract: This project is to develop an integrated synthesis that provides forest land managers with comprehensive, up-to-date knowledge on ecological values and options for management of hazardous fuels within ponderosa pine / mixed conifer (PP/MC) forests. Our project will focus on PP/MC forests that occur throughout the interior West, Utah, Cascade Range, Blue Mountains, Klamath Mountains, and Pacific Coast. There is substantial documentation on fire ecology and appropriate hazardous fuel management practices for pure ponderosa pine forests. The PP/MC forest type, however, is less well understood, and is typified by greater productivity, complex vertical and spatial structure, diverse species assemblages, and varied fire regimes. Practices borrowed from the pure ponderosa type may be inappropriate for the different conditions presented by the PP/MC forest type. This project will be implemented by an interdisciplinary team (ecology, silviculture, fuels management, and forest operations) comprising researchers and experts who will perform a thorough scientific literature search to integrate up-to-date knowledge associated with fuels treatment within PP/MC forests. Land managers' input and feedbacks are another primary component of the project that will be incorporated to better understand their needs and challenges in fuels management. At the end of the project we will deliver a comprehensive handbook for fuels treatment and provide managers with web-based access to our project objectives, methods, timeline, links and summaries of the deliverables and results.

Assessing Efficacy of Landscape Restoration in Juniper Savannas in Southern Arizona

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Abstract:
The Clifton Ranger District on the Apache-Sitgreaves National Forest is restoring large tracts of juniper savanna and grassland in southern Arizona using prescribed fire, mechanical thinning, and livestock grazing manipulations. Their use of fire is innovative both in efficiency and application. Treatment blocks are large, ranging in size from 3-10 thousand hectares and fire is allowed to burn freely within natural barriers during hot, dry, windy summer conditions. Fire is applied by small teams of practitioners funded mostly by consortia of state and private wildlife organizations, and is used to reduce tree canopy densities and tree encroachment, increase forage production, and maintain hiding cover for wildlife. This study examines the cumulative effectiveness of treatments at reducing canopy cover. Canopy cover change is quantified systematically using a dot-grid approach on conventional 1:15,840 aerial photography acquired in 2000 and 2008. Preliminary results from the Mesa Treatment Area (totaling 3890 ha) indicate that canopy cover was reduced by 26% ($n = 3465$, $p < 0.001$) in units that received fire and 42% ($n = 3080$, $p < 0.001$) in units receiving mechanical thinning and fire. Adjacent control units saw an increase in canopy cover of 8% ($n = 2310$, $p < 0.001$). Results also suggest that certain soil associations with deeper soil beds, greater water retention, and reduced erosion may support more positive fire effects. If the latter results hold up to scrutiny, it is thought that significant efficiencies can be gained in restoration by identifying areas where fire alone will meet resource objectives and more precisely targeting mechanical treatments to landscapes where fire will not have the desired effect.

Smoke Modeling and Validation Field Design: CO, PM2.5, CO2 and Smoke Monitoring

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Abstract: The purpose of this study is to monitor low level smoke from prescribed burns: wind turbulence, temperature profiles, PM2.5 monitoring for validation of smoke transport models. The approach is a three year modeling and field validation study using tall towers (10m, 20m, 30m), and short towers (10m) inside and outside of fire perimeter equipped with smoke, temperature, RH sensors and sonic anemometers.

We will give preliminary results from field tests, comparing the performance of low cost CO monitors, modified smoke monitors, and CO2 analyzers against reference PM2.5 monitors at prescribed fires in Calloway Forest, NC and Brendy Bryran State Forest, NJ this winter.

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Quantifying the Effects of Wildland and Prescribed Fire on Three-dimensional Forest Structure and Fuel Loading using a 50 Year Fire History and Landscape-scale Scanning LiDAR in the Pine Barrens of New Jersey

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Abstract: Understanding the effects that varying fire regimes have on the structural attributes (leaf area distribution, branching distribution, vertical fuel loading) of forested ecosystems is fundamental within the realms of both fire ecology and fire management. By accurately quantifying the structural attributes that result from wildfire, fire management activities or some combination of the two; we can better manage the landscape to meet specific goals. By using continuous, high-resolution, datasets to examine these questions, we are able to take into account the entire landscape's fire history.

We utilized a scanning LiDAR dataset (8 returns m^{-2}) that encompassed two counties within the Pine Barrens of New Jersey. This data has been post-processed using methods described in Skowronski et al. (2007) into a raster-based dataset with 25 meter horizontal resolution, where each pixel represents a 0-25 m vertical canopy height distribution. Distributions were calibrated to canopy bulk density (CBD) sampled in the field, as described in Skowronski et al. (In Press), where a CBD value was assigned to 1 meter vertical increments through the canopy (CBD_{bin}).We coupled this data to spatial fire history records spanning 50 years and analyzed the effects of varying fire histories on forest structure.

Fuel loading observed in pure pitch pine stands with no history of fire had an average CBD_{bin} of 0.023 kg m^{-3}, similar to average values in stands that had three wildfires (0.021 kg m^{-3}) and three prescribed fires (0.019 kg m^{-3}). The maximum CBD (CBD_{max}) in the undisturbed stands occurred in the 1 meter bin closest to the forest floor, and averaged 0.050 kg m^{-3}. In the stands impacted by wildfires, CBD_{max} was 0.067 kg m^{-3} in this lowest height bin, reflecting denser understory vegetation. In the stands where prescribed fires had been conducted, CBD_{bin} was only 0.029 kg m^{-3} in the 1 meter height bin and the CBD_{max} value (0.030 km m^{-3}) occurred in the 9-10 meter height bin, illustrating a much different fuels distribution than the untreated and wildfire stands. Our results indicate fundamental differences in forest canopy structure based on the fire history of a stand.

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Monitoring Mechanical Fuels Reduction Effectiveness and Effects in Shrublands (Coastal Sage and Chaparral)

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Abstract: Due to increasing citizen concerns and regulations regarding prescribed fire, management of shrub-dominated defensible space in the wildland-urban interface (WUI) is now mostly accomplished with hand crews or mechanical equipment. These vegetation treatments are also increasingly intended to provide for both wildland fire safety and habitat values'. Over the decades that the WUI has been managed in shrublands in southern California, little monitoring data has been gathered to assess the effectiveness and effects of mechanical fuels reduction in coastal sage scrub and chaparral vegetation. Such long-term data is essential to establishing and adapting appropriate regulations that consider structures, landscaping, and natural vegetation as a system. The species composition and vertical structure of vegetation were examined at 20 brush-management sites in the Tierrasanta area of San Diego. Paired plots were established at each site, either in the brush management zone and in relatively undisturbed natural habitat downslope, or pre- and post-treatment in areas where crews cut and chipped or removed vegetation. Species composition, height classes, and ground cover were recorded at 1-m intervals along the 50-m transects, using the point-intercept method. Brush management treatments reduced the cover of both native and non-native species, as is intended with fuel reduction. Brush management treatments reduced native plant species diversity, and preferentially reduced native species cover, particularly the coastal sage scrub shrub species and vegetation between 0.5 and 2 meters above the ground.

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Numerical Simulation of Fuel Treatment Effectiveness in Preventing Structure Ignitions

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Abstract: The purpose of this study is to demonstrate the potential of physics based fire behavior models in the assessment of fuel treatment effectiveness in the wildland-urban interface (WUI). This study used the WUI Fire Dynamics Simulator (WFDS) developed by National Institute of Science and Technology (NIST) in cooperation with VTT Technical Research Center of Finland. WFDS uses computational fluid dynamics (CFD) to solve three-dimensional time-dependent equations governing fluid motion, combustion, and heat transfer. WFDS accounts for both radiant and convective heat flow in the gases and vegetation, as well as drag of the vegetation on airflow. WFDS is capable of simulating fire spread and smoke transport in vegetative and structural fuels. Structure ignition simulations based on critical heat flux values were run through WFDS under various fuels treatments. WFDS has considerable implications as management tool for the development and evaluation of the effectiveness in current and planned fuels treatments. The graphical representation of fire behavior in WFDS also has implications as a tool for overcoming human dimensional resistance to the implementation of Firewise practices. Preliminary results show the importance of spatial arrangement of fuels and structures on the landscape as a sufficient radiant heat flux is generated for piloted ignition, not only the by the adjacent vegetation but also from surrounding structures. Results show fuel treatment to be effective in reducing the home ignition via radiant and convective heat flux when implemented at or above Firewise standards.

Forest Restoration and Fire Hazard in a High Severity-fire Regime

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Abstract: Forest managers at the Cedar River Municipal Watershed (CRMW) are actively implementing restoration in the western hemlock (*Tsuga heterophylla*) and Pacific silver fir (**Abies amabilis*)*** ecosystems. CRMW managers began thinning treatments in early 2000 and majority of the restoration treatments have been in Pacific silver-fir stands. The goals of thinning are to accelerate forest succession of early seral stands, restore and sustain natural processes, and protect and enhance water quality and quantity. In this study, we used the Fire and Fire Extension to the Forest Vegetation Simulator (FFE-FVS) and FlamMap, to quantify the effects of restoration thinning on fire hazard and fire behavior at the smaller spatial scale ($< 10^3$ ha) and at larger spatial scale (10^3 to 10^6 ha). We installed permanent sample plots to quantified fuelbed characteristics (fuelbed loadings, fuelbed depth) following restoration treatments to obtain baseline measures for monitoring changes over time. We also measured the effects of two surface fuel treatments (lop and scatter and mastication) on fuelbed characteristics. Finally, we discuss how study results of have influenced the future management direction within the watershed.

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Accomplishing Stand and Landscape-Scale Fuel Management through a Balanced Fire Management Program

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Abstract: Exclusion of fire for over a century in areas that historically burned on a regular basis, along with other land-use practices and the proliferation of invasive exotic species, have resulted in heavy fuel accumulations and altered vegetation composition and structure in much of the western United States. These conditions are contributing to increased fire intensity, spread, and resistance to control and are a direct cause for abnormal negative post-fire effects. A compounding factor has been the growth of communities in areas adjacent to open public lands, putting homes and other structures closer to areas where large fires occur.

Increased vegetative manipulation and treatment is prerequisite to accomplishing necessary spatial and temporal scale fuel management and achieving ecosystem restoration and maintenance. The wildland fire management program must be endorsed not as a single focus program but as a balanced program. Such a program should be solidly based on a foundation of use of the full spectrum of fire management scales, techniques, timing, location, and combination of strategically mixed planned and unplanned treatments across wildland areas. Fundamental to the success of a balanced program are several factors. First, a balanced program must be able to address those factors of sequencing, scheduling, scale, changing needs, and collaboration. Second, this type of program cannot be focused on only a portion or single objective of the overall program, but must account for the role of planned and unplanned treatments as part of a viable stand and landscape fuel management strategy. Finally, for a fire management program to contribute in a meaningful way to stand and landscape scale fuel management, it must address a strategic vision for the appropriate application focus. That is, it must foresee how the program can be moved from a concentration on remotely-based areas to a broader based focus across all land use situations, including population-based areas. Fuel management strategies can be, at times, confusing and conflicting. These significant attributes are associated with stand and landscape scale fuel management strategies and their importance is such that a successful program of action cannot be developed and implemented without addressing them.

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Post-burn Fire Hazard in Mixed Severity Fire Regimes in the Cascade Range

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Abstract: Fire severity influences the post-burn structure and species composition of a site and the potential for future disturbance. This study focuses on post-burn site characteristics in mixed conifer ecosystems. Fires in mixed conifer ecosystems vary widely in frequency and severity. Four fires that burned on the east side of the Cascade Range between 2007 and 2008 were stratified by fire severity, and vegetation and fuels were quantified within the fire perimeter. The Fuel Characteristic Classification System (FCCS) (Sandberg et al. 2007) was used to convert those structure and composition characteristics into an estimate of fire hazard, which is based on the potential surface fire behavior, crowning potential, and fuel consumption. Understanding variability in fuels and vegetation is important for management practices including the classification of high-risk areas, the assessment of re-burn potential, and the identification of fuel breaks. Knowledge of post-burn fire hazard will help guide fire managers to meet fire and fuels management objectives in mixed severity fire regimes.

Evolution of 20th-century Climate-fire Relationships in the US Northern Rockies

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Abstract: Numerous studies link the occurrence of large fires to monthly and seasonal climate, but the extent to which climate-fire linkages change over time is less clear. Here we quantify links between monthly temperature, precipitation, and sea-surface temperature (PDO, ENSO indices) with area burned in the US Northern Rockies (Idaho and Montana, west of the Continental Divide) from 1902 to 2003. Climate-fire relationships displayed greater variability through time than across three major forest types (cold, mesic, and dry). Moving correlations at 20-yr time scales suggest three broadly coherent periods, independently related to variability in climate and fire management: 1902-1930, 1930-1980, 1980-2003. In the early 20th century, when over half of the total area burned in the record occurred, ca. 90% of the variability in annual area burned was explained by spring precipitation and summer temperature. During the mid 20th century (1930-1980; accounting for 12% of the total area burned in the record), late summer temperature and precipitation became more important and helped explain ca. 75% of the variability in annual area burned. March and April temperatures were important predictors from 1980-2003 and helped explain ca. 80% of the variability in annual area burned. Our results demonstrate that the climate drivers of annual area burned have changed over the 20th century, with the relative importance of temperature and precipitation shifting and a greater importance of spring vs. summer temperatures since ca. 1980. Such non-stationarity has important implications for understanding the biophysical mechanisms controlling fire occurrence and for forecasting annual area burned in the context of climate change.

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A Mountain Wind Model for Assisting Fire Management

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Abstract: Forestry organizations responsible for managing prescribed fire or controlling wildfire rely on weather forecasts of wind speed and wind direction for planning and allocation of resources. At the locations of fire sites in mountainous areas, winds are highly variable and may differ from winds at distant weather stations or from winds collected at safe sites just a few kilometers from fire lines. These uncertainties in winds can upset plans and place fire fighters in jeopardy.

A recursive rule-driven “mountain wind model” (MWM) replaces terrain with a “pressure potential” equation to simulate wind fields in complex terrain. Wind fields are developed for a 100m deep layer draped over terrain. The MWM is demonstrated with flow around a simple obstacle (Stone Mountain, GA), flow over western canyon lands, flow over a ridgeline in the central Appalachians, and for the Esperanza fire in California on 26 October 2006.

Untangling the Roles of Dry Air Aloft and Downward Instability in Fire Growth

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Abstract: Previous studies have indicated that dry air 1000 to 3000 m above the ground is often associated with episodes of large fire growth. This is the motivation behind the dryness, or B, component of the Haines Index. More recent preliminary work has suggested that the instability of air at these same heights to downward motion also correlates with such episodes. The downward instability used in this preliminary work, however, has depended partly on the same dryness aloft. The current study seeks to separate the influence of the dryness from the downward instability in order to better indicate the physical processes that lead to these factors influencing fire growth events.

Progress Towards a Lightning Ignition Model for the Northern Rockies

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Abstract: We are in the process of constructing a lightning ignition model specific to the Northern Rockies using fire occurrence, lightning strike, ecoregion, and historical weather, NFDRS (National Fire Danger Rating System), lightning efficiency and lightning "possibility" data. Daily grids for each of these categories were reconstructed for the 2003 fire season (184 days- May through October) in an area defined by the boundaries of USFS Region 1. Logistic Regression analysis will be used with the binary dependent variable being the occurrence of a lightning ignited fire that has been recorded to the appropriate agency in a grid cell. The independent variables listed above will be tested and coefficients developed for each one found to be statistically significant. This analysis will be done spatially for each grid cell in each grid created for each variable during the 184 day time span. The models developed can be used by fire management agencies to estimate fire occurrences directly after fire season lightning events. Daily estimated fire occurrence maps can be created giving managers a refined view of areas where resources should be targeted.

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Season Ending Events, a Matter of Perspective

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Abstract: Agency managers are often faced with making difficult wildland fire management decisions based on collating a significant amount of information regarding a fire. Supporting the decisions is understanding how long an incident may persist, especially if the fire has potential for resource benefits. Analysis of historical season ending events has occurred since the mid-1990's and was initially incorporated into the Rare Event Risk Assessment Process (RERAP) computer program. Definition of the season ending event has always been subjective and typically included a substantial rain event across a two or three-day period. For instance, ½ inch of rain over three days is commonly used in the northern Rocky Mountains. Data from Remote Automated Weather Stations (RAWS) are frequently used to determine the dates these events occurred each year in the past. Then a Weibull distribution ('term distribution') is developed from which to predict the probability of an event occurring by a particular date. A review of several term distributions developed by different analysts for the northern Rocky Mountains during the 2007 fire season was completed to compare season ending criteria and date selection in a relatively small geographic area. These distributions had a vast spread in season ending dates that caused the Weibull distribution to shift as much as three months. This paper highlights the differences among several term distributions, demonstrates the need for consistent definitions and determinations of season ending events within a small geographic area, and proposes a potential solution for greater consistency and thus higher reliability in season ending event distributions.

Climate Change and Fire Danger Rating in the Northern Rockies

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Abstract: Studies have indicated that changes in wildland fire activity are, at least in part, a product of climate change. Fire danger indices, driven by climatology, should reflect these changes. Energy Release Component (ERC) is considered to be an effective indicator of drought conditions and seasonal drying of forest fuels and is often used in fire management planning. McHugh (2010) found that ERC has increased in the Greater Yellowstone Area over the past fifty years. We expand upon prior work to examine possible trends in both climate driver variables and the fire danger rating indices in the Northern Rocky Mountains. Further, we examine the seasonal trends in fire danger rating indices to ascertain if the indices reflect the increases in the length of the fire season that have been published previously. Increased ERCs may indicate a lengthening of fire season and increase the length of time during which more intense fires may occur, which have implications for staffing and preparedness.

Integrating the Fuel Characteristic Classification System and the Forest Vegetation Simulator

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Abstract: The Fuel Characteristic Classification System (FCCS) captures the structural complexity and geographical diversity of fuels across landscapes and provides the ability to assess the impacts of human change. FCCS stratifies fuelbeds into six horizontal strata to represent every fuel element that haste potential to combust, and to better assess potential fire effects from each combustion phase of a fire. The Forest Vegetation Simulator (FVS) is the USDA Forest Service's nationally supported framework for forest growth and yield modeling. We are developing an interface between FVS and FCCS that will allow forest managers to evaluate the effectiveness of proposed fire and fuel management treatments in the context of potential fire effects on short-and long-term stand dynamics, important to silviculture, wildlife habitat, and fuel hazard based on realistic fuelbeds.

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Simulating Fire Hazard Across Landscapes Over Time Through Integration of the Vegetation Dynamics Development Tool (VDDT) and the Fuel Characteristic Classification System (FCCS)

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Abstract:
The Vegetation Disturbance Dynamics Tool (VDDT) and the Fuel Characteristic Classification System (FCCS) are two valuable products used by many land managers throughout the United States. VDDT is a state and transition model that simulates changes in vegetative composition and structure across a landscape under different disturbance regimes and management scenarios. The FCCS is a software application that allows users to record fuel characteristics as fuelbeds and analyze fire potential of wildland and managed fuels. Although the utilities of VDDT are many, VDDT does not directly assess fire hazard for different vegetation states.? We are integrating VDDT and FCCS to enhance the utility of VDDT and enable simulation of vegetation composition, structure and related fire potential across a landscape over time. Multiple FCCS fuelbeds will be created, based on plot data, for every VDDT state class (vegetation structure and cover combination) in mid-scale (5th field watershed) models covering the states of Oregon, Washington, Arizona and New Mexico. Fire potential, including fire behavior potential, crown fire potential, and available fuel potential, will be calculated for each fuelbed in FCCS, and mean fire potential will be calculated for each VDDT state class. The resulting link between VDDT state classes and fuelbed fire potential will allow users to assess the effects of disturbance regimes and management activities, such as fuel treatments, on vegetation communities and related fire hazard across a landscape over time.

Fire Effects Tradeoff Model (FETM): A Landscape-Scale Ecosystem Model for Land Managers

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Abstract: Fire management planning requires the consideration of many different factors that interact with each other and affect the potential for wild land fire. This poster describes a quantitative planning tool to assist land managers, fire ecologists, and air quality specialists in assessing the tradeoffs between land management practices over large areas. The Fire Effects Tradeoff Model (FETM) is a vegetation dynamics model that simulates the long-term consequences of natural disturbances and land management practices under diverse environmental conditions, natural fire regimes, and fuel and fire management strategies. FETM uses historical weather data, fire history data, vegetation maps, fuel treatment planning scenarios, and surface and stand composition data to simulate future annual wild land fire area burned, landscape composition, smoke emissions, and economic costs and benefits of fire suppression and fuel treatments over time periods up to 100 years. The model has been applied in many areas of the United States. This poster describes two of these FETM applications: 1) An evaluation of the economic costs of different fire suppression and prescribed fire combinations for chaparral on the Angeles National Forest, California, and 2) an evaluation of different fuel treatment scenarios to reduce the fire risk on the Boundary Water Canoe Area Wilderness, Minnesota, after a major wind storm significantly increased dead and down woody fuels. These and other recent model applications indicate that FETM is a valuable tool to support fire planning efforts.

Fuel Heterogeneity at Stand Boundaries in the Elk Creek Watershed of Southern Oregon

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Abstract: In a multi-ownership landscape with a diverse array of land management goals, the spread of wildfire from one stand to the next is a management concern. The structure and composition of fuel at stand boundaries will have a meaningful impact on the rate of spread and change in behavior of fire from one stand to the next. The Elk Creek study area has a mixture of ownerships and management objectives that range from private industrial timber production to late-seral reserves on public land that are managed for northern spotted owl (NSO) habitat. Land managers face different objectives and constraints due to the often divergent goals of private and public landowners. Because both wildfire and NSOs move across landscapes without regard to landownership boundaries, one landowner's decisions influence the decisions of other landowners, particularly neighbors. Regardless of the individual landowner's goals, the landowner decisions jointly create a landscape and affect the quality and quantity of NSO habitat and the behavior of landscape-level fire.

This study will use field data collected from stands of various ages, ownerships, compositions, and landscape positions to quantify changes in fuel character at multiple spatial scales across stand boundaries. The objective of the research is to determine if there are optimal management techniques for reducing the rate of spread and intensity of wildfire over small spatial scales at the intersection between stands with different management objectives. The results will be used to determine larger-scale management implications for fire risk reduction and NSO habitat protection at the scale of a 330,000 ha landscape.

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Fuel Dynamics On Sites with Strong Potential to Paludification and Fire Behavior Modeled from Empirical Data in the Spruce-feathermoss Domain of Northwestern Quebec

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Abstract: Fire is the most important disturbance affecting forest successions in the boreal forest of Canada. Among other factors like climate and topography, fuel plays a major role in controlling fire behavior. However, very few studies pertaining to fuel accumulation in the boreal forest of Canada have been made; even less in forests with a strong potential to paludification like the spruce feathermoss domain of North-western Quebec located on the clay belt. In this region, we can observe a successional convergence whatever the initial post-fire composition of the stands, and again, very few studies have examined the links between the modification of the forest structure with time and fuel. The main objectives of this paper were then to study the interactions between time since fire, successional pathways and fuel biomass for this particular region. Other objectives included the testing of fire behavior models (*FBP* and *Behave* +) to see if the differences in fuel dynamics observed in the forests could translate into significatively different fire behaviors. To succeed in our objectives, we inventoried fuel characteristics in 61 different stands aged between 11 and 356 years and categorized them within 4 different successional pathways based upon initial composition (poplar, jack pine, black spruce from a non-severe fire and black spruce from a severe fire). Anovas were performed for age class and/or successional pathway effects on fuel biomass and structure variables. Regression analyses were also performed to test for tendencies with time since fire (TSF) for each fuel variable. In general, the fuel biomass and fuel structure results show that the successional pathway has a significative impact on fuel dynamics, whereas TSF shows no effect. Briefly, the black spruce from a non-severe fire successional pathway almost always has a lesser fuel biomass and a more open structure with less continuity between fuel layers. Testing for fire behavior effects is still a work in progress. Implications of such findings is that paludification might cause a negative feedback loop on fire behavior, causing future fires to be non-severe and thus, cancel its restarting effects on forest succession.

High Resolution Fuel Mapping: Wildland and Urban Interface Areas Application in the Iberian Peninsula

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Abstract: The lack of adequate scale fuel mapping is a major issue on the development of operational tools to offer fire behavior predictions or risk analysis.

The appearance of new VHR imagery and tools to develop its analysis has opened an efficient way to provide quick and economic fuel mapping in areas that need better than 40-50 meters resolution, as Landfire data.

An evaluation of different sensors (25 cms Vexcel, 5 m Spot, 15 m Aster and 30 m Landsat) and different techniques is presented, with results in 4 test sites in the Iberian Peninsula.
Differences between wildland and urban interface areas needs and results are remarked.
The EC VI Framework program on R+D GMES funded this project during 2005-2009 (http://www.preview-risk.com/).

Fireline Assessment Method (FLAME)

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Abstract: The NWCG Fire Environment Committee and its subcommittees are making efforts to adhere to these standards. As others have, the Fire Behavior Subcommittee has focused on the application of the best available science in fireline assessment of expected fire behavior. In pursuit of that, our support for Fireline Assessment Method, or FLAME, as a learning tool and fireline process, is intended to insure that situation assessment is accurate and meaningful.

Fire behavior assessment on the fireline is a required skill, included as part of the fire orders established in 1958. "Base all actions on current and expected behavior of the fire" is usually among the most frequently remembered and repeated by fire personnel at all levels. In pursuit of that, the National Wildfire Coordinating Group has long required training in fire behavior beginning at the introductory level. In that training, it becomes clear that the order is stated more easily than accomplished. Effective fire behavior assessment requires a combination of knowledge, experience, and clear thinking that must be developed over time.

In 2000, the National Fire Plan raised the bar by stating that the "best available science" needs to be utilized in fire management. The Joint Fire Science Program, Forest Service Research Programs, interagency initiatives and cooperating universities have seen their efforts accelerate in response. Determining what is "best" and what is "science" can be difficult, but these terms suggest a level of critical inquiry and evaluation that is appropriate for fire behavior assessment.

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Restoring Habitat Diversity in the Centennial Sandhills Ecosystem; a Collaboration Employing a Unique Application of Prescribed Fire

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Abstract: Before European settlement the Centennial Sandhills in Southwestern Montana saw regular fire that cleared sagebrush and migrating bison that grazed bunchgrasses, allowing wind to scour the ground and move sand. These natural processes maintained a mosaic of seral habitats that sustained a diversity of plants and animals, including several rare plants on early seral blowout habitat. In the absence of fire and bison the mosaic has shifted to late-seral sage brush steppe. A late-season burn followed by livestock grazing was designed to restore the early-seral habitat which is characterized by an increased bare ground, decreased sagebrush cover, and a shift from bunchgrasses to rhizomonous grasses. Our preliminary analysis suggests that two years after the fire, there were no significant changes in bunchgrass and rhizomonous grass frequency. However, we did find significant increase in the amount of bare ground and significant decrease in the cover of sagebrush; and, both horned lark and sandhill crane detections rose significantly while western meadowlark detections declined. Monitoring will continue to determine if the combined effects of the prescribed fire and grazing will be sufficient to restore habitat diversity. Poster presentation will include photos and graphs showing the study area before, during, and after prescribed fire and livestock grazing.

Wildfire Analyst: Taking Fire Behaviour Analysis to the Field

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Abstract: The use of simulations tools in operations is growing with the appearance of tools lake FSpro, evolution of the well-known Farsite and Flamap Firelb's tools.
But there is a gap in the crisis cycle use of these tools: the short time propagations in real time, so any alarm could have a quantitative evaluation, or in the field, with no web connectivity and not high skilled users available.

An approach to give real time evaluations of fire behavior focused on operational user's need is presented, in the form of the tool Wildfire Analyst, and ESRI´s ArcGIS extension developed by Spanish firm Tecnosylva. (http://www.wildfireanalyst.com/)

The tool has been implemented in the WFDSS of Andalucia, Aragon, Murcia and Extremadura regional services, and the Spanish Military Emergency unit. It has been presented and positively evaluated by CALFIRE and BLM technical staff, and it´s planned to be offered to users community late 2010.

The EC VI Framework program on R+D GMES funded this project during 2005-2009 (http://www.preview-risk.com/).

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A Synthesis of Insect Outbreaks and Subsequent Wildfire

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Abstract: We present an updated synthesis of the existing literature on the effects of insect outbreaks on subsequent wildfire. We have reviewed the scientific literature and interviewed fire managers and field personnel to build a conceptual framework for understanding how insect-killed trees modify fire characteristics. We focus on the characteristics of changing fuels, fire behavior, and probability of occurrence in the decades following insect outbreaks, considering the different stages of red-attack (red needles on trees), gray-attack (following needle drop), and subsequent snagfall and stand regrowth stages. Generally, field observations support increased fuel loads and modeling supports more extreme crown fire behavior during red-attack and snagfall/regrowth stages, with reduced crown fire potential and spread during gray-attack stages. Model results report that surface fires, on the other hand, are more intense during the gray-attack and snagfall/regrowth stages associated with increases in surface fuels and regrowth of understory vegetation. A separate class of studies that uses historical databases and statistical methods typically does not support enhanced fire severity or increased probability of occurrence following insect outbreaks. We conclude by noting the limitations of current fire behavior models for simulating effects as well as the difficulties associated with historical studies.

Predicting Dust Emissions in Post-fire Areas with Complex Terrain

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Abstract: There is a need for more accurate wind modeling in post-fire areas with complex terrain. Improved wind predictions would help Burned Area Emergency Response (BAER) teams quickly assess and treat areas that are most susceptible to high winds and wind erosion in the post-fire environment. Wind erosion has been less studied than water erosion in post-fire environments; however, there seems to be a growing consensus among land managers that wind erosion can pose a serious risk in these areas. Because response teams have a narrow window of time in which to make assessments and because it is generally not feasible to treat an entire burned area, erosion models are extremely useful tools for BAER teams, as they allow the teams to focus on the most susceptible areas and minimize treatment costs. A wind erosion model would be beneficial to these teams for use in targeting hillslope treatments and predicting their performance in terms of treatment stability during wind events. Limitations to existing models include the ability to accurately predict local winds in complex terrain and the lack of knowledge regarding ash erodibility and transport processes. This paper describes the coupling of an open-source computational fluid dynamics (CFD) code (OpenFOAM) with an existing dust algorithm to predict dust emissions in areas of complex terrain. The CFD code is capable of predicting local wind effects induced by mountainous terrain such as wind speed-up over ridges and channeling through canyons. Preliminary results suggest that a coupled wind-dust emissions model can be developed that produces results in reasonable runtimes and requires readily available input data that are routinely used by BAER teams for other assessments (e.g., digital elevation maps, soil maps, and burn severity maps). The CFD code investigated in this study is also being used in current fire behavior modeling efforts and thus is a logical choice for use in this study.

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Effectiveness of Post-fire Mulches in the Santa Barbara Front Country

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Abstract: Use of aerially-applied hydromulch for erosion control after wildland fire has increased in areas where high winds are expected to make straw mulch ineffective. Hydromulch consists or wood or paper fiber held together with a tackifer that also binds it to the soil. Several recent, large wildland-urban interface fires in southern California were treated with aerial hydromulch due to postfire erosion threats to homes, highways, and other critical infrastructure. Past studies have shown mixed effectiveness for this expensive (around $4000/ac) treatment, and public concern is high over hydromulch effects on native plant recovery, especially in chaparral where a rich native herbaceous flora takes advantage of the light and nutrients available after fire. We examined the erosion-control effectiveness and vegetation impacts of postfire hydromulch on two urban-interface burns near Santa Barbara, California, and we took advantage of the burned areas to test two other mulch materials – wood shreds and woodstraw – as alternative treatments. Erosion was measured with silt fences, and we estimated vegetation cover and species composition in 1-m^2 plots.

On the 2008 Gap fire, hydromulch reduced hillslope sediment movement by over 60% compared to untreated control plots the first year after fire. Wood shreds were only slightly less effective. Rainfall was under 60% of the long-term average during the first postfire year, and intensity was moderate. During the wetter second year hydromulch was still effective, even though it is generally expected to break down after 6 to 12 months, as were the wood shreds despite some loss of cover. Vegetation recovery – in terms of total plant cover, shrub seedling density, and species richness – was unaffected by hydromulch or wood shreds. Rainfall was greater after the 2009 Jesusita fire, resulting in more first-year hillslope sediment movement. Effectiveness of hydromulch varied with slope aspect, as it did with woodstraw, which largely blew away on west-facing slopes and was much less effective than hydromulch or wood shreds. Vegetation regrowth was abundant in 2009-2010; measurements made in spring 2010 will be presented.

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Using remotely sensed information to identify trends in burn severity related to: daily fire growth, aspect, elevation, slope, and vegetation coverage

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Abstract: Wildfire is a subject of interest for land managers and fire scientists due to the significant impact it has upon numerous systems. There has been work done to define terms and assessment methods of wildfire impacts but there has been little research done into factors that influence burn severity. This study compared remotely sensed measurements of burn severity (dNBR) to daily fire growth, aspect, elevation, slope, and vegetation coverage within ten fires throughout the western US (41 days growth and >120,000 ha area burned). Random effects models showed significant relationships between burn severity and three of the five tested variables (P-Values: Growth = 0.0595, Aspect = 0.2496, Elevation < 0.0001, Slope = 0.0011, and Vegetation Coverage < 0.0001). This study showed that within each fire, one could expect to see changes of burn severity associated with changes of elevation, slope, and vegetation coverage, but not with substantial increases in the amount of area burned within a day or differing aspects. Further research into these relationships is encouraged following this preliminary survey so that fire managers can effectively include ecological impacts into their decision making process with knowledge of conditions prior to and during the event of a wildfire.

Charcoal Quantification of the Biscuit Wildfire-LTEP Soils

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Abstract: In the summer of 2002, the 200,000-ha Biscuit Wildfire consumed a portion of the 150-ha Long-Term Ecosystem Productivity (LTEP) experiment in the Siskiyou National Forest, Oregon. The wildfire burned previously established 100-year-old conifer control and thinned experimental units, which allows comparison with prescribed burn units and unburned units. The wildfire caused substantial losses of forest floor and mineral soil C and N, which were quantified by pre- and post-fire sampling. This poster evaluates the mineral soil charcoal, a key fire-related soil component that affects physical and chemical properties, such as water holding capacity, sorption of organic compounds, and carbon sequestration. Charcoal C was quantified by a weak nitric acid—peroxide digestion method developed for forest soils. This method yielded char C as 7.7% of the organic C for a reference Australian mollisol soil and 5.2% of a German chernozem. Published values report 1.2 – 8.7% for both soils by chemo-thermal oxidation at 375C. The gentle oxidation of weak nitric acid—peroxide allow high recovery of charcoal with low variability. The char C of the Siskiyou LTEP soils was quantified in the <4-mm fraction of the A (0-3 cm depth) and B (3-15 cm depth) horizons. The soils contained substantial amounts of char C: 14 g char C/kg in A horizon and 7 g char C/kg in B horizon. These represent 18 and 21% of the organic C, respectively. On an area basis, char C constitutes 3,100 kg C/ha in A layer soils and 2,100 kg C/ha for B layer soils. Fire-induced changes in char C areal masses varied considerably among experimental units. The A layer of a high-wood unit burned in the wildfire may have lost as much as 860 kg char C/ha, perhaps coincident with loss from volatilization and convective erosion during the fire. Three other wildfire or prescribed burn units showed less change. Uncertainty involved with sampling and analysis is evident in the 1995 and 2003 unburned units, which showed an increase in char C where no change was expected. Decreases in char C from burned plots reflect the severe nature of the Biscuit Fire and require further investigation.

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Coupling Fire Behavior Models with other Decision Support Tools

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Abstract: Fire behavior models have been used significantly to predict wildfire spread and intensity as input to suppression strategy and tactics. Increasing costs, limited suppression resources and recognition of the benefits of fire have raised questions in the United States about suppressing all wildfires at the smallest possible size. One way to facilitate better informed wildfire decisions is to provide information to make a risk-based decision. Simply put, what values and quantities are threatened by a given wildfire? Coupling fire behavior model output with economic principles can provide decision makers with information needed to make risk-informed decisions in the fast paced wildfire environment. In the Wildland Fire Decision Support System (WFDSS) economic output is automatically generated with the usual fire behavior characteristics and provided as values-at-risk and value inventory tables. Economic information from fire behavior simulations is just the initial efforts to provide wildfire decision makers with rapid information on potential wildfire impacts. Future opportunities to use wildfire simulations to estimate impacts include; estimating post fire watershed concerns and rehabilitation costs, using atmospheric plume modeling to predict air quality impacts, estimating future fuel reduction benefits and, simulating positive and negative wildlife effects.

The Wildland Fire Decision Support System- Decision Support for Fire Management

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Abstract: The Wildland Fire Decision Support System (WFDSS) system is intended to assist line officers, fire managers and analysts in decision making, planning, and management of wildland fire incidents. It replaces and consolidates the WFSA (Wildland Fire Situation Analysis), Wildland Fire Implementation Plan (WFIP), and Long-Term Incident Planning (LTIP) past processes with a single process that is more intuitive and easier to use.

WFDSS provides the ability to turn raw data into information vital to informed decision-making. WFDSS information can be accessed and shared with unprecedented speed and agility among all decision-makers fostering collaboration "from the bottom up" and enabling flexibility. This provides the federal wildland fire organization the opportunity to provide significant improvements in large wildland fire strategic decision making.

WFDSS was conceived as a way of integrating the various applications used to manage incidents into a single system, which streamlines the analysis and reporting processes and provides the following advantages over previous systems: Combines desktop applications for fire modeling into a web-based system for easier data acquisition; Provides an easy way for fire managers and analysts to accurately document their decision-making process by allowing results of analyses to be attached to the decision point and included in the final incident report; Provides one decision process and documentation system for all types of wildland fires; Is a web-based application for easier sharing of analyses and reports across all levels of the federal wildland fire organization; Introduces economic principles into the fire decision process.

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Numerical Simulation of Crown Fire Hazard Following Bark Beetle-caused Mortality in Lodgepole Pine Forests

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Abstract: The purpose of this study is to investigate how varying amounts of MPB-induced tree mortality affects the amount of crown fuels consumed and the fire intensity across a range of lodgepole pine stands of different tree density and spatial arrangements during the early stages of a bark beetle outbreak. Unlike past studies which have relied on semi-empirical or empirical mathematical prediction models to predict surface fire behavior and crown fire hazard this study utilizes the Wildland Urban Interface Dynamics Simulator which is a spatially dependent physics based model that does not assume fuel homogeneity within or across a stand and accounts for both fire and atmospheric and fuel and atmosphere interactions. Based on preliminary results, we conclude that the level of crown fuel consumption, the average fireline intensity, the maximum fireline intensity and the total heat release are all positively related to increases in the amount of standing dead trees for times when red-dead needles are still present in the overstory. We also found that for a given set of stand level properties clumpy spatial arrangements resulted in increased fuel consumption, and fire intensities. Our results also show that as surface fire intensities increase the relationship between crown fuels consumed and the level of mortality decreases. Crown consumption and fire intensities for time periods which represent the loss of dead needles from the overstory are currently being conducted and early results from these simulations suggest that there is still a significant increase in crown consumption and fireline intensity at high levels of mortality. The results from this study indicate that both spatial arrangement and the level of mortality have significant influences on the intensity and consumption of crown fuels in the early stages of a bark beetle outbreak and should be considered in assessing crown fire hazard.

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Modeling a Burning Shrub with and without Wind using a Semi-empirical Model

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Abstract: Experimental data from individual leaf combustion experiments were used to develop a semi-empirical multi-leaf Manzanita shrub model. This model describes the propagation of a flame through a simulated manzanita shrub. Leaves are distributed evenly and randomly throughout a shrub structure. Individual leaf physical parameters are based on sample measurements and cross correlations. Experimentally-derived correlations predict the time to ignition, flame height, flame angle, and flame duration of each leaf based on physical parameters and the wind speed. The leaf nearest the bottom edge of the bush on the up-wind side is ignited and begins an ignition sequence illustrating the propagation of flame through the bush. Leaves ignite after being heated by surrounding flames for the predicted time to ignition. This model predicts burning rate, fire path, and the amount and location of unburned fuel remaining following combustion.

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Effects of Wind on Flame Characteristics of Leaves and Needles

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Abstract: Individual cuttings from five plant species were burned over a flat-flame burner under wind conditions of 0.75-2.80 m/s. Flame angles and flame lengths were measured both manually and using a MATLAB code that was created for this purpose. The measurements from the MATLAB code were slightly lower than those measured manually. Flame angles were found to correlate linearly with wind speed. Flame angles also correlated with the Froude number when either the flame length or flame height was used. These correlations for individual leaves were compared with published Froude number correlations. The predicted flame angles from the individual leaf correlations were much smaller than predicted from literature correlations. Additionally, times and temperatures to ignition, maximum flame height, and burnout were determined from video and IR images. In general, samples took longer to ignite and ignited at lower temperatures than under no-wind conditions. Most samples were found to still contain moisture at the time of ignition, in accordance with previous data under no-wind conditions.

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Fire Behaviour in Simulated Mountain Pine Beetle Attacked Stands

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Abstract: The current mountain pine beetle epidemic in western North America has raised concerns about elevated wildfire hazard due to widespread Lodgepole Pine mortality. The red attack phase, although relatively short duration, poses a potentially serious challenge to wildfire suppression efforts due to elevated needle flammability. Wildfire management agencies have little experience with this fuel type as most fire behavior documentation has been done informally. Alberta Sustainable Resource Development and FPInnovations conducted test burns in simulated pine beetle attacked stands in order to get a better understanding of potential crown fire initiation and crown fire rate of spread differences between red attack and non affected trees. The site was located in Jack Pine stands in northeastern Alberta where crown fire tests could be done with little risk of escape. Trees were girdled in 2007 to simulate beetle attack. Test burns took place in 2008 and 2009. Two ignitions were done simultaneously for each test to allow a direct comparison between girdled and healthy trees, and burns were done across a range of weather conditions. Fire behaviour in both stands ranged from slow moving surface fire to active crown fire. Initial observations indicated a more rapid transition to active crown fire in the girdled stands; however, a difference in spread rate was not observed. Observations indicate that fire in girdled stands changed from intensity class 3 to 5 (Canadian Forest Fire Behavior Prediction System), whereas the untreated stand transition from intensity class 3 to 4. There was no difference in fire behaviour below intensity class 3 (surface fire). The small plot size may have limited our ability to detect a difference in rate of spread. Results from fire instrumentation sensors, fuel moisture samples and weather will be presented.

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Evaluation of the FCCS Crown Fire Potential Equations in Conifer Stands in the Western United States

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Abstract: The Fuel Characteristic Classification System (FCCS) described by Ottmar et al. (2007) provides a quantitative framework for characterizing diverse fuel beds in the United States, as well as their potential for supporting surface and crown fires. The FCCS crown fire equations, developed by Schaaf et al. (2007), are based on an extension of the work by Van Wagner and Rothermel but introduces several new physical concepts to the modeling of crown fire behavior, including reformulated Rothermel surface fire modeling concepts. The conceptual FCCS crown fire potential equations have been compared with observed fire behavior in black spruce (Pinus mariana) stands in Alaska, as well as Aleppo pine (Pinus halepensis Mill.) stands in Greece, both yielding encouraging results. This analysis compares the FCCS predicted crown fire potentials, specifically, Torching Potential (TP), Active Crown Fire Potential (AP), and predicted (crown) fire rate of spread, against modeled crown fire potentials reported for several treated and untreated conifer stands in the western United States, reported by Scott (USFS publication RMRS-RP-58, 2006). The results of this comparison suggest that the FCCS crown fire potentials might be a useful tool for fire managers in the western United Stated to consider when evaluating the relative behavior of crown fires in vegetated canopies.

A Fire Simulation using a Chemically Reacting Plume in a Crossflow

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Abstract: A wildland fire's plume is one of the primary features related to the fire's behavior. The plume structure is determined by the fire's ground geometry, fuel composition, and surrounding conditions, and by the character of the atmosphere. The plume in turn influences the fire's intensity and airflow – including turbulent, gusty winds that can result in sudden changes in fire behavior and endanger fire fighters. Plume dynamics also determine the transport and dispersion of smoke produced by the fire, possibly affecting air quality for hundreds of miles downwind of the fire. Plume dynamics in general are poorly understood, and the nature of the turbulence and entrainment associated with and influencing a fire's plume is a particularly large gap in our scientific knowledge.

As the configuration of masses and forces in gas-gas and liquid-liquid mixing are alike, they can be compared. This paper constructs a simple model of a buoyant plume based on using the ratio of the buoyant flux to the cross flow speed to predict the characteristics of the mixing process. This concept is applicable to both gas and liquid mixing scenarios.

The experiments in this were conducted in a Low Speed Water Tunnel capable of circulating water through a 70cm x 70cm x 250cm test section up to 50 cm/s. The motivation for using a liquid environment instead of an air environment is because of the convenience of the slow developing entrainment, the easier variability of flow configurations, enhanced precision, and the ease of chemistry. While an air entrainment scenario presents several difficulties such as stronger deviations from average results and sensitivity to interference from the surrounding environment. The flame length of a plume is measured by injecting a salt water solution containing a ph indicator and a base into the top of a test section of the water tunnel which contains a dilute acid. When an element of injected fluid mixes with sufficient ambient fluid, the pH indicator disappears. The flame length is the station at which the flume becomes clear.

These findings in buoyancy driven turbulence compared with momentum driven turbulence based on a simple physical model.

Fire Spread Modeling in the Tropics: Coupling Fire Spread, Atmospheric, Dynamic Vegetation and Land-use Change Models

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Abstract: Fire dynamics in tropical biomes (including occurrence, behavior and consequences) are poorly understood, compared to those within temperate biomes. While there has been active research on numerous aspects of fire in temperate forests for the last few decades, research on fire in the tropics is comparatively scarce. Fire in the tropics is linked to intensive Land-Use and Land-Cover Change (LUCC) processes. Climate is also a powerful regulator of fire occurrence and behavior, controlling fuel availability and moisture as well as live vegetation composition and characteristics. Projections of climate change show possible increased drought condition in the tropics, which can combine with LUCC and fire processes and decrease the resilience of forests and savannas to fire and drought.

Deforestation of tropical forests for logging and agriculture is the main driver of fire occurrence within tropical forests such as the Amazon. It is also a main contributor of CO2 emissions from biomass burning and the elimination of a potential CO2 sink. Prescribed burning of cleared areas can lead to accidental and uncontrolled under-story fires, which are known to increase the fire susceptibility of adjacent low fire-resilient tropical forests and may change them into savanna-like ecosystems. Maintenance burning of pastures in managed lands within tropical forests and savannas, such as the Brazilian Cerrado, are also a significant source of fire. Natural savannas are the result of interactions between climate, fire and grazers, but in recent time's fire within savannas such as the Cerrado are almost exclusively due to human activities.

As the processes of LUCC and associated fires occur at local scales, linking them to large-scale atmospheric processes requires a means of up-scaling higher resolutions processes to lower resolutions. Our approach is to couple models which operate at various spatial and temporal scales: a Global Climate Model (GCM), Dynamic Global Vegetation Model (DGVM) and local-scale LUCC model and fire behavior and spread model. Fire spread and behavior is modeled using BEHAVE and FARSITE. As fuel models do not exist for the tropical forests and savannas, custom fuel models will be developed from past and future prescribed burnings in various tropical sites within Brazil.

Modern Developments for Ground-based Monitoring of Fire Behavior and Effects

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Abstract: Advances in electronic technology over the last several decades have been staggering. The cost of electronics continues to decrease while system performance increases seemingly without limit. We have applied modern techniques in sensors, electronics and instrumentation to create a suite of ground based diagnostics that can be used in laboratory (~ 1 m^2), field scale (~ 100 m^2) and landscape scale (10^6 m^2) experiments. These sensor suites are inexpensive, compact, and lightweight and measure relevant physical fire behavior measurable like fire power, total energy release, mass flow (3-D, vector), weather (wind speed, direction, relative humidity and air temperature) and gas concentration. The instruments are small and inexpensive enough that many can be deployed by a small crew during a fire experiment to provide a better understanding of fire behavior (through a better spatial understanding) than could be obtained with only one or two instruments. The sensors employ low cost opto-electronic components, micro-electromechanical systems (MEMS), electrochemical gas sensors, ultra-low power microprocessors and high density circuit layouts to meet cost and weight goals.

These instruments have been deployed in prescribed and wild fires dozens of times on fires in the Eastern and Western United States. We will discuss the design and performance of the present versions of these instruments, and speculate about the future, where we envision hundreds of such instruments scattered throughout the fire to obtain a synoptic understanding of the fire event.

Large Eddy Simulation of Canopy Structure Effects on Smoke Dispersion from Prescribed Fire

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Abstract: This paper presents results from high-spatial resolution modeling of air quality and smoke dispersion from a low-intensity prescribed burn in the New Jersey Pine Barrens. We used the Regional-Atmospheric-Modeling-System (RAMS)-Based Large Eddy Simulation (RAFLES) model to simulate the effects of canopy structure on within canopy and above canopy smoke dispersion. The RAFLES model incorporates 3-D heterogeneous effects of tree canopies on wind flow and turbulence in the atmospheric boundary layer. It runs at high spatial resolution (1 m^3) over domains ranging from 1 to 8 km^3. It includes a stochastic-Lagrangian dispersion of prescribed scalars and particles, including heavy particles. The shaved grid cell method is used to represent physical obstructions to the flow from tree stems. Model parameters include leaf density, tree stems, the vertical distribution of leaf density, and the horizontal differences between individual tree crowns. The detailed 3D canopy is generated by the Virtual-Canopy Generator (V-CaGe), which generates canopies based on remote sensing, and ground observations, and species-specific allometric equations. For the present study, atmospheric, canopy, fire and smoke data to parameterize the forcing of our simulations. Smoke emission and heat were prescribed as a dynamic spatially heterogeneous forcing. Virtual experiments with the same forcing but different (e.g., sparser or denser) canopy structures determined the interactions between canopy structure, ejection height, and near-source concentrations of the smoke plumes.

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Simulation and Evaluation of Smoke Plume Rise with Modified Daysmoke

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Abstract: This study investigates performance and importance of smoke plume rise simulation with Daysmoke. Plume rise is a smoke property required by regional air quality models such as CMAQ in simulating the air quality effects of wildland fires. A number of smoke plume rise modeling tools, including Daysmoke, have been developed based on the fundamental fluid dynamical equations, dimensional analysis and similarity principles, or statistical relationships of observed parameters. Daysmoke describes smoke particle movement of moving up with a plume, dropping out of plume, and irregular movements due to turbulence. It has been applied specifically for prescribed burns. This model was modified recently based on improved understanding of smoke plume processes and case evaluation. In this study, the modified Daysmoke was used to simulate plume rise of a number of prescribed burns. Smoke plume rise measurements obtained from a ceilometer were used to evaluate the Daysmoke simulations. CMAQ simulations were further conducted to examine the sensitivity of the air quality effects of prescribed burns to plume rise calculation. The CMAQ simulations were evaluated using the measured ground concentration. The simulation and evaluation results will be presented, which would to provide fire and air quality managers and modelers with quantitative information and tools for understanding the accuracy, limits, and uncertainty in plume rise calculation, and their impacts on simulation and prediction of regional smoke transport and air quality effects.

BlueSky Modeling Framework: Status, Products, and Future Developments

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Abstract: This presentation announces the latest version (3.6) of the BlueSky Smoke Modeling Framework (BlueSky Framework). The BlueSky Framework is a modular modeling system that combines fuel loading, fire consumption, time profile of consumption, and emissions models along with plume rise and smoke dispersion models. The BlueSky Framework enables many different models at each modeling step. To accomplish this, individual models are placed in a thing wrapper, allowing them to read and write to a standard interface, these interfaces are a series of model output levels. This standardization allows for unprecedented flexibility as the models for each modeling step can be picked independently from the previous or subsequent model. The BlueSky Framework also provides additional utility through a base framework; for example, any model enabled within BlueSky can automatically be served in a web-services environment, thereby enabling novel applications reliant on distributed processing.

The BlueSky Framework's modular nature has resulted in its use in many different kinds of modeling applications ranging from real-time smoke and air quality predictions to emissions inventory calculations to future climate air quality simulations.

In version 3.6 the user will begin to see the addition of satellite based emissions models, and satellite based fuel moistures. In addition, there is a new choice for plume rise that allows for better fire information and more accurate plume heights. The associated SMARTFIRE system now allows for better fire information. We present the design ideas and current functionality as well as a discussion of future modeling framework development.

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Comparison of Measured PM2.5 Data from Two Prescribed Burns in North Carolina

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Abstract: Two experimental prescribed burns were conducted on the Nature Conservancy's Calloway Forest/Sandhills Preserve near Fort Bragg, North Carolina, as part of a larger project to develop a sub-canopy smoke dispersion model to be incorporated in the BlueSky Framework. PM2.5 monitors (EBAMs) were deployed just outside the burn units during and after the period of active burning. The first burn occurred on a 90 acre unit on gently rolling terrain. The fuels consisted primarily of pine needle litter and grasses, with some scattered 10-hour and 1000-hour fuels. The second burn was on a smaller 60-acre unit, with steeper terrain than on the first unit. Also, there were more grass fuels than on the first unit, but fewer dead fuel elements. The PM2.5 data collected showed marked differences between the two burns. During the first burn, PM2.5 concentrations were higher than the second, because of favorable winds and higher fuel loadings. Additionally, the steeper terrain with drainages on the second burn unit tended to channel the smoke up-drainage and loft it away from the monitors. There is a clear signal during the second burn of plume edge effects at the monitors. Finally, smoldering was observed for more hours overnight after the burn on the 90-acre unit compared to the 60-acre unit; however concentrations overnight varied with burn unit. The EBAMs at burn unit two recorded higher concentrations, likely because of downslope advection of the smoke plume and pooling at the monitor locations.

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Measurements of Smoke Concentrations and Inversions in the Lake Tahoe Basin

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Abstract: The Lake Tahoe Basin is known for its natural resources, but also as a place subject to significant air quality issues as inversions can trap smoke and pollution within the crater rim. As part of a larger project to develop meteorological data and monitoring tools to aid in burn day decisions for prescribed fires in the Lake Tahoe Basin, we have developed a database by deploying eight weather stations in two transects ranging from near the shoreline to the ridgeline of the basin. The stations were placed in the field from snow pack melt through first snow, thereby covering the burn season. This record of temperature, relative humidity, and wind speed and direction probes, and some PM2.5 data is being used to characterize inversion layers and high-resolution meteorological features. These data are being used in a further step of the same project to evaluate an ultra-fine scale model climatology of the region being produced by the Desert Research Institute, and to help tune to the model to be able to predict the timing of the onset and break-down of the inversion layers.

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The Smoke and Emissions Model Intercomparison Project (SEMIP) Community Data Warehouse

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Abstract: The Smoke and Emissions Model Intercomparison Project (SEMIP) is a community project to examine the complex uncertainty caused by model chain-to-model chain variability in fire information, fuel loading, fire consumption, fire emissions, plume rise, and smoke dispersion modeling, and where possible, to evaluate the results of various model chains against observations. To accomplish this, SEMIP has collected numerous model output, satellite and remote sensing, and field observation datasets. These datasets are stored in a data warehouse that can serve multiple purposes, including the archiving and sharing of datasets within and for the greater community. To use this warehouse, no submitter is required to share their data - a researcher is able to submit only the metadata about their dataset - but SEMIP encourages data sharing by providing a set of rules that must be agreed to by anyone wishing access to the data. These rules provide for proper accreditation of the dataset and the ability of the dataset creator to comment on and participate in any work undertaken. A list of the data currently in the SEMIP warehouse is provided, as is an explanation of how the data warehouse works and how to use it.

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Identifying the Conditions Necessary for CONUS Fires to Impact the Arctic

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Abstract: We present preliminary results from a back-trajectory study aimed at determining the necessary conditions required for a contiguous U.S. fire to impact the Arctic. New regulations for black carbon (BC) currently under consideration by Congress and the EPA could affect management decisions on wildfires and the ability to conduct prescribed burning. Congressional testimony has suggested various mitigation strategies for Arctic BC including shifting the seasonal timing of continental U.S. prescribed burning. However, many questions remain regarding when and how continental U.S. fires contribute to Arctic BC. In particular, what regions, type of fires, timing, and plume injection heights along with transport meteorological patterns are most likely to result in continental U.S. fires affecting the Arctic? To address these questions, we are conducting a 30-year high-resolution back-trajectory study coupled with map typing of the synoptic meteorological patterns required for BC transport, the first of its kind focused directly on contiguous U.S. (CONUS) fires. The result of this work will determine the necessary conditions for emissions from a CONUS fire to potentially reach the Arctic based on fire type (e.g. wildfire vs. prescribed), fire location, time-of-year, and plume injection height. It will further determine, region by region, what synoptic meteorological progressions are required to allow Arctic transport and their frequency of occurrence. While other factors may limit the Arctic impact from any given fire (for example, smoke washing out in rainstorms), by determining the basic necessary conditions, this study will be able to focus future, more complex modeling studies, as well as current policy discussions, to those times and places of greatest interest. It can also provide an answer to the corollary question of Arctic impact. What are the times, places, and conditions where CONUS fires have little or no chance of impacting the Arctic?

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Uncertainties in Fuel Loading, Fire Consumption, Plume Rise, and Smoke Concentration Calculations

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Abstract: Many models exist for calculations of fuels, consumption, emissions, plume rise, and smoke impacts from fire. Recent work done through the Smoke and Emissions Model Intercomparison Project (http://semip.org) has shown that inter-model differences can have a profound effect on the resulting answers. Additionally, interactions between models can also result in unexpected or unwanted dependencies between model choices at different steps (e.g. fuel loadings and fire consumption). We present an overview of the work done by the SEMIP project to date, including the cross comparisons between LANDFIRE, the new FCCS fuel maps, and other fuel loading maps, as well as analyses of fire location and plume rise calculations based on their effect on modeled ground smoke concentrations. A companion poster presents these results in greater detail, as well as how to access the full set of results via the SEMIP Viewer website. For users interested in information from a specific fire or in a regional inventory or smoke analysis these comparisons can be useful in understanding the uncertainties resulting from different model choices

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Integrating Air Quality Tools into the Wildland Fire Decision Support System (WFDSS-AQ)

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Abstract: The Wildland Fire Decision Support System (WFDSS) is intended to assist fire managers and analysts in making strategic and tactical decisions for fire incidents. It is designed to replace the WFSA (Wildland Fire Situation Analysis), Wildland Fire Implementation Plan (WFIP), and Long-Term Implementation Plan (LTIP) processes with a single process that is easier to use, more intuitive, linear, scalable, and progressively responsive to changing fire complexity. Efforts are underway to implement air quality (AQ) and smoke related tools into WFDSS so that air quality can be considered along with the suite of other considerations when tactical decisions are being made on fire incidents. A web-based portal has been developed which uses data from WFDSS to drill-down into existing AQ/smoke tools for relevant information. The existing tools are: smoke guidance point forecasts, smoke guidance regional maps, diurnal surface wind pattern analysis, climatological ventilation index point statistics, current air quality conditions map, fire information and smoke trajectories, probabilistic smoke impacts based on past weather, and customized fuels, consumption and smoke modeling. This information is customizable to the WFDSS users needs based on attributes such as: instant access (speed of tool/info delivery), easy to use (simple or more complex), desired scale (local, regional), and desired format of information (graphics, text). Products available via the National Fire Consortia for the Advanced Modeling of Meteorology and Smoke will be discussed.

The Interagency Fuels Treatment Decision Support System (IFT-DSS): Simulating Fire Behavior and Fire Effects to Support Fuels Treatment Decisions.

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Abstract:
The Software Tools and Systems Study was initiated by the Joint Fire Science Program and the National Interagency Fuels Coordination Group in March 2007 to address the proliferation of software systems in the fire and fuels treatment domain. In 2008, the Interagency Fuels Treatment Decision Support System (IFT-DSS) software framework was designed to organize and manage the many software systems and data used for fuels treatment planning and to make these tools available to fuels treatment planners through a single user-friendly web-based system. In 2009 a Proof-of-Concept system intended to illustrate potential IFT-DSS functionality was designed and released in early 2010. In this presentation, we discuss the current progress of the IFT-DSS. We discuss what fire behavior and fire effects models have been included in the system to data and how each of the models are intended to be used within the system to support fuels treatment decisions. We provide case studies that illustrate possible field applications of the system. Using these case studies, we show how the IFT-DSS can be used to simulate potential fire behavior and fire effects before and after simulated fuels treatments.

Effectively Engaging and Addressing Natural Resource Smoke Management Issues – A Focus of the National Wildfire Coordinating Group (NWCG) Smoke Committee (SmoC)

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Abstract: Smoke Committee (SmoC) is one of 14 Committees chartered under NWCG and provides interagency leadership, coordination and integration of air resource and fire management objectives to support overall land management goals. In a time where fuel treatment programs have never been more important for ecosystem health and public safety, and national ambient air quality standards designed to protect human health are tightening, the need for addressing smoke issues has never been more critical.

SmoC strives to do this through an interagency membership of air quality and land management experts from the federal and state land management agencies, associate members from clean air agencies, agencies who work with private land managers, and other subject matter experts. SmoC provides the natural resource community with communication methods & materials, innovative online training, and analyses how the latest and changing air quality regulations, policies and executive orders impact wildland management. These efforts can be viewed at www.myfirecommunity.net and www.nifc.gov/smoke.

Geospatial Fire Analysis, Interpretation, and Application – Developing and Maintaining Fire Analysis Training for Multiple Audiences

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Abstract: The ability for land managers and fire practitioners to model wildland fire behavior has advanced significantly since the development of the fire spread model and computer processing capabilities. Training content and training methods regarding foundational fire behavior and basic modeling has remained relatively stable over the past three decades. However, basic training on advanced applications, particularly geospatial modeling, has constantly evolved since the mid-1990s. Common to both cases is a traditional classroom format. The latest rendition of advanced training, S495 Geospatial Fire Analysis, Interpretation, and Application, addresses weather and climatology; statistics; working with geospatial data; and short-, mid-, and long-term fire analysis. The course provides instruction in FireFamilyPlus, ArcMap, FlamMap, FARSITE, and FSPro computer systems to develop deterministic and probabilistic fire behavior analyses. Nearly two hundred hours of instruction are provided online, through webinars and in a classroom. Future developments include easy online access for any audience and additional exercises for the planning environment to complement fire behavior prediction for incidents. Developing and presenting training on broad subject matter for a wide audience has required using non-traditional training venues. This presentation will provide an overview of this advanced training, how online instruction is utilized, future plans, and lessons learned.

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The Pacific Northwest Fire Science Consortium: Towards a New Paradigm for Technology Transfer

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Abstract: Since the Pacific Northwest Consortium for Fire Science Delivery and Adoption successfully competed for a Joint Fire Science Phase 1 grant in 2009, we have made significant progress in clarifying objectives and building teamwork. The consortium is made up of fire science professionals from Federal, state, NGO, and university sources, and both management and research are well-represented. Our focus is on the dry forest ecosystems of Oregon and Washington, but we are keeping our consortium boundaries fluid to encourage coordination with adjacent consortia, notably that for the Great Basin.

A central premise of our effort is the distributed leadership model. With this approach individuals organize informally to address problems, propose solutions, and move forward. Formal workshops were held in Burns (jointly with the Great Basin Consortium) and in Portland. The Burns meeting focused on sagebrush ecosystems; in Portland the scope was regional and all agencies and disciplines provided field representatives. Additionally, small group meetings attached to workshops (such? as the dry forest workshops in Redmond and Bend) are proving to be effective forums for communication. Our experience so far seems to be validating the distributed leadership approach. Moreover, we have taken the innovative step of using an advisory board made up solely of field practitioners. We have also recruited a social scientist (on contract and as a co-PI) with long experience in studying and advising on group dynamics in a natural resource context.

We intend to build on this, and use the processes mutually agreed on at our workshop for three Vehicles: 1) Regional coordination of science delivery and adoption; 2) Developing field leadership by adopting science in site-specific projects; and 3) forming a Community of Practice, a virtual consortium, and science delivery methods that facilitate learning and adoption. Our goal is to become a respected voice on fire science issues in the region.

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The National Fire Decision Support Center- Supporting Decision Making

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Abstract: The National Fire Decision Support Center (NFDSC), a collaborative effort between Fire and Aviation Management and Research and Development, is tasked with providing state-of-the-art wildland fire decision support to interagency fire managers. The NFDSC is comprised of five components: Fire Economics Research, Fire Spread Research, Fire and Aviation Management, Human Factors and Risk Management Research Development and Applications (RD&A), and the Wildland Fire Management RD&A. The Wildland Fire Management RD&A portion of the NFDSC consists of specialists that provide timely decision analyses in support of large wildland fires in the areas of fire behavior, economic analysis, and management response capability.

The center is available seven days a week to provide support through a variety of mechanisms. The NFDSC staff members provide and support analysis with the fire behavior and economic assessment tools within the Wildland Fire Decision Support System (WFDSS). Specialists run and interpret results from the Basic Fire Behavior (BFB), Short Term Fire Behavior (STFB), Mid Term Fire Behavior (FARSITE), and Fire Spread Probability (FSPro) tools. Assistance and support is also provided with the Stratified Cost Index (SCI) and the Rapid Assessment of Values at Risk (RAVAR) tools. The analyses and output from these tools provide direct information for fire managers in making strategic and timely decisions. As needed and requested NFDSC staff can provide input and advice regarding WFDSS tool analysis into strategic planning and decisions.

By working collaboratively with local fire managers, the NFDSC provides real-time decision support for large fires, considering incident-specific fire behavior, values at risk, performance, and decision analysis. The decision support tools that the NFDSC supports are integrated within the decision support system (WFDSS) that federal fire manager's use for all wildland fires therefore speeding assistance and support time. The result is better risk-informed strategic and tactical decisions for wildland fires; reduced firefighter exposure; improvement in the basic science for large fire decision making; and improved capability to manage large fire expenditures.

Transforming Fire Fighters into Fire-Guiders: Firefighters United for Safety, Ethics, and Ecology (FUSEE)

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Abstract: Firefighters United for Safety, Ethics, and Ecology (FUSEE) is a nonprofit organization promoting safe, ethical, ecological wildland fire management. FUSEE believes firefighter and community safety are ultimately interdependent with ethical public service, wildlands protection, and ecological restoration of fire-adapted ecosystems. Our members include current, former, and retired wildland firefighters, other fire management specialists, fire scientists and educators, forest conservationists, and other citizens who support FUSEE's holistic fire management vision.

FUSEE's primary function is to provide public education and policy advocacy in support of a new, emerging paradigm that seeks to holistically manage wildland fire for social and ecological benefits instead of simply "fighting" it across the landscape. We seek to protect fire-affected wildlands, restore fire-adapted ecosystems, and enable fire management workers to perform their duties with the highest professional, ethical, and environmental standards. Our long-term goal is the creation of fire-compatible communities able to live safely and sustainably within fire-permeable landscapes, and the establishment of a high-skill, high-wage, year-round fire management workforce whose focus is on restoring fire ecology processes and fire-adapted landscapes.

This poster will display FUSEE's philosophy, mission, and key concepts, including the FUSEE triad of safety, ethics and ecology. Special emphasis will be focused on our vision of fire-guiders—fire managers and field workers who help stop/steer wildfires to prevent them from burning places that cannot tolerate fire (e.g. rural communities), and start/steer wildfires to promote them burning into areas that fire planners and land managers have determined to require fire (e.g. fire-adapted ecosystems).

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Firefighter Math - A Web-Based Learning Tool

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Abstract: Firefighter Math is a web based interactive resource that was developed to help prepare wildland fire personnel for math based training courses. The website can also be used as a refresher for fire calculations including slope, flame length, relative humidity, flow rates, unit conversion, etc. The website is designed to start with basic math refresher skills and advance to topics that directly apply to advanced wildland fire calculations. Firefighter math was established as a tutorial, and users are encouraged to focus on chapters that are most relevant. The site is interactive which allows users to practice online with examples that are checked for accuracy to enhance learning. If an example question is answered incorrectly, feedback is provided in the form of step by step problem solving to ensure that the correct answer in achieved. Users are encouraged to visit the website prior to taking specific training courses and continue to revisit specific pages as individually needed. Our goal is to make math fun again and to show how it applies to wildland fire on a daily basis.

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Blending Fire Management Tools In Support Of Planned Fire Ignitions on Organic Soils – A Case Study at Camp Lejeune / Jacksonville, North Carolina

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Abstract: The effectiveness of revisions to the North Carolina Smoke Management Program is dependent on the integration of new science and tools to meet the combined pressures of controlled burning, regulatory requirements and the increasing complexity of NC's air-sheds. In this state, land management agencies would like to increase controlled burning opportunities at a time when air quality standards are changing with the intent of improving air quality for human health.

Increases or maintenance of existing prescribed burning programs are dependent on better, finer scale tools that can provide timely information that support burning decisions. The results of the prescribed burning study presented here demonstrate the use of the available tools in support of control burning. Pre-burn analysis supported a Go Decision and the burn unit was burned in early April 2010. Smoke dispersion, fuel consumption and lack of smoldering combustion in the organic soil were all consistent with our pre-burn analysis.

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The Australian Dry Slot Theory - Causes, Recognition, Occurrence, and Implications

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Abstract
This presentation will educate and inform readers of the *Dry Slot Theory* occurring in Australia and most likely in North America. In Australia, it is a well-documented, well-recognized, and utilized tool to predict radical fire behavior due to rapid atmospheric drying. To fully understand this theory, the reader should also refer to Schoeffler (Weather Modification and Geoengineering Implications on Wildland Fire Weather (2010) this proceedings) which is based primarily on the works of Dr. Graham Mills.

The dry slot theory is a significant indicator of radical fire behavior based on rapid and intense drying due to atmospheric changes. Although common knowledge in Australia, it is not as well known elsewhere. Case studies of numerous fires both in Australia and North America will be covered. Causes, contributing factors, precursors, and indicators will be discussed.

The goal of this paper is to galvanize fire behavior analysts, researchers and meteorologists in North America to further study the subject and to inform and educate fireline supervisors about this phenomenon and the radical changes that dry slots cause.

Additional Keywords: rapid atmospheric drying, fire behavior, blow-up conditions, fire weather

Weather Modification and Geoengineering Implications on Wildland Fire Weather

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Abstract
The phenomenon of Weather Modification, presently being referred to as Geoengineering, is a constant and ongoing occurrence that can adversely affect fire weather and hence fire behavior. Its various indicators need to be recognized by meteorologists, fire behavior analysts, and wildland fire supervisors in order to make better decisions to safely and effectively perform their jobs.
The paper describes the various indicators of weather modification.As Wildland Fire Supervisors, we use various indicators to determine changes in the weather, mainly clouds in order to safely complete our missions. Wildland Fire Supervisors often use weather indicators to comply with the first of the Ten Standard Orders ("Keep informed on fire weather conditions and forecasts."). The various types of weather modification (Geoengineering) reveal different types of clouds, cloud formations, and other weather indicators that need to be recognized. This recognition is important in order to heed present and expected fire weather and associated fire behavior in order to better predict the changes they may foretell. Other weather modification implications will be discussed, such as the weather effects from chaff in and around military bases and the health and safety implications working in and around military bases involved in cloud seeding operations.
Weather Modification (Geoengineering) is an ongoing, ever-present, almost daily occurrence that can and does influence fire weather and hence, fire behavior. NOAA admits to well over 70 on-going weather modification projects to date. In 1996, the military authored a paper titled "We Own The Weather" that still holds true today. Learning about several of the many weather modification (Geoengineering) projects and their indicators will help meteorologists, fire behavior analysts, and wildland fire supervisors to better recognize these occurrences and make sound judgments based on these indicators.

Additional keywords: weather modification; geoengineering; HAARP, chemtrails, chaff, TMA Cloud project, trimethylaluminum, cloud seeding; fire weather; fire behavior; clouds, cloud formations, weather indicatorsmilitary bases; health and safety

Thermal troughs in the Pacific Northwest

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Abstract
The term ‘thermal trough’ refers to a surfaced-based area of low pressure caused by a very warm layer of air in the lower sections of the atmosphere. In the Pacific Northwest, thermal troughs have repeatedly been associated with large fire growth and extreme fire behavior making them a critical weather feature to track during the summer. The fire seasons of 2008 and 2009 provide a spectrum of examples showing how thermal troughs can enhance fires. Prolonged hot, dry weather with poor night time humidity recoveries precondition fuels as the thermal trough builds. Instability increases rapidly as the thermal trough shifts overhead encouraging vertical motion through deep layers of the atmosphere and the formation of strong updrafts in convection columns over fires. The low pressure at the core of a thermal trough creates convergence and can alter local wind patterns counteracting the more typical diurnal mountain valley circulations. In extreme cases thermal troughs can increase the cross mountain pressure difference enough to generate strong downslope winds. Four thermal trough cases which resulted in large fire growth have been examined to identify common upper level ridge patterns associated with thermal troughs. Comparison with detailed surface analyses show how these broad scale upper ridges can be used to forecast and track the finer scale surface-based thermal trough.

Additional keywords: critical fire weather patterns, case studies, extreme fire behavior, blow-up fire conditions

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Experimental fire in two different grassland ecosystems in the Southwestern United States

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Extended Abstract
Over the last 150 years there have been profound changes in semiarid and aridland ecosystems, including overgrazing and shrub encroachment. Millions of dollars are spent annually for post-fire rehabilitation and restoration activities, yet rehabilitation and restoration is often not successful. Although the re-establishment of periodic fire is fundamental to the ecological restoration of southwestern grasslands, current management policies must be based less on historical fire regimes and more on land-use legacies along with dynamic climate change. Global change is leading to a more variable climate that includes more frequent extreme events, along with a potential shift in winter/summer rainfall patterns. Given the uncertainty of future scenarios for climate change and climate variability in the southwestern US we need to know now how fire seasonality - and over the long-term fire frequency – affect biodiversity and ecosystem functioning in semiarid and aridland ecosystems. We compare and contrast the results of a long-term, 18-year study examining effects of fire in the growing-vs. dormant season at return intervals of 3, 6, and 9 years on shortgrass steppe ecosystem components; with new experimental fire research in Chihuahuan Desert grassland examining the effects of spring, summer and winter fires on desert grassland ecosystems. Caution is warranted when interpreting the effects of prescribed fire on southwestern grasslands due to differences in season of occurrence, weather conditions, grassland uses, fire history, and fuel conditions in which a burn can occur. The length of time between fire and post-fire data collection will also greatly influence perceptions about fire effects.

Do non-native species invade chaparral from fuel breaks after fire?

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Abstract

Fuel modification zones are often colonized by ruderal species after overstory canopy is removed. In southern California chaparral, colonizers are typically non-native grasses and forbs. Previous work (Merriam *et al.* 2006, *Ecological Applications* **16:**515-527) has found that repeated disturbance can allow non-native species to spread into adjacent vegetation stands. This may increase future fire risk due to the presence of flashy fuels. We took advantage of a system of historic fuel breaks in the North Mountain Experimental Area (foothills of the San Jacinto Mountains) to examine the extent to which non-native species present in the fuel breaks appeared in adjacent vegetation 1 and 2 years after the 2006 Esperanza fire. Plots were sampled along 30 transects running from 10 m inside a fuel break to 40 m into adjacent chaparral. We expected to see greater cover of common non-native species, especially grasses, farther from fuel break edges the second year postfire.

Fourteen transects fell within areas burned by the Esperanza fire, while 16 were unburned. Cover of non-native grasses, predominantly bromes (*Bromus* spp.) and foxtail fescue (*Vulpia myuros*), increased from the first to second year after fire in burned fuel breaks and adjacent vegetation; however, variability was high. Many of the transects that didn't burn in the Esperanza fire had burned one year earlier in the Soboba fire, and grass cover tended to be higher on those plots. Shrub cover increased from one to two years post-fire. Overall, non-native species expansion into burned chaparral was not as dramatic as we expected. At the same time, only minor colonization of the fuel breaks by chaparral shrubs occurred. The infrequently-maintained fuel breaks at North Mountain appear highly stable.

Additional keywords: Esperanza fire, fuel modification, North Mountain Experimental Area, red brome.

Development and validation of modeling tools for predicting smoke dispersion during low-intensity fires

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Abstract
Prescribed burning can be a viable tool for managing forest ecosystems. However, smoke from prescribed fires that often occur in the vicinity of the wildland-urban interface (WUI) can linger in an area for relatively long periods of time and have an adverse effect on human health. Smoke from low-intensity prescribed fires can also reduce visibility over roads and highways in the vicinity of these fires, reducing the safety of our transportation system. Improved tools that quantitatively predict the potential impacts of smoke are necessary in order to maximize the benefits of prescribed fires and balance the conflicting needs of ecological fire use and effective smoke management.

This study, funded by the U.S. Joint Fire Science Program, is focused on the evaluation of fine-scale atmospheric dispersion modeling systems for predicting short-range, near-source smoke transport and diffusion within and above forest vegetation layers. These modeling systems include the Weather Research and Forecasting (WRF) – FLEXPART system, the Regional Atmospheric Modeling System – Forest Large Eddy Simulation (RAFLES) system, the Advanced Regional Prediction System (ARPS) - FLEXPART system, and the Atmosphere to Computational Fluid Dynamics (A2C) system. Smoke concentration and meteorological measurements via surface and tower-based instrumentation within and in the vicinity of prescribed burn units in the New Jersey Pine Barrens are being used to validate the modeling systems. Through this study, we seek to (1) improve our understanding of the effects of different forest canopies on particulate matter and water vapor transport and diffusion within and above those canopies, (2) examine how those effects could be included in operational smoke prediction systems, (3) determine the uncertainties and limitations of current models in predicting smoke dispersion from low intensity fires, and (4) develop new observational data sets for effective validation of smoke dispersion models.

Additional keywords: Modeling, model validation, monitoring, forest canopies, smoke management, prescribed fire

Comparison of fuel moisture changes in spring and fall in Korean pine forests of the East Sea Region

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Abstract

We measured fuel moisture changes according to forest density (sparse, medium, and dense) and fuel layer (fallen leaves layer, humus layer, and soil 1, 2 layer) in pine forests of the East Sea Region after rain during the spring and fall forest fire periods. Three days after rain, fuel moisture content was 17% and forest fire danger was high in fallen leaves layer under sparse forest density in both spring and fall. In medium and dense forests, the threshold for high fire danger was reached one day earlier in the spring than in the fall.

In humus layer, fuel moisture was 80-160% for all periods, while under sparse forest density it was still over 40% six days after rain. The probability of ignition is very low under such conditions. The fuel moisture contents of soil 1 layer were 30-60% one day after rain, but were still over 20% six days after rain in both seasons. Fuel moisture contents on 'soil 2 layer' were about 18-30% in all forest density classes throughout both, seasons.

Additional keywords: Forest fire, Fallen leaves layer, Humus layer, Soil layer

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