United States Department of Agriculture

Proceedings of the Large Wildland Fires Conference

Missoula, Montana

May 19-23, 2014

Forest Service | Rocky Mountain Research Station | Proceedings RMRS-P-73 | July 2015

Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. **Proceedings of the large wildland fires conference;** May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Keywords: fire ecology, fire behavior, smoke management, fire management, social and political consequences

Papers were edited to a uniform style; however, authors are responsible for content and accuracy.

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Technical Editors

Robert E. Keane
Matt Jolly
Russell Parsons
Karin Riley

Preface

Large fires or "megafires" have been a major topic in wildland fire research and management for over a decade. There is great debate regarding the impacts of large fires. Many believe that they (1) are occurring too frequently, (2) are burning abnormally large areas, (3) cause uncharacteristically adverse ecological harm, and (4) must be suppressed at all costs. Others believe that large fires can effectively reintroduce fire back into those declining fire-prone ecosystems where fires have been excluded for decades, thereby (1) improving ecosystem health, (2) reducing future fire hazard, (3) providing critical fuel breaks, and (4) increasing ecosystem resilience in the face of climate change. Adding to the dilemma is the fact that little is known of the short- and long-term ecological impacts of large fires on historical, contemporary, and future landscapes and this lack of knowledge fuels the debate that surrounds both the causes and consequences of large fires. Just because a fire is large doesn't necessarily mean that it is unnatural or undesirable, unless, of course, it threatens human life and property. Large fires may provide unique opportunities to restore ecosystems and treat fuels across extensive areas.

The purpose of this conference was to present the latest science on large fires and their ecology and management, to shed some light on the social, political and ecological consequences of these fires, and provide a forum for discussing all perspectives of the debate. This conference brought together ecologists, wildland fuels specialists, fire behavior researchers and analysts, social scientists, managers, and researchers in the broad fields of wildland fire sciences to present the latest findings and to provide potential solutions. In addition, this conference allowed presenters to share their state-of-the-art scientific findings in fire ecology, wildland fuels, fire and human behavior or other topics outside of large fires. It was held in Missoula, Montana, USA, from May 19 to May 23, 2014 at the University of Montana's University Center.

Attendees included researchers, educators and managers in the wildland fire community. Over 630 participants from 15 countries were in attendance. There were over 380 presentations covering the full range of wildland fire management and science topics delivered over the course of three days. This involved five plenary sessions including one panel discussion, 114 oral presentations, 14 special sessions, 35 micro-talks and 101 poster presentations. The conference also included exhibitor displays, a film festival featuring Dr. Stephen Pyne, an awards banquet featuring author and videographer Michael Kodas, 15 pre-conference workshops, 8 field trips and an art competition fundraiser in support of the Mike da Luz Memorial Student Scholarship Funds and the families of the firefighters who lost their lives in the Yarnell Hill Fire.

This conference was somewhat unique in that it was co-hosted by the ***Association for Fire Ecology*** and the ***International Association of Wildland Fire*** with major support by the ***Joint Fire Science Program***. It had 21 sponsors, 12 exhibitors, and 8 attached meetings, which included the Quadrennial Fire Review. Other major sponsors included the USDA Forest Service, Neptune Aviation Services, Wildland Fire Management Research Development & Application (WFM RD&A), Phos-Chek, Canadian Interagency Forest Fire Centre, Fire Smart Roofing, Northern Rockies Fire Science Network, Firewise Communities—NFPA, International Carbide Technology, FireSafe Montana, FUSEE: Firefighters United for Safety, Ethics, and Ecology, FRAMES: Fire Research And Management Exchange System, Rite in the Rain, Desert Research Institute (DRI), National Wildfire Coordinating Group Fire Behavior Subcommittee, Montana Department of Natural Resources and Conservation, Federal Employee Defense Services, Budenheim, and the University of Montana Bookstore.

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Plenary Paper

Between a Rock and a Hard Place: Toward a More Effective Protection Strategy as Wildfire Threats Intensify

Jerry T. Williams, Former National Director of Fire & Aviation Management, United States Forest Service, Retired

IN REMEMBRANCE

This paper is dedicated to the memory of Dr. Robert Edward Martin (1931-2013).
Fire Science Professor, Mentor and Friend.

Context and Terminology

Before I get started, let me suggest that context and terminology are fundamentally important in the large fire discussion. Many will see large fires as bad; others not so. Whatever our leanings, judgments surrounding wildland fire are based on a number of perspectives: social, political, economic and ecological, as the theme of this conference reflects. It goes without saying that these effects will take on different meanings as we move across wildland-urban interface values, the general forest zone, large natural areas, and wilderness. Effects also often change over time.

Some forests are adapted to high-intensity, stand replacement fires; others are not. The fire regime concept offers a useful contextual gauge that helps in determining fire's short- and long-term ecological effects by framing the characteristic frequency, intensity, scale and seasonality of historic fire rhythms with respect to forest type. Departures from characteristic fire behavior to uncharacteristic fire behavior offers a basis for determining the ecological implications involved (Hardy, 2005).

Value laden terms such as "disastrous" or "catastrophic" are more suited to describe social, political and economic impacts. These words are defined by Federal Emergency Management Agency (FEMA) with reference to the Stafford Act (FEMA Definitions, 10/27/2008). Wildfire disasters cause "substantial damage or injury to civilian property or people." A catastrophe is a "disaster so overwhelming that a large segment of society is affected and extraordinary resources and skills are required to cope, some from other areas of the country or from other nations." Let me note that this may be a good place to thank our friends from Canada, Mexico, Australia, New Zealand, and the other countries that have helped us deal with wildfire disasters over the years.

This paper draws attention to the unplanned, unwanted wildfires occurring in the densified dry forest types of the Interior West (e.g., ponderosa pine and associated species)[1]. Their impacts are measured against the sum of suppression costs, private property losses and environmental damages. Sometimes, human fatalities are included. These altered forests are often where the social, political, economic and ecological measures of significant adverse impact all converge. Although this paper draws conclusions that may have similarities or parallels in other forests, we would be mistaken to apply them universally. Each fire regime has its own ecologies, its own measures of impact and presents its own management challenges.

Introduction

In an era when preparedness budgets have never been higher, when cooperation between partners has never been better, when predictive models have never been more sophisticated, and when technological support has never been more available…we are suffering from the worst wildfires since America organized to eliminate the large fire problem at the turn of the last century (Figure 1).

High-cost, high-loss wildfires—at unprecedented scales—are becoming the new normal, particularly in the West. The emergence of these recurring, record-setting incidents signals a new reality that challenges us to re-think protection strategies.

Federal, state and local governments are struggling to meet their mandates for protection, ensure the safety of their firefighters, and control fire suppression costs. Within the U.S. Forest Service, in the early 1990s, Fire & Aviation

[1] Although a 2009 Federal Fire Policy change allows managers to use wildfires to achieve resource objectives, as of this writing, the term "wildfire" is defined by the National Wildfire Coordinating Group (NWCG) as "an unplanned, unwanted wildland fire where the objective is to put it out (NWCG, 7/2012"). In this paper, where the word "wildfire" is used, the meaning reflects the NWCG definition.

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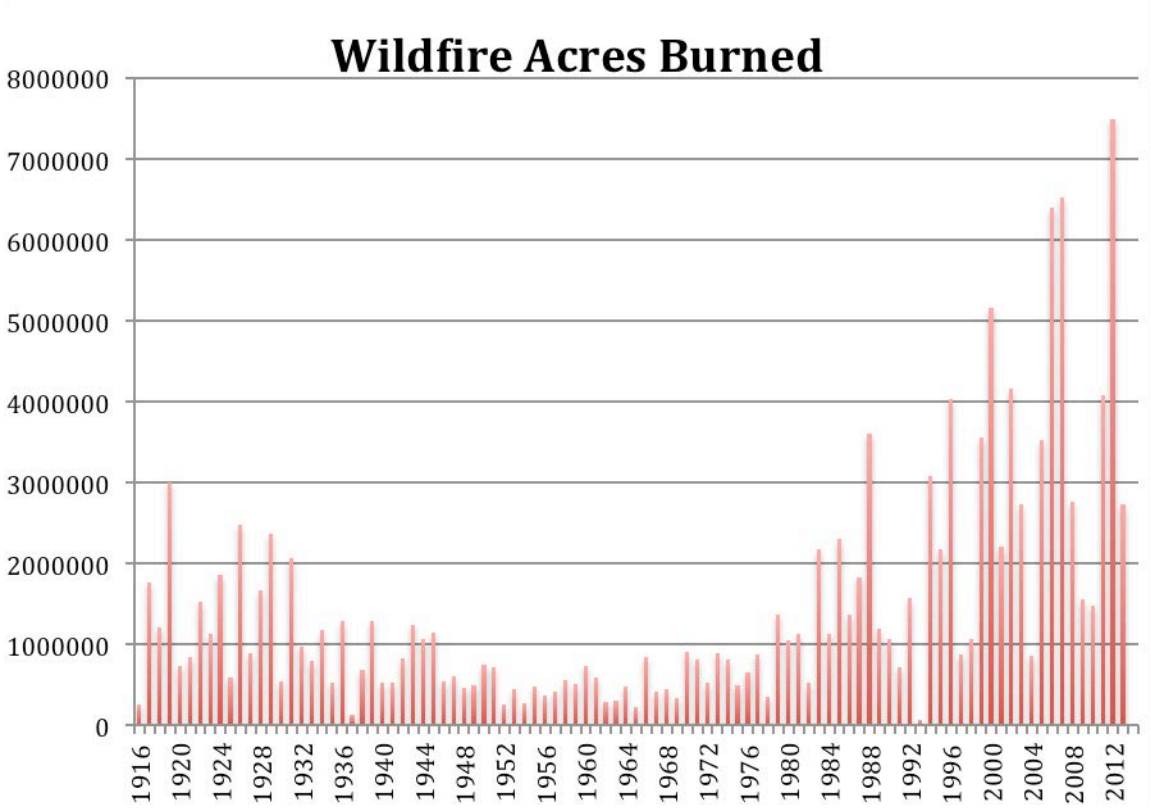

Figure 1—Reported wildfire acres burned on state and federally protected lands in the eleven states in the western United States (1916-2013)

Management activities represented about 8% of the total agency budget. Today, it is nearing 50% and still growing. In this same period, there has been a four-fold increase in firefighting preparedness budgets in the Forest Service. Recent projections indicate that the federal government will spend upwards of $1.8 billion in firefighting this year. In a zero-sum budget environment, fire-fighting costs have been eating into other programs, including those that might further reduce the fuels that might mitigate these large fires.

Catastrophic wildfires fall under the emergency exemptions in policy. In regulation, they are accepted as an accident of nature or excused as an act of God. However, more lately, the public seems in a less forgiving mood when it comes to the management of wildfires. There has been a growing tendency to find fault, point out an operational failure, and assign blame. In the aftermath of a wildfire disaster, there is a predictable wave of investigations, Town Hall meetings, Blue Ribbon Panels, Governor's Commissions, and Congressional hearings. Most call for a faster, more determined initial attack response, larger firefighting capacity or a better fire policy. However, the problem persists.

Perhaps because our after-action assessments are confined to firefighting response or the incident's management between time of detection and time of containment, we tend to focus too narrowly on operational performance and overlook that these extraordinary wildfires usually trace to a long-developing, but unrecognized land management problem. The large fire phenomenon is often less about how we fight fire than how we attend to fire-dependent forests.

Although some might dismiss this as "eco-babble," we cannot bemoan the costs, losses and damages that follow in the aftermath of catastrophic wildfire, and at the same time, remain unknowing or indifferent to fundamental disturbance processes and successional dynamics that define fire-dependent ecosystems. We cannot overlook how fuel accumulations and the densification of these forests predispose them to disaster.

In the West, we use the term "between a rock and a hard place" to describe a vexing, most difficult dilemma. These problems are not ones where a political solution reaches for an altogether good outcome; there is none. Lacking public and political will to act, these problems remain under the domain of the managers and on-the-ground responders to, somehow, deal with in the absence of a realistic plan. Fire managers and firefighters are between a rock and a hard place because they are unable to control the worst wildfires, but neither can they work at large-enough scales to mitigate the hazards that predispose them.

- The consequences of the few wildfires that escape initial and extended initial attack have become enormous. A remarkable success rate may be masking a deeper problem that strikes to the heart of protection aims. Fair or not, firefighting forces are not judged by how many wildfires they put out; they are judged by how they perform at the highest level of threat[2], when the protection of lives, property and natural resources matters the most.
- Expectations for protecting houses at the wildland-urban interface is growing, while the willingness to

accept thinning, prescribed burning and government-recommended fire-safe building codes on private lands is often unwelcome. Fire danger warnings are often ignored until there is smoke in the air.

- Despite knowing the value of fuel reduction treatments in mitigating wildfire risks, active management is often met with a series of discouraging and near-insurmountable obstacles. High costs, long planning horizons, and a number of regulatory requirements impede hazard reduction work at effective scales. "No-action" has become the default alternative, compounding the problem over time.
- Finally, although we maintain that firefighter safety comes first in policy, in practice pressures to get the job done and take risks are intensifying, especially at the wildland-urban interface. Lacking clear limits in an increasingly unforgiving environment, we are left wondering where the boundaries are, in terms of acceptable loss. Whether measured in lives lost, homes lost, public values lost, or money expended, we wonder what threshold must be crossed before we pause and insist on change.

So, at an impasse between a suppression strategy that comes up short under extreme burning conditions and a mitigation strategy that is largely hamstrung, firefighters soldier on, getting more deeply invested in pushing an untenable position.

How do we break this impasse? How do we get out from between this "rock and a hard place"? Why do we need to re-think wildfire protection strategies and consider changing course?

Objectives

Increasing drought, deteriorated forest conditions, and expanding development at the wildland-urban interface have combined to change the calculus of wildland fire protection. An over-reliance on suppression-centric protection strategies, where increasing wildfire threats are met with greater firefighting force, are failing to work under extreme burning conditions. The onset of mega-fires and forecasts for deeper, more prolonged droughts are clear indication for a new, more comprehensive wildfire protection strategy.

This paper maintains that safer, more cost-efficient, and more sustainable fire protection strategies will need to look beyond operational and fire policy "fixes" and address the causal and contributory factors involved. The paper calls for a more comprehensive wildfire protection strategy; one where the idea of protection is expanded to include the land management policies, land-use behaviors and regulatory requirements that influence and govern the condition and vulnerability of the Interior West's fire disturbance regimes.

In the spirit of this conference's call for exploring solutions, this paper will propose some thoughts on a set of management actions going forward.

Background

Large wildfires are relatively rare (only about 1 or 2% of all starts), but they account for about 95% of the total burned acres and roughly 85% of all suppression costs (Hyde and Williams 2007; Figure 2). Over the past several years, there has been a growing number of nationally significant wildfires in this country. At least 7 of the 11 Western states have suffered their worst wildfires on record; some more than once. So-called "mega-fires" (Omi 2005; Williams 2007; Williams and Hyde 2009) may be extraordinary for their size, the magnitude of response, and their cost, but they are better defined by the deep and long-lasting social, economic, and environmental consequences involved. They commonly evoke a governor's disaster declaration to support the emergency. Politically, their repercussions reach the highest levels of government. Lives are often lost. Hundreds, sometimes thousands of houses are destroyed, local economies are disrupted and community infrastructure is often left in shambles. People don't easily "move on" from these catastrophic fires.

Throughout the 1950s, 1960s and 1970s, however, large wildfires were unusual. In fact, under the old reporting system, the "G" size class was the largest, describing those incidents of 5,000 acres or greater. Throughout the West in this three-decade period, relatively few "G" fires were reported. Today, a 5,000 acre fire may not make the Daily Situation Report because it is not big enough. In Arizona—up until the beginning of the 21st century—the largest forest fire reported in state history was the tragic Dude Fire in 1990, at 28,000 acres. In 2002, the Rodeo-Chediski Fire burned a shocking 468,000 acres. A short nine years later, it was eclipsed by the Bear-Wallow Fire (469,000 acres in Arizona and 538,000 acres in Arizona and New Mexico combined). In the past twenty years, one expert estimates that nearly 20 percent of Arizona's forests have burned over, resulting in near-complete mortality (Swetnam, 2012). Alarmingly, these enormous wildfires are often occurring in altered forests that have higher fuel loads and are more dense and more vulnerable than they were before the turn of the last century. In these forests, changed conditions have resulted in changed fire behavior. Historic low-severity, stand-maintenance burning has given way to severe stand replacement burning. These changes have occurred throughout much of the Interior West's ponderosa pine forests.

[2] The highest level of threat describes those conditions where the exposure to risk and likelihood of loss is high or near-certain. It is where extreme fire behavior challenges all efforts at control. Fireline intensities preclude direct attack by any means. Long-range spotting often inhibits indirect attack. The combined effects of drought, hot, dry and windy weather, along with dried-out, desiccated fuels ranging, uninterrupted, across whole landscapes result in rates of spread that far out-pace ground and aerial fireline production rates. The level of threat is often exacerbated by a serious draw-down of firefighting assets, due to demand from other, simultaneously occurring wildfires and the emergence of new starts.

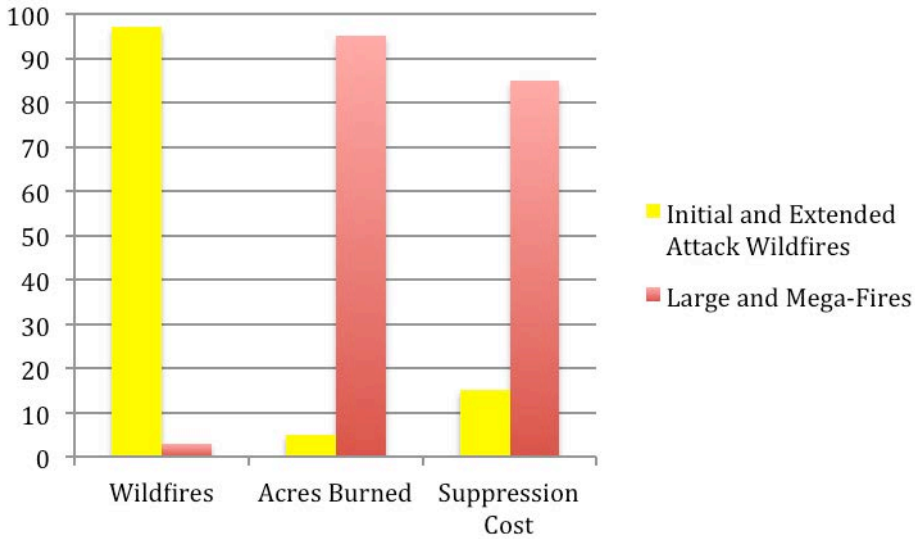

Figure 2—Approximate distribution of acres burned and suppression costs between initial and extended attack wildfires and large or mega-fires, by percentage.

Some years ago, we examined recent worst-on record wildfires to see if we could identify any common characteristics (Williams and Hyde 2009). Here are a few:

- Most large fires were in the Interior West. Nearly half were person-caused. Of these, most were the result of carelessness, but some were intentional.
- Although many mega-fires burned through a variety of forest types, much of the total burned acreage was in forests once dominated by ponderosa pine and associated dry-site species (Figure 3)

Most forests had undergone significant changes in species composition, stand structure, stand density, and fuel accumulation. These once-open forests, with about 50 large trees per acre are now commonly choked with 500 to 1,000 or more smaller trees per acre. Over-accumulated biomass, dried out in the presence of drought, has resulted in severe fire behavior in these altered forests. These wildfires did not "just happen," as an accident might; they have been incubating for over a century. The effects of fire exclusion, over-grazing, high-grade logging, and, more recently, preservation or "hands-off" forest management approaches have manifest themselves in forest conditions that fuel severe wildfires(Figures 4 and 5). Ironically, many of today's worst wildfires are occurring in forests that were among the most benign in terms of potential fire behavior 100-years ago.

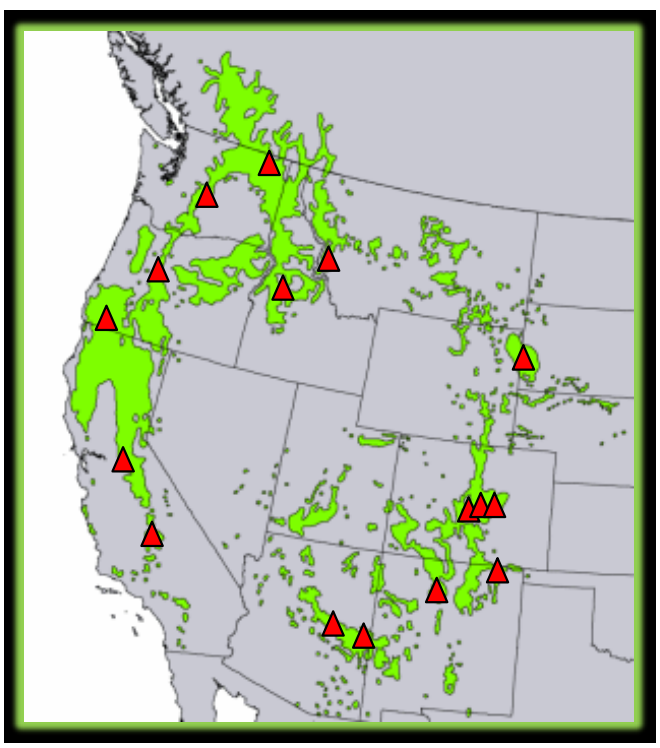

Figure 3. Recent highest cost, loss and/or damage forest fires in relation to native ponderosa pine distribution (2000-2013).

- The once-open forests, commonly at valley-bottoms, historically afforded something of a "buffer" between the stand-replacement fire regimes in forests higher in elevation and removed from the settlements below. That "buffer," now, is all but gone. At the wildland-urban interface, this shift from open, low fuel- load conditions to dense, high fuel-load conditions has important implications for protection. Much of the West's wildland-urban interface is concentrated in these forests.
- All incidents occurred under extreme burning conditions. Energy Release Components (ERC: a measure of drought) were above the 100th percentile during the life of most of these fires.
- These record-setting wildfires exceeded all efforts at control until they burned to a break in fuel or there was relief in weather. Perimeter growth remained far greater than fireline production rates (both ground and air) until severe fire behavior abated.
- Wildland urban interface values were common on these incidents and almost always given the highest priority for protection. "Point protection" strategies usually resulted in greater perimeter growth elsewhere, often onto public lands *perceived* to be of lower value. It was not clear that the cumulative impacts to watersheds, wildlife habitat, old growth, endangered species, viewsheds, air quality

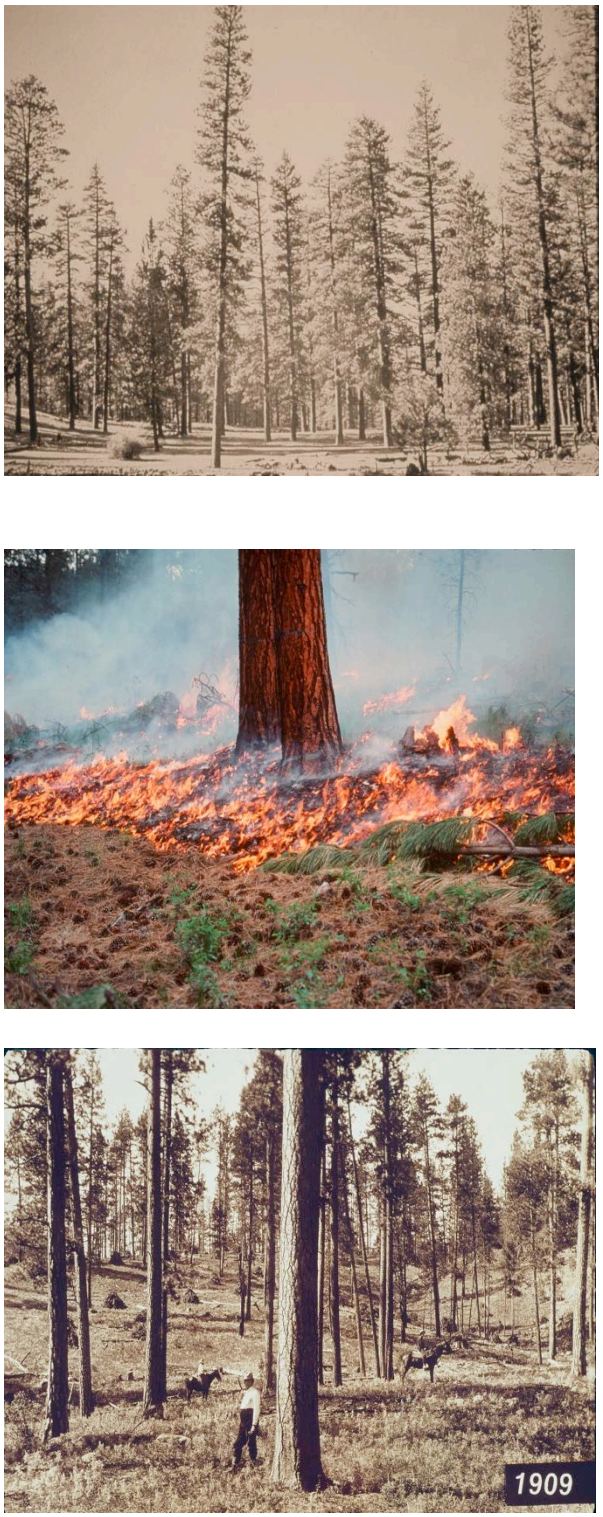

Figure 4—Representative stand conditions, burning characteristics and aftermath of a historic fire-maintained ponderosa pine forest.

Figure 5—Representative stand conditions, burning characteristics and aftermath of a modern undisturbed ponderosa pine forest.

and other public values were being adequately weighted in making tactical decisions or establishing protection priorities.

- The land and resource management plans where these fires occurred called for maintaining undisturbed conditions for a variety of resource needs (e.g., watershed, wildlife habitat, roadless, recreation, etc.). These undisturbed conditions, on these dry sites, were characterized by dense stands with high volumes of biomass and heavy fuel loadings. Under extreme fire weather conditions, these conditions contributed to severe fire behavior.
- Notably, within the perimeter of many of these incidents, there were relatively small areas that were treated and prior understory thinning and/or prescribed underburning had been accomplished. In these treated areas, fire-intensity was much lower. Consequently, mortality and damage was also much lower (Figure 6).

Figure 6—Comparison in post-fire mortality between treated areas (in green) and un-treated areas (in black). From: Tyee Fire, Wenatchee National Forest (1994).

Discussion

Policy objectives are important benchmarks that are used to evaluate performance. When objectives are no longer attainable, there is strong indication that our approach needs to change.

The wildfire protection objective has long been to:

> *"Protect people and property and—without compromise to firefighter safety—minimize natural resource losses and environmental damage at the least suppression cost,"*

As the number of disaster wildfires has increased, most observers would have to acknowledge that our current protection strategy has run up against clear limits under extreme burning conditions. The worst wildfires defeat virtually every component of the protection objective (lives, property, natural resources and cost). When it gets hot, dry, and windy, and there is too much fuel and too much biomass, accumulated over too many years, recent disaster wildfires have become too much to control.

It was many years ago that pioneer fire ecologist Dr. Harold Biswell described the move from fire control to fire management as more balanced. If memory serves, he described fire management as one-third suppression, one-third fuels reduction and one-third prevention. We've been slow to achieve that balance. In fact, most post-disaster recommendations and actions have us "retreating" to more suppression (Zimmerman 2014).

In the aftermath of a disaster, there are often public and political calls for a faster response and a more determined effort...next time. Many argue that we need to "double down" on suppression, invest more in preparedness and fight fire more aggressively. Some argue that we need to return to the "10 a.m. Policy," whereby all new starts are to be controlled by 10 a.m. the following day at less than 10 acres. A few suggest that we need to go "all-in" with suppression and move away from a natural resource orientation to a Federal Fire Service.

Other themes are sometimes surfaced, as potential solutions to the large wildfire problem:

Protect Houses and Let More Fires Burn Into the Wildlands. Some say we should fireproff homesites, emphasize FIREWISE planning and take other precautions around high values, letting fires run their course and burn more freely in the general forest zone where values-at-risk are *perceived* as lower.

Large Wildfires Are Going to Happen…Some argue that large wildfires are going to happen and that not all is bad about it. Given that we cannot prevent them all and that restoration work is too expensive or too contentious, they say, "why not let nature take its course and let fire play its role, in order to clean out over-accumulated fuels?"

Accelerate Fuel Reduction Work...No one promises that reducing fuels will prevent wildfires, but the severity of those wildfires should be lessened, particularly in the short-interval fire-dependent ecosystems. Many experts contend that fuel reduction works at reducing wildfire impacts, but most also agree that we don't do enough of it.

Among the Western forests, perhaps none has the science supporting fuel reduction and fire-use more than the ponderosa pine type. Long before we began managing these forests, Native Americans routinely underburned them for food, forage and access (Barrett and Arno 1982; Barrett and others 2005). Early in the twentieth century, Aldo Leopold observed the importance of frequent, low-intensity burning in maintaining these forests (Leopold 1924). Other scientists, over the decades, have supported the benefits of fuel reduction and low-intensity fire-use in ponderosa pine (Weaver 1943; Sweeney and Biswell 1961; Biswell and others 1973; Hall 1976; Gruell and others 1982; Agee 1993; Arno and Allison-Bunnell 2002; Keeley and others 2009).

Our own firefighters emphasize the importance of fuel reduction. In 1996, following the disastrous Storm King Mountain Fire, a landmark national survey found that an astounding 83% of firefighters ranked fuel build-ups as among the most important factors affecting their safety (Tri-Data, 1996).

In 1999, at the behest of Congress, the Government Accounting Office (GAO) issued a report in response to a series of disaster fires (GAO 1999). The report found,

> *"The most extensive and serious problem related to the health of national forests in the Interior West is the over-accumulation of vegetation, which has caused an increasing number of large, intense, uncontrollable and catastrophically destructive wildfires."*

The report estimated that some 39 million acres were at highest risk. It identified much of the highest risk in altered ponderosa pine forests. It cannot be overlooked that these forests are often at the interface and typically closest to people and communities.

The Forest Service answered the report the next year and described what it would take to address the Interior West's wildfire problem (USDA Forest Service 2000). "Protecting People and Sustaining Resources in Fire-Adapted Ecosystems:

A Cohesive Strategy" called for a ten-fold increase in fuel reduction treatments in the Interior West, eventually reaching 3 million acres per year. It prioritized ponderosa pine and associated dry forest types in the highest hazard condition for treatment. The strategy anticipated a 15-year treatment time frame to begin realizing a reduction in wildfire costs, losses and damages. It estimated that fuel treatment costs would eventually reach $600 million per year.

In the early 1990s, the Forest Service fuels budget increased from $12 million to $50 million, nationwide. At the time when the Cohesive Strategy was submitted, the Forest Service was treating about 300,000 acres per year in all fire regimes throughout the West.

Perhaps the most important features of the 2000 Cohesive Strategy was that it was the first agency report scaled to the size of the problem and that it established a priority for treatment. But, its ambitions were thought too costly. Its goals were not fully implemented. However, it did establish the need for far greater levels of fuel reduction work. It became the basis for a significant jump in fuels funding through the National Fire Plan (2002) and the Healthy Forest Restoration Act (2004)—from $50 million per year to $350 million per year. Yet, there has not been a corresponding increase in treated acres on high-priority sites. The agency treats little more today than it did before the budget took a seven-fold increase (Peterson 2011). Higher treatment costs near the wildland-urban interface, restrictive regulatory constraints, a general lack of consensus among stakeholders, and higher pool and overhead costs seem to be implicated in this inability to increase treatments commensurate with increased funding levels.

There are isolated areas where progress is being made, but they remain the exception rather than the rule. Demonstration areas near Sisters in Oregon, Flagstaff in Arizona, the White River-Apache Indian Reservation in the Mogollon Rim country of New Mexico, the east slope of the Sierras and, here, near Missoula—among others—are places where people are supporting more mitigation work. Other long-standing fire-use programs in Yosemite National Park and several large wilderness areas (Gila, Selway-Bitterroot, Frank Church, and Bob Marshall Wilderness Areas) also offer examples where fire risks have declined as new starts are limited in growth potential by the size, distribution and arrangement of earlier fires (Teske and others 2012). Today, many of these places may be among the safest, most resilient and least costly-to-protect landscapes in the Interior West. Despite the historical Native American use of fire in these forests, the early observations of Leopold, a 50-year history of supporting research from fire ecologists and fire scientists, testimony from our own firefighters, GAO reports and agency responses, evidence from demonstration areas and observations from treated areas within mega-fire perimeters, we continue to favor suppression and remain unable to make much progress with fuel reduction, prescribed burning and restoration.

Formidable obstacles preclude getting more done, but these barriers, left unchallenged, will perpetuate the large fire problem.

Thoughts on a Way Forward

This paper argues that the Interior West's wildfire problem is rooted in the vulnerable condition of its dry forests. In the ponderosa pine type, especially, high fuel loadings, over-accumulated biomass, and dense, multi-storied canopies have developed over a period of many decades. More recently, a "hands-off" approach to forest management continues to exacerbate the densification of these forests. The condition of these forests is enabled by a regulatory framework that punishes mitigation treatments, while giving a "pass" to the consequences associated with "no-action." The problem is further abetted by an incomplete and inconsistent accounting of total wildfire-related costs, losses and damages that mask the true impacts, making hazard mitigation appear un-economical. In some cases, more fuels "pile-on" as a result of incompatible forest plan objectives and ill-fitting land-use expectations.

There are five areas that I believe need attention if we are to get out from between this "rock and this hard place." They might be the elements of a next generation wildfire protection strategy.

Analysis at the program level

Program level analysis evaluates long-term trends against policy objectives. It aims to establish a basis for direction. It can reflect the need to change direction. It is used to develop budgets, staffing, priorities, and overarching strategies. Its usefulness depends on reliable data and a willingness to dispassionately assess the facts surrounding a program's implementation.

Last August, the GAO issued a fire-related report that expressed concern over:

> *"...a firefighting culture that values experience and history over data and scientific analysis (GAO, 2013)."*

Federal wildland firefighters can be proud of their "can-do" attitude and their traditions, but GAO has a point. In many areas, we have done a good job with project-level or implementation analysis, but many of the larger program-level or strategic questions are left unanswered. Many of us are familiar with the National Fire Management Analysis System (NFMAS), Aerial Delivered Firefighter Studies, Aerial Platform Studies, engine studies, firefighter qualification studies, mobilization reports, and a host of other analyses to determine the mix, positioning, and numbers of "the most efficient level" of firefighting assets.

We do very well at achieving protection objectives almost all of the time, but—given the enormity of consequences involved when severe wildfires occur—we have to ask if we might be fine-tuning the tactical applications of a fundamentally flawed strategy; a strategy that relies almost entirely on the ability to put fires out and carries with it the implicit assumption that we ***can*** put all fires out. If a suppression-centric strategy has clear limits of effectiveness at the highest level of threat, and these fires account for almost all of the total costs, losses, and damages, we have to ask if this strategy can continue to achieve protection objectives.

We also have to ask if a suppression-centric strategy can be sustained, as forest and climate conditions worsen.

What other wildfire protection strategies might be more effective under these conditions? What would a rigorous analysis show, if we evaluated the short- ***and*** long-term social, economic, and ecological costs, risks, and benefits among alternative protection strategies? How does suppression compare with other alternatives if we continue to emphasize it in the future? What are the eventual risks to public values like water, wildlife, air quality and other values if we choose to protect private property and houses over public lands? What does it mean if we accept that large fires are inevitable and "let nature take its course?" What are the pros and cons if we accelerate fuels reduction work to more meaningful scales? And, of the alternatives we might decide upon, which one (or combinations of several) best meets our wildfire protection objective? Over the long-term, which is economically feasible and ecologically appropriate?

This need for program-level or strategic analysis is not confined to firefighting. In land management policies and plans managers are required to evaluate proposed actions at the project-level, but, at the program-level, wildfire risks are seldom identified, much less accurately assessed among broad forest plan alternatives.

If the need arises to reduce wildfire threats somewhere, we will enlist a number of interdisciplinary specialists and pull together an Environmental Assessment (EA) to navigate the selective logging, thinning and prescribed burning impacts that are likely to affect the project area. Before it is completed, we will have probably spent most of the project's allocation. The project plan will probably take a couple of years to complete and gain internal approval. Chances are better than even that the project will get appealed or scaled-down. It may stall altogether for the weight of its costs and constraints.

On the other hand, in the absence of action, a much larger wildfire threat may continue to incubate. When the eventual serious wildfire happens, many will be surprised or, even, outraged. This wildfire may grow to many times the size of our proposed project, cost many times more than our project, and result in many times greater impacts than our project. Before the smoke clears, intense scrutiny will be brought to bear in how the incident was managed. Operational performance will be reviewed and, maybe, investigated. It may be litigated. An Incident Commander may get sued.

For all of the scrutiny that will be brought to bear after a high-consequence wildfire, little attention will be directed to the causal and contributory factors that predisposed the disaster in the first place. There are no regulatory requirements to evaluate the factors that predispose wildfires. In fact, wildfires are exempt from the kind of analysis that is required for the proposed actions that would prevent them.

When it comes to the best way to protect against high-consequence wildfires, whether it's Biswell's balanced 1/3-1/3-1/3 formula or one or more of the protection options we outline above, evidence- and science-based analysis helps us find, or at least document, the optimal, most sustainable alternative and avoid settling on the most expedient, but socially, economically and ecologically ***wrong*** solution over the long-term. Credible analysis helps us understand what problems our "solutions" may bring over time. Analysis done right helps us avoid un-intended consequences.

The regulatory exemption for wildfires

In the past few years, some have urged re-visiting the environmental laws that govern the management of federal lands (Bosworth 2006; Thomas 2011; and Engel 2013). They argue that, altogether, these laws have become a hodgepodge of single-focus requirements that work at cross-purposes with one another and overlook larger ecosystem needs.

Many of these laws were enacted in a cooler, wetter climate cycle of the 1930s to 1970s, before the onset of extended drought conditions that we experience today. Prior to the 1970s, we did not see the kind of fire behavior at the scales that we see today. The science of fire ecology was in its infancy and not many plans addressed the disturbance dynamics of fire. With the exception of the 1964 Wilderness Act, most legislation was silent on fire's ecological role. Although the current regulatory framework, such as that employed by the Environmental Protection Agency, tends to accept wildfire impacts as unavoidable, it holds prescribed fire, hazard mitigation and fire-use proposals to a different, more stringent standard. Smoke from a prescribed fire is subject to EPA's air quality standards, while smoke from a wildfire is considered "natural" and, in regulation, exempt from the standards. In the laws' interpretation, active management decisions are subject to regulatory controls that wildfires are not. In the laws' application, using fire must "compete" against possible short-term impacts to a wide range of values. This disparity or bias begs attention in fire-dependent ecosystems.

In practice, environmental regulations typically subject proposed actions to series of requirements and a long, costly planning process, but the wildfire outcome, in the absence of treatment, gets a "pass" in the language of the law. Wildfire impacts are considered an act of God or an accident of nature. Their impacts fall under emergency exemptions; they don't count against air quality, greenhouse gas emissions, endangered species habitat, watershed integrity or other objectives. In practice, there is no consequence for "no action." The West's large fire problem in dry forests is being abetted by a regulatory framework that makes the high-severity wildfire outcome all but certain. This bias in the law is almost certainly perpetuating the large fire problem in the West's dry, fire-dependent ecosystems.

Are safer, more cost-effective wildfire protection strategies unattainable in fire-prone ecosystems because the selective logging, under story thinning and prescribed burning projects might be perceived as too contentious, too costly or too risky? What are the tradeoffs? Are healthy, resilient and diverse fire-adapted ecosystems realistic if the treatments that get them there are constrained by a regulatory bent for stasis?

Dismissing wildfires as acts of God or accidents of nature does not hold when we consider the effects of 100 years of human-induced changes, especially in the West's interior

dry forests. These changes have predisposed these forests to severe burning and large fire potential. Removing the wildfire exemption in altered dry forests strikes the perception that "no action" equates to no consequence. In fire-prone ecosystems, it forces the realization that significant social, economic and ecological effects can and do result from "no action."

Full accounting for total wildfire impacts

Over the years, Agency Administrators, Comptrollers and Budget Examiners have been critical of federal spending on wildfires. Some believe that there is a lot of waste in firefighting: the Fire Services spend money recklessly and Incident Management Teams spend so much money simply because they can.

We are between a rock and a hard place because many of the highest cost wildfires involve threats to high values (e.g., houses and private property). Any opportunity to rein in spending on these kinds of wildfires is invariably met with public and political demands to do and spend more, regardless of effectiveness. It doesn't matter that fuel accumulations went un-addressed for years before the incident. It is never a good time to broker savings in the middle of an emergency.

A full accounting of wildfire costs includes much more than the suppression component. Private property and infrastructure losses, natural resource damages, burned area emergency re-habilitation costs, human health impacts, post-fire impacts (e.g., mudslides and flooding), and costs related to settling lawsuits are all a part of large fires' true costs. Some high-consequence wildfires have control costs that represent less than 15% of the true, total costs. For example, the Rodeo-Chediski Fire cost $46 million to suppress, but another $308 million to cover losses and damages. It is not unusual for property losses and natural resource damages to exceed three-quarters of total wildfire costs (Western Forestry Leadership Coalition, 2010).

The costs of reacting to an emergency, rather than proactively preventing a disaster are where the real savings lay. The costs of "no action" are enormous and getting bigger.

When Administration Budget Examiners and Congressional Appropriators realize the full costs of these wildfires, they might better support fuel reduction strategies that, before, were dismissed as too costly.

Linking land management direction to wildfire risks

Modern large wildfires are often blamed on yesterday's land management practices (e.g., a century of fire exclusion, high-grade logging and over-grazing). But, the mega-fire assessment revealed a number of examples where many of today's land management plans call for maintaining dense, late-successional conditions un-interrupted over broad landscapes for a number of resource aims (watershed protection, endangered species habitat, roadless natural areas, and others).

An effective wildfire protection strategy must look beyond the management of fire; it must more broadly focus, also, on the management of fire-dependent ecosystems. This paper calls for a more comprehensive wildfire protection strategy that takes into account how land management policies, plans, and practices influence wildfire outcomes. Specifically, it calls for better aligning land management approaches with the ecological dynamics of fire-dependent forests as an important means of reducing wildfire impacts and protecting key values.

Perhaps after decades of over-exploitation, our notions of protection became aligned with an emphasis on preservation, "hands-off," and maintaining undisturbed conditions. In fire-dependent forests, this is proving a costly and unsustainable approach. In fact, we may actually be imperiling the very values we hope to sustain by insisting that altered fire-dependent forests can be held in stasis by relying on suppression (Figure 7).

A policy requirement that connects the long-term risks of land management decisions to likely wildfire outcomes needs to be put in place in the post-fire review process. This linkage is seen as critical so there will be a more defensible basis to revise land management plan objectives as the means to reduce wildfire impacts. Until we better align land management plans with the dynamics of dry, fire-dependent ecosystems, we run the risk of "piling on" more fuel and adding more complexity onto an already-dangerous situation (Williams 2012).

Address agency firefighting's limitations

There is another issue that waits on wildland fire managers and firefighters: the need to acknowledge the limits of suppression. Safety concerns, funding issues, and the ability of local, state, tribal, and federal agencies to continue building ever-bigger firefighting capacity have reached critical limits with the onset of the large fire problem. There remains an important place for firefighting, but it is time to make clear the

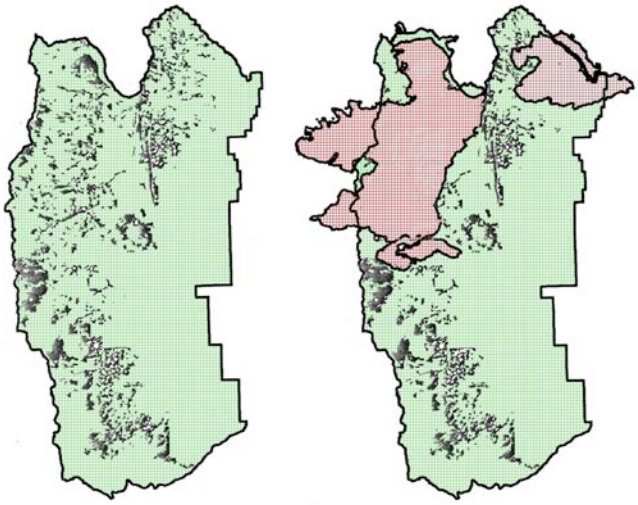

Figure 7—Wildfire perimeters from 2002 and 2003 overlayed onto Northern Spotted Owl habitat areas, Sisters Ranger District, Deschutes National Forest.

need to confront the high-hazard forest conditions that predispose or set the stage for many of these disastrous wildfires. The structural fire services did something similar nearly a century ago, when they turned to managing for safer, more fire-resistant conditions in our cities instead of only building bigger fire departments.

As long as public and political perceptions hold that bigger and better firefighting assets can solve the large wildfire problem, real solutions will remain elusive. We are sometimes seduced into thinking that more and larger assets will solve the large wildfire problem. However, when bigger budgets, bigger aircraft, bigger engines and bigger organizations don't live up to our promises (real or implied) public and political scrutiny will turn to focus on failures in operational performance. As you are perhaps already seeing, fire managers and, even, firefighters will increasingly find themselves being blamed or sued for wildfire outcomes.

Conclusions

We are between a rock and a hard place because, in the West's interior ponderosa pine forests, the idea that we can somehow keep these forests as they are, suspended in stasis, is incompatible with the disturbance dynamics that define these ecosystems. Unless we reconcile this belief, we will not only see more costly, more dangerous wildfires, we will also run the risk of imperiling the very values that we hope to preserve.

Caught between a suppression-centric strategy that does not work at the highest level of threat and a regulatory process for fuel reduction that too often defaults to inaction, wildfire protection for people and natural resource has arrived at a dangerous and costly impasse. We do not want to linger here long.

Experienced firefighters know that to ignore troubling indicators and "push" an untenable position invites disaster. The costs, losses and damages that are trending upwards with a growing number of large, uncontrollable wildfires are a powerful indicator that we need to adapt. This paper argues that we need to *comprehensively* deal with the barriers that enable and abet these severe, high-cost wildfires. The onset of these fires challenges us to expand our focus from tactical, technical and operational to more long-term social, economic and ecological.

Of all the natural disasters that Americans deal with, high-consequence wildfires that burn in altered dry forests of the Interior West may be among the least natural. Contrary to widespread belief and the prevailing language of the law, this "natural disaster" is rooted in the way we use, manage, attend to, and protect fire-dependent ecosystems. Unlike most other natural disasters, this one has solutions.

At this conference, the International Association of Wildland Fire and the Association for Fire Ecology are confronting this important problem at a pivotal time. Your standing gives you an opportunity to bring land managers, policy-makers, and law-makers to confront the large wildfire problem. In large measure, it is a problem that only they can solve.

'We have been the architects of our own danger."
-Mayor Jorge Castro, following Valparaiso,
Chile, fire disaster
13 April, 2014

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Papers

Fire in Ghana's Dry Forest: Causes, Frequency, Effects and Management Interventions

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Abstract—*This paper describes the number of fires, area burned, causes and seasonality of fires over a ten year period from 2002–2012 and investigates different fire management strategies and their effectiveness in the Afram headwaters forest reserve in Ghana. Data were collected from interviews of stakeholders in two communities adjacent to the reserve, and from 2002–2012 fire reports of the Ghana National Fire Service and Forest Service Division. For the period studied, nearly all fires were human-caused, and most arose through land use activities such as farming (19 percent) or hunting (15 percent) or from other activities such as charcoal production (10 percent) carried out in the forest. We also found out that, at least six fire incidences affected an area averaging approximately 31 hectares annually between 2002 and 2012. Nearly all fires occurred during the dry season (November–April) with the highest number of fires as well as largest area burnt occurring in January and February. Fire management efforts were more directed towards fire prevention than pre-suppression and suppression. However, other factors limited the effectiveness of fire management, including a lack of incentives for people to help put out fires and an absence of protective and suppression equipment. We recommend that there should be continuous education and capacity building, alternative farming methods, enforcement of wildfire laws, intensive patrols and inspection, maintenance of fire breaks, provision of lookout towers and other detection systems, provision of suppression equipment and collaboration between stakeholders.*

Key words: *forest fire, causes, fire frequency, management, prevention, pre-suppression, suppression*

Introduction

Each year fires destroy considerable forest resources in Ghana. Most fires are anthropogenic in origin and are directly linked to livelihood activities (FORIG 2003). Burning is embedded in the cultural values and traditional farming systems of the people in Ghana (Nsiah-Gyabaah 1996) so changes in these practices can be difficult to achieve. Anthropogenic fires are the dominant threat to forests in Ghana (Kalame and others 2009) as well as agriculture and can lead to changes in vegetation, invasion of certain species and weeds, soil degradation and low agricultural crop yields (Amissah and others 2011). Within the Afram headwaters forest reserve, anthropogenic fires may thus threaten the long term capacity of the reserve to achieve its intended purposes. Forest fires in Ghana can significantly affect the economy, accounting for an annual loss of 210 million US Dollars, or roughly 3 percent of the Gross Domestic Product (GDP) (FORIG 2003; MLFM 2006). In 1994, about 98 million US Dollars were lost to forest fires representing 2 percent of the GDP of Ghana (Barnes and others 2004). Forest fires contributed to a decrease in total forest area in Ghana from 1990 to 2010 as reported in the global resources assessment (FAO 2010). Concerns regarding forest fires have stimulated Ghana to adopt a comprehensive fire management strategy emphasizing a community-based approach (MLFM 2006), permitting stakeholders to participate in the use and management of fire. Effective fire management can include several different approaches, such as prevention, pre-suppression and suppression (Wingard and Moody 2000). Essential to the success of fire management is an understanding of the causes, seasonality, frequency and extent of fires, as well as of what management practices are being used, and how effective they are. At present, little such information is available in Ghana. This study was carried out to examine the causes, the frequency of fire, seasonality and area burnt and finally reveal the management strategies implemented.

Methodology

Brief Description of the Study Area

The study was carried out in the Afram headwaters forest reserve (Figure 1) involving two communities (Asempanaye and Asuboi). This particular forest reserve and two communities were selected due to prevalent fires over the years and the experience of the local people on forest fire and management. This forest reserve was designated and mapped in 1950 in the Offinso forest district with an area of 201 km^2. The forest reserve is characterized as

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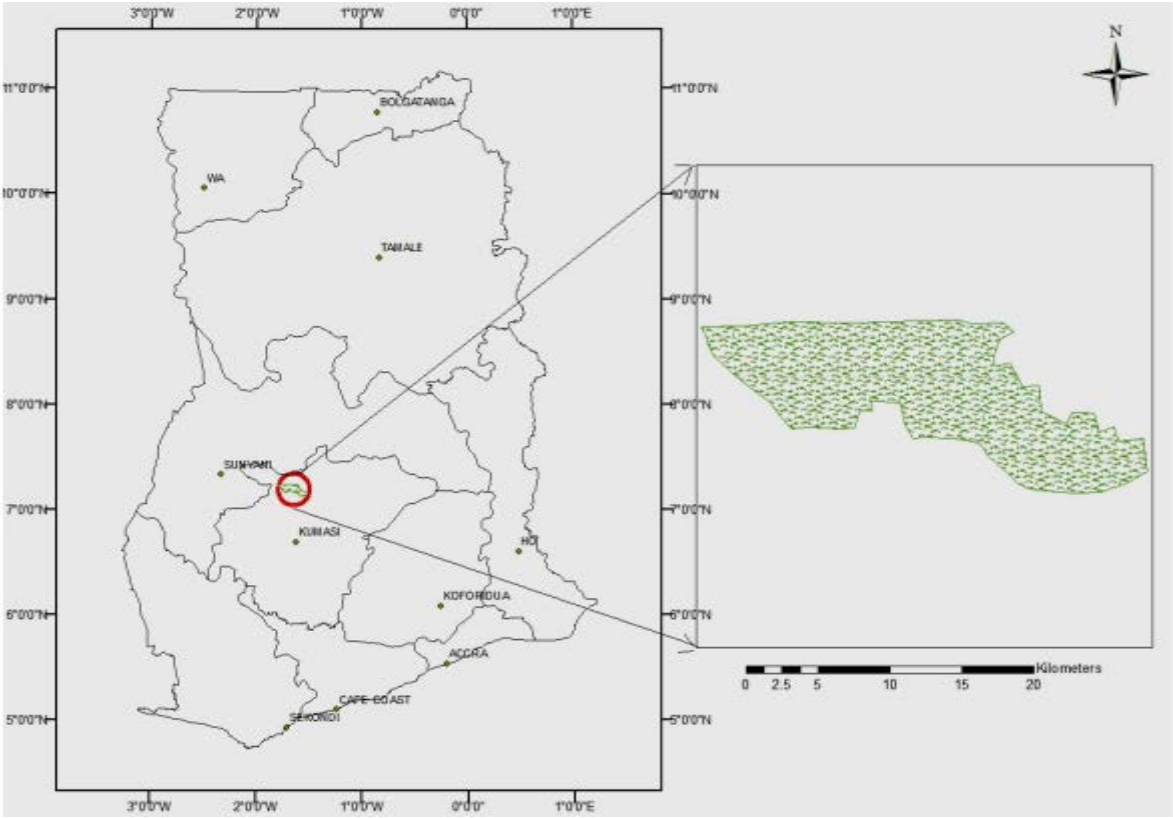

Figure 1—International Institute for Geo-information Science and Earth Oberservation Enshcede, The Netherlands and Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. Map of Ghana with the location of Afram headwaters forest reserve (Dwomoh 2009).

Dry Semi-Deciduous Forest Fire Zone Subtype (DSFZ). It has 773.5 ha of *Tectonia grandis*, *Triplochiton scleroxylon* and *Mansonia altissima* plantation (Hawthrone and Abu-Juam 1995). It lies between longitude 1º 32" and 1º 48" W and latitude 7º 0" and 7º 15" N. The forest reserve rests inside the Tropical Humid Climatic zone characterized by bimodal rainfall period in June and October. The daily mean temperatures are 30 ºC maximum and 22 ºC minimum with mean humidity of 80 percent. The mean annual rainfall ranges between 1,250-1,500 mm (Hall and Swaine 1976; Forest Services Division 1999). The floristic compositions of the forest are mainly *Broussonetia papyrifera*, *Milicia excelsa*, *Triplochiton scleroxylon*, and other indigenous species with dense understorey of *Chromolaena odorata,* and *Griffonia simplicifolia* (Hawthrone and Abu-Juam 1995; Hall and Swaine 1976). Most (70 percent) of the people are involved in agriculture. They cultivate food crops such as plantain, maize, cassava, and cash crops like coffee, cocoa and cashew (Ghana Districts 2006). Asempanaye, Asuboi, Akrofua and Kwapanin are some of the surrounding communities around the forest reserve. Annual forest fires, over exploitation and illegal logging are the major threats to the forest reserve.

Data Collection, Sampling and Analysis

To characterize patterns of fire cause, frequency and area burned, and associated management practices, a series of interviews were conducted between March and June 2012. Interviews were conducted with stakeholders through the use of semi-structured questionnaires. Secondary data was obtained from monthly reports and collated data on forest fires from Forest Services Division (FSD) and Ghana National Fire Service (GNFS) between 2002 and 2012 and existing literatures. The primary data was collected through rapid rural appraisal with a combination of tools such as field observation, key informant interviews and meetings. In all, a total of 109 respondents were interviewed in the selected communities together with the representative of the Forest Services Division and Ghana National Fire Service in the Offinso forest district. A total of 53 people were interviewed in Asempanaye and 54 people were interviewed in Asuboi. Random sampling was used to select respondents in both selected communities. Emphasise was placed on being a farmer, hunter or fire volunteer since they are knowledgeable on forest fires or have their livelihood activities near and within the forest. Respondents were asked about fire causes, existing management strategies in prevention, pre-suppression and suppression while data on fire frequency and area burned from reports. Data was summarized, and where appropriate, analyzed using Microsoft Excel and Statistical Package for Social Sciences (SPSS version 17). T-test was used to test the differences between the fire occurrences and area burnt.

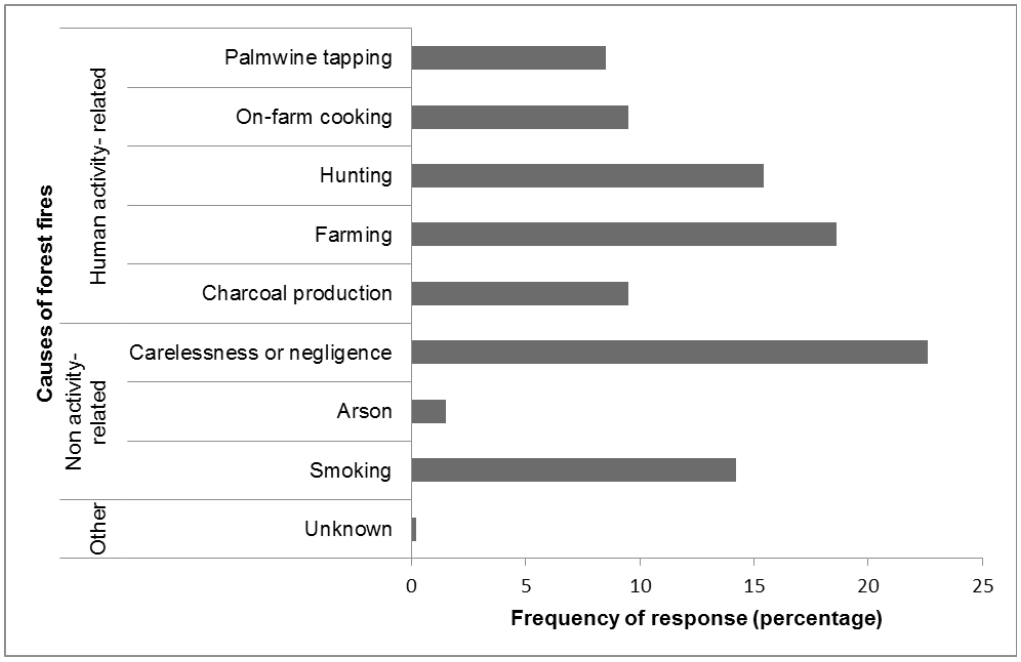

Figure 2—Cause of forest fires in Afram headwaters forest reserve.

Results and Discussion

Causes of Forest Fires

As expected, the overwhelming majority of fires were anthropogenic in origin. Natural fires were not mentioned as a cause. The human-caused fires were further categorized into human activity-related, such as farming, and non-activity related, such as carelessness. The human activity causes were related to livelihood activities carried out by people. The study revealed that human activities constituted 61 percent of the total causes of forest fires. Out of this total, 19 percent were originating from farming followed by hunting (15 percent) and charcoal production (10 percent) (Figure 2).

In Ghana, most farmers prepare land using fire which is considered as the fastest, easiest and most economic way for land preparation. This is very common in the taungya farms (in which crops are planted together with tree seedlings on the same land until tree canopy closure) within the forest and farms outside the forest. After clearing the land, the debris is allowed to dry for some weeks. Later, fire is set to the debris for easy planting of crops which can be annual, biennial and perennial. This type of farming practices and the flammability of a particular vegetation type make the environment susceptible to wildfires (Amissah and others 2010). During hunting, fire is used to smoke out animals from holes such as the ground squirrels. Sometimes, hunters perceive that animals are hiding in thickets and therefore set fire to trap them. Many fires are started by cigarette butts dropped by smokers. Generally all these findings correspond to some studies carried out in some parts of Ghana and other tropical countries (Appiah and others 2010; FORIG 2003; Kunwar and Khaling 2006). Carelessness and negligence caused 37 percent of the fires. Unknown was the least with less than 1 percent (Figure 2). Carelessness or negligence is a common problem, where people carelessly forget to control fires that they start. Farmers and hunters are mostly blamed because they use the fire for their gains without controlling it. Some of the rural people do not want to take responsibility for fires that might extend into the forest. Appiah and others (2010) and Kunwar and Khaling (2006) have described these situations as common factors in other areas.

Forest Fire Frequency and Area Burnt

The forest fire occurrences and area burnt were presented according to yearly and monthly incidences from 2002 to 2012.

Annual frequency of forest fire frequency and area burnt

Over the period of 2002 to 2012, there were at least 6 fires per year, and a mean area burned of 31 ha within the forest reserve. However, there were distinct periods with very different characteristics during this ten year period. Between 2002 and 2003 fire occurrences and area burnt were very high (Figure 3), followed by rapid declines from 2004 to 2011, most likely related to the inception of wildfire management project between the Forestry Commission of Ghana and the Netherlands Government (MLFM 2006). This project contributed funds to research, education and management of forest fires during this period. The decline during 2004 to 2011 was followed by a significant increase in fire frequency and area burnt from 2011 to 2012, corresponding to a lack of funds and logistical support after the end of the project. An additional potentially contributing factor is the restoring of degraded lands through forest plantation development, enrichment planting and community forestry by the Forestry Commission enshrined in the Ghana forest and wildlife policy (2012). It seems likely that this policy could provide an incentive for burning land

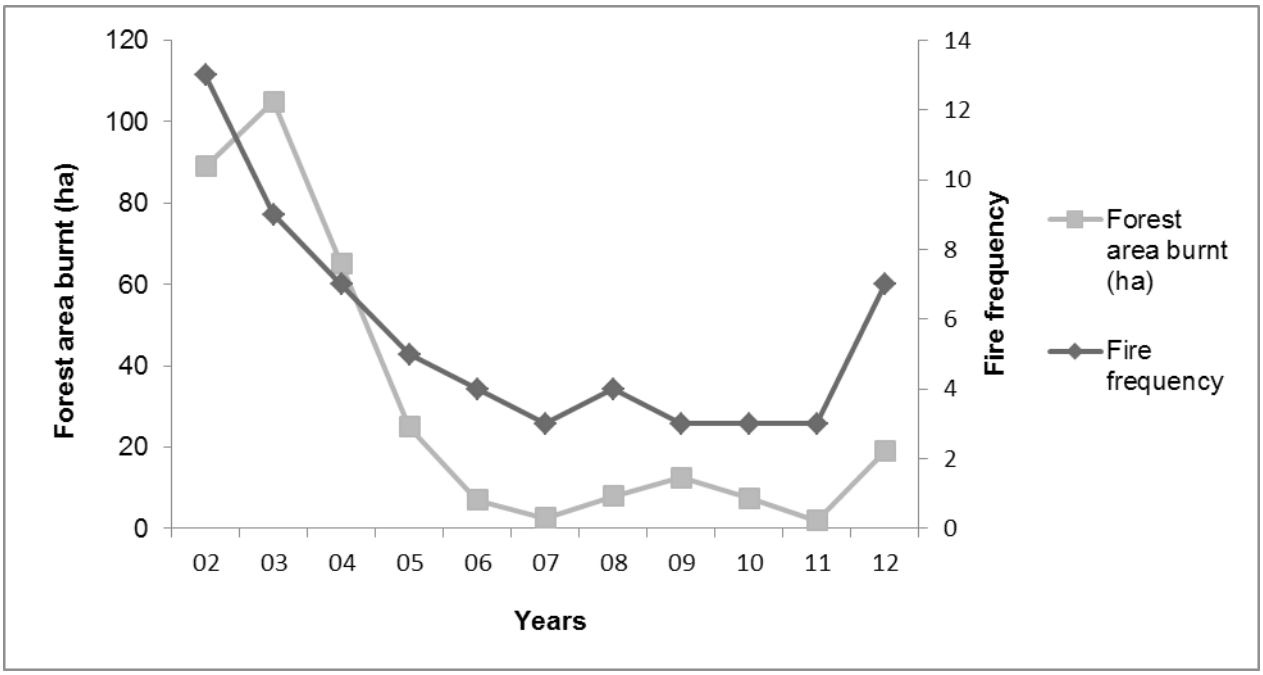

Figure 3—Annual forest fire frequency and area burnt over the period of 2000 to 2012 in Afram headwaters forest reserve.

to make it possible for such activities. For many farmers, burning land provides one of the few ways to prepare land for use; these fires can then get out of hand. It is also evident that the higher the number of fires the higher area burnt (R^2 = 0.88**, P = 0.001). The increase in forest fire frequency to the increase area burnt is related to increased activity of humans in and around the forest (Xanthopoulos 2000).

Monthly frequency of forest fire and area burnt

Analysis of monthly occurrence of fires shows a strong seasonal trend, in which, forest fires usually started from November and ended in April. January and February were observed to be the peak forest fire season in the Afram headwaters forest reserve. The fire season tends to disappear from May to October which was also attested by the local people (Figure 4). Generally, the dry season marks the occurrences of forest fire in the tropics (SCBD 2001). The dry season which starts from November to April is also the period of "harmattan" where the air is dry with high current and increased leaf litter on the forest floor that influences fire ignition. Amissah and others (2010) studied the high risk months for burning slash which coincided with the period mentioned. The peak of the fire season was in agreement with other studies (Adedoyin and Olanrewaju 2006; Yanek 2000). In relating this to the causes, the hunting season runs from January through July where some hunters illegally use

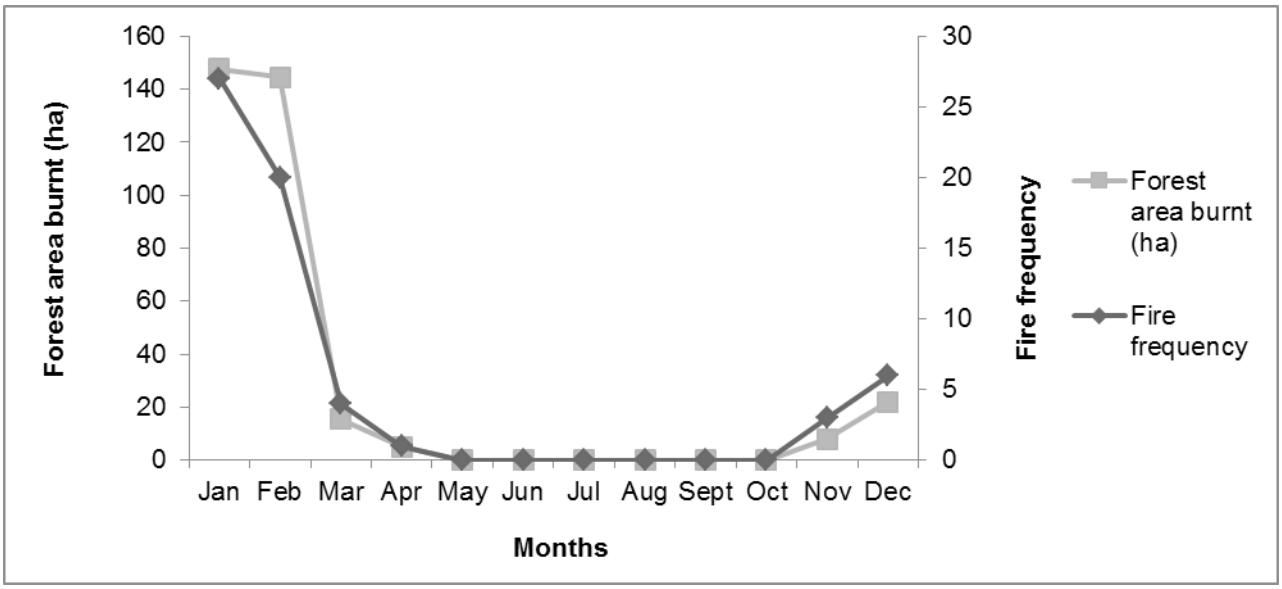

Figure 4. Seasonal pattern of forest fire frequency and area burnt over the period of 2000 to 2012 in Afram headwaters forest reserve.

fire for hunting. On the other hand, those fire season peaks are the time for burning slash for cultivation of crops by farmers (Amissah and others 2010). The fire season can also be related to prolongation of drought as rainfall reduces during this period of time. Rainfall as a climatic factor plays a significant role in forest fires.

Operational Forest Fire Management Strategies

The fire management strategies were divided into prevention, pre-suppression and suppression. Several stakeholders are supposed to be involved in forest fire management as indicated in the national policy. However, those pointed out by respondents were the FSD (55 percent), GNFS (10 percent) and communities (35 percent) located adjacent to the reserve. The prevention focused on actions and activities carried out to avoid the start of fire. The study revealed that prevention was focused on awareness creation, education and law enforcement excluding fire engineering. A combination of these elements is necessary for human caused ignitions (FAO 2006). Several means used to enforce prevention were signing, dramatization, community meeting, leaflet and pamphlet distribution, mobile van education, permits and inspections, talk show and use of national laws (Table 1). Questionnaires revealed that some practices were considered effective, while others were not. Communities around the Afram headwaters forest reserve considered community meeting as a more effective means of education than other approaches (54% agreement, Table 1).

These forms of prevention activities are considered as low-tech but somehow effective and preferred in sharing information (Appiah and others 2010; Blay and others 2011). Law enforcement plays an important role in fire prevention. However, the people around this forest reserve do not recognize the national laws and even the bye laws in the community concerning the use of fire. Although national and local laws punish offenders with arrest and fines, (between 50 to 100GH Cedis (US Dollar 26 to 53 June, 2012)), depending on the damage caused, these punishments seemed ineffective as a deterrent. A common problem in enforcement of these punishments is corruption, where in some cases, if the offender is a relative of the person in authority, they can go scot free. In this case, a person would have little concern of starting another fire. Additionally, taking offenders to court requires a long process, which is considered too time-consuming by authorities; community leaders thus prefer fines instead of going through the legal process to prosecute offenders. Therefore fines and taboos as deterrent measures should be strengthened to reduce fire risk and fire causes (Appiah and others 2010).

Table 1. Respondents response on means of prevention activities.

Prevention means	Percentage of response	Ranking
Signing (bill boards)	4.6	5
Dramatization	2.8	6
Community meeting	54.1	1
Leaflet and Pamphlet	1.8	7
Mobile van education	18.4	2
Patrol and inspection	9.2	3
Talk shows	7.3	4
National and bye laws	1.8	7

Pre-suppression were strategies laid down to ensure preparedness for suppression. As at the time of the study, there were only low-tech detection systems, monitoring systems and operational fire early warning systems or alarms in Afram headwaters forest reserve. Major detection methods were through flame (1 percent), smoke (65 percent), fire embers (22 percent) and report from people (11 percent). All these activities were dependent on the abilities of the communities and considered ineffective. All these methods differ from other methods of accomplishing effective forest fire detection (FAO 2006). The methods cannot be used to identify fire danger in advance of their occurrences until fire started. Delay in fire detection strongly affects forest area burnt as preparedness is delayed. This gives fire the chance to grow steadily in size until the fire is brought under control (Alexander 2000). As a result, severe damages occur to the natural resources. In some cases, firebreaks that had been established around the reserve had many weeds and accumulated dead leaves serving as fire hazard. Bare-ground firebreaks or fire roads were not maintained sufficiently well to serve as barriers to fire spread. Training of community members to manage fire was also irregular due to lack of funds and logistics. However, other pre-suppression activities such as early burning and fuel treatment at fire hot spot areas were sometimes carried out to reduce fire frequency and severity.

Suppression appears to be spontaneous, with little formal procedures of preparedness, training and safety mechanisms to fight fires. However, in case of fire outbreak, all the people available within the community, and particularly the fire volunteers, help in extinguishing the fire. Equipment available for fire suppression were hand tools (71 percent) such as machetes, gallons of water, pick axes and mattocks. Improvised tools (23 percent) like palm fronds were also used with farm clothes, wellington boots and slippers as protective clothes (5 percent), while the only power equipment (1 percent) was the chainsaw at the community level. From the study, it was revealed that tools for suppression belong to the individual people and are considered ineffective for suppressing fires. Appiah and others (2010) found out that these simple tools are effective for suppressing small-scale fires but not large-scale fires. Respondents explained that when fire is large they resort to indirect method of suppression and as a result, burnt area increased. Meanwhile, the Manual of Procedures (2002) mentioned that proper equipment enhances effective fire suppression. However, this statement has been ignored without enforcement. According to respondents, no incentives were given for suppression at the time of the study and the suppression operations were considered as voluntary service. According to respondents, this adversely affected

their response to fire calls. Blay and others (2011) indicated that due to lack of incentives and law enforcing involvement has made people reluctant to engage themselves in fire suppression.

Conclusion

Most fires in the Afram headwaters forest reserve were originating from human activities. The most dominant cause of forest fires was carelessness and negligence (37 percent), farming (19 percent) and hunting (15 percent). Between the periods of 2002 to 2012, forest fires adversely affected forest area through repeated occurrences, with at least six fire occurrences with mean area burnt of 31 hectares annually. The forest fires occurred in the dry season from November and ended April. Peak forest fire seasons were identified in January and February. The existing management strategies were focused on fire prevention more than pre-suppression and suppression. However, fire prevention excluded fire engineering. Pre-suppression strategies were considered low-tech. The significance of fire monitoring, detection systems and early warnings were less regarded. Fire suppression activities were typically carried out without prior planning while suppression equipment were often inadequate and ineffective. Finally, the absence of incentives has affected the response of local people to fire calls.

Recommendation

Though fire is important for many local livelihoods, those contributing to forest fires must not be carried in and near the forest. Additionally, the causes, underlying drivers and effects are still unclear and inadequate which calls for more detailed research in other forest types in Ghana. Detailed analysis on cost of damage, quantity of trees and carbon emission can be significant for estimating economic and environmental losses. The Forest Services Division should actively collect all data and characteristics of forest fires to understand the trend and behaviour of fire to ensure effective forest fire management. Considering management interventions under prevention, there should be continuous education and capacity building particularly in the dry season in all forest communities. Farmers should opt for other farming methods than the use of fire. Ploughing and other forms of land preparation can be used by local people. There are many relevant laws and documentation on forest fires which need to be enforced to reduce forest fire losses while instilling strong punishments to deter offenders. For pre-suppression, detection of forest fires must be a major priority which has to be intensified to reduce damages. Firebreaks and bare-ground fire breaks must be maintained to serve intended purposes. Management should include scheduled prescribed fires to try to reduce fuel accumulation in the forest. Concerning suppression, appropriate equipment and protective wear should be provided by the Forestry Commission to ensure safety and successful suppression. Finally, there should be better collaboration among all stakeholders involved in forest fire management.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Conflicting Short and Long-Term Management Goals: Fire Effects in Endangered Golden-Cheeked Warbler (*Setophaga chrysoparia*) Habitat

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Abstract—*Decades of fire suppression have significantly altered the vegetation structure and composition of savannas, woodlands, and forests. The presence of endangered species and other species of conservation concern in these fire-suppressed systems makes re-introducing fire more challenging. In oak-juniper woodlands of central Texas, we are presented with the challenge of re-introducing fire to attempt to increase oak regeneration, while simultaneously not substantially altering the vegetation structure and composition of the burned areas to avoid degrading habitat that is currently occupied by an endangered species, the golden-cheeked warbler (Setophaga chrysoparia). This bird breeds in Texas red oak (Quercus buckleyi) and Ashe juniper (Juniperus ashei) woodlands with an average combined canopy cover greater than 70 percent. To better understand the effects of fire on golden-cheeked warbler habitat, we examined the effects of four different wildfires on canopy cover and on the abundance and sizes of hardwoods and of Ashe juniper. Burned sites differed in fire frequency, fire seasonality, and time since fire. Burned sites had fewer Ashe juniper seedlings, saplings, and mature trees. Texas red oak and other hardwood trees and saplings sprouted after fire, but effects on hardwood seedlings were mixed. In the short-term, burned areas retained enough canopy cover to maintain golden-cheeked warbler habitat, but in the long-term, if oak regeneration failure continues in fire suppressed areas, these woodlands will likely become Ashe juniper woodlands and no longer provide quality habitat. It may be that more intense and severe fires are needed to sufficiently increase light availability and hence oak seedling abundance. We propose that pre-settlement vegetation was a fire-driven shifting mosaic of oak-savanna, shrubland, and oak-juniper woodland. Savanna and shrubland may mature into oak-juniper woodland under fire suppression, and more intense fires in oak juniper woodland may result in savanna or shrubland. If this proposition is correct, permanent designation of endangered species habitats to specific sites may be unattainable, as the suitability of habitat is dynamic and dependent on the natural fire cycle. We expect that conflicts between short and long-term management goals will increase in the future as stressors such as fire suppression, invasive species, and climate change continue to interact and drive novel plant and animal community dynamics.*

Introduction

The presence of endangered species presents significant challenges to the use of prescribed fire and other management interventions such as invasive species removal (Lampert and others 2014; Severns and Moldenke 2010). Decades of fire suppression have altered the habitat of many endangered species. Efforts to restore the natural fire regimes in habitats where fire has been suppressed have included the use of prescribed fire to restore jack pine (*Pinus banksiana*) to produce habitat for the endangered Kirtland's warbler (*Dendroica kirtlandii*) (Payne and others 2012) and open pine woodlands for the endangered red-cockaded woodpecker (*Picoides borealis*) (US Fish and Wildlife Service 2003). In both of these examples the birds were not currently occupying the burned sites at the time of the prescribed fire. However, in our study system, oak-juniper woodlands of central Texas, we are presented with the challenge of re-introducing fire after decades of fire suppression while simultaneously not substantially altering the vegetation structure and composition of the burned areas so that we do not degrade habitat that is currently occupied by an endangered species. Here, fire is being used to maintain, rather than create or restore, breeding habitat. Our situation is in some ways closer to the challenges faced by many managers when there are conflicting uses of the same site at the same time. For example, efforts to remove invasive tamarisk (*Tamarix* spp.) to restore native riparian vegetation are complicated by the use of the invasive tamarisk by the endangered willow flycatcher (*Empidonax traillii extimus*) (Dudley and Bean 2012).

Conflicting Management Goals

In many cases, as described above, decades of fire suppression have changed the vegetation so much that the target endangered species no longer occupies that area. However, in oak-dominated forests, woodlands, and savannas, fire suppression reduces light availability, causing a failure of oak (*Quercus* spp.) regeneration while leaving

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the existing oak-dominated canopy intact (Brose and others 2013; Nowacki and Abrams 2008; Russell and Fowler 2002). Oak regeneration failure is widespread. It is occurring in forests and woodlands of the eastern United States (US) (Arthur and others 2012), the Ozark Mountains in the central US (Dey and Hartman 2005), parts of the western US (Tyler and others 2006), and parts of Texas (Doyle 2012; Russell and Fowler 2002). On the Edwards Plateau of central Texas, the endangered golden-cheeked warbler (*Setophaga chrysoparia*) breeds in woodlands that contain mature Texas red oak (*Quercus buckleyi*), which is not regenerating, and Ashe juniper (*Juniperus ashei*), with an average total canopy cover greater than 70 percent (Groce and others 2010). Animals like the golden-cheeked warbler that forage predominately in the canopy can persist relatively unaffected in areas where oak is failing to regenerate. However, once enough overstory oak individuals die and are not replaced, the area will become unsuitable for the golden-cheeked warbler. Oak regeneration failure has therefore been identified as a threat to the golden-cheeked warbler (Groce and others 2010).

The restoration of oak regeneration, and consequently the re-introduction of fire, is therefore essential to the long-term persistence of the golden-cheeked warbler. Nevertheless, in the shorter-term, the areas targeted for the re-introduction of fire must maintain current golden-cheeked warbler habitat quality. Therefore, the current challenge is to try to restore oak-regeneration while not decreasing canopy cover below the 70 percent threshold that golden-cheeked warblers prefer. Although conflicts between fire management goals and conservation efforts for animal species of concern are common (Bisson and others 2003; Perry and others 2009), this situation is unique, to our knowledge, in that the target endangered species will eventually benefit in the long-term from the use of fire, but there is a definite limit on how severely an area can be burned in the short-term. However, as land managers increasingly confront conflicting short- and long-term management goals (in our system, open canopy for oak regeneration versus closed canopy for current animal habitat), similar challenges will become more common.

Central Texas Woodland

In central Texas woodlands, Texas red oak and Plateau live oak (*Q. fusiformis*) are not regenerating, while Ashe juniper (*Juniperus ashei*) is increasing in abundance (Murray and others 2013; Van Auken 2008). Therefore, the current fire suppression seems to be converting these woodlands from oak-dominated systems to juniper-dominated ones. We introduced the term 'juniperization' to describe the phenomenon of oak regeneration failure combined with increasing juniper density and cover (Andruk and Fowler 2014). Juniperization is also occurring as eastern red cedar (*Juniperus virginiana)* replaces native oaks in the Ozark Mountains and Cross Timbers regions of the US (Burton and others 2010; DeSantis and others 2011; Hanberry and others 2014), potentially causing conservation conflicts similar to the ones in central Texas.

Ashe juniper is a non-resprouting multi-stemmed tree. It is killed by high-intensity wildfires and has low re-establishment after such fires (Reemts and Hansen 2013, 2008). In contrast, Texas red oak resprouts after both low- to moderate- intensity prescribed fires (Andruk and Fowler 2014; Andruk 2014) and high-intensity wildfires (Reemts and Hansen 2013). Other common native hardwoods in these woodlands include black cherry (*Prunus serotina*), cedar elm (*Ulmus crassifolia*), and Texas persimmon (*Diospyros texana*); all three resprout after fire (Andruk and Fowler 2014). The pre-settlement fire frequency in these woodlands is unknown. Historic documents suggest that frequent fires maintained much of central Texas as savanna (Bray 1904). These fires were likely frequent, low-intensity surface fires that occurred primarily in dry years (Murray and others 2013). The estimated fire return interval for post-oak (*Q. stellata*) woodlands in northeast Texas prior to 1820 (i.e., prior to settlement) is 6.7 years (Stambaugh and others 2011); central Texas woodlands probably had a similar fire frequency.

Objectives

At the time of this study, the use of prescribed fire in golden-cheeked warbler habitat was usually not allowed (but see Andruk and Fowler 2014). We therefore studied the impacts of wildfires at four sites that had burned accidently. Study sites differed in fire frequency, fire severity, time since fire, and prior management history. We measured the effects of fire on the number, size, and growth of Ashe juniper and hardwood individuals. We were particularly interested in whether Texas red oak recruitment had been restored in burned areas, and whether fire reduced the canopy cover below 70 percent, making burned areas potentially unsuitable for golden-cheeked warblers.

Methods

Experimental Design and Surveys

We surveyed vegetation response to wildfire at four woodland sites in Balcones Canyonlands National Wildlife Refuge (table 1). Woodlands of this type are common on hillsides on the limestone-derived soils on the eastern Edwards Plateau (Van Auken 2008). We call them woodlands because their canopy height rarely exceeds 10 m. Each site contained an area that was burned and a paired unburned control area. Each site burned when a nearby prescribed fire in a savanna escaped its intended boundary. See table 1 for a description of the study sites, which we name 'two-fires,' 'one-fire-old,' 'one-fire-recent,' and 'one-fire-thin' to reflect their fire history. The one-fire-thin site had numerous large-diameter Ashe juniper stumps. We interpreted this to be evidence of past cutting and removal of large Ashe juniper trees. There were no stumps in the other sites. Control areas had slopes and aspects similar to their paired burned areas. Within each of these four sites, we randomly located two 11-m radius plots in the burned area, and two additional 11-m radius plots in the adjacent unburned control area, for a total of 8 burned and 8 unburned plots. This

Table 1. The four sites surveyed in this study. Each was burned when a nearby-prescribed fire escaped its intended boundary at Balcones Canyonlands National Wildlife Refuge.

Site	Date of fire(s)	Fire season
two-fires	Feb. 1998, Jan. 2009	dormant season
one-fire-old	Mar. 2006	growing season
one-fire-recent	Jan. 2009	dormant season
one-fire-thin	Mar. 2009	growing season

design includes spatial variation at two scales: site level (site: 3 df; site X burn: 3 df) and plot level (plot, which was nested within burn treatment X site: 8 df).

Vegetation surveys were completed using FIREMON (Fire Effects Monitoring and Inventory Protocol), a standard methodology used in fire-effects research (Lutes and others 2006). All of the sites were surveyed in June 2009, except for the one-fire-recent site (table 1), which was sampled in June 2010. Seedlings (woody plants < 1.5-m tall that were not part of a larger individual) were surveyed in a 3.57 m radius (40 m^2) circle in the center of each plot, while saplings and mature trees were surveyed in the entire 11 m radius plot. We recorded species and height class (0-0.2 m, 0.2-0.4 m, 0.4-0.8 m, 0.8-1.2 m, or 1.2-1.5 m) of each seedling. Species, number of stems in each DRC (diameter at root crown) class, and height to the nearest 0.1 m were recorded for each sapling (woody individual > 1.5 m tall, with a DRC < 10.16 cm) and mature tree (woody plant with a DRC ≥ 10.16 cm). We also measured DBH (diameter at breast height) of each mature tree. A sprout was defined as stem with a DRC < 5.08 cm that arose from the base of a mature tree (woody plant with a DRC ≥ 10.16 cm). The number of sprouts in each DRC class and the height of the tallest sprout in each DRC class were recorded for each mature tree.

Canopy photographs were taken at 9 locations per plot in 2 sites (two-fires, one-fire-recent) with a fisheye lens (Sigma 8mm f/3.5 EX DG circular fisheye lens). The photographs were converted into binary images (canopy vs. sky) using the program Gap Light Analyzer. Canopy openness was calculated from binary images and compared between sites and between burned and unburned areas.

Statistical Analyses

We used a generalized linear model with a Poisson distribution and log link to analyze the effects of fire, site, and their interaction on the number of Ashe juniper seedlings and saplings, Texas red oak seedlings, pooled non-oak hardwood seedlings, pooled hardwood saplings, and pooled hardwood sprouts. Pooled non-oak hardwoods include all hardwood species except for Texas red oak. Pooled hardwood saplings and sprouts contain all hardwood species, including Texas red oak. The generalized chi-square / degrees of freedom was used to assess fit to the Poisson distribution.

We used analysis of variance (ANOVA) to analyze the effects of fire, site, and their interaction on hardwood sapling and sprout height. We calculated a weighted average sprout height for each mature tree, by weighting the height of the tallest sprout in each DRC class by the number of sprout stems in its DRC class. Ashe juniper sapling height could not be analyzed because there were too few sapling individuals in the burned plots.

Some hardwood individuals had their main stem (DRC ≥ 10.16-cm) killed by fire; many of these individuals were producing basal sprouts after the fire (i.e., they were top-killed). We used a generalized linear model with a binomial distribution and logit link (logistic regression) to analyze the effect of fire, site, species (Ashe juniper, Texas red oak, pooled non-oak hardwoods), and the interaction of fire and species (fire X species) on the proportion of mature trees whose main stem was alive. A separate analysis was done to examine the effect of fire, the number of living sprouts per tree, and their interaction on the proportion of living hardwood trees whose main stem was alive. This was done to determine whether hardwood trees whose main stem was killed by fire were more likely to have a greater number of sprouts. In both of these analyses, a random factor 'plot' was included to account for the nesting of plot within site X fire. Plot was included because the dependent variable was the number of sprouts per tree; hence there were multiple observations per plot. Plot was not included in other analyses because there was one observation per plot (e.g., number of seedlings). In analyses that included plot, the denominator degrees of freedom for the F-tests was 8, that is, the degrees of freedom associated with plot.

We used an ANOVA to analyze the effect of fire, site and their interaction on canopy openness. Percent canopy openness, i.e., 100 minus percent canopy cover, was log-transformed to meet normality requirements.

In all of the above analyses, if site was significant, pairwise comparisons between sites were made. If fire X site was significant, we compared burned and unburned plots within each site with the Tukey-Kramer HSD test.

Results

There was no significant main effect of fire on Texas red oak seedling abundance: the number of red oak seedlings did not differ significantly between fire treatments. Sites differed significantly in red oak seedling abundance (P = 0.0037). There was also a significant fire X site interaction effect on red oak seedling abundance (P = 0.027, figure 1). There were significantly fewer Texas red oak seedlings in the burned than in the unburned area of the one-fire-recent site (P = 0.0342) and the one-fire-thin site (P = 0.0043). There were significantly more Texas red oak seedlings in the burned than in the unburned area of the one-fire-old site (P = 0.0056). There was no significant effect of fire, site, or their interaction on Ashe juniper seedling abundance. Although sites differed in non-oak hardwood seedling abundance (P = 0.0218), the two treatments (burned v unburned) did not differ significantly in their effects on non-oak hardwood seedling abundance; the fire X site term was also not significant in the analysis of non-oak hardwood seedling abundance.

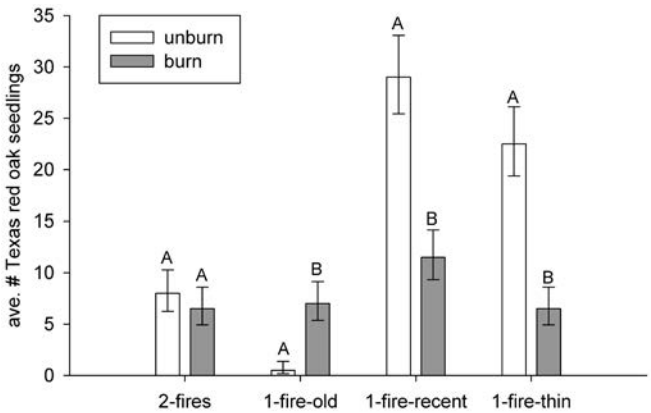

Figure 1—There was a significant fire x site interaction effect on Texas red oak seedling abundance (P = 0.027). Seedlings are individual woody plants < 1.5 m tall. Graph shows average number of seedlings per 11-m radius plot. Letters indicate significant differences between unburned and burned areas within each site. Bars represent ±1 SE.

There were significantly more pooled hardwood saplings in burned plots than unburned plots (P = 0.0005, figure 2a). Sites differed in pooled hardwood sapling number (averaging across burned and unburned plots, P = 0.0034): the two-fires site had significantly more hardwood saplings than the one-fire-thin site (P = 0.029), as did the one-fire-recent site (P = 0.042), and the one-fire-old site (P = 0.027). There was no significant fire X site interaction. There were significantly fewer Ashe juniper saplings in burned plots than in unburned plots (P = 0.0005, figure 2b); there was no significant effect of site or fire X site interaction.

Hardwood saplings growing in the unburned plots were 1.5 times taller on average than those growing in the burned plots (P = 0.001); this indicates recent growth of smaller individuals into the sapling size class. Averaging across burned and unburned plots, the one-fire-recent hardwood saplings were significantly shorter than those in other sites (P = 0.007). There was no significant fire X site interaction.

A large number of hardwood saplings and mature trees were observed producing sprouts in the burned areas. Woody species that had sprouts in the burned areas included *Ageratina havanensis* (Havana snakeroot), *Baccharis neglecta* (Rooseveltweed), *Cercis canadensis* var. *texensis* (Texas redbud), *Diospyros texana* (Texas persimmon), *Forestiera pubescens* (stretchberry), *Fraxinus texensis* (Texas ash), *Garrya ovata* ssp. *lindheimeri* (Lindheimer's silktassel), *Ilex decidua* (possumhaw*), Ilex vomitoria* (yaupon), *Juglans microcarpa* (black walnut), *Melia azedarach* (chinaberry, an invasive species), *Mimosa texana* (Texas mimosa), *Ptelea trifoliata* (common hoptree), *Prunus serotina* (black cherry), *Q. buckleyi*, *Quercus sinuata* (shin oak), *Rhus aromatica* (fragrant sumac), *Rhus lanceolata* (flameleaf sumac), *Sideroxylon lanuginosum* (gum bully), and *Ulmus crassifolia* (cedar elm).

There was no overall effect of fire on the average number of sprouts per tree, but there was a significant fire X site interaction (P = 0.0002, figure 3). Mature trees in the burned areas of the two-fires and one-fire-old sites had significantly more sprouts than mature trees in the unburned areas of those sites (P = 0.0044 and P = 0.0035, respectively, figure 3). There was no significant difference in sprout number between burned and unburned areas in the one-fire-recent site. There was no significant effect of fire, site or their interaction in the analysis of average sprout height. However, the average height of unburned sprouts was 2.44 ± 0.43 m, taller than that of burned sprouts, 1.81 ± 0.25 m, suggesting recent sprout growth in the burned areas.

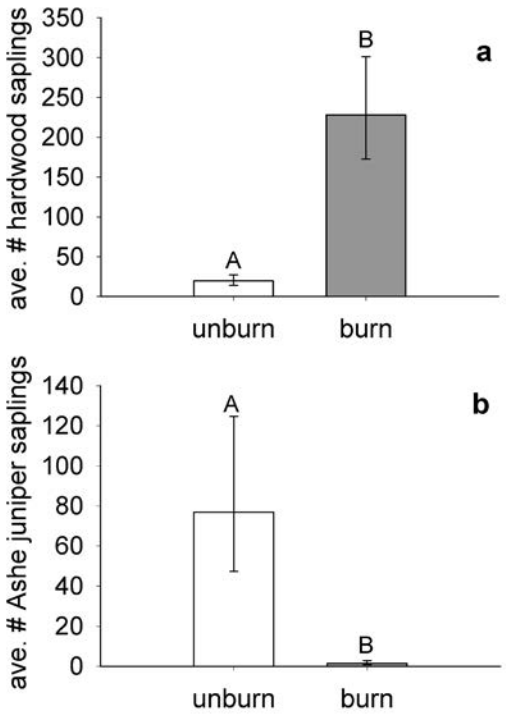

Figure 2—Effects of fire and site on saplings (individuals > 1.5 m tall with a DRC < 10.16 cm). (2a) There were significantly more pooled hardwood saplings in burned than unburned areas (P = 0.0005); (2b) there were significantly fewer Ashe juniper saplings in burned than unburned areas (P = 0.0005); letters indicate significant differences between groups. Bars represent ±1 SE.

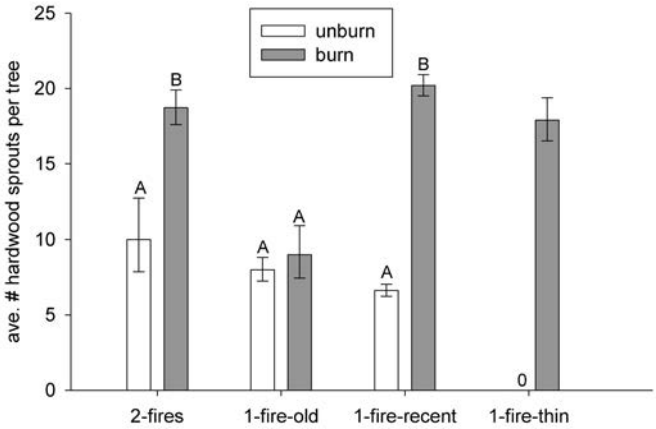

Figure 3—There was a significant fire x site interaction effect on average sprout number per tree (P = 0.0002). Letters indicate significant differences between burned and unburned areas within each site. None of the unburned trees in the one-fire-thin site had sprouts; this is indicated by the 0. Bars represent ±1 SE.

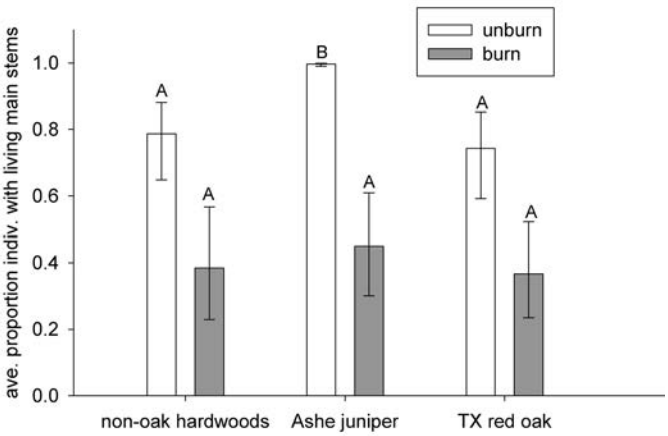

Figure 4—There was a significant fire x site interaction on the proportion of mature hardwood trees with living main stems (P = 0.0203). Non-oak hardwoods refer to all hardwood individuals other than Texas red oak (*Quercus buckleyi*). Letters indicate significant differences between burned and unburned areas within each species group. Bars represent ±1 SE.

Significantly more mature trees (DRC ≥ 10.16 cm) had living main stems in unburned areas than in burned areas (94.06 percent as compared to 39.99 percent, P = 0.0035). On average, 78.13 percent of the mature hardwood trees with dead main stems had basal sprouts, so these individuals had not completely died, but were instead top-killed. There was no significant relationship between the number of sprouts a mature hardwood tree had and the probability that its main stem was alive.

There was a significant fire X species interaction in the analysis of proportion of mature trees with living main stems (P = 0.0203, figure 4). The proportion of living Ashe juniper trees was significantly lower in burned than in unburned areas (figure 4, P = 0.0051). Since Ashe juniper does not resprout, trees with dead main stems were completely dead.

The average canopy openness in burned areas was 29.38 percent, significantly more than the 14.94 percent in unburned areas (P < 0.001). There was no significant effect of site or fire X site, although plots in the burned two-fires site were more open than those in the one-fire-recent site.

Discussion

Burned areas had fewer Ashe juniper seedlings, saplings, and mature trees. They had more hardwood saplings and sprouts, including Texas red oak. Oaks were also found to sprout vigorously after fire in other studies in central Texas (Andruk and Fowler 2014; Doyle 2012; Reemts and Hansen 2013; 2008; Yao and others 2012), the nearby Cross Timbers region (Burton and others 2010; Clark and Hallgren 2003), and the eastern US (Brose and others 2013). The high sprouting rate of the diverse central Texas hardwood community suggests that these species are adapted to periodic fire. Fires had much less success in promoting oak seedling establishment in this study. Effects on oak seedling establishment in other studies, if present, have also been mixed (Arthur and others 2012; Brose and others 2013; Green and others 2010). Fire effects on oak seedlings may be mixed because reproduction from seed is extremely rare (mast events), or because very intense and severe fires are required to sufficiently increase light availability and trigger seedling production. We discuss these potential reasons and their implications for the endangered golden-cheeked warbler below.

Reproduction From Seed vs. Resprouting In Oaks

Prescribed fire can increase oak seedling abundance by increasing flowering, acorn production, germination, and establishment, and can also stimulate the growth of existing saplings (advanced regeneration) (Arthur and others 2012). However, fire can limit oak seedling abundance by killing acorns, especially those at the soil surface (Greenberg and others 2012). These opposing mechanisms make it difficult to determine the overall effect of fire on oak seedling abundance. However, it is clear that resprouting is an important functional trait that allows trees, especially oaks, to persist after fire (Clarke and others 2013). In this study, a large number of common central Texas shrubs and trees were observed producing sprouts in the burned areas of which Texas red oak was the most common. Another study found that blackjack oak (*Quercus marilandica*) and post oak (*Q. stellata*) reproduced primarily by resprouting in a Cross Timbers woodland (Clark and Hallgren 2003), indicating that resprouting is an important mechanism of oak persistence in nearby woodlands. In general, resprouting is the dominant method of oak reproduction and persistence (Brose and others 2013; Lawes and Clarke 2011; McEwan and others 2010).

Due to the predominance of sprouting, oak reproduction from seed is relatively rare. In this study, there were significantly fewer Texas red oak seedlings in the burned areas than in the unburned areas in two of the four sites, presumably because the fire killed them. However, there were significantly more Texas red oak seedlings in the burned area than in the unburned area of the one-fire-old site, which was surveyed 4 years after the fire. It is possible that Texas red oak seedling recovery takes at least 4 years, or that it exhibits mast seed production. In oaks, mast seeding is characterized by large variations in seed production between years and between individuals within a population (Kelly 1994). Masting is common in North American oak forests; for example, large individual and year-to-year variation in acorn production was observed in oak communities in Massachusetts (Healy and others 1999) and southern Appalachia (Greenberg 2000). If Texas red oak exhibits a masting pattern similar to other red oaks, this may explain why we did not observe new oak seedlings: it is possible that we did not survey the plots following a mast year, or that the plots did not contain the "superior producers" that often produce the majority of a population's acorn crop.

Are Repeated Fires Necessary?

Oaks have high light requirements and consequently may only produce seedlings after a sufficient increase in light availability from a more severe fire. Indeed, multiple

fires in combination with thinning were found to increase oak seedling abundance in southern Ohio, probably due to large increases in light availability (Hutchinson and others 2012). In this study, two fires were not any more successful than one fire in increasing hardwood seedling abundance or sprouting rate. However, a large increase in sprouts was observed after two high-intensity wildfires in another central Texas woodland (Reemts and Hansen 2013). This seems to be true of other oak-dominated communities in the region as well. Repeated prescribed fires increased the cover of shin oak (*Quercus havardii*) in Oklahoma more than single prescribed fires (Harrel and others 2001). Oaks in the Ozark Mountains also vigorously resprouted after repeated fires (Fan and others 2012). These authors argue that repeated fires favor oak in the long-term due to its conservative reproductive strategy. Repeated fires are likely successful because oaks tend to allocate more carbon to root development than shoot development, making them better resprouters than their competitors (Arthur and others 2012; Brose and others 2013). These studies suggest that thinning or multiple fires may be necessary to restore oak regeneration in central Texas woodlands as well. If only fires of greater intensity and severity can promote oak regeneration, then the short-term goal of maintaining habitat for the golden-cheeked warbler (or any other target species) will likely be in conflict with the longer-term goal of promoting oak regeneration.

Management Solutions for Endangered Species

One possible solution is to identify sites that do not presently have the target species, open up the canopy to increase light availability sufficiently, and use them in the future as replacement habitat for the target species when the presently occupied sites are burned. This strategy assumes that sufficiently opening the canopy will successfully restore oak regeneration and the desired structure and composition of the plant community. Even if this is possible, this is a long-term, high-risk solution because we do not know all of the factors that make habitat suitable. It also depends on large areas of protected land not currently occupied by the target species and not already dedicated to another use. In central Texas, this would be sites (a) with enough Texas red oaks to have a good seed source; (b) not currently occupied by golden-cheeked warblers, so that intense and severe fires or thinning could be used; (c) not currently dedicated as habitat for other species of concern; and (d) not used for incompatible recreational or economic uses.

As these conditions are restrictive, another, potentially more realistic scenario, is to relax the assignment of the target species to specific sites; i.e., to stop permanently designating endangered species habitats to specific sites and instead simply ensure that enough total habitat is maintained for each target species (taking into account dispersal limitations, if appropriate). In central Texas, this might involve using the habitat for the endangered black-capped vireo (*Vireo atricapilla*) as a successional pathway to golden-cheeked warbler habitat. The black-capped vireo breeds in fire-maintained shrubland composed of scrubby deciduous trees generally less than 2 m tall; common plant species include shin oak and flame-leaf sumac (US Fish and Wildlife Service 2007). It seems possible that pre-settlement oak savannas, shrub savannas, shrublands (black-capped vireo habitat), and oak-woodlands (golden-cheeked warbler habitat) existed in a shifting spatial mosaic driven by fire. Therefore, if only intense fires (or thinning) can promote oak regeneration in former woodlands, these areas may have to go through a 'black-capped vireo stage' during the process of restoring mature oak-dominated woodland. If so, management for a shifting mosaic would have the added benefits of recreating potential pre-settlement dynamics.

Land management for bird conservation in oak-savanna and oak-woodland has also been conceptualized as a shifting mosaic in the northern Midwestern US (Mabry and others 2010); they found that site-level restorations for breeding birds were influenced by the composition of the surrounding landscape. Landscape configuration should also be taken into consideration in central Texas. Although shrubland is probably the highest quality habitat for the black-capped vireo, they can also breed successfully in oak-juniper woodlands (Pope and others 2013). The golden-cheeked warbler is also somewhat flexible in habitat preference. Marshall and others (2013) studied golden-cheeked warbler breeding success in Texas red oak and post oak. They found that the proportion of territories that successfully fledged young was higher within Texas red oak habitat, but there were no significant differences between the habitats in nestling survival. Additionally, golden-cheeked warblers exhibit a wide range of preferences for different tree species. They have been observed in habitats that range from 10 to 90 percent Ashe juniper and 10 to 85 percent hardwood trees. Habitats with higher hardwood abundance (75-90 percent) have been found to be positively related to warbler occurrence (Groce and others 2010). However, warblers have also been found to prefer areas with higher Ashe juniper abundance (DeBoer and Diamond 2006). We therefore suggest that the relaxation of the assignment of target species to specific sites may be good policy because (a) evidence suggests that the pre-settlement landscape may have existed in a shifting mosaic of savanna, shrubland, and woodland, and (b) both the black-capped vireo and the golden-cheeked warbler use resources in shrubland and woodland, which could make rigid site assignments less necessary.

Effects of Fire Seasonality

Mature trees growing in sites that burned during the winter dormant season (two-fires, one-fire-recent) had significantly more sprouts than mature trees growing in their respective controls. Trees growing in sites that were burned in the early spring growing season (one-fire-old, one-fire-thin) did not have significantly more sprouts than their controls. These results suggest that dormant season fires trigger more vigorous resprouting than growing season fires in central Texas hardwoods. Plant carbohydrate reserves are generally lowest early in the growing-season after leaf-out (Harrington 1989), possibly explaining why plants that were

burned at this time sprouted less than those burned in the dormant-season. Most prescribed fires in central Texas, and elsewhere, occur in the winter dormant-season when it is typically safer to burn. Growing-season fires are generally of higher intensity than dormant-season fires (Barnes and Van Lear 1998). A meta-analysis found that oaks sprouted at a higher rate than mesophytic species after growing-season fires, but there was no difference in sprout production between these two groups after dormant-season fires (Brose and others 2013). Therefore, contrary to our results, in many regions growing-season fires are more effective than dormant-season fires, especially if the goal is mesophytic species control. Ashe juniper, a more xeric species than Texas red oak, is most flammable during the winter and early spring (Owens and others 1998), suggesting that it will be equally susceptible to winter dormant-season fire and early growing-season fires. Therefore, due to the superior hardwood sprouting rates observed after dormant-season fires in this study, we recommend their use in central Texas woodland restoration projects.

Conclusions

This study is the first step toward understanding how fire structures oak-juniper woodlands. We found that fire generally promotes hardwood sprouting, but effects on seedlings are unclear. More intense and severe fires may be needed to sufficiently increase canopy openness and oak seedling regeneration. If so, the short-term goal of protecting golden-cheeked warbler habitat is in conflict with the long-term goal of maintaining the oak component of that habitat. We suggest that flexible land management is needed to address this conflict. It is likely that the pre-settlement vegetation in this region was a complex spatial mosaic of savanna, earlier successional shrubland, and later successional woodland. This shifting mosaic hypothesis suggests that plant successional trajectories in black-capped vireo habitat may lead to suitable habitat for the golden-cheeked warbler under fire suppression. Conversely, burning in golden-cheeked warbler woodland may create black-capped vireo habitat. This study explored the conflicts between short and long-term management goals. We expect these conflicts to increase as stressors such as fire suppression, invasive species, and climate change continue to interact and drive novel plant and animal community dynamics.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Recent Findings Relating to Firefighter Safety Zones

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Abstract—*Designation of safety zones is a primary duty of all wildland firefighters. Unfortunately, information regarding what constitutes an adequate safety zone is inadequately defined. Measurements of energy release from wildland fires have been used to develop an empirically based safety zone guideline. The basis for this work is described here.*

Introduction

Wildland firefighting by its nature is inherently dangerous. There have been 699 wildland firefighters die in fire related accidents between 1910 and 1996 in the United States; 384 of those were directly related to fire entrapments (National Wildfire Coodinating Group 1997). Wildland firefighters must consider all risks to themselves and others when approaching, suppressing, and managing wildland fire, and then take appropriate action to minimize those risks (National Wildfire Coodinating Group 2004).

One of the critical decisions made by fire fighters on any wildland fire is the identification of suitable safety zones; areas where firefighters can safely wait for the fire to burn around them (Beighley 1995). The term "safety zone" first appears in official literature in the United States in the aftermath of the Inaja fire where 11 firefighters were killed and the United States Forest Service issued a report that highlighted the need for better training and recommended that all firefighters identify safety zones at all times when fighting fire (McArdle 1957; Ziegler 2007). The United States Forest Service defines a safety zone as "a preplanned area of sufficient size and suitable location that is expected to protect fire personnel from known hazards without using fire shelters" (National Wildfire Coodinating Group 2004). Safety zones should be available and accessible in the event that fire behavior or intensity increases suddenly making current suppression tactics unsafe. We propose that the primary variable of interest be safety zone radius or its operational equivalent safe separation distance (SSD).

Until 1998, regulatory agencies responsible for wildland fire management in North America did not provide quantitative information about safety zone characteristics other than that proposed by Butler and Cohen (1998), which was included in the Fireline Handbook (National Wildfire Coodinating Group 2004). All wildland firefighters in the United States are required to identify safety zones when working on or near fire. However, results from a survey of perceived size of area or distance required to be safe from fire, conducted as part of a presentation to groups of wildland fire managers in 1999 and 2000, indicated wide discrepancies in size and/or distance (Steele 2000). In that study, more than 330 firefighters were shown pictures of vegetation, listing the time of year (summer, fall, winter, spring), air temperature, relative humidity, and seasonal rainfall. Each firefighter was then asked to predict the size of area or separation distance from flames to remain safe from injury. When shown pictures of fire burning under the stated conditions, 51 percent of the participants increased their estimates of the required safe separation distance while 8 percent decreased their estimates. The survey indicated that the minimum safe distance from fire estimated by firefighters varied by three orders of magnitude. The study presented in this paper highlights the difficulties faced by firefighters in visualizing representative fire behavior given weather and vegetation conditions and in estimating safe separation distances from fires.

Past research funded by the Interior Fire Coordinating Committee (IFCC) resulted in the development of a theoretical model for quantifying firefighter safety zones (Butler and Cohen 1998). The model simulated the spatial distribution of radiant energy in front of a linear vertical flame. 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. Unfortunately, the paucity of quantitative measurements of radiant and convective energy distributions from wildland fires prevented evaluation of the model by comparison with measurements. Instead, the authors compared the predicted minimum separation distances recommended by the model against data and records from past fires. The comparison indicated that the model was at least reasonably accurate over the four test cases that were explored. Recognizing the need for further evaluation of the model, in 2003 the Joint Fire Science Program (JFSP) funded a Rapid Response Team (JFSP project 03-2-1-03) to explore through direct measurement and theoretical modeling the accuracy of safety zone guidelines and assess their effectiveness in protecting firefighters from injury. Field measurements were collected on fire incidents in Florida, Arizona, Montana, California, Oregon, Washington and Idaho. These data were used to calculate the distribution of energy in and around

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

those fires (Butler and Cohen 2000). Measurements and analysis of fires and safety zones on flat terrain showed that current safety zone guidelines were adequate with the assumption that both the fire and safety zone were on flat terrain. Additional guidelines were developed that related safety zone size in acres to flame height in feet and to account for changes in safety zone size necessary to accommodate equipment and multiple personnel. An additional outcome was that locating safety zones on slopes introduces additional complexity that was not addressed in the existing guidelines. It was recommended that future efforts focus on developing guidelines for safety zones on slopes where the effect of convective heating may be significant.

Current safety zone guidelines for wildland firefighters are based on the assumption of flat ground, no wind, and radiative heating only. Recent measurements in grass, shrub and crown fires indicate that convective heating can be significant especially when fire is burning under the influence of wind or slope. Measurements and computer modeling supports this finding and suggests that convective energy transport should be considered when assessing safety zone effectiveness any time wind or slope is present. The results of the research are presented along with recommendations for modifications to current safety zone guides.

There has been a general decline in fatalities on a per year basis from 1925 to present (dashed line, right vertical axis) as well as average fatalities per year based on Cook's analysis (solid line, left axis) (Cook 2004) (figure 1). When considering the information presented, two observations come to mind: 1) it appears that there is a 3 to 5 year periodicity in the large entrapment years (that is more than 8 fatalities occur every 3 to 5 years), and 2) there is an indication that over the past 20 years we are seeing a large entrapment every 15+ years. Given these observations, one is prompted to ask what caused the decreases in annually averaged entrapments (red solid line), and what efforts can lead to further declines in injuries?

The decrease in average annual fatalities appears to have occurred around 1960, just three years after the Inaja Fire where the term safety zone was developed and promoted by the Forest Service. In 1960, the 10 standard fire orders and 13 watchout situations were also implemented. The 13 watchouts were subsequently modified to 18 watchout situations. In the absence of any other obvious causal factors one could argue that the implementation of the concept of safety zones, the 10 standard fire orders and the watchout situations contributed to a decrease in fatalities from more than 6 to around 4 per year after 1960. Between 1960 and 1990 the trend remained essentially constant at approximately 4.5 fatalities per year.

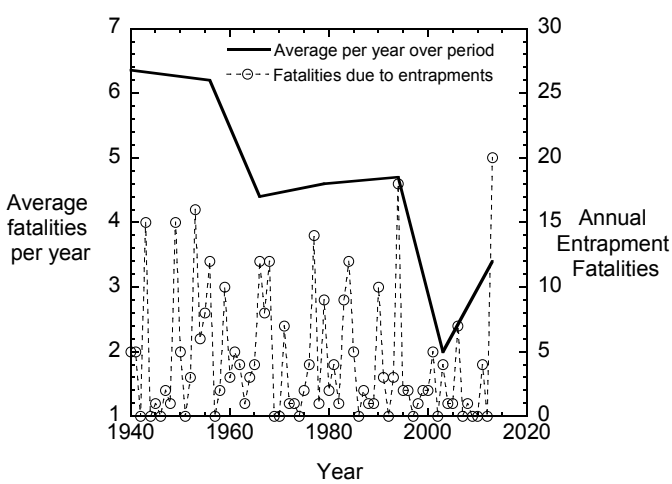

Figure 1—Wildland firefighter entrapments from 1940 to present. Dashed line represents annual entrapments (right axis), solid line represents entrapments averaged over a 8- to 12-year period on an annual basis (left axis).

In 2000, annual average fatalities decreased from 4.5 to approximately 2 per year. The major fire event for this period was the South Canyon fire where 14 firefighters were killed (Butler and others 1998). The decrease in annually averaged fatalities in this period could be intuitively associated with the policy and fire incident management changes that were implemented in the wake of the South Canyon Fire. Additionally, quantitative safety zone guidelines were published in 1998 (Butler and Cohen 1998). One interpretation is that the policy, work practices, additional information, and training developed after the South Canyon fire did have a beneficial impact on future fatalities. One could argue that the quantitative safety zone guidelines contributed to that decline. Again the implication is that changes to policy, work practice and enhanced situational awareness can save lives.

The rise in the red curve from 2002 to present is due to the Yarnell Hill fire where 19 firefighters were killed. Comparing this event to the South Canyon Fire in 1994 suggests that there may be a tendency for large entrapment events to occur every 15 to 20 years. However, considering the decrease in annually averaged entrapments around 1960 and 1995 there is evidence that cultural, political, and work practice changes can save lives.

In general it has been widely accepted that fire spread is driven primarily by radiative energy transport. The relative contributions of radiation and convection heat transfer depend in a complex way on the prevailing wind speed, fuel distribution, buoyancy-induced in-drafts, terrain slope, and so on. A variety of measurements have been collected from fire experiments including but not limited to flame spread rate (Fons 1946; Hottel and others 1965; Catchpole and others. 1998), high speed photography to determine flame shape (Anderson 1968), and flame temperature (Anderson 1968; De Mestre and others 1989). However fewer observations of fire intensity in terms of total, radiative, and convective heat levels have been reported. Consequently the relative balance between radiative and convective heating is largely undetermined. Thus one of the primary objectives of this project was to collect direction measurements of energy transport in laboratory and naturally burning fires.

Measurements

As part of the study presented here, two sets of laboratory experiments were designed to develop new understanding into the mechanisms driving energy transport in wildland fire. The first explored the influence of convective heating on single particle heating (Frankman and others 2010b). The

measurements were combined with a theoretical model of particle temperature as a function of heating mode, duration, and magnitude. Results indicated that ignition of fine dead fuel elements is unlikely by radiative heating alone and then only under circumstances where the fire is very intense (i.e., crown fires). However convective heating and piloted ignition is critical for lower radiant heating levels.

Laboratory fuel configurations are largely limited to packed fuel beds composed of a variety of different fuel types (Fons 1946; Hottel and others 1965; Van Wagner 1967; Anderson 1968; Pagni 1972; Konev and Sukhinin 1977; De Mestre and others 1989; Butler 1993; Catchpole and others 1993; Catchpole and others 1998; Santoni and others 1999; Dupuy 2000). Fuel arrays composed of generally homogeneous randomly oriented fuel elements have been shown to provide nominally consistent fire behavior and repeatability. However, the mechanism by which flame spreads across a gap from one fuel element to another is not well understood. No direct/simultaneous measurement of radiation and convection in wildland fires has been reported in the archival literature. Further, the temporal dynamics of the convective and radiative flux have gone unexplored. As part of this work, a series of laboratory experiments were performed to characterize radiant and convective energy proportioning in fires burning through beds of wood shavings and pine needles. The experiments and measurements are described in detail elsewhere (Frankman 2009; Frankman and others 2010a).

The results from a fire in grass are presented in figure 2. Radiation transfer is sensed long before flame arrival; however, it is accompanied by rapid short duration convective heating and cooling. The convective heating increases abruptly when the combustion occurs. Radiant heating is characterized by relatively (in comparison to convection signal) steady heating through the flame approach, burning and departure. Convective heating fluctuates widely from heating to cooling.

To complement the laboratory measurements, time-resolved irradiance and convective heating were measured in natural and prescribed wildland fires from Alaska to Florida on a variety of terrain types and under a broad range of burning conditions between 2006 and 2010. These measurements comprise more than 50 separate instrument deployments. The measurements show that convective transfer varies widely in magnitude over time whereas irradiance is much less variable in time, increasing nearly monotonically with approach of the flame front and declining exponentially with its passage. Irradiance beneath crown fires peaked at 300 kW m^{-2}, peak irradiance associated with fires in surface fuels reached 100 kW m^{-2} with a mean value of 70 kW m^{-2}; the peak for fires burning in shrub fuels was 132 kW m^{-2} with a mean value of 127 kW m^{-2}. Crown fires in lodgepole pine (*Pinus contorta*) resulted in 2 second averaged convective fluxes from 15 to 20 percent of the peak radiative fluxes. However, fires in surface fuels characteristic of a southern longleaf pine (*Pinus palustris*) ecosystem showed convective heating equal to or greater than the radiative flux. Fires burning in sagebrush (*Artemisia tridentata* subsp. *Wyomingensis*) dominated ecosystems produced peak convective heating 20 to 70 percent of the radiative heating magnitudes.

Figure 3 presents energy levels as a function of vegetation type which is intended to be a surrogate for fire intensity. A burn injury threshold of 7 kW m^{-2} is displayed. Based on these groupings, the decay in intensity with distance can be simulated using a model of the form m/r^n were m is a constant, r is distance from the flame, and n is an exponent (0.75 for these data). The values for m scale nominally with the observed peak total heating values measured in each grouping, the exponents (n) were held constant. The largest discrepancy between this model and the data occurs for the moderate intensity crown fire data. These data are based on measurements over a range of topographical and vegetation types. Also the arbitrary nature of the grouping could alter the results. However, there is

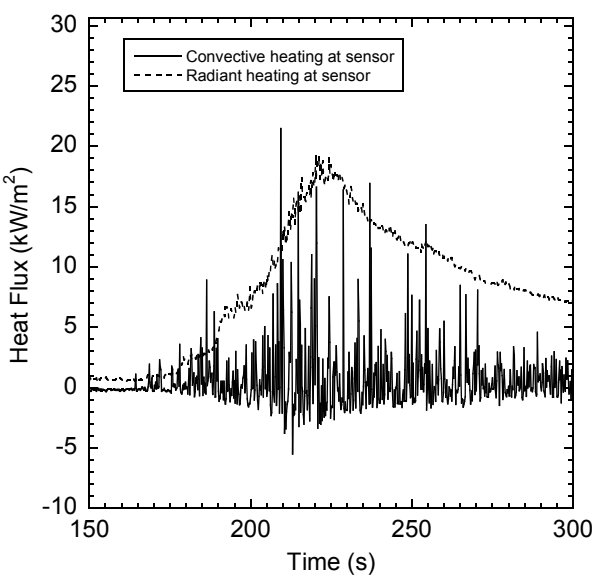

Figure 2—Direct measurements of radiant and convective heating from fire in 0.5 m tall grass. Negative heat flux indicates that energy is being absorbed by the air or essentially that convective cooling is occurring.

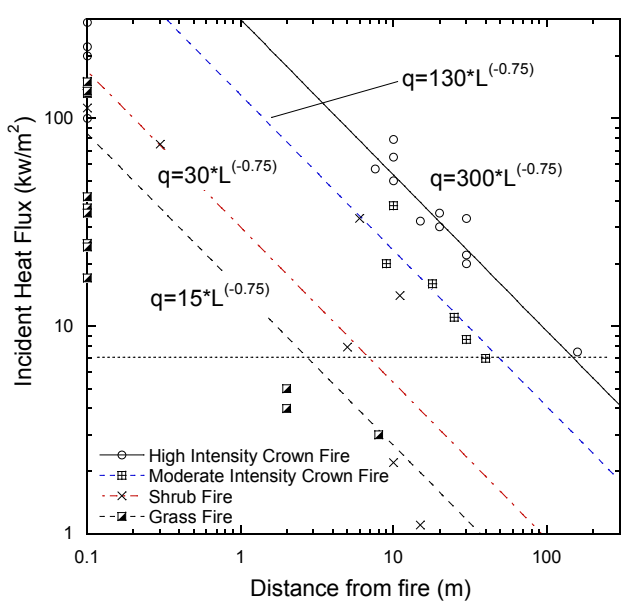

Figure 3—Exponent based models for energy decay with distance for wildland fires. L represents distance from fire.

some intuitive comfort derived from the correlation between peak total heating values and the constant multiplier values.

Empirical Model

Four heating regimes are identified for these data. The lowest being that associated with fire in grass vegetation. These measurements are best fit by a line defined as $q = 15/L^{0.75}$ where L is the distance between the receptor and the fire. The next highest heating level is associated with shrub vegetation similar to sage brush. Nominally, these shrubs are 1 to 2 m tall. The best fit for heating level as function of distance from flame is $q = 30 / L^{0.75}$. For taller shrubs (i.e., gamble oak) or low intensity crown fires the fit is $q = 130 / L^{0.75}$. Finally the most intense fires such as those typically associated with forest crowns the best fit is $q = 300 / L^{0.75}$. The horizontal dashed line represents the level at which second degree burn injury will occur in roughly 30 to 60 seconds. Logically the point at which the best fit for energy distribution crosses the burn injury limit would represent the minimum distance required from a fire in the particular vegetation type to prevent injury. Thus for the highest intensity crown fires nominally 105 m is required, for moderate intensity crown fires or fire in 2 to 4 m tall shrubs the minimum distance is 60 m, for fires in 1 to 2 m tall shrubs or grass the minimum distance is 8 m and for fires in grass less than 1 m tall the minimum separation distance is 3 m. This approach includes wind and slope implicitly in the data set. There is no direct accounting for steep slopes or strong winds. Additionally only a few data points were collected in steep terrain or windy conditions, thus this empirical model does not have a strong slope or wind component. Recent efforts have been focused on using the field measurements to tune the parameters required for a computer simulation of the energy distribution in front of a fire. The simulations are underway.

Escape Routes

Escape routes are the paths that firefighters must travel to reach a safety zone in the event of a change in fire behavior. Clearly, a complete analysis of safety zone effectiveness is impossible without considering the time it takes for a fire crew to get to a safety zone prior to arrival of the fire. Cheney and others (2001) noted a doubling of flat terrain fire spread rate for slopes of 18 percent and another doubling for slopes of 36 percent and state that firefighters often overestimate distance to fires when observing fire through a forest and are thus lulled into a false sense of security. Butler and others. (1998b) proposed that differences in time for the fire to reach the safety zone be compared against firefighter travel times along their escape route as yet another method for assessing safety zone and escape route effectiveness as a function of vegetation type and environmental conditions. Three studies report data on firefighter travel rates for various vegetation and firefighter crew types, and slope (Butler and others 2000; Ruby and others 2003; Alexander and others 2005). Travel on moderate slopes (nominally 26 percent) is 30 percent slower than those on flat terrain. Dropping packs and tools increased travel rates by 20 percent. Travel rates increase by 40 percent when moving over moderately improved and marked trails. Recent firefighter fatalities suggest that considerable work should be done to increase firefighter awareness and capability to evaluate transit times within the context of fire spread rates and safety zone accessibility when moving from one area to another on wildfire incidents.

Water as Safety Zone

Water bodies have been used effectively as safety zones, but they have also resulted in some drownings. Some considerations are temperature of the water and potential for hypothermia. Immersion in even seemingly warm water can result in hypothermia in relatively little time. For moving bodies of water, the potential for the current to cause a person to lose their footing and be swept downstream is real. This is especially true if firefighters are wearing packs or multiple layers of clothing that have become soaked with water. Water quality should also be considered; immersion in fetid water could introduce unnecessary risk and may warrant looking elsewhere for safety. However, even with the above considerations, water can provide a high degree of protection from thermal damage. Even a shallow water body (as little as 0.1 to 0.3 m) will provide significant thermal protection. There have been reports of entire ponds evaporating when exposed to heating from a nearby crown fire. This does not seem possible from an energy transport point of view, but it could be associated with strong winds associated with a fire that effectively evaporate a shallow water body away. As a caveat it is important to emphasize that soaking ones clothing with water will only increase the thermal conductivity of the clothing and thereby facilitate burn injury. However, drinking water when in an entrapment can be beneficial. Further analysis of water bodies as safety zones should be considered.

Conclusions

Many questions remain regarding how energy is generated and released from wildland flames. It is only recently that measurements have identified the range of heating magnitudes that can be expected from wildland flames. The prediction of fire behavior, especially during dynamic fire operations can be very difficult even with access to sophisticated computer models and hardware. The studies summarized here suggest that heating levels of 6 to 7 kW m^{-2} generally represent burn injury limits; however, a more appropriate metric is thermal dosage unit that includes both heating magnitude and exposure time. Many published studies (Butler and Cohen 1998; Zarate and others 2008; Rossi and others 2011) suggest that SSD is not accurately approximated by a constant multiplier of flame height for flames less than 20 m tall; however, as flames exceed this height, separation distance can be approximated as 2 to 4 times the flame height. Comparison between these studies and fire entrapments suggests that the Butler-Cohen model overestimates SSD, especially for large flames,

while the Zarate' and Rossi models predict minimally survivable conditions. Intuition, professional observations, and the few experimental measurements that have been reported indicate that when fires are located on or adjacent to slopes or ridges or are exposed to winds convective energy transfer may reach distances equal to 2 to 3 or more flame lengths ahead of the fire front. This implies that the current safety zone guidelines will underestimate SSD in some situations and that the impact of convective heating on SSD should be considered. Recent measurements suggest that in the context of wildland firefighter safety zones on slopes an accurate accounting of energy transport requires consideration of both convective and radiative heating. The inclusion of convective heating implies that slope steepness, ambient wind, and safety zone geometrical location relative to terrain slope are all relevant.

Acknowledgments

This work could not have been accomplished without the financial support provided by the Joint Fire Sciences Program, as well as support from fire managers in the Bureau of Land Management and the National Park Service when we were deploying sensors in and around fires. We also acknowledge the enthusiastic support from many fire crews, district, and forest staff.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Vegetation Clearance Distances to Prevent Wildland Fire Caused Damage to Telecommunication and Power Transmission Infrastructure

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Abstract—*Towers and poles supporting power transmission and telecommunication lines have collapsed due to heating from wildland fires. Such occurrences have led to interruptions in power or communication in large municipal areas with associated social and political implications as well as increased immediate danger to humans. Unfortunately, no studies address the question of what is the appropriate clearance needed to prevent damage to the conductors and support towers by wildland fires. This study presents preliminary findings from two independent studies focused on this question. Findings suggest that steel towers provide the greatest resistance to fire damage; however, when failure occurs it is catastrophic, wood poles and towers do not fail catastrophically and thus may provide longer term resistance to failure. Minimum clearance for steel towers in surface and crown fires is 1 to 21 m. The minimum clearances for wood poles exposed to surface fires of low to moderate intensity are on the order of 1 to 33 m. For crown fires in tall brush and tree canopies, wood poles and towers require clearances of 20 to 33 m. The susceptibility of wood poles to ignition and sustained burning is dependent on the age and condition of the wood surface: aged poles that present fissures for ember accumulation have the greatest risk. Clearance around telecommunication towers is dependent on the exposure of cables, guy wires, and other materials near the ground. Analysis and conclusions from this study should be characterized as preliminary.*

Introduction

Flames and smoke from wildland fire can increase the possibility of phase-to-phase, phase-to-tower, or phase-to-ground faults that could lead to subsequent power outages and electrocution risk to humans (Martinez-Canales and others 1997; Andrade 2006; Vosloo and others 2008; Wu and others 2011; Kirkham 2012). Measures taken to reduce fire intensity and thereby minimize risk of faults include expansion of vegetation clearance around towers, reduction of vegetation maintenance intervals in high risk locations, identification of zones warranting more intensive vegetation management based on vegetation and fuel type, slope steepness, or other fire risk factors to reduce the likelihood of crown fire occurrence (i.e., reduction of vegetation load to less than 10 tons/acre [4.5 Mg/ha]), removal of ladder fuels, thinning to a canopy density less than 40% closure, alteration of species composition from high flammability to lower flammability vegetation types, and modification of line patrol frequency (Blackwell and others 2011). Unfortunately, no studies have been found to date that address the question of what is the appropriate clearance needed to prevent damage to the conductors and support towers by wildland fires.

The California Public Resource Code (PRC) section 4292 suggests a "clearance of flammable fuels for a 10-foot (3.3 m) horizontal radius from the outer circumference of power line poles and towers." Section 4293 requires "clearance of all vegetation for a specific radial distance from conductors, based on the voltage carried by the conductors: four feet for 2.4-72 kV, six feet for 72-110 kV, and ten feet for 110 kV." In addition it requires the removal or trimming of trees, or portions of trees, that are dead, decadent, rotten, decayed or diseased and which may fall into or onto the line and trees leaning toward the line (Anon 2008, 2011). One utility company in southern California (SDG&E) specifies a "minimum clearance from ground to any transmission conductor of 500 kV be at least 40 ft (12.3 m) when the conductor is at maximum designed sag." The California Public Utilities Commission (Commission) recommends a minimum clearance of 18 inches (46 cm) must be maintained between line conductors and vegetation under normal conditions. One study concluded that in "any mountainous land, or in forest-covered land, brush-covered land, or grass-covered land," electric utilities maintain an 18 inch (46 cm) clearance around the power lines carrying less than 2.4 kV but they must still keep a 10 ft (3.3 m) clearance around poles or towers "which support a switch, fuse, transformer, lightning arrester, line junction, or dead end or corner poles" (Kim). Southern California Edison recommends that any wildland firefighter activity be minimized within 1.5 times the tallest portion of any power transmission or distribution line

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

(personal communication with T. Whitman, Edison Fire Management April 23, 2014). All of these documents specify the clearance distance required to prevent fire ignition or risk to human safety due to arcing from conductors to ground or other conductors. None address the question of how to minimize the risk of fire-induced thermal damage to the transmission or telecom support structure caused by fire burning nearby. This question is the focus of the work described here.

The Fire Sciences Laboratory (USFS) and Xcel Energy Corporation, through its Colorado operating company, have each analyzed this question. This report summarizes the findings from the two studies and presents preemptive vegetation management procedures that could minimize fire-induced thermal damage to transmission and telecommunication infrastructure in wildland fires.

Past Work

Wood poles ignite but don't mechanically fail until a substantial portion of the diameter has been burned (Smith 2011). Galvanized steel poles can fail catastrophically at temperatures above 515 °C (Sakumoto and others 2003; Smith 2011); however, fire resistant steel alloys and temperature resistant coatings can be used to extend time to failure. Generally, aluminum's tensile strength rapidly drops and elongation accelerates as temperatures exceed 200 °C (Rincon and others 2009). Aluminum stranded conductors steel reinforced (ACSR) power lines are primarily used for power transmission and distribution. Of these lines, it was found that *"when ACSR conductors are exposed or heated, their mechanical strength is reduced below the rated values of new conductors while their extension rate is increased. Moreover, the zinc layer on the steel strand may be removed and subsequent galvanic corrosion accelerated. This tends to corrode the aluminum strand in the interior layer as well as the bare steel strands. Thus any wildland fire could be an important factor in reducing the life of ACSR conductors in service"* (Kim and Morcos 2003). Porcelain insulators start to fail at 300 °C and are affected more by heating duration than heating cycle (Lee and others 2008b). Polymer insulators exhibit little-to-no fire-induced effect (Lee and others 2008a). However, deposition of smoke particles or fire retardant on either type of insulator can increase the potential for phase-to-tower faults. These and other related questions are being addressed in Canada and southern California (Anon 2008; Blackwell and others 2011).

Method

Vegetation clearing distances are dependent on three variables: the energy released from the fire, the time of exposure to that heat, and the thermal properties of the item of interest.

Two methods were used to analyze the energy release from fires: 1) the USFS approach used the Fire Dynamics Simulator (FDS) developed at the National Institute of Standards and Technology (McGrattan and others 2010) to simulate the energy release from fire and the thermal response of materials exposed to the heat, and 2) the Xcel Energy Corporation approach, which was based on simulation (using BEHAVE plus 5.0) and expert opinion.

The USFS simulations used the FDS model formulated to simulate fires in various vegetation types and compute the thermal impact on power transmission lines, telecommunication lines, and support poles/towers composed of wood, steel, aluminum, and fiberglass. This study also explored thermal impacts on telecommunication towers and ground located transformer and junction boxes. Using fire intensity data collected from actual wildland and prescribed fires (Frankman and others 2012), simulations were formulated to replicate fires in three broad types of natural fuels (grass, brush, conifer forests) for a range of topographical and weather conditions.

TheXcel Energy Corporation approach was based on simulations using BehavePlus 5.0 (Andrews and Bevins 2003) to estimate energy exposure levels for fires in various fuels. Simulations were based on 90th percentile weather. Reaction intensity and flame length were used to gauge surface fire intensity and crown bulk density and canopy cover to quantify crown fire potential. BehavePlus defines reaction intensity as the rate of energy released per area (square feet or square meters) within the flaming front. Forty to fifty percent canopy cover is the generally recognized threshold below which crown fires do not occur.

Fire intensity simulations produced from FDS were controlled by specifying a burning area, surface heat flux, flame front residence time, and rate of fire spread. Increasing the surface flux and decreasing the surface area resulted in taller and narrower flames. Conversely, decreasing the surface flux and increasing the surface area resulted in shorter and thicker flames. All simulations indicated decreasing temperature with height. Flame height was defined as the height at which the gases above the burning surface decreased below the draper point (temperature above which materials emit visible radiation –525 °C or 977 °F). Simulated flames were: grass 9 ft (3 m), brush ft (6 m), crown 98 ft (30 m). These values exceeded observations by nominally 30 to 50%, which was considered a "built in" safety factor.

For the FDS simulations all poles were simulated as vertical rectangular prisms. Virtual surface temperature sensors at different heights along the pole were used to determine when thermal failure occurred. For towers, conductors, and transformer enclosures, failure was specified when the exterior temperature exceeded a specified material failure temperature limit. In all cases the temperature limits were determined from published literature. The temperature limits varied for the two studies, the FDS limits were steel 538 °C (1000 °F), aluminum 162 °C (325 °F), wood 300 °C (572 °F) and fiberglass 350 °C (662 °F). The BehavePlus temperature limits for steel and aluminum towers were 260 °C (500 °F) and 162 °C (325 °F) respectively. In the case of fiberglass simulations in the FDS study, the temperature limit is based on approximations to published values for

mechanical elongation and ignition temperature. Published values for piloted wood ignition temperatures vary from 210 to 497 °C (410–927 °F). A median temperature was selected as the threshold 300 °C (572 °F). Any of these assumptions could be varied based on the application, surface condition of the material and heating conditions.

Results

Findings were grouped into the dominant vegetation type sustaining the fire (i.e., grass, brush, and conifer forest) (Burgan and Rothermel 1984) and by study type (i.e., FDS versus BehavePlus)

Conductors

Power transmission lines are usually bare aluminum conductor (All Aluminum Conductor, AAC) that may be steel reinforced (Aluminum Conductor Steel Reinforced or ACSR). For telecommunication lines, polymer jackets are placed around the wires to provide protection from ultraviolet (U.V.) rays, weathering, and human interference. These materials consist of high density polyethylene (PE), poly(vinyl) chloride (PVC), and cross-linked polyethylene (XLPE), the preferred material.

It has been observed that the spiral wound wires forming ACSR cable expand resulting in lower cable height, but constrict upon cooling. As stated above there is some evidence in the literature that exposure to heating from fires may compromise the zinc coating on the steel core wire of ACSR lines and may result in lessened conductor service life.

Table 1 presents the clearance distances required to prevent thermal failure based on material thermal properties. The Xcel Energy study did not consider conductors.

Utility Towers/Poles

Wood, steel, aluminum poles and towers were evaluated

Table 2 presents vegetation clearance distances for steel, aluminum and wood poles based on the FDS simulations. Table 3 presents findings from the Xcel Energy BehavePlus based approach.

Wood poles are a special case as the failure criteria is ignition rather than degradation of mechanical strength. Data reported elsewhere (Babrauskas 2003: pp. 965) indicates that when there is an impinging flame on wood, ignition occurs in 100 to 800 seconds for a heating magnitude of 20 kW/m^2. As wood poles age they develop large cracks aligned with the long axis of the poles. These cracks provide points where embers can accumulate, ignite, and sustain long term combustion that can cause failure of the pole. Thus greater pole age reduces ignition limits which in turn lead to increased vegetation clearance distances.

One advantage of wood poles is that failure does not occur catastrophically during the fire, but rather occurs after main fire event has passed and smoldering combustion in wood joints or cracks has reduced the strength of the structure through combustion of the load bearing member. Thus fire risk is highly dependent on the age of the wood and to a lesser extent on the preservative treatment type.

Telecommunication Towers

The study considered telecommunication towers (i.e., cellular network towers with guyed or free standing). Towers and guy wires are typically constructed of galvanized or stainless steel, but towers may also be constructed of fiberglass and wood. In the case of free standing towers, the clearance distances should be developed based on the limiting material. For guyed towers additional consideration should include clearance around guy wires. As a result of the fire simulations, we found that a 40 ft (12 m) vertical clearance and 13 ft (4 m) horizontal clearance was adequate for towers and guy wires. When galvanized guy wires are used, the zinc coating can melt at temperatures of 750 °F (400 °C). Once melted the corrosion protection can be compromised. Inspection of telecommunication tower sites suggests that signal cabling at the base of the tower is likely the most vulnerable point. Typically cabling in this area is encased in PVC or similar insulation, but has no specific protection from fire damage. Thus the focus from a wildland fire point-of-view should be to eliminate combustible materials below or near the signal cables and possibly install steel or aluminum cable enclosure around the cabling in this area.

Table 1—Recommended clearance distances for overhead electrical or power lines base on USFS study.

Fuel Type or Fire type	FDS based minimum distance from vegetation to overhead transmission lines (m/ft)		BehavePlus based minimum distance from vegetation to overhead transmission lines	
	Bare wire	Insulated	Pile height (m/ft)	Minimum height to line (m/ft)
Grass/litter	N/A1	N/A1	1.25/4	--[1]
Low Brush	N/A1	4.5/15	1.5/5	10/32
Tall Brush[2]	-2	-2	2/9	--[3]
30 m tall Crown Fire	5/16 horizontal 20/65 vertical	25/80 vertical		

[1] Clearance distance much less than nominal height of conductor.
[2] Tall brush was not simulated in USFS study.
[3] Should never be burned under conductors.

Table 2—Pole and Tower Vegetation Clearance Distances based on USFS Simulations.

Material	Temperature (°C/°F)	Reaction	Grass clearance (m/ft)	Brush clearance (m/ft)	30 m tall crown fire clearance (m/ft)
Wood	300/572	Wood chars indefinitely	3/9	5/16	20/65
Steel	538/1000	Steel softens and breaks	0[2]	0	5/15
Aluminum	162/325	Aluminum begins to lose strength	0[2]	0	5/15
Fiberglass	350/662	Fiberglass begins to deform	0[2]	--[3]	15/49

[1] Depends on slope and wind exposure see Table 4 for additional information.
[2] Simulations indicated little to no vegetation clearance needed.
[3] This material not simulated.

Table 3—Pole and Tower Vegetation Clearance Distances Based on Xcel Energy approach.

Fuel Model[1]	Type[2]	Reaction Intensity (kW/m^2)	Surface Flame Length (m)	Crown Fire Flame Length (m)	Aluminum Surface Fire	Wood Surf Fire	Steel Surf Fire	Aluminum Crown-Fire	Wood Crown Fire	Steel Crown Fire
Clearance Distance (m)										
8	g	194	0.6	9.2	4.0	1.5	1.2	13.2	17.2	10.5
TL5	g	322	0.9	9.8	5.2	2.2	1.5	15.1	18.5	11.4
6	g	401	2.5	10.2	5.8	4.9	1.5	16.0	21.2	11.7
11	s	466	1.2	10.8	6.2	2.8	1.8	16.9	22.8	12.6
9	g	508	1.2	9.8	6.5	2.8	1.8	16.3	18.5	11.7
5	b	602	2.8	10.5	7.1	5.5	1.8	17.5	19.4	12.3
2	b	718	2.8	10.2	7.7	5.5	2.2	17.8	21.2	12.3
SB2	s	1038	2.5	11.7	9.5	4.9	2.5	21.2	21.5	14.2
10	s	1224	2.2	12.3	10.2	4.3	2.8	22.5	22.8	15.1
12	s	1338	3.1	14.5	10.8	6.2	3.1	25.2	26.8	17.5
SB3	s	1434	3.7	12.6	11.1	7.1	3.1	23.7	23.4	15.7
SB4	s	1508	5.2	12.9	11.4	9.8	3.1	24.3	24.0	16.0
TU5	s	1677	3.1	15.4	12.0	6.2	3.4	27.4	28.3	18.8
13	s	2012	4.3	17.2	13.2	8.3	3.7	30.5	31.7	20.9
4	b	2474	8.3	15.7	14.5	15.4	4.0	30.2	28.9	19.7

[1] Fuel models based on BehavePlus system.
[2] g—grass, b—brush, c—crown fire, s—slash.

Junction Boxes

The analysis considered thin wall steel junction and transformer boxes. PVC insulated cable at the center of the box was modeled. The failure criterion was the failure temperature for the insulated cable at the center of the box. In no cases did the cable temperature reach the critical threshold prior to the failure temperature of the steel. Therefore the limiting case was the steel box temperature (Table 4).

Discussion

The study indicates that steel towers provide the greatest resistance to fire-caused failure. However when they do fail it is sudden and likely unexpected, while wood towers will survive some exposure and even outlast the fire event but can sustain longer term smoldering combustion that may ultimately result in failure after the fire event has passed. Minimum clearance for steel towers in surface and crown fires is 3 to 16 ft (1 to 5 m). The minimum clearance for wood poles exposed to surface fires of low to moderate intensity are on the order of 3 to 16 ft (1 to 5 m). For crown fires in tall brush or conifer tree canopies, wood poles and towers require clearances of 65 to 100 ft (20 to 30 m). The study indicates that aluminum towers are most similar to steel in terms of clearance distances for fires in all vegetation/fuel types. Regarding overhead power transmission or distribution lines, proximal fire can result in degradation of material strength and elongation of the line that may result in increased risk of fault (arcing) to nearby structures or ground and associated increased safety concerns. Heating may also impact expected service life. However, no observations of failure due to heating and separation of such lines have been reported or documented to date. Regarding overhead telecommunication lines, the study indicates that 16 ft (5 m) clearance in brush and an 80 ft (25 m) clearance for areas exposed to crown fires. All conditions simulated in the study indicated no risk of failure for ground located steel encased transformer enclosures.

In the absence of any other quantitative work, this paper represents the most relevant information available in the

Table 4—Junction/transformer Enclosures Vegetation Clearances Based on USFS study.

Material	Temperature (°C/F)	Threshold used to determine failure	Grass clearance (m/ft)	Brush clearance (m/ft)	Conifer fire clearance (m/ft)
Steel	300/572	Steel properties start to change	<1/3	4/13	12/39
	538/1000	Steel softens and breaks	<1/3	<1/3	7/23

open literature to date. The findings are based on limited observations, computer simulations, and broad assumptions regarding material properties, ignition thresholds, and fire descriptors; therefore they should be considered preliminary at best.

Conclusions

This paper summarizes the findings from two studies based on different analysis approaches. The studies address questions from land and utility managers about appropriate clearance distances to minimize damage to power and telecommunication infrastructure from wildland fires.

Anecdotal observations and the simulations suggest that while rare, the potential for failure of power transmission line towers due to heating from wildland fire is real. The greatest risk of failure appears to be associated with towers located on or at the top of steep slopes covered with trees that can sustain crown fire where the magnitude and duration of heating can be high enough to cause material failure. Conductors fail even more rarely than towers and their failure seems to be linked to high intensity long term fire durations (i.e., flame front residence times greater than a few minutes). The analysis suggests that telecommunication lines are susceptible to fire-caused damage, primarily due to the lower temperature limits of the insulation on the surface of the line. Telecommunication sites (i.e., cell phone system towers) present unique risks, primarily as a result of the signal and power supply lines at the base of the tower. A reduction in vegetation cover in these areas and possibly the addition of protective coverings would be beneficial.

The clearance distances presented here are based on idealized computer simulations of fire, energy release in relation to support towers and overhead lines. The results have been compared against limited observations in the field, primarily because they are difficult to obtain. Future research should focus on collecting observational date in the field. Due to the lack of data with which to verify the recommendations presented in this paper they should at this point in time be considered preliminary.

Acknowledgments

Funding for this work was provided by the Joint Fire Science Program, the U.S. Forest Service and Brigham Young University. The reviews provided by Marty Alexander and Jim Gould are appreciated.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

An Exploration of Warfighting and Firefighting Doctrine

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Abstract—*Over the past two decades, wildland fire professionals have been confronted with worsening conditions and complex challenges that cry out for change and new ways of thinking. However, change requires a framework within which people reliably translate policy into timely, effective action. Doctrine, or a body of teachings, instructions, taught principles, or positions, may represent a framework within which land management agencies and rural fire services might change to confront their challenges. A good doctrine should:*

1) establish a common purpose;
2) create a common language for expressing organizational strategy; and
3) institutionalize a common structure for action.

Some agencies have invested in doctrine, naturally turning to established experts—the military—for inspiration. However, while parallels between warfighting and firefighting seem obvious, the analogy breaks down quickly because firefighting is a civilian undertaking with no moral equivalence to war, and the mission is not paramount over the safety of individual firefighters. In short, firefighting is not warfighting. However, nine cognitive demands underlying United States Marine Corps doctrine and six principles of that doctrine appear relevant to wildland fire; and the authors of this paper explore how those nine demands and six principles might form the core of a fire operations doctrine.

Introduction

Over the past two decades, wildland fire professionals have confronted, and continue to confront, worsening conditions including the effects of climate change, severe fire behavior, escalating threats to communities, mounting costs, undesired fire effects, unacceptable threats to firefighter safety and survival, and considerable indiscriminate public scrutiny through media and post-crisis inquiries and litigation. These trends attest to the need for change and new ways of thinking to better address these rising and complex challenges. However, change requires a framework within which people reliably translate policy into timely, effective action.

Change also requires that we examine how we have done things in the past, and ask whether we have done those things as best we might. Because rural fire services and land management agencies with responsibilities for wildland fire share many of the dynamics contributing to military success on the battlefield, many of those agencies have adopted, over the past 20 years, methods that military organizations find effective in improving performance (DeGrosky and Parry, 2011.) However, much of that adoption occurred within the context of grassroots efforts to acquire promising solutions to pressing organizational needs through trial and error, rapidly prototyping them, and seeing what worked; rather than achieving optimal performance (DeGrosky and Parry, 2011.) We propose that wildland fire agencies would be wise to re-examine their approaches to important tools such as after action review (AAR) and leader's intent to better address the rising, complex challenges they face, and that doctrine may provide both the opportunity and the framework within which they may do so.

Doctrine

Doctrine is a body of teachings, instructions, taught principles, or positions in a branch of knowledge or a belief system. In organizations, one might think of doctrine more directly as what the organization chooses to teach and an element of organizational culture. The world's militaries commonly use doctrine, both written and unwritten, to describe established procedures they apply to complex operations in warfare. Often, militaries transmit their doctrine through training.

It has been suggested that doctrine represents the framework within which land management agencies and rural fire services can adapt, in order to confront their 21st century wildland fire challenges (Bosworth, 2006, p. 15). A good doctrine meets three needs; establishing common purpose; creating a common language for expressing organizational strategy; and institutionalizing a structure for action. Some land management agencies with responsibilities for wildland fire have invested in doctrine, naturally turning to visible experts—the military—for inspiration. Doctrine is

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

fundamental to war. As defined in *Warfighting*, the United States Marine Corps' handbook on strategy and operations, doctrine is "the fundamental beliefs of the Marine Corps on the subject of war, from its nature and theory to its preparation and conduct. Doctrine establishes a particular way of thinking about war and a way of fighting. It also provides a philosophy for leading Marines in combat, a mandate for professionalism, and a common language. In short, it establishes the way we practice our profession." (USMC,1997, p. 56).

Limitations of the Analogy

While on the surface parallels between warfighting and firefighting may seem apparent, the analogy between warfighting and firefighting breaks down quickly. According to Marine Corps doctrine, "War is a violent clash of interests between or among organized groups characterized by the use of military force", and goes on to say, "The essence of war is a violent struggle between two hostile, independent, and irreconcilable wills, each trying to impose itself on the other" (USMC, 1997, p. 3). Considering this definition of war, no "war on fire" exists. There is no enemy. The human effort is directed at overpowering, not other humans, but a natural force that occurs in places, at times, and with intensities that we find socially, and as a matter of public policy, unacceptable. Under those circumstances, we choose to fight fire. However, only one will exists, that of humans to impose our preference upon the forces of nature. Because, in most countries, firefighting is a civilian undertaking with no moral equivalence to war, the mission is not paramount over the safety of individual firefighters.

Why a Warfighting Doctrine Can Serve as a Template for Firefighting Doctrine

Despite the previously discussed limits on comparing a warfighting doctrine to wildland firefighting doctrine, nine demands underlying United States Marine Corps doctrine (1997)—friction, uncertainty, fluidity, disorder, complexity, the human dimension, psychological and physical forces, evolution, and art and science—appear relevant to wildland fire. The United States Marine Corps (1997) refers to these as "moral, mental, and physical characteristics and demands" (p.3); though the authors of this paper conceive of them simply as cognitive demands. In addition, six principles embodied in Marine Corps doctrine (USMC 1997)—leadership, training, professional education, philosophy of command, decision-making, and commander's intent—have potential to form the core of a doctrine for wildland fire operations. The U.S. Marine Corps (1997) uses its theory of war as the foundation for the way they prepare for and wage war (p.23) and we propose that land management agencies and rural fire services can similarly employ doctrine as their foundation for firefighting and other wildland fire operations.

Nine Underlying Cognitive Demands

Friction

Wildland fire personnel inevitably work in extremely dynamic environments in which they must make critical decisions while confronted by innumerable stresses both internal and external. Decisions in the wildland fire environment depend on complex variables such as weather, fire behavior, resource availability, and social and political forces. In this environment, decisions are necessarily situational and dependent on temporal elements which are hard to predict with a high level of confidence. Consequently, the wildland fire operating environment can often seem complex, highly variable and, perhaps, nearly unknowable.

Because of the countless dynamic factors that impinge on fire operations, those operations are often high risk, high stakes, and conducted at a high operating tempo. We may call these factors *friction*; be they internal (mental or physical), external, or self-induced. According to the U.S. Marine Corps (1997), "While we should attempt to minimize self-induced friction, the greater requirement is to *fight effectively* despite the existence of friction. One essential means to overcome friction is the will; we prevail over friction through persistent strength of mind and spirit" (p.6). From this perspective, one might argue that only through experience and consciously developed organizational capacity can fire personnel come to appreciate the complexity and friction they confront in their operating environment; develop and maintain a realistic appreciation, one might say wisdom, for both what is possible in fire operations and what is not; and summon the force of personal will necessary to overcome the friction that they can. Practically, while training should attempt to approximate the conditions of fire operations, we must realize it can never fully duplicate the level of friction of real fire operations. We have observed, in the most reliable and resilient of land management agencies and rural fire services, a growing recognition of the concept of friction; and a shift in workforce development efforts toward a focus on developing capacities for leadership, reliability, and resilience.

Uncertainty

The nature of fire and firefighting makes certainty impossible. Frequently, firefighting actions will be based on incomplete, inaccurate, and often contradictory information. All decisions are made based on assessment of what is possible and what is probable. A number of times, over the last twenty years, inquiries into firefighter accidents and fatalities have implied that events surrounding unwanted

outcomes had been assessed as improbable. However, those unexpected events have proven to be those with the greatest adverse impact. One could argue that, given that we are not opposing other humans, whose actions we can predict and whose intent we can attempt to understand, the firefighting environment may prove every bit as uncertain as war or maybe even more uncertain. Given that degree of uncertainty, wildand fire agencies would be wise to focus on preparing their personnel to consider alternative scenarios during operations.

The wildland fire operating environment, always uncertain, grows quickly and dramatically less predictable in the face of unprecedented change in biomass accumulation, climate change, persistent drought, and resulting fire behavior; population growth in the wildland-urban interface; larger fires and longer fire seasons; and hyper-politicized land management issues, among other factors. Consequently, wildland fire personnel must learn to fight fire in an environment of increasing uncertainty, which we can do by teaching fire personnel to develop simple, flexible plans. Such plans enable us to be purposefully alert to weak signals of failure, plan for contingencies, and evaluate progress against objectives, all of which may lead to adapting actions and fostering initiative among subordinates.

Learning to fight fire in an environment of increasing uncertainty will require a certain acceptance of risk, but wildland fire personnel must clearly understand that the acceptance of risk does not equate to the imprudent willingness to gamble the welfare of people or the chance of success on a single improbable event.

Fluidity

Like friction and uncertainty, fluidity represents an inherent characteristic of the nature of fire operations. Many challenges confronted by wildland fire personnel result from unique combinations of circumstances, requiring original solutions. Each condition or circumstance merges with those preceding it and those that follow; shaping and being shaped by other forces. What results is a continuous, fluctuating fabric of opportunities and threats, punctuated by unexpected events. Success in a fluid situation depends in large part on the ability to adapt to a constantly changing situation.

Like the fluidity of the warfighting environment, fluidity in the firefighting environment requires a high operational tempo that, while necessary and advantageous, proves impossible to sustain indefinitely. Consequently, the tempo of firefighting operations fluctuates from intense activity to periods during which weather and fire activity allow firefighters to make gains toward fire containment, gather information, rest and rehabilitate, or redeploy. Success in the wildland fire operating environment requires both individual and organizational alertness; individual, team, and organizational situation awareness; emergent leadership; and responses to unexpected change that prove both timely and effective.

Disorder

As it does in war and crisis, disorder represents an inherent characteristic of firefighting; an inevitable characteristic of a dynamic situation. Like the U.S. Marines, wildland fire personnel strive to impose a framework of order over the disorder of the operating environment and strive to influence the situation by establishing a command structure and a flow of intended action, while acknowledging the limits of their control. The limits of control can prove particularly true during emerging fire incidents, particularly when significant numbers of resources respond to chaotic incidents in the wildland-urban interface.

Often, these situations require firefighting forces to improvise continuously, to engage in a sort of guerrilla firefighting that may push the limits of established policy and procedure, and can get firefighters in serious trouble; physically, organizationally, and politically. However, improvisational resilience and effectiveness, in the face of a disorderly environment, is something that wildland fire organizations value, admire, encourage, and, one might argue, even need. A responsible fire operations doctrine would take advantage of firefighters' native ability to improvise, while both preparing personnel to improvise sensibly and acknowledging the limits of such improvisation by establishing sideboards, within which, firefighters operate.

Though disorder represents a common characteristic of both warfare and firefighting, it also represents an area in which the two vocations diverge. Marine Corps (1997) doctrine says, "It is precisely this natural disorder which creates the conditions ripe for exploitation by an opportunistic will" (p.11.) However, this axiom holds little relevance for wildland fire personnel. Disorder is never the friend of, or an advantage for, wildland firefighters.

On a much more relevant note, *Warfighting*, the Marine Corps doctrine, (1997) states that, "As the situation changes continuously, we are forced to improvise again and again until finally our actions have little, if any, resemblance to the original scheme" (p. 11). Like warfighting, this statement aptly describes the life cycle of plans in the wildland fire operating environment. As civilian bureaucracies, fire agencies depend on plans and place a great deal of faith in plans. One might argue that to succeed in an inherently complex and disorderly operating environment, wildand fire organizations need incident action plans, and plans for decision support, communication, safety, and medical support; and that all have enormous value in readying an operation. However, plans also present a pitfall. Plans offer starting points that require constant re-evaluation. The problem with plans is that they shape what we actually see, set our expectations, and can lead to confirmation bias - the tendency to search for information that confirms our expectations, correct or otherwise. The inherent disorder, fluidity, and uncertainty of the wildland fire operating environment demand that planners of wildland fire operations acknowledge uncertainty and state, right up front, that their plan is a living document that will require adaptation to

changes arising during the shift; thereby provoking firefighters to think about what might change and how they might effectively respond.

Complexity

Like war, firefighting represents a complex undertaking, often engaged in a complex operating environment, and requiring a compound organizational structure in which each organizational element must adapt to local conditions and requirements while working cooperatively with other elements to accomplish common goals and a cohesive effort. In addition, a complex firefighting operation involves many independent but interrelated decisions and actions being undertaken simultaneously throughout the organization. Like military operations, efforts to fully centralize command, control and decision-making prove impractical in an operating environment in which events, and response to events, are inherently complex and distributed. Consequently, a command culture that distributes decision-making to people within the organization who share leader's intent, mission clarity, and comfort with their assigned tasks, seems most appropriate. In this inherently complex environment, wildland fire personnel often find that they confront added complexity brought about by conflict over competing fire suppression, land management, and ecological objectives that are not easily resolved; as well as conflicting social wants and needs and frequent difficulty communicating with, and engaging, citizens during the decision-making process.

Historically, land management agencies and rural fire services became very efficient and effective at suppressing fire in a number of fire adapted ecosystems worldwide; inadvertently creating long-term ecological and biodiversity issues. Given the accumulating biomass in fire adapted ecosystems, coupled with climate change, where the natural role of fire has been disrupted, wildland fire personnel increasingly confront severe fire behavior exceeding what they had traditionally considered initial attack thresholds. More escaped, unwanted fires present the potential for more damage—to property, infrastructure and the environment—increased water yield and degraded water quality, as well as negative impacts on biodiversity.

The Human Dimension

Just as in warfare, the effort, danger, fear, and exhaustion have a great impact on people who fight fire. While individual stress tolerance determines to what extent individuals are affected, human factors, including communication, workplace safety, human error, human capability, human behavior, and human perception significantly shape human performance and organizational effectiveness in the wildland fire operating environment. Because fire operations are a human undertaking, the human dimension proves centrally important to success and effectiveness in fire operations; it is the human dimension that infuses fire operations with intangible psychological and emotional friction. Fire operations are shaped by human nature and are subject to the complexities, inconsistencies, and peculiarities which characterize human behavior. Despite this fact, most fire management agencies invest much more heavily in technology and equipment than they do in workforce development, including improving their capacities for leadership.

Psychological and Physical Forces

Like warfighting, firefighting is characterized by the interaction of both psychological and physical forces. The physical characteristics of firefighting are generally easily seen and understood; the psychological characteristics less so. However, one might argue that psychological and emotional forces may, on occasion, exert greater influence on the nature and outcome of fire operations than do physical forces. While wildland fire agencies rarely systematically prepare their personnel for the psychological and emotional impact of their decisions and actions, wildland fire personnel are frequently thrust into complex social situations, for example, winning the hearts and minds of people being impacted by a fire, deciding what they can and cannot save, choosing one community over another, confronting line of duty deaths, and making choices about competing resource values. While the U.S. Marine Corps doctrine treats physical and psychological forces of warfighting as a characteristic or demand of warfighting separate from the human dimension, we regard the psychological characteristics of firefighting as integral to the human dimension and vice versa.

Evolution

The challenges of wildland fire are both timeless and ever changing. One need only examine the changing nature of fire management in Victoria, Australia, to understand both the timeless and rapidly transforming nature of both wildland fire and firefighting.

In Victoria, large, damaging bushfires and changing social values have transformed the fire management approach. Following devastating fires in 1939, many independent fire brigades merged into a single agency to facilitate fire coordinated suppression. It was at this time that Australia initiated its robust program of forest and fire research, emerging as a leader in planned burning. Again, following a series of severe fires in 1983, the State of Victoria turned its attention to better organized extended attack, importing the Incident Command System, and adapting it to the Australian context. Coincidentally, it was around this time that Victoria's citizens began to show increased concern about rare and threatened species, leading to reductions in the size of many planned burn units. In combination, less burning and more effective suppression have allowed a significantly increased fuel load across the Victorian landscape. The resulting fuel load, combined with rising average temperatures and decadal drought have created conditions facilitating landscape scale fires that land management agencies and rural fire services have witnessed in Victoria since 2000, including the devastating and traumatic Black Saturday events of 2009. In response,

separate fire services and land management agencies with fire responsibilities have moved, not only toward stronger cooperation and interoperability on fire suppression, but toward more holistic, integrated planning and action including a return to employing fire in land management activities. In addition, both land management agencies and rural fire services recognize that communities in and around fire-adapted landscapes represent an integral part of any effective solution to wildland fire problems and must be genuinely consulted and engaged in, rather than simply informed of, fire management planning.

We propose that given changes in climate, society, and fire-scale, this evolutionary arc will continue, not only into the foreseeable future, but over increasingly large swaths of the world. Consequently, wildland fire professionals, and the agencies they serve, will continue to confront worsening conditions including climate change, severe fire behavior, ever-increasing threats to communities, swelling costs, undesired fire effects, intolerable threats to firefighter safety and survival as well as often indiscriminate public scrutiny through both media and post crisis inquiries and litigation. The envisioned trends attest to the need for significant changes to thinking and approaches, both institutional and individual that have served wildland fire agencies for decades. Change of the magnitude envisioned requires a framework within which people can reliably translate policy into timely, effective action; and the authors of this paper contend that doctrine represents the framework within which land management agencies and rural fire services can bring about the change necessary to confront their modern wildland fire challenges.

Art and Science

Like waging war, fighting fire represents a blend of both *art,* a skill acquired by experience, study, or observation and an occupation requiring knowledge or skill; and *science*, a body of knowledge that can be rationally explained and reliably applied. The science of firefighting includes topics such as understanding fire behavior and meteorology or the use of technology. However, science cannot describe the totality of firefighting, given the human element and the mysteries of human performance as well as the many unpredictable environmental factors that wildland fire personnel confront. For example, historians credit the ancient Chinese military general, strategist and philosopher Sun Tzu as saying, "Invincibility lies in the defense; the possibility of victory in the attack. One defends when his strength is inadequate; he attacks when it is abundant" (as translated by Cleary, 1988, p. 86); a lesson, perhaps, that the global wildland fire community still must learn and apply, both as a matter of policy and individual behavior. No amount of science can tell a firefighter either to engage the fire or disengage from it; this is a matter of professional judgement and wisdom. Marine Corps (1989) doctrine states that, "Our theory of war will in turn be the foundation for the way we prepare for and wage war." The authors contend that a theory of fire operations (doctrine) must also serve as the foundation for preparation to fight fire as well as the conduct of firefighting. Such a doctrine might include the idea that firefighting does not exist for its own sake, but as an extension of policy with the aim that all fire operations must serve policy.

Six Principles of Marine Corps Doctrine Relevant to Wildland Fire

Leadership

Marine Corps doctrine (1997) demands professional competence among its leaders. According to that doctrine, "As military professionals charged with the defense of the nation, Marine leaders must be true experts in the conduct of war" (p. 56). Similarly, we contend that an effective wildland firefighting doctrine must rest, first and foremost, on a foundation of both technical and leadership competence born of effective workforce development. As Marines represent a corps of professionals charged with national defense, wildland fire personnel serve people, communities, and nations. People expect wildland firefighters to protect them, their property and their natural resources from the ravages of unwanted wildfire; and, in today's operating environment, achieving those expectations requires mastery of a suite of complex technical, conceptual, and human relations skills.

Land management agencies and rural fire services routinely invest significant resources to develop the technical skills of their personnel. However, they often invest far less on promoting development of skills associated with leadership, teamwork, adaptiveness, and resilience. Leadership development in a wildland fire agency too often means voluntary participation in limited, often highly competitive, development opportunities. An agency desiring to adapt to the challenges of 21st century fire, must possess a capacity for systematic and widespread leadership development with a focus on performance reliability and both individual and organizational resilience, particularly in high-risk operating environments. Success will require substantial and sustained investment in leadership development that reaches broadly and deeply into workforces, emphasizing leadership development interventions that rest on a credible research foundation.

Leadership is a relationship: a phenomenon that occurs between people and an act in which people engage together. Consequently, the ability to foster and maintain effective working relationships represents a key skill of leadership. Leaders generate leadership, and leaders in the wildland fire agencies must teach their protégés the importance that trusting interpersonal relationships play in effective wildland fire operations. Such relationships are more important than written agreements and contracts. For example, during the 2006/2007 and 2009 fire seasons in Victoria, Australia, both interstate and international agencies provided substantial support based on trust relationships, even absent current agreements.

According to t'Hart (2010) achieving fully developed collaboration and partnership can prove difficult in emergency management, and not enough emphasis is given to collaboration. Traditionally, wildland fire agencies rely on joint exercises to foster collaboration, but neglect other avenues of network development that may, ultimately, prove more effective in nurturing interpersonal trust between key representatives of cooperating agencies. According to t'Hart (2010) such trust represents a crucial asset during major emergencies, providing "short cuts" and informal coordination mechanisms. However, it is inherently vulnerable because it relies on key individuals. To overcome these shortcomings, t'Hart (2010) proposes the following:

- The articulation of a *set of common purposes*, based on a deep-rooted awareness of interdependency among the parties involved;
- An *inclusive membership* relative to the purposes or tasks at hand;
- An agreed upon *authoritative decision-making and conflict resolution structure* at the level of the network as a whole;
- Ways of *allocating resources that provide incentives to organizations to take collaboration seriously*, by defining, funding and evaluating network-level projects and outcomes to supplement and partly replace existing funding/accountability streams of individual organizations; and
- A *self-sustaining culture of collaboration* by means of network-level venues for dialogue, socialisation and training, staff exchanges, symbols/artefacts and external 'branding' of the network.

Training (Learning and Development)

Marine Corps doctrine (1989) regards the purpose of all training to be the development of forces that can win in combat, and training as the key to combat effectiveness. Consequently, training represents the focus of Marine Corps effort in peacetime. According to their doctrine, basic, individual, and common skills provide an essential foundation of Marine Crops effectiveness, but unit skills and combined effort, of course, prove extremely important. Similarly, faced with the challenges of fire in the 21st century, both civilian rural fire services and land management agencies with fire responsibilities must invest significantly in workforce development in order to succeed in the current operating environment, as well as in the future operating environment that the authors of this paper envision.

For many land management agencies and rural fire services, workforce development means training, but for many wildland fire agencies it is past time that they transform their training. It is not uncommon to hear agency personnel openly disparage their standard courses in the most unflattering terms. This is particularly true of training participants from the Generation Y, or Millennials. These personnel, in their early 20s to mid-30s, are digital natives who have been interacting with digital technology since an early age. In 2014, wildland fire personnel are attending lecture-and-workbook training while their counterparts in private industry benefit from state-of-the-art gamifiction out of the reach of many fire agencies who face grim fiscal realities—budget cuts, travel caps, and staffing reductions that are crippling existing training systems.

However, we cannot stop developing our workforces. The questions are:

- How do we effectively prepare people for dangerous work, in high-risk environments where leadership, decision-making, and risk management reign supreme?
- How do we do that when it will just keep getting harder and harder to get people to quality training and other development opportunities?

People responsible for training and workforce development in civilian land management agencies and rural fire services should carefully consider four elements of the Marine Corps training ethos:

- Individual managers in the organization must allot subordinates sufficient time and freedom necessary to conduct the training necessary for both individuals and the unit to achieve proficiency; and that higher level demands do not deny subordinates adequate opportunity for training.
- Over-centralization and over-supervision do not deny autonomous training that allows leaders the opportunity to train their people as they see fit. Senior management establish goals and standards, communicate intent, and establish focus, but do not dictate the mechanisms for delivering training.
- Training should reflect practical, challenging, and progressive goals beginning with individual and small unit skills and culminating in comprehensive exercises involving actual resources and approximating mission conditions as much as possible.
- All effective training must conclude with a high quality after-action-review (AAR) focused on why participants made the decisions and took the actions that they did, and the outcomes of those decisions and actions.

While Marine Corps doctrine (1997) focuses on training, the authors suggest that training alone will not deliver appropriate results. For example, the Victorian fire agencies have adopted the 10:20:70 model for capability development (Lombardo, M. M. and Eichinger 1987; Slijepcevic and others, 2012.) The 70:20:10 model described by Lombardo and Eichinger (1987) explained the learning process as:

- 10% is being learned from courses that provide for example an underpinning knowledge and tools for a leadership toolbox;
- 20% is being learned from others which includes peer feedback, coaching, mentoring and lessons learned; and
- 70% is being learned on the job through practice which also includes exercises (problem solving).

Figure 1—Victorian Model for Capability Development.

Professional Education

By Marine Corps doctrine, the intent of a professional military education is to develop creative and thoughtful leaders in a continuous process of development in which, at each stage of a person's career, they prepare for the next stage (Warfighting, 1997, p. 64). According to U.S. Marine Corps doctrine (1989), "A leader's career, from the initial stages of leadership training, should be viewed as a continuous, progressive process of development" (p. 64). Similarly, the effective 21st century wildland fire agency will invest heavily in the professional education of its career leaders. The U.S. Marine Corps (1997) envisions its professional development responsibilities residing in three organizational tiers: the education establishment, the commander, and the individual. The authors envision a similar three-tiered approach to the professional development of fire career personnel. In the first tier, the education establishment includes schools, both agency run and otherwise, providing formal education in the art and science of fire management. In the second tier, an effective fire management agency would foster an organizational culture in which individual leaders accepted the professional development of their subordinates as a primary responsibility of their own leadership. Finally, in the third tier, individuals must take responsibility for, and actively pursue, their own professional development.

Philosophy of Command

Marine Corps doctrine maintains that their philosophy of command must support the way in which the Marine Corps fights. For the Marine Corps, that means decentralized command, given their desired operating tempo, and their need to cope with the uncertainty, disorder, and fluidity of combat. Given the aforementioned relevance of operating tempo, uncertainty, disorder and fluidity to the wildland fire operating environment, the authors contend that a similar decentralized command philosophy, one that emphasizes individual initiative and accountability and enables subordinate leaders, present at or near the point of decision, to make decisions on their own initiative given established clear leader's intent, has merit in the wildland fire operating environment. By doing so, a wildland fire agency capitalizes on the professional competence among its informal leaders, generates leadership and accountability within the organization, and fosters a high level of collaborative teamwork. In addition, decentralized decision-making enables emergent leadership; enabling timely and effective responses to unexpected changes by competent, well-prepared and trustworthy personnel. In the final analysis, deference to expertise, leadership development, accountability, and teamwork facilitate performance by the organization that proves both reliable and resilient. One might argue that ICS and AIMS currently offer such a command philosophy, but neither takes full advantage of command decentralization in their application.

Like warfighting, firefighting constitutes a human undertaking, one in which no degree of technology can diminish the human dimension of command and, like the U.S. Marine Corps' philosophy of command, an effective philosophy of command in wildland firefighting must focus on human factors rather than either equipment or procedures. While communications technology and well developed team procedures can enhance the quality of fireground command, the authors contend that agencies must not attempt to use or to replace elements of human interaction in command relationships. In fact, the authors contend that not only must fireground command accommodate the human element, but that commanders in the modern wildland fire operating environment produce reliable performance and organizational

resilience when they encourage, foster, and model effective two-way communication, interpersonal interaction, and interdependence, as well as deference to expertise (Black and McBride, 2014). Clear leaders' intent and unity of command must remain at the heart of the wildland fire command philosophy.

Decision-Making

Decision-making, both good and bad, affects every aspect of our lives, but is especially true for leaders, and vital for leaders in the fire service. Good decisions can make the difference between success and failure of an organization. Moreover, poor decisions can lead to all sorts of negative consequences; and in high-risk environments, those negative consequences include injury, death and dramatic property loss. Given the gravity of decision-making in the wildland fire operating environment, rural fire services and land management agencies with fire responsibilities have an obligation to prepare their personnel, both as individuals and as teams of people, to make sound and timely decisions. Wildland fire agencies can best prepare their personnel for decision-making by developing their capacities to understand decision-making processes and to develop both the skill and the confidence to effectively engage those processes.

Leader's Intent

In a complex and dynamic operating environment in which command is decentralized, leaders in closest proximity to a problem or decision point must adapt plans and exercise initiative in order to accomplish desired objectives in the absence of direction from superiors; particularly when events render planned actions invalid. In both authors' countries, wildland fire agencies have adopted the concept of leader's intent, often described as a clear, concise statement of task, purpose, and desired end-state. For example, in the U.S., the publication Leading in the Wildland Fire Service (NWCG, 2007) declares that "translating vision *into clear leader's intent* is at the heart of our command philosophy" (p. 15). This conception of leader's intent derives from an element of military command philosophy called commander's intent. In fact, Ziegler and DeGrosky (2008) described a clear U.S. Marine Corps influence in this conception of leader's intent.

Unfortunately, reflecting on its military origins, and an interesting historical bending of the original commander's intent concept by the U.S. Military (Ziegler and DeGrosky, 2008), the practice of leader's intent in wildland fire agencies tends to translate into an individual state and a one-way, transmission model of communication. As Shattuck (2000) pointed out 'there is no discussion of social norms, expectations, trust, or intimate personal knowledge of subordinates' in the US army's uptake of the concept (p. 67). Instead, the primary emphasis is on 'structure and content', or communicating the ends to be achieved, without recognizing the importance of creating what the Germans called 'imparting presence' (p. 71). By privileging commander's intent, the army lopped off this equally important concept (Shattuck, 2000). Shattuck interpreted this concept as commanders imparting to subordinates 'a sense of them' (p. 71) by establishing a firm yet just command climate and by explaining the reasoning process they used to arrive at their decisions. On the latter point, he explained that 'frequent interaction—formal and informal, professional and social—will provide subordinates additional opportunities to learn how their commanders think' (p. 72).

Shattuck (2000) criticized the tendency of the army to primarily emphasize the initial message. He explained that when the battlefield situation changes, the context in which the 'intent' statement was originally interpreted also changes, and therefore the intent message itself must also be reinterpreted. But, he complained, soldiers tend to receive too little training and coaching in interpreting and implementing intent. Wildland fire personnel, like Shattuck's soldiers, receive too little training and coaching on how to implement their leader's intent, and too many leaders in wildland fire agencies are currently entrenched in a less-than-effective model of leader's intent. We propose an immediate exploration of an alternate concept of leader's intent that prepares emerging leaders in wildland fire agencies to understand the subordinate's critical role in constructing the meaning of intent.

Conclusion

Change requires a framework within which people reliably translate policy into timely, effective action. We contend that a just, ethical, and effective doctrine for wildland firefighting would stress that firefighting is a civilian undertaking with no moral equivalence to war, and that the mission is not paramount over the safety of individual firefighters.

However, despite limits on drawing analogies between a warfighting doctrine and a wildland firefighting doctrine, the nine cognitive demands described in this paper—friction,uncertainty, fluidity, disorder, complexity, the human dimension, psychological and physical forces, evolution, and art and science—underlying United States Marine Corps doctrine prove as relevant to the wildland firefighting environment as they do to the warfighting environment. Like war, firefighting represents a complex undertaking, typically engaged in a complex operating environment, and requiring a compound organizational structure in which each organizational element must adapt to local conditions and requirements while working cooperatively with other elements to accomplish common goals and a cohesive effort. In addition, a complex firefighting operation involves many independent but interrelated decisions and actions being undertaken simultaneously throughout the organization. Consequently, when contextualized to the wildland fire operating environment, six principles embodied in Marine Corps doctrine, leadership, training, professional education, philosophy of command, decision-making, and commander's intent provide a template that rural fire services and land management agencies with responsibilities for wildland fire can use to form the core of a wildland fire operations doctrine.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

How Fuel Treatment Types, Locations, and Amounts Impact Landscape-Scale Fire Behavior and Carbon Dynamics

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Abstract—*When managing for fire across a large landscape, the types of fuel treatments, the locations of treatments, and the percentage of the landscape being treated should all interact to impact not only potential fire size, but also carbon dynamics across that landscape. To investigate these interactions, we utilized a forest growth model (FVS-FFE) and fire simulation software (FlamMap, Randig), integrated through GIS software (ArcMap9.3), to quantify the impacts that varied landscape-scale fuel treatments have on burn probability, fire size, short-term carbon loss, and long-term carbon storage. Thirteen fuel treatment scenarios were simulated on a 42,000 hectare landscape in the Klamath Mountains of northern California including one untreated, three proposed by the U.S. Forest Service, and nine that were spatially optimized and developed within the Treatment Optimization Model in FlamMap. The nine spatially optimized scenarios varied by treatment type (prescribed fire, mastication, and thin + burn) and landscape intensity (10 percent, 20 percent, and 30 percent of the landscape treated). Each treatment scenario was subjected to 10,000 simulated wildfires with random ignition locations in order to develop burn probability and mean fire size for each scenario, which subsequently impacted long-term carbon storage projections.*

Our results show that both fire behavior metrics (mean burn probability, fire size) and carbon dynamics (short-term carbon loss, long-term carbon storage) are indeed highly dependent upon the treatment type, spatial arrangement, and proportion of the landscape treated. The thin + fire treatment at 20 percent treatment intensity most reduced fire size while prescribed fire at 10 percent landscape intensity least reduced fire size and did not differ from the untreated landscape. However, prescribed fire treatments resulted in the greatest onsite long-term carbon storage across the landscape after 50 years. Treating 20 percent of the landscape appears to be the optimal treatment landscape intensity for both reducing fire size and for maximizing long-term onsite carbon storage; treating beyond 20 percent of the landscape produces diminishing returns in both parameters.

Introduction

Various fuel management strategies can be employed to reduce the intensity and subsequent severity of wildland fires in forest ecosystems (Stephens 1998; Stratton 2004; Agee and Skinner 2005; Schmidt and others 2008). A large body of work on stand-scale fuel treatments exists that demonstrate their ability to reduce fuel loading (Sackett 1975; Stephens 1998; Vaillant and others 2009; Large 2010; Hamma 2011), limit initiation of crown fires (Martinson and Omi 2003; Murphy and others 2007; Vaillant and others 2009), and slow rates of spread (Stephens 1998; Vaillant and others 2009).

However, while critical to an individual stand's resiliency to fire, isolated fuel treatments may have little impact on the spread of fire across the landscape (Finney and others 2005). Therefore, land managers across the western US are focusing on landscape-scale vegetation management strategies to alter fuel conditions and subsequently protect both the natural and the built environment (Sexton 2006; Weatherspoon and Skinner 2006; Reinhardt and others 2008; Collins and others 2010). To date, landscape-level fire dynamics has received considerably less scientific inquiry than stand-level studies. Existing work, however, suggests that the treatment type, spatial arrangement, and landscape intensity (percentage of the landscape being treated) of various treatment strategies can impact the size and severity of wildfires (Stratton 2004; Ager and others 2007; Finney and others 2007; Schmidt and others 2008; Ager and others, 2010b; Moghaddas and others 2010).

In contrast to the benefits fuel treatments provide, they can also adversely impact various ecosystem services, including carbon sequestration and storage (Tiedemann and others 2000; Dicus and others 2009), which are of growing concern in the fire management community because of the potential to influence global climates and the potential financial implications of developing carbon markets (Westerling and others 2006; Hamilton and others 2007; Mignone and others 2009). Stand-level simulations suggest that alterations in short-term carbon emissions and long-term carbon storage do occur following fuel treatments (Hurteau and North 2009; Large 2010; Reinhardt and Holsinger 2010; Hamma 2011; North and Hurteau 2011), with the effects dependent upon the ecosystem and treatment type (Reinhardt and others 2010; Wiedinmyer and Hurteau 2010; Hurteau and others 2011).

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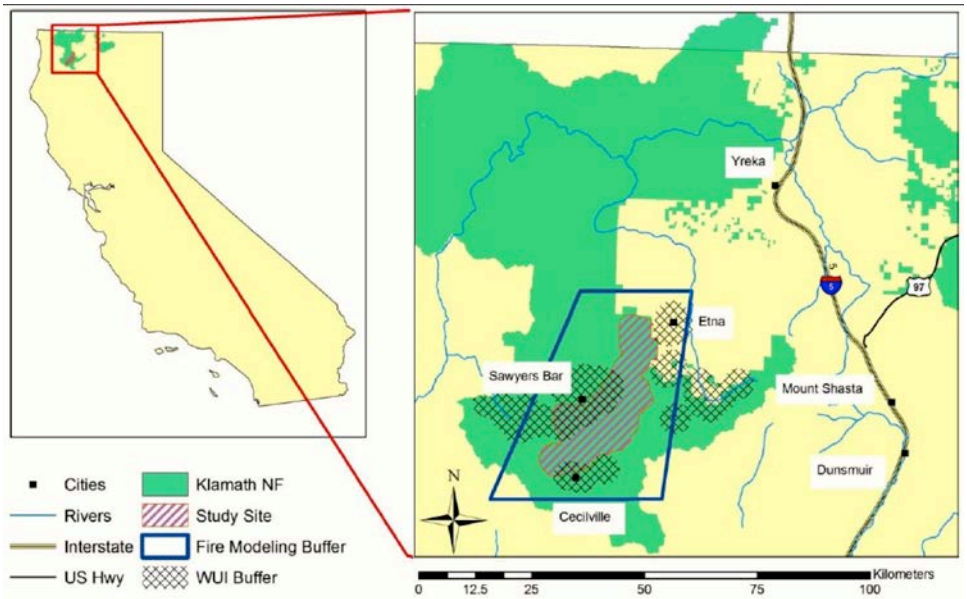

Figure 1—Location of the study site, which included the Eddy Gulch Late Seral Reserve on the Klamath National Forest and a larger buffer used in fire modeling simulations.

In this study, we simulated how various landscape-level fuel treatment strategies simultaneously impacted both fire size and carbon dynamics on a fire-prone 42,000 ha landscape in the Klamath Mountains of northern California that consisted primarily of montane mixed-conifer forest. Specifically, we compared the burn probability, fire size, onsite short-term carbon loss (after 5 years) and long-term onsite carbon storage (after 50 years) on an untreated landscape to three fuel treatment scenarios proposed in a Klamath National Forest management plan and to nine spatially optimized treatment scenarios that varied in treatment type, spatial arrangement, and landscape intensity.

Methods

Study Site

The study site was a 42,000-hectare area on the Salmon River Ranger District of the Klamath National Forest in Siskiyou County, California (123 4.72 W 41 1554 N), which consisted of the Eddy Gulch Late Successional Reserve (LSR), which was implemented to protect critical habitat and adjacent residential communities (USDA Forest Service and DOI Bureau of Land Management 1994), and also a buffer around the LSR (Figure 1). Elevation ranged from approximately 300 m to 2,500 m, with steep terrain crossed by numerous ridges and watercourses (USDA Forest Service 2010). Climate in the area is Mediterranean, with hot, dry summers and cold, wet winters.

Vegetation consists largely of multi-layered, multi-aged forests. Douglas-fir (*Pseudotsuga menziesii* Mirb.) and ponderosa pine (*Pinus ponderosa* C. Lawson) dominate at lower elevations. Douglas-fir, white fir (*Abies concolor* Gord. and Glend.), and red fir (*Abies magnifica* A. Murray) dominate at higher elevations where moisture is more abundant (Taylor and Skinner 1998).

Historic mean fire return intervals were ~12 years, but due to fire exclusion in the previous century, fire return intervals have increased to an average of ~22 years (Taylor and Skinner 1998; Taylor and Skinner 2003). At present, as much as 73 percent of the area within the LSR is at risk for passive or active crown fire activity under extreme weather conditions (USDA Forest Service 2010).

Treatment Scenarios and Modeling Procedure

We assessed 13 fuel treatment scenarios, including an untreated scenario, three scenarios derived from a Forest Service proposal to treat fuels within the LSR (U.S. Forest Service 2010; hereafter KNF-proposed treatments), and nine spatially optimized treatment scenarios that varied by treatment type, spatial arrangement, and landscape intensity (percent of the total landscape treated). Figure 2 depicts the overall procedure used to generate the various GIS landscapes, fire outputs, and carbon outputs. A simplified methodology is described here; a more detailed methodology for this project is found in Osborne (2011).

Forest inventory and analysis (FIA) data for the Klamath National Forest were obtained from the USFS Region 5 Remote Sensing Lab (USDA Forest Service 2009), which also provided a digital elevation model, fuel model data, and GIS vegetation attribute layers (canopy base height, crown bulk density, crown height, and height to live crown). We used these data to build an ArcFuels project (Vaillant and others 2013) within ESRI's ArcGIS software (V. 9.3.1; ESRI 2009). We then used the ArcFuels project to build a GIS landscape that served as our untreated control landscape as well as the initial point for developing landscapes for the 12 other treatment scenarios.

The KNF-proposed treatments for the LSR were composed of mechanical units and prescribed fire units (Figure 3; USDA Forest Service 2010). The mechanical units, which included mastication treatments and thin + burn treatments along ridge tops, covered 9 percent of the study site. The

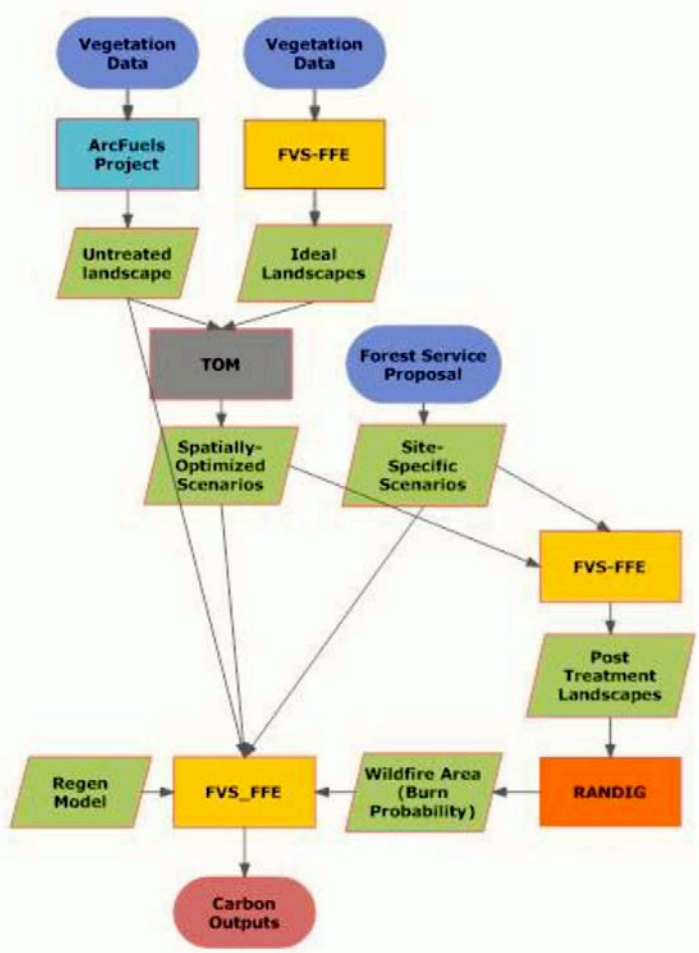

Figure 2—General flow chart representing the major inputs and processes used to generate fire size and carbon outputs.

prescribed fire units, located primarily on south and southwest aspects, covered 17 percent of the study site. The total design, which combined all mechanical and prescribed fire units, covered 26 percent of the study site.

We also created nine spatially optimized fuel treatment scenarios utilizing the Treatment Optimization Model (TOM) within FlamMap (v 3.0) (Finney 2006; Finney 2007). These nine scenarios included three treatment types (prescribed fire, mastication, and thin + burn), each at 3 landscape intensities (10 percent, 20 percent, and 30 percent of the landscape treated; Figure 4). The percentage of area treated represented logical increases, which closely matched the percentage of the landscape treated in each of the KNF-proposed treatment scenarios, and which also mirrored those used in previous work with landscape fuel treatment arrangements on the Klamath National Forest (Schmidt and others 2008).

For the spatially optimized treatments, we generated our "ideal" landscapes for TOM with the FVS-Fire and Fuels Extension (FFE; Inland California variant) (Rebain 2010) within ArcFuels (Vaillant and others 2013) so as to implement treatment vegetation alterations in all stands within our study site. We did this for each of the three treatment types (prescribed fire, mastication, and thin + burn), resulting in three ideal landscapes. We assigned fuel models to each stand based on pre-treatment conditions and expected post-treatment conditions for each type of treatment (Fites-Kaufman and others 2007), basing our custom mastication fuel model on an average of slash fuel models as described by Knapp and others (2008).

We used FireFamilyPlus (v 4.1) (Rocky Mountain Research Station Fire Lab and Systems for Environmental Management 2002) and historical fire weather data from the Blue Ridge Remote Automated Weather Station (RAWS) to develop our fuel moisture parameters and fire weather conditions (Table 1). Moderate values for wind and temperature were based on 20-year (1984–2004) RAWS data for May through October, discussions with Klamath National Forest fire management staff, and values used by Large (2010), whose work was conducted in the Klamath Mountains. The fuel moisture and weather parameter values used for prescribed fire simulations approximate the 50th percentile level, which previous work has used to represent moderate fire behavior (Ager and others 2010b; Large 2010). Given constant wind and moisture parameters, the TOM used a minimum travel time algorithm to calculated arrival time contours and the paths where fire moves fastest across the landscape (Finney 2002; Finney 2004; Finney 2006), and then placed treatments to optimally reduce the overall landscape ROS given the area treated (Finney 2007).

The FlamMap treatment location outputs created with the TOM were converted into ArcGIS raster files within ArcFuels. We then used these raster layers to assign treatments to stands based on the percentage of stands covered by treatment cells when we overlaid the stand polygon layer with a treatment raster.

Figure 3—Landscape fuel treatment scenarios proposed in a management plan at the study site.

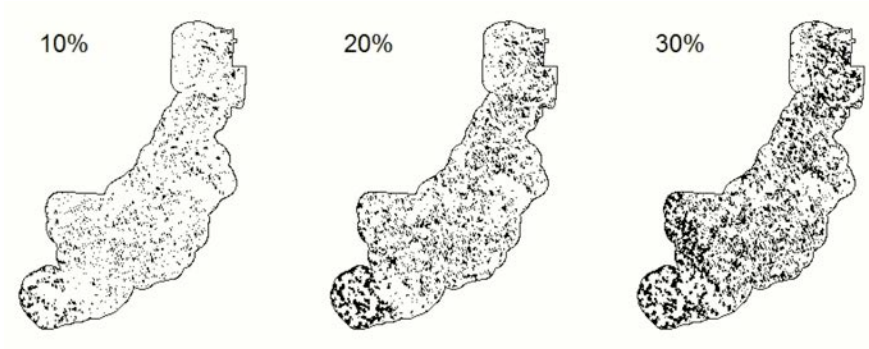

Figure 4—Example of placement of spatially optimized treatments with increasing landscape intensity, which was determined by the Treatment Optimization Model in FlamMap. 3.0. The thin + burn fuel treatment is shown.

Table 1. Weather Scenario.

Weather Parameter		Rx Fire (50th percentile)	Wildfire (97th percentile)
	Windspeed (km hr^{-1})	16.1	42.3
	Wind Direction (Azimuth)	238	238
	Temperature (C^o)	21.1	32.2
Fuel Moisture (%)	1-hr (<.64cm)	4	2
	10-hr (0.64-2.54cm)	5	3
	100-hr (2.54-7.62cm)	10	5
	1000-hr (>7.62cm)	11	8
	Duff	30	10
	Live Woody	77	70
	Foliage	100	80

We placed the untreated landscape and each of the post-treatment landscapes into Randig (Mark Finney, U.S. Forest Service Rocky Mountain Research Station), a command line version of FlamMap to determine burn probability for each pixel (raster cell) of the study site for a given scenario, which was calculated as the number of times the pixel burned divided by the number of ignitions in the simulation (10,000). The weather conditions for the Randig simulations were at the 97th percentile. We used burn periods ranging from 600 to 1100 minutes for each of the 10,000 random ignitions per scenario in order to create a distribution of fire sizes that mirrored an observed distribution of extreme growth events on the Klamath National Forest.

To incorporate future wildfire into the long-term FVS-FFE simulations, we used burn probability to represent areas with the highest chance of experiencing wildfire post-treatment. Stands with a mean burn probability over 0.0067 were assigned wildfires 5 years post-treatment in subsequent long-term carbon simulations in FVS-FFE. We chose this threshold based on the percentage of the untreated landscape (33.86 percent) that received a wildfire assignment. We chose wildfires at 5 years post-treatment to account for the range in which we expected treatments to maintain maximum effectiveness before needing retreatment.

After assigning wildfire locations and creating a tree regeneration model, we completed a separate FVS-FFE simulation for each of the 13 scenarios (1 untreated, 3 KNF-proposed, and 9 spatially optimized designs). These FVS-FFE simulations used the same weather conditions for prescribed fire (50th percentile) and wildfire (97th percentile) as previous simulations.

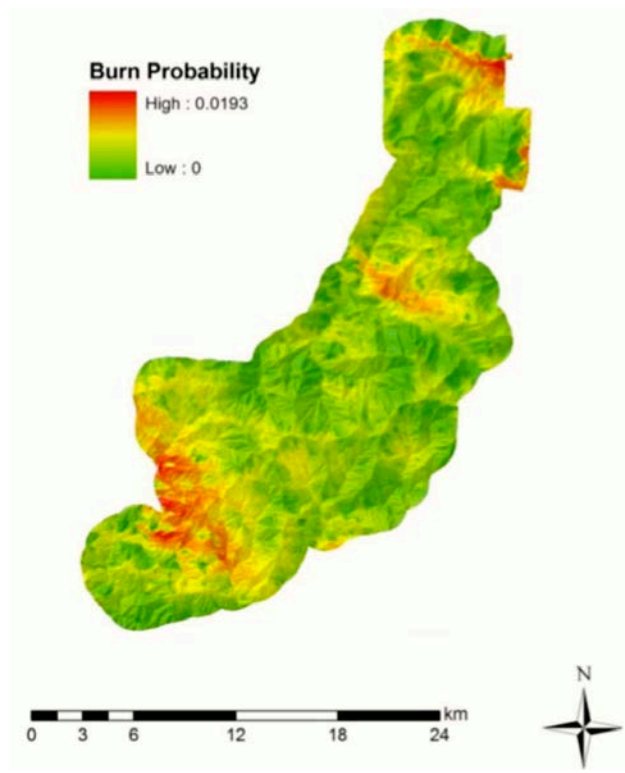

Figure 5—Burn probability (number of times a pixel burned /number of ignitions) in the untreated landscape. Burn probability was also calculated for all treatment scenarios.

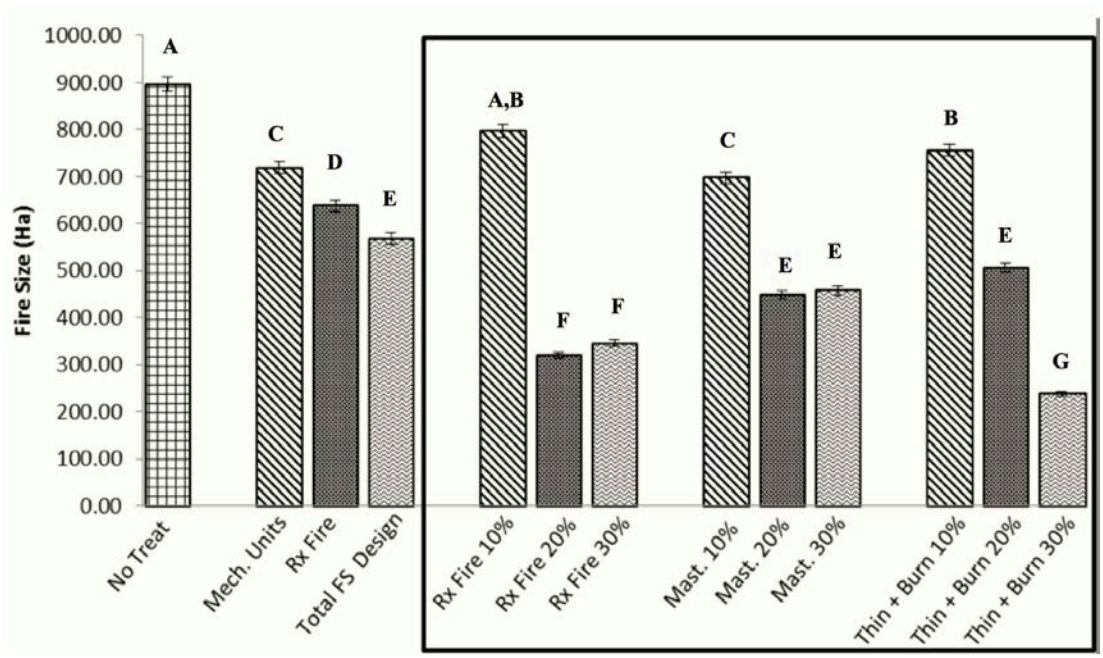

Figure 6—Mean fire size (at 5 years) for each treatment scenario. Scenarios that share a letter have mean values that did not significantly differ from one another at alpha = 0.05. Treatments inside the solid box are spatially optimized; treatments outside the box are treatments proposed in a management plan at the study site.

After completing the 13 FVS-FFE simulations, we used the FFE carbon report to compile short-term carbon loss from fuel treatments, short-term carbon loss from wildfire (5 years post-treatment), and long-term carbon storage (50 years post-treatment) for each treatment scenario. We considered the onsite total stand carbon as the sum of the following carbon pools: aboveground live and dead, belowground live and dead, forest floor (litter and duff), herbs, shrubs, and dead/down woody debris. The carbon reports also include carbon emissions due to fire (it did not distinguish between prescribed fire and wildfire), which we grouped with harvested carbon as the carbon lost from our site.

Statistical analysis for mean burn probability and carbon outputs were precluded because the outputs represent the entire population. We statistically analyzed the mean fire size using a Kruskal-Wallis non-parametric test and a Dunn's method for median separation at pooled alpha level of 0.05 with individual Bonferroni alphas of 0.00064. This individual alpha was derived by dividing the pooled alpha of 0.05 by 78, the total number of possible pairwise comparisons between the 13 scenarios.

Results

Areas with higher burn probability tended to be clumped as opposed to being scattered across the landscape (Figure 5), which was anticipated given localized areas of steep topography and of high fuel loading and continuity. As expected, the untreated landscape had the highest mean burn probability of all scenarios (0.0057).

Figure 6 illustrates mean fire size for each of the scenarios. The mean fire size (for 10,000 random ignitions in each scenario) was significantly larger in the untreated landscape than in all treated scenarios except the prescribed fire treatment type at the 10 percent landscape intensity ($p < 0.001$). Mean fire size among the KNF-proposed treatment scenarios decreased significantly ($p < 0.001$) with increasing landscape intensity, with the largest mean fire size present under the prescribed fire scenario (719.39 ha) and the smallest under the total design scenario (349.56 ha). Mean fire size across the spatially optimized treatment scenarios was highly variable. Prescribed fire at the 10 percent treatment intensity had the largest mean fire size (719.39 ha^{-1}), which was not significantly different from the untreated landscape (Figure 6). The thin + burn treatment at the 30 percent intensity significantly ($p < 0.001$) reduced fire size more than any other treatment scenario (238.31 ha^{-1}).

Figure 7 illustrates onsite short-term carbon loss in each of the scenarios, which was calculated as treatment-induced carbon loss + wildfire emissions (5 years post-treatment). With no treatment, the landscape did not experience short-term carbon loss from treatments, but lost 6.24 Mg ha^{-1} of carbon via emissions during the wildfire simulated five years post-treatment. As expected, increasing landscape intensity reduced carbon emissions from wildfire, but also increased onsite treatment-induced carbon loss. The relationships were not equal however. As the proportion of the landscape treated increased, the treatment-induced carbon loss grew more rapidly than decreases in carbon lost from wildfire emissions. This was true for all treatment types except spatially optimized mastication treatments, which did not have any treatment-induced losses since they did not include thinning or prescribed fire.

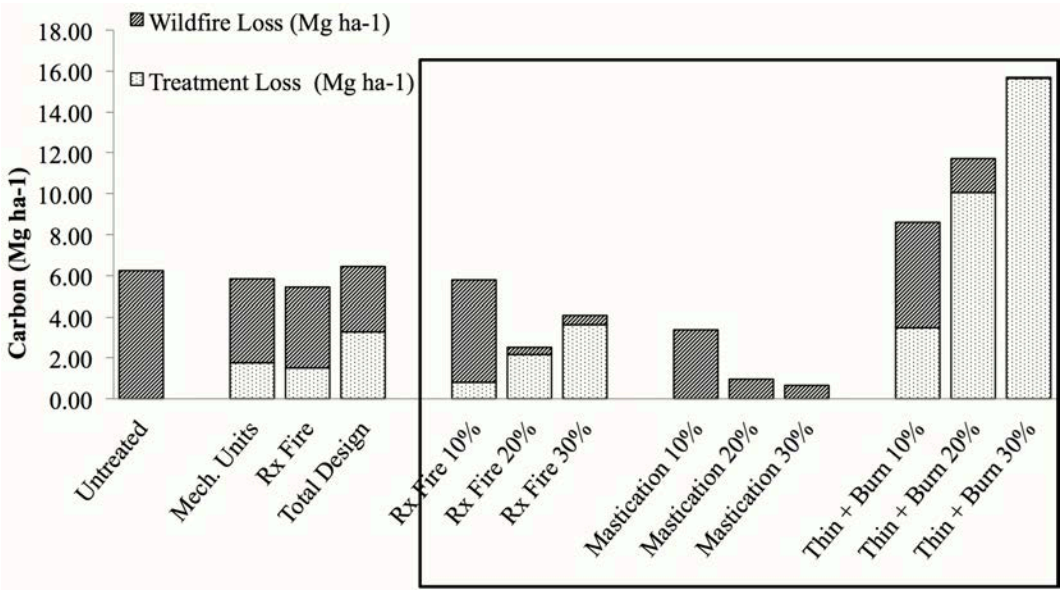

Figure 7—Short-term (at 5 years), onsite carbon losses (Mg ha^{-1}) for each treatment scenario. Stacked bars for wildfire and for treatment-induced carbon losses represent total onsite carbon loss for each scenario. Treatment-induced losses include prescribed fire emissions and vegetation removed in thinning operations. Treatments inside the solid box are spatially optimized; treatments outside the box are treatments proposed in a management plan at the study site.

Short-term carbon loss (treatment-induced + wildfire emissions) for the spatially optimized treatments was highly variable and depended upon treatment type and landscape intensity (Figure 7). Of all spatially optimized treatment designs, mastication at the 30 percent treatment intensity had the lowest short-term carbon loss (0.65 Mg ha^{-1}) and thin + burn at the 30 percent treatment intensity had the largest short-term carbon loss (15.72 Mg ha^{-1}).

Figure 8 illustrates onsite long-term carbon storage (50 years post-treatment). Of all treatments, the spatially optimized prescribed fire only scenario at 20 percent landscape intensity had the largest long-term carbon storage (370.63 Mg ha^{-1}). For the spatially optimized treatments, the smallest long-term storage was with thin + burn at the 10 percent treatment intensity (356.04 Mg ha^{-1}) and the greatest long-term carbon storage level was with prescribed fire at the

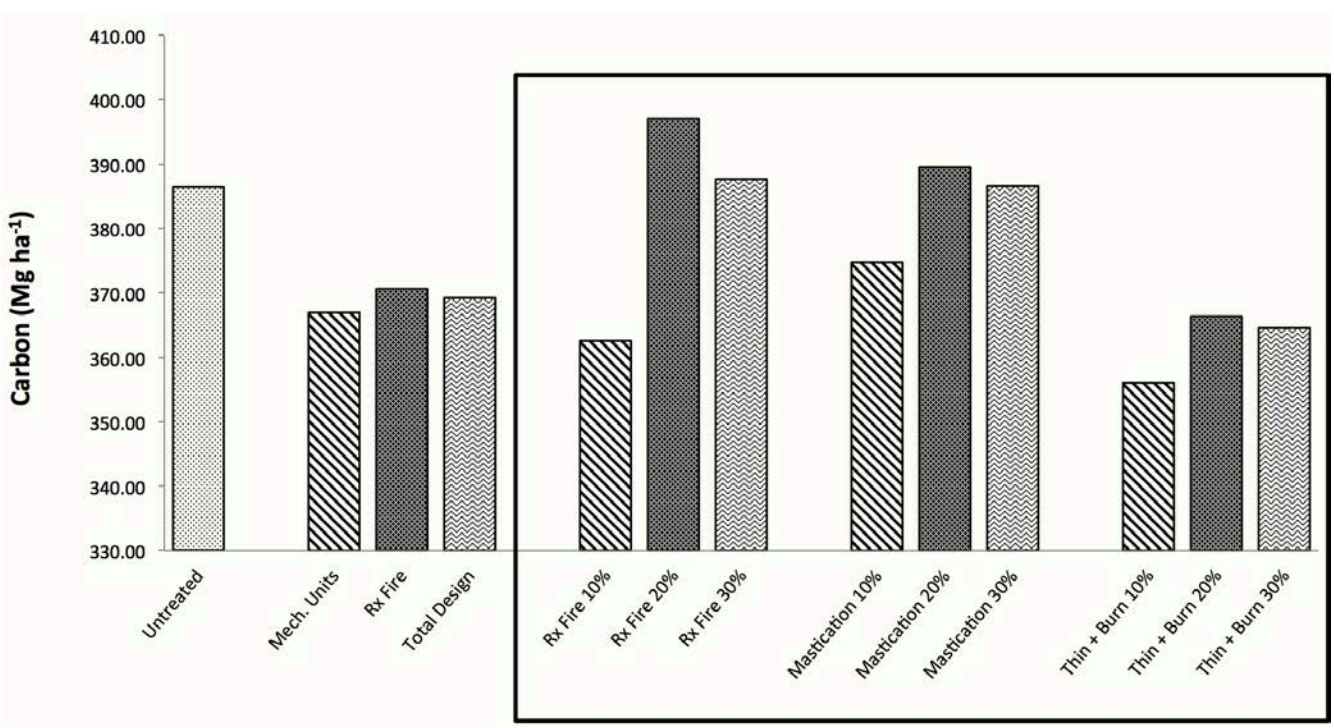

Figure 8—Long-term (at 50 years), onsite carbon storage (Mg ha^{-1}) for each of treatment scenarios. Treatments inside the solid box are spatially optimized; treatments outside the box are treatments proposed in a management plan at the study site.

20 percent treatment intensity (397.06 Mg ha^{-1}), which was larger than the amount of long-term carbon storage on the untreated landscape. For all spatially optimized treatment types, the long-term carbon storage increased from 10 percent of the area treated to the 20 percent of area treated, but then decreased from 20 percent to 30 percent of the area treated (Figure 8).

Discussion

The complex nature of modeling requires accepting a number of assumptions, including constant weather, a defined burn period, the accuracy of fire spread algorithms, and the accuracy of the growth and yield models. However, all the treatments were subject to the same assumptions, resulting in outputs that should be looked at as relative comparisons between treatments rather than precise predictive values. Our location represents an individual set of fuel loading values, topographic features, and assumed weather parameters, and therefore our results may not be representative of other locations. However, the process utilized here could be utilized on other landscapes to determine the potential impacts varied landscape-scale fuel treatment scenarios have on fire behavior and wildfire exposure.

Our results clearly show that landscape-scale fuel treatments can reduce potential wildfire exposure across the landscape (as measured by burn probability), dependent on treatment type, spatial arrangement, and proportion of the landscape being treated. Treatment type appeared to have less influence on the overall effectiveness of a fuels management strategy than did the proportion of the landscape being treated and the spatial arrangement of those treatments.

At the lowest treatment intensity, mean fire size in the KNF-proposed mechanical treatment design was equal to or significantly lower ($p < 0.001$) than all spatially optimized treatments at the 10 percent landscape intensity (Figure 5). However, as the treatment intensity increased, the KNF-proposed designs no longer outperformed the spatially optimized treatment designs at the analogous treatment intensity. The strong performance of the KNF-proposed treatments at the lowest treatment intensities is likely due to spatial arrangement. The KNF-proposed treatments effectively compartmentalized ignitions due to being placed on ridgetops and their linear nature, which did not allow a fire to flank around the treatment units into untreated corridors. In contrast, the spaces between the spatially optimized treatments at the lowest landscape intensity could have been sufficient to allow development of a heading fire. The changing effectiveness in the spatially optimized designs with landscape intensity confirms previous studies on landscape-scale fuel treatments (Finney 2001; Schmidt and others 2008; Ager and others 2010b).

Like fire size, short-term on-site carbon loss varied widely with treatment type, spatial arrangement, and landscape intensity (Figure 7), a fact that has not been examined in previous studies. Long-term carbon storage values showed similar patterns across treatment intensities for all treatment types, but the specific values varied between arrangement and treatment type (Figure 8).

The results indicate that if onsite short-term carbon loss and long-term onsite carbon storage are concerns for land managers, fuel treatments that include the combination of thin + burn treatments may not be desirable (Figures 7 and 8). Short-term losses of this treatment is most likely due to the removal of trees up to 71 cm DBH during commercial thinning and the slash left from thinning activities increased surface fuel loading, thus increasing the amount of carbon released during prescribed fire (North and others 2009; Tao and Allen 2010). These results are consistent with short-term stand-level analysis of this treatment type (Stephens and others 2009). Thin + burn units did have the lowest area impacted by wildfire fire at the 30 percent treatment intensity, resulting in reduced carbon loss from wildfire emissions (Figure 7). This result is consistent with stand-level studies that show reductions in carbon loss from wildfire following thin + burn treatments (Finkral and Evans 2008; Hurteau and others 2008; Hurteau and North 2009). However, the reduction in carbon emissions from wildfire at our level of simulation was not sufficient to offset the large onsite losses from thinning and prescribed fire emissions.

The mechanisms that altered short-term carbon loss in the thin + burn scenarios also altered long-term carbon storage. The thinning activity removed large trees that account for the majority of carbon storage, immediately reducing carbon storage on the landscape. The thinning activity also removed healthy, rapidly growing trees (Nowak and Dwyer 2007), reducing the rate of carbon sequestration, and resulting in a slower recovery to pre-treatment carbon storage levels. Increasing the percentage of the area treated should increase storage by reducing the area that experiences wildfire, thus reducing emissions from fire and improving sequestration by preventing the death of vigorously growing trees (Hurteau and North, 2009; Stephens and others 2009; Hurteau and North 2010). However, in this study, the loss in carbon sequestration rate and storage from thinning was greater than the increased carbon that resulted from reduced wildfire.

For minimizing onsite short-term carbon loss, mastication treatments appear to be the most effective due to there being no harvested carbon and no prescribed fire carbon emissions. As the area treated with mastication increased, the carbon loss decreased due to less area being affected by wildfire, resulting in very low short-term carbon loss for mastication at the 30 percent treatment intensity (Figure 7). Over 50 years, the mastication treatments do not have the largest carbon storage but are capable of increasing storage beyond the level of the untreated landscape (Figure 8). A probable cause for this is the removal of the young, vigorously growing trees. Though large trees are the largest pool of carbon, smaller, more rapidly growing trees are a large source of sequestration, which influences storage levels over time (Nowak and Dwyer 2007). Removing large numbers of intermediate and small trees does not alter current storage, but can alter future storage by reducing the present sequestration rate (Hurteau

and North 2009; Large 2010). However, these small trees are often suppressed, so their removal may allow for the remaining trees to increase growth rates through reduced competition, allowing the long-term onsite storage under this treatment type to outperform the proposed site-specific treatment scenarios (Figure 8). Increasing mastication treatment landscape intensity reduced the area burned in wildfire (Figure 6), subsequently reducing carbon loss from wildfire emissions and maintaining storage by reducing large tree mortality (Hurteau and North 2009; Stephens and others 2009; Hurteau and North 2010). However, the reduction in small trees slowed sequestration rates sufficiently to limit carbon storage at year 50, resulting in lower carbon accumulation rates and ultimately lower carbon storage at the 30 percent treatment intensity when compared to the 20 percent treatment intensity.

Spatially optimized prescribed fire treatments demonstrated an inverse relationship between treatment-induced carbon emissions and wildfire-induced carbon emissions (Figure 7). The relationship is not linear however, indicating that if spatially optimized, the reductions in wildfire-induced emissions were large early, but became smaller as the landscape intensity increased. In this study, it appears that the balance point between increasing emissions from prescribed fire and decreasing emissions from wildfire is at the 20 percent landscape intensity. Balancing the treatment-induced emissions with wildfire-induced emissions resulted in the 20 percent landscape intensity having the smallest short-term carbon loss of the prescribed fire treatment scenarios (Figure 7).

Over a 50-year cycle, prescribed fire at the 20 percent landscape intensity had the largest pool of carbon storage of all treatment designs and intensities (Figure 8). Prescribed fire reduced surface fuels and protected large trees from experiencing wildfire mortality, thereby creating fire-resistant stand structures (Hurteau and North 2009; Hurteau and North 2010). This is similar to thin + burn treatments but without the large tree removal or increased slash fuels prior to burning (Stephens and others 2009). When compared to mastication treatments, prescribed fire scenarios lost more carbon in the short-term, but did not remove as many of the small to medium trees, and therefore did not reduce the sequestration rate, allowing for the long-term carbon storage level to increase more rapidly than in mastication treatments, more than compensating for the loss of carbon from the prescribed fire. At the 20 percent treatment intensity, the reduction in wildfire-induced emissions and saving of large tress due to reduced area experiencing wildfire balanced the treatment-induced carbon emissions, while increasing to the 30 percent treatment intensity caused sufficient increase in treatment-induced loss to reduce the long-term storage level.

The KNF-proposed treatments (USDA Forest Service 2010) all experienced a short-term loss of carbon that was close in value to the untreated landscape (Figure 7). Of note is the amount of carbon lost from wildfire (Figure 7), which was not as strongly influenced by treatment intensity as it was when treatments were arranged in spatially optimized patterns. This illustrates that though the KNF-proposed treatments in the LSR may be more practical to implement than the spatially optimized designs, they were not as effective at reducing the area that experienced wildfire (Figure 6), and as such, were not as effective at reducing short-term carbon loss from wildfires (Stephens and others 2009).

Over 50 years, all KNF-proposed treatment scenarios had lower carbon storage than the untreated landscape and similar or lower carbon storage than all optimized designs at the analogous treatment intensities (Figure 8). An explanation for this is that the limited ability of these treatments to influence wildfire area resulted in a reduced ability of these treatments to protect large trees from wildfire. This resulted in high mortality of mature trees during wildfire, removing the largest source of carbon storage over a larger portion of the landscape (Nowak and Dwyer 2007; Hurteau and others 2011). Just as with the spatially optimized treatment designs, the carbon storage was greatest at the 20 percent treatment intensity (prescribed fire), indicating that as treatment intensities increase past the medium treatment intensity (~20 percent), the prescribed fire-induced carbon emissions and vegetation removals outweigh the protection of mature trees from wildfire and reductions in wildfire carbon emissions.

Overall, the medium treatment intensity (20 percent of the landscape) appears to be the best treatment intensity for maximizing onsite long-term carbon storage. For each treatment type and arrangement, the 20 percent intensity had the largest long-term carbon storage pool. However, across treatment types and arrangements at the 20 percent intensity, the amount of carbon in the storage pools was not equal (Figure 8). This indicates that if long-term carbon storage is a concern for land managers, once the treatment type and design are selected, the percentage of the landscape treated should not exceed 20 percent. In our study site, this result is valuable because it indicates that the more practical site-specific KNF-proposed treatments can minimize onsite short-term carbon loss and maximize long-term carbon storage at the same treatment intensity (Figures 7 and 8).

Finally, it should be noted that this work only considered on-site carbon dynamics and did not consider off-site storage of carbon such as wood used in building construction. Future work on carbon cycling over the short and long term should take a more life cycle approach to the problem, tracking carbon that may be stored offsite and accounting for other short-term carbon emissions stemming from the implementation of fuel treatments.

Another consideration in the interpretation of this study is the implementation of wildfire only one time (5 years post treatment) during the 50-year cycle. Over 50 years, it is likely that more fire would be present on the landscape (Taylor and Skinner 2003) and one would therefore need to recursively implement fire simulations on the landscape, accounting for the impacts previous fires would have on fire spread and intensity as well as carbon emissions. Doing this would be possible using the Randig and FVS programs in a repetitive loop, assigning fire based on burn probabilities generated from the previously burned landscape. The implementation of such a process was logistically impractical for this study given the time consuming nature of the modeling

(each combination of Randig and FVS simulation took 20 to 24 hours). However, such a process could create a more complete picture of the duration of fuel treatment influence on carbon storage across a landscape of this scale.

Acknowledgments

This project was funded in part by the Joint Fire Science Program Project 07-1-6-11 administered through the Pacific Southwest Research Station, the California State University Agricultural Research Initiative (ARI), and the McIntire-Stennis Cooperative Forestry Research Program. The authors are grateful for the insight and technical advice that was provided throughout this project by Clint Isbell of the Klamath National Forest, Mark Finney of the U.S. Forest Service Rocky Mountain Research Station, Alan Ager of the U.S. Forest Service Pacific Northwest Research Station, and Michael Landram of the U.S. Forest Service Pacific Southwest Region. Drs. Walt Bremer and Scott Sink provided technical reviews of an earlier version of this manuscript.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Wildland Fire Potential: A Tool for Assessing Wildfire Risk and Fuels Management Needs

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Abstract—*Federal wildfire managers often want to know, over large landscapes, where wildfires are likely to occur and how intense they may be. To meet this need we developed a map that we call wildland fire potential (WFP)—a raster geospatial product that can help to inform evaluations of wildfire risk or prioritization of fuels management needs across very large spatial scales (millions of acres). Our specific objective with the WFP map was to depict the relative potential for wildfire that would be difficult for suppression resources to contain. To create the 2012 version, we built upon spatial estimates of wildfire likelihood and intensity generated in 2012 with the Large Fire Simulation system (FSim) for the national interagency Fire Program Analysis system (FPA), as well as spatial fuels and vegetation data from LANDFIRE 2008 and point locations of fire occurrence from FPA (ca. 1992 – 2010). With these datasets as inputs, we produced an index of WFP for all of the conterminous United States at 885 ft (270 m) resolution. We present the final WFP map in two forms: 1) continuous integer values, and 2) five WFP classes of very low, low, moderate, high, and very high. On its own, WFP is not an explicit map of wildfire threat or risk, but when paired with spatial data depicting highly valued resources and assets such as structures or powerlines, it can approximate relative wildfire risk to those specific resources and assets. WFP is also not a forecast or wildfire outlook for any particular season, as it does not include any information on current or forecasted weather or fuel moisture conditions. It is instead intended for long-term strategic fuels management, and we provide an example of its use within the U.S. Forest Service to date.*

Introduction

Risk analysis for wildland fire management has become the subject of much research in recent years (Miller and Ager 2013). Both fire managers and policy makers increasingly want tools and information to project when and where wildfires are likely to burn, and what the potential consequences of those wildfires may be. The fundamental components involved in evaluating wildfire risk include: 1) identifying the *likelihood* (probability) of fire, 2) describing the possible *intensity* of fire should it occur, and 3) based on specific resources and assets that may be affected by fire, identifying the *effects* (positive or negative) of fire on those resources (Miller and Ager 2013, Scott and others 2013). Simply put, how likely is a place to burn; if it does burn, how likely is it to burn at certain intensities; and if there are things we care about at that place, how susceptible are they to damage (or benefit) from fire at each intensity level? Scott and others (2013) lay out a framework for wildfire risk assessment, and conceptualize the three components of risk as the wildfire risk triangle (figure 1). Their risk assessment framework has been developed and applied at various spatial scales (Calkin and others 2010; Scott and others 2013; Thompson and others 2013a; Thompson and others 2013b), and represents the current paradigm for consistent and scalable wildfire risk assessments on US public lands (Calkin and others 2011).

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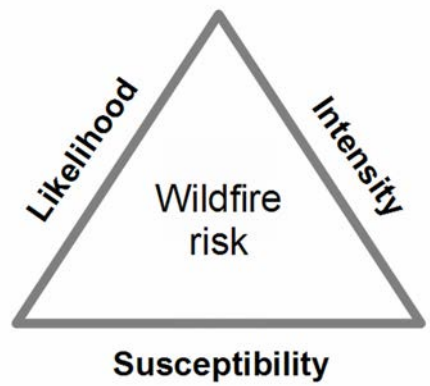

Figure 1—The wildfire risk triangle composed of the three fundamental components of wildfire risk – likelihood and intensity of fire, and the susceptibility of particular resources or assets to fire. From Scott and others 2013.

One tool developed to address the questions of likelihood and intensity is the Large Fire Simulation system (FSim) created for the national interagency Fire Program Analysis (FPA) system (Finney and others 2011). FSim was developed to produce estimates of the probabilistic components of wildfire risk, and produces spatial surfaces of burn probability and the conditional probabilities of six fire intensity levels defined by flame length classes (0 to 2 ft, 2 to 4 ft, 4 to 6 ft, 6 to 8 ft, 8 to 12 ft, and greater than 12 ft). For FPA, these spatial FSim products are output for all lands in the United States, including Alaska, Hawaii, and Puerto Rico, and are based on a number of input data sources including

spatial fuels data from the LANDFIRE project (Rollins 2009), and historic weather station and fire occurrence data from recent decades. Together, estimates of likelihood and intensity from FSim can be used to characterize the *integrated wildfire hazard*, or potential for fire to cause harm to (or produce benefits for) particular resources and assets (Scott and others 2013).

While the measure of hazard that can be obtained from FSim products is useful on its own, it does not take into consideration the third leg of the wildfire risk triangle: susceptibility. Typically in a risk assessment, this third component is captured by defining and spatially mapping a set of highly valued resources and assets (HVRAs), and conceptually outlining the percent of net value change (positive or negative) each HVRA would experience with fire at defined intensity levels. HVRAs are the things on the ground that we care about; they may be either positively or negatively affected by fire, and include facilities and infrastructure, wildland urban interface (WUI) areas, municipal water supplies, and habitat and ecosystem characteristics. The estimates of net value change for each HVRA define a response function (figure 2) that can be used in the calculation of wildfire risk to that HVRA (Scott and others 2013). The process of defining and mapping HVRAs and developing a response function for each, however, can be time consuming, complex, and costly, particularly for assessments covering a large geographic area with a diversity of fire ecology and land management concerns.

In the absence of wildfire response functions for specific HVRAs, wildfire management organizations still require information on the relative degree of suppression difficulty at any location across the landscape to aid in identifying fire management and risk mitigation opportunities and challenges. Therefore, our objective was to produce a spatial index of the relative potential for wildfire that would be difficult for suppression resources to contain. An extension of the integrated wildfire hazard concept, we call this index Wildland Fire Potential (WFP). Areas mapped with higher WFP values represent fuels and other landscape conditions with a higher probability of experiencing high-intensity fire with torching, crowning, and other forms of extreme wildfire behavior under conducive weather conditions. We chose to produce the WFP map for all lands in the conterminous United States (CONUS). In lieu of a full national-scale risk assessment (which is currently in progress), the WFP map provides a strategic CONUS-wide tool for identifying and prioritizing areas most in need of fuel treatments to reduce potential fire intensities. Further, in conjunction with other spatial data depicting particular HVRAs such as residential communities or watersheds important for municipal drinking water, prioritization with the WFP map can be narrowed to areas meeting particular fire and land management objectives.

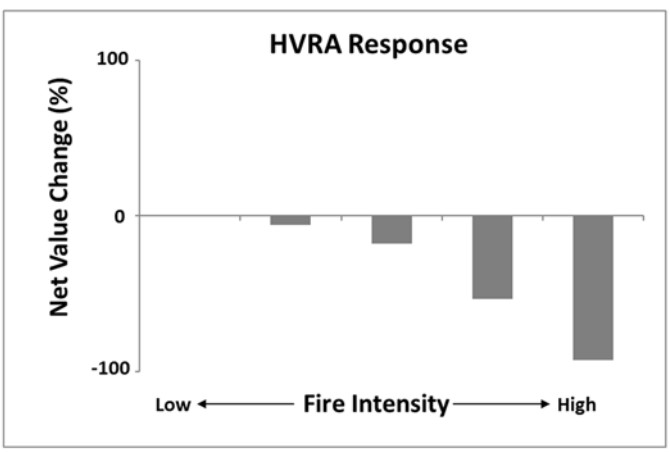

Figure 2—A wildfire response function illustrating the estimated net value change for a particular highly valued resource or asset (HVRA) with different fire intensity levels. In this example, fire negatively impacts the HVRA at all flame lengths, with the impact increasing with flame length.

This current effort builds upon previous iterations of the WFP map produced in 2007 (Menakis 2008) and 2010, but differs significantly from those earlier products. Considerable improvements in input data sources and wildfire simulation modeling methods, refinements to the 2010 WFP mapping methods, and a general evolution in wildfire risk assessment concepts have all occurred since 2010. This paper focuses primarily on the methods used to generate the 2012 WFP map, with an example of how it is being used within the USDA Forest Service to aid in prioritizing national-scale fuels management needs.

Methods

To develop our map of WFP, we integrated CONUS FSim modeling outputs generated for FPA in 2012 (FPA and USFS 2012), point fire occurrence records from 1992-2010 (Short 2014), and spatial vegetation and fuels data from the LANDFIRE project (Rollins 2009) (figure 3). The process can be summarized by five main stages: 1) calculate a large wildfire potential using the FPA FSim products and weighting different intensity levels according to the difficulty they pose to suppression efforts; 2) create a separate surface of small wildfire potential based on ignition locations for fires smaller than 300 acres (which are not the focus of FSim modeling); 3) integrate the large wildfire potential and the small wildfire potential; 4) apply a set of resistance to control weights based on fireline construction rates in different fuel types; and 5) produce the final WFP products.

Calculate the Large Wildfire Potential

This first step in the process of mapping WFP is to integrate the FSim burn probability (figure 4) and conditional probabilities for flame length classes (figure 5). The CONUS FSim products are 885 ft (270 m) raster mosaics from wildfire simulations performed individually in 132 Fire Planning Units (FPUs) across the country, and provide the foundation for the WFP map. In each FPU, daily ignitions and fire spread are modeled over at least 20,000 contemporary fire seasons (in other words, not future projections), given statistically possible weather conditions based on observations from recent decades (Finney and others 2011). At the

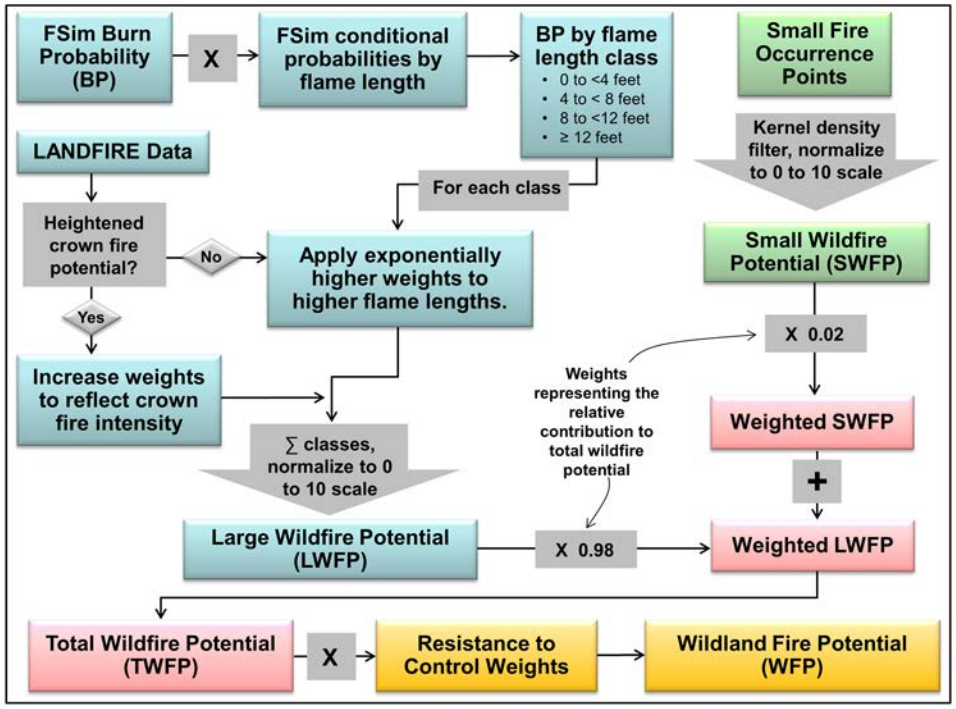

Figure 3—Generalized flowchart of the WFP mapping process. Creation of the Large Wildfire Potential layer is in blue; creation of the Small Wildfire Potential layer is in green; integration of the two is in pink; and the application of resistance to control weights and final processing to create the WFP product are in orange.

end of a simulation run, the number of times a given pixel burned is divided by the total number of simulation years to get the pixel-level burn probability (for example, 200 times in 20,000 runs yields a probability of 0.01). The proportion of times that a pixel burned in a particular flame length class provides the conditional flame length probability (for example, if out of the 200 times the pixel burned, 150 were with 8 to12 foot flames, then the conditional probability for that flame length class is 0.75). FSim outputs conditional probabilities for six classes of flame length, but we aggregated the data into four classes: 0 to < 4 ft, 4 to < 8 ft, 8 to < 12 ft, and ≥ 12 ft. By multiplying the overall burn probability by the conditional probability for each of our four flame length classes we get the actual burn probability for each flame length class (figure 6).

Next, we used established mathematical relationships between flame length and fireline intensity (Andrews and others 2011), to weight the potential hazard represented by each of our four flame length classes. In a sense our weighting approach is similar to the response functions used in risk assessments, although here we are not focusing on the relative susceptibility of a resource or asset but rather variable levels of suppression difficulty. To develop our weighting scheme, we followed the logic that as flame lengths (and fireline intensities) increase, fires become increasingly difficult to control. This logic has long been recognized by fire scientists and fire managers alike, and is represented in the surface fire behavior fire characteristics chart, also known as the "hauling chart" (Andrews and Rothermel 1982). Using the lowest flame length class (0 to <4 ft) as our baseline, along with an equation for surface fireline intensity (Byram 1959), we derived weights by simply determining how much greater the average fireline intensity is in each of our flame length classes compared to the baseline (table 1).

While FSim modeling does incorporate crown fire to the extent possible with our current modeling capabilities, the conditional flame length probabilities represent surface fire flame lengths calculated from Byram's (1959) equation (Finney and others 2011). As a result, they likely underrepresent the actual flame lengths (heights) possible during a crown fire event (Short, personal communication). Therefore, we sought to identify places with a heightened potential for crown fire based on the vertical fuel profile and weight them accordingly as the upper end of the fire intensity spectrum (figure 2). We used spatial data from the LANDFIRE project[1] depicting forest canopy characteristics (canopy cover, canopy height, and canopy base height) to accomplish this. We first identified areas that met two basic criteria we defined for closed-canopy forest: 1) forest canopy height > 16 ft (5 m); and 2) forest canopy cover > 50 percent. Next, we evaluated each of the original FSim flame length classes above 4 ft with the following criteria: 1) conditional probability for the flame length class is greater than zero; and 2) the upper value for flame length overlaps with the canopy base height (for example, canopy base height < 6 ft and flame length of 4 to 6 ft). Evaluating these criteria on a pixel-by-pixel basis, we developed a spatial mask identifying areas with forest crown fire potential (figure 7).

Recognizing that high intensity crown fire behavior is also possible in some non-forest vegetation such as California chaparral, we used an additional set of criteria to add these pixels into our crown fire potential mask. We

[1] Because the spatial resolution of LANDFIRE data is 97 ft (30 m), and the FSim data are at 885 ft (270 m), we resampled LANDFIRE data layers up to 885 ft (270 m) resolution. LANDFIRE fuels layers were used as input to the FPA FSim runs, and they were also resampled up to 885 ft (270 m) by FPA. All LANDFIRE layers used in both the FPA FSim runs and our 2012 WFP mapping were LANDFIRE Refresh 2008 (v 1.1.0).

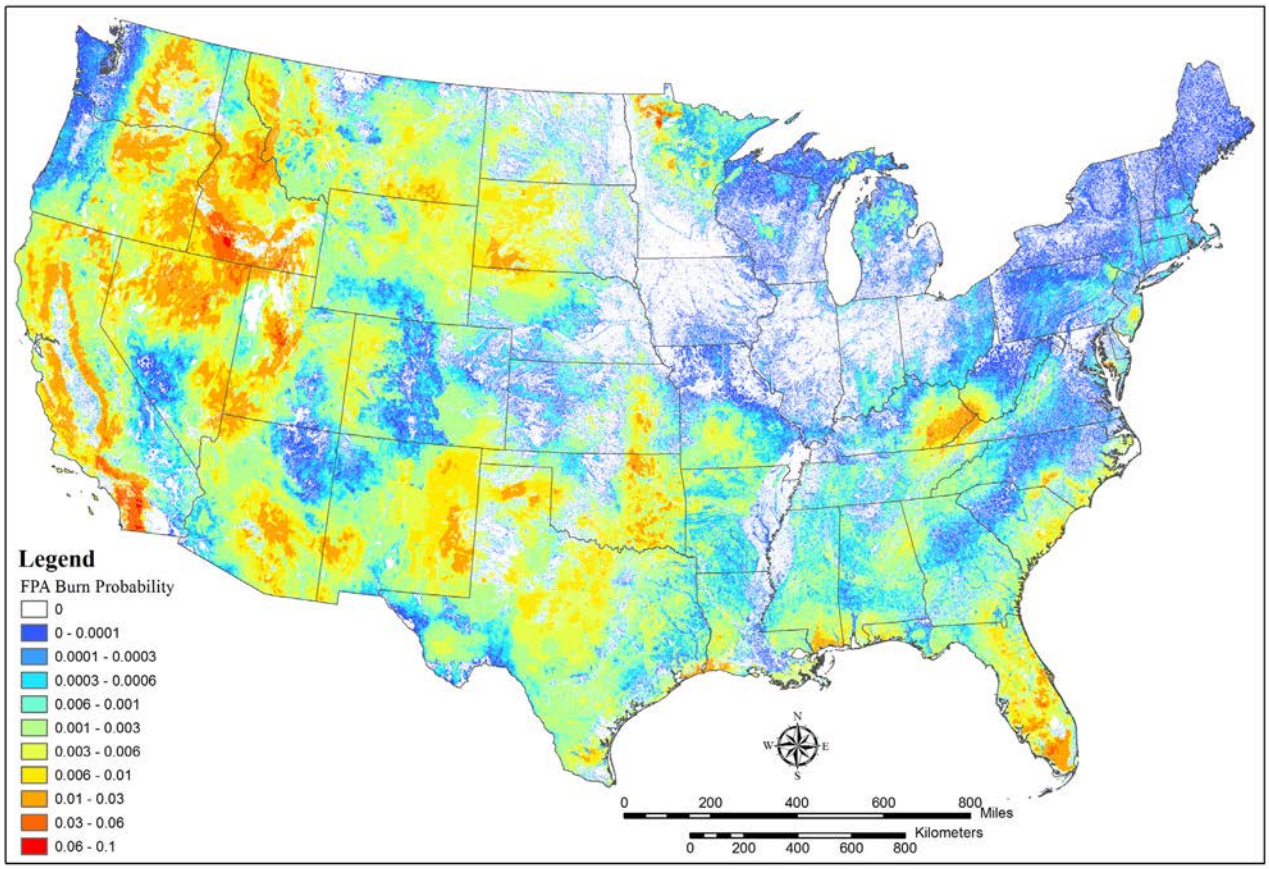

Figure 4—Annual burn probability from the Large Fire Simulator (FSim), generated for the national Fire Program Analysis (FPA) system in 2012 from LANDFIRE 2008 fuels data (FPA and USFS 2012).

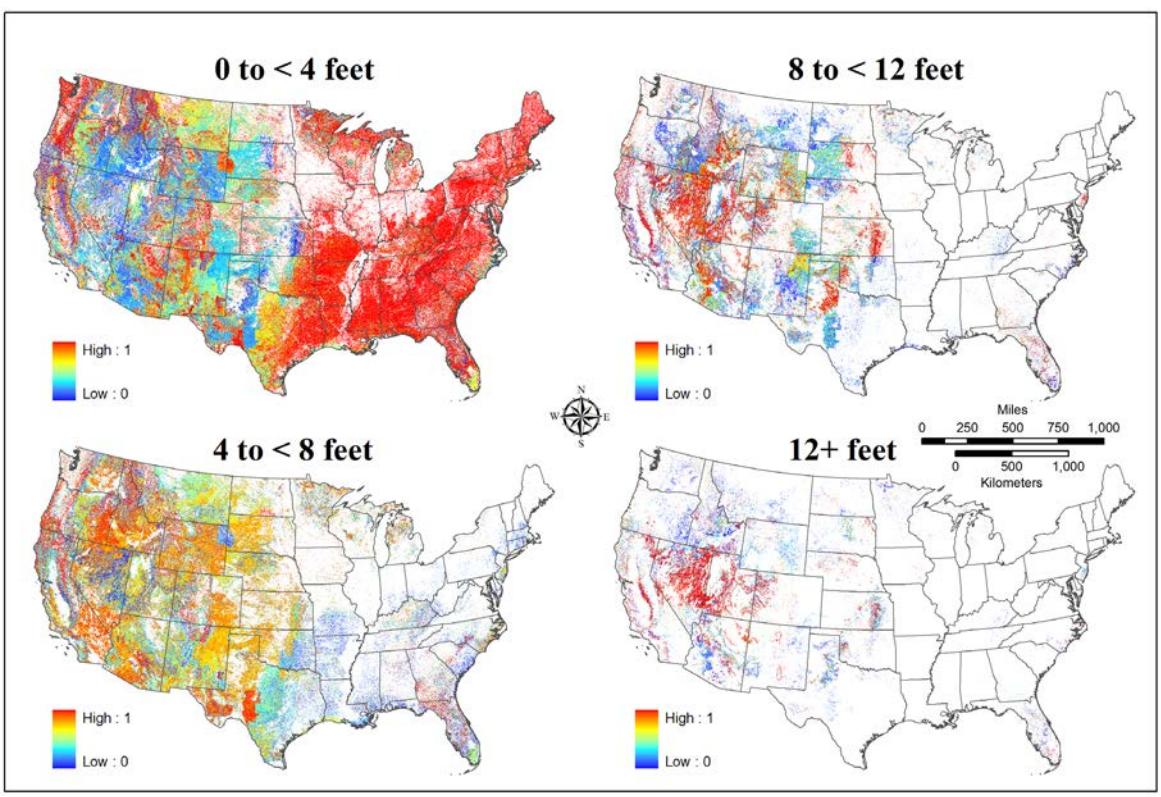

Figure 5—Conditional probability from the large fire simulator (FSim) for each of four aggregated flame length classes, generated for the national Fire Program Analysis (FPA) system in 2012 from LANDFIRE 2008 fuels data (FPA and USFS 2012).

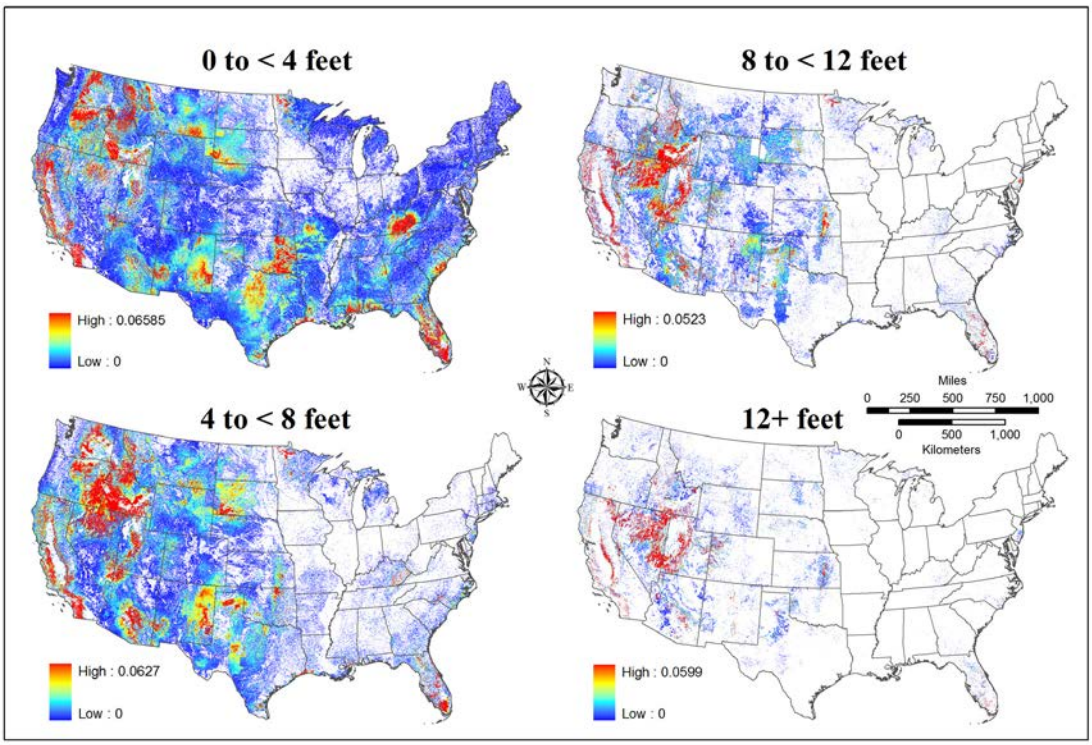

Figure 6—Burn probability for each of four aggregated flame length classes, calculated as the product of the large fire simulator (FSim) burn probability and conditional flame length probabilities (FPA and USFS 2012).

Table 1—Derivation of weights based on fireline intensities for surface fires.

Surface flame length (ft)	Fireline intesity (Btu/ft/s) [a]	Average intensity	How many "times as intense" as < 4 ft flames? [b]	Weighting used for WFP
1	5.67	31.03	1.0	1
2	25.60			
3	61.82			
4	115.53	243.03	7.8	8
5	187.67			
6	278.95			
7	389.99			
8	521.34	770.86	24.8	25
9	673.48			
10	846.84			
11	1,041.80			
12	1,258.73	2,430.67	78.3	75
13	1,497.97			
14	1,759.82			
15	2,044.59			
16	2,352.55			
17	2,683.95			
18	3,039.06			
19	3,418.10			
20	3,821.31			

[a] Calculated as: (Flame Length / 0.45)2.173913 based on Byram (1959).
[b] Calculated as: (Average intensity of current flame length class / average intensity of 0 to <4 ft flame lengths).

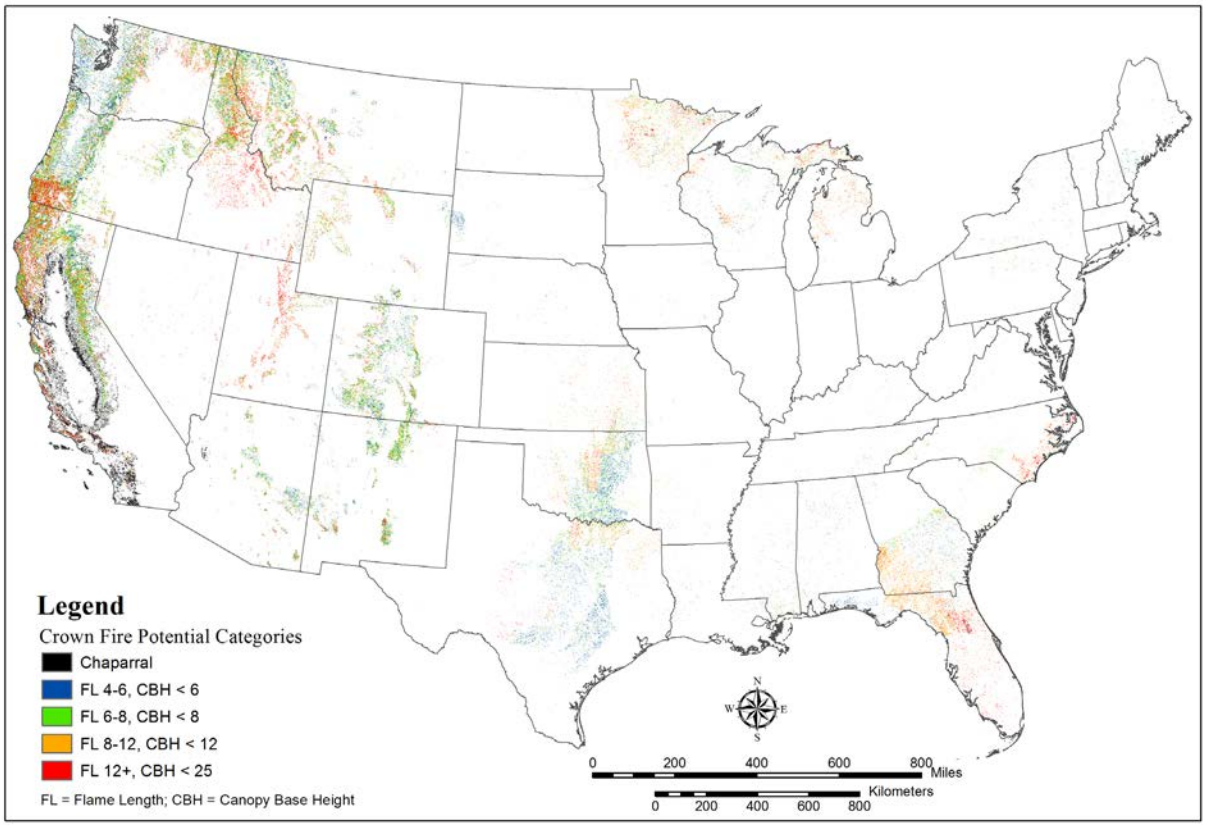

Figure 7—Map of areas meeting criteria for crown fire potential. Burn probabilities by flame length class were multiplied by the crown fire weight of 130 in all colored pixels, and by appropriate weights for surface fire flame lengths in all other areas.

identified chaparral pixels using the LANDFIRE Existing Vegetation Type layer (EVT) (table 2). Out of the chaparral EVT classes, we considered pixels with > 30 percent shrub cover in the LANDFIRE Existing Vegetation Cover layer to be capable of supporting crown fire. In addition to other criteria, Fried and others (2004) defined the highest hazard class in chaparral as having > 25 percent shrub cover; 30 percent was the closest LANDFIRE cover class break to this value.

Table 2—LANDFIRE Existing Vegetation Type (EVT) classes used to identify chaparral crown fire potential.

EVT Code	EVT Name
2096	California Maritime Chaparral
2097	California Mesic Chaparral
2098	California Montane Woodland and Chaparral
2099	California Xeric Serpentine Chaparral
2105	Northern and Central California Dry-Mesic Chaparral
2110	Southern California Dry-Mesic Chaparral
2092	Southern California Coastal Scrub
2128	Northern California Coastal Scrub
2108	Sonora-Mojave Semi-Desert Chaparral [a]

[a] Mapped in Southern California mountains and around Central Valley

To derive a weight for areas with crown fire potential, we again used established relationships between flame length and fireline intensity. Using an equation for crown fire intensity (Thomas 1963), we chose a representative range of flame lengths that could be expected under generalized crown fire conditions (20 to 80 ft) and calculated the average fireline intensity within this range. This resulted in a weight of 130 for areas where crown fire flame lengths are possible (average fireline intensity of 4,075 Btu/ft/s, approximately 130 times greater than the intensity of 0 to 4 ft surface flames).

Once we had derived weights and identified pixels with crown fire potential, we applied the weights to the burn probabilities in each of our four flame length classes. For each class, for pixels where the criteria for crown fire potential were met, we multiplied the burn probability for that class by the crown fire weight (130). For pixels where the criteria for crown fire potential were not met, we multiplied the burn probabilities by the appropriate weight for surface fire (table 1).

After applying weights to the burn probabilities in each flame length class, we summed the resulting values at each pixel to get a measure of large wildfire potential (LWFP). It is important to note that at this point in the process, we no longer have burn probabilities; instead we have a dimensionless index. The raw values range from 0 to approximately 8.8. To better align this index with the independently-derived small wildfire potential (SWFP) index, we normalized the LWFP to a scale of 0 to 10.

Calculate the Small Wildfire Potential

FSim modeling focuses on large fires because they account for over 90% of the total area burned in wildfires (Finney and others 2011; Short 2013). As such, simulated fires are more likely to grow large in areas where large fires have been more common on the landscape, based on the ignition density of fires > 50 to 300 acres since 1992. Areas that have experienced mostly smaller fires, therefore, tend to get very low burn probabilities. For the WFP, however, we wanted to reflect that areas with predominantly small fires in recent decades also represent some potential for future fires. Particularly where management strategies (for example, hazardous fuels treatment or preparedness efforts) may have been successful at limiting large fires in the past, burn probabilities based on large fires alone may underestimate the wildfire potential. Since the WFP product could be used for prioritizing locations of hazardous fuels treatments or moving preparedness crews we did not want to limit our analysis to only large fires.

To account for small fires in the WFP, we created a smoothed ignition density surface using the same method that FPA uses to create their large fire ignition density grid. Using FPA's point fire occurrence database (Short 2013), we first selected out all points representing fires with a final size < 300 acres. Next, we applied a kernel density function (Silverman 1986, equation 4.5) to the small fire points in ArcGIS, specifying a search radius of 31.07 mi (50 km) and an output raster cell size of 885 ft (270 m) to match all raster layers used for the LWFP. Values in each cell of the kernel density surface represent number of ignitions per square kilometer during the period of the database (1992-2012), averaged across a 31.07 mi (50 km)-radius area around each cell. Values ranged from 0 to 1.56. To convert this to a SWFP index, aligned with the LWFP, we normalized it to a scale of 0 to 10 (figure 8).

Calculate Total Wildfire Potential

With the LWFP and SWFP created and normalized to the same scale, we assigned each a weight to reflect the relative contribution of each to total wildfire potential (TWFP), then added the weighted values to calculate the TWFP. We tested several weights, starting with 0.5 for each, representing an equal contribution of LWFP and SWFP to TWFP. Using equal weights, however, it was obvious that the spatial patterns from the SWFP overpowered any contribution from the LWFP and we incrementally increased the weight for the LWFP until the product looked reasonable. To evaluate this, we examined the TWFP visually in ArcGIS (ESRI 2011), overlaying observed fire perimeters from recent decades (acquired from the Monitoring Trends in Burn Severity project; http://www.mtbs.gov), and comparing the relative output values between areas that experience a lot of fire and areas that have little to no fire. This process led to the final weights of 0.98 for LWFP and 0.02 for SWFP, which, despite being very lopsided, allowed for the SWFP to have a noticeable influence on the TWFP but not overpower the

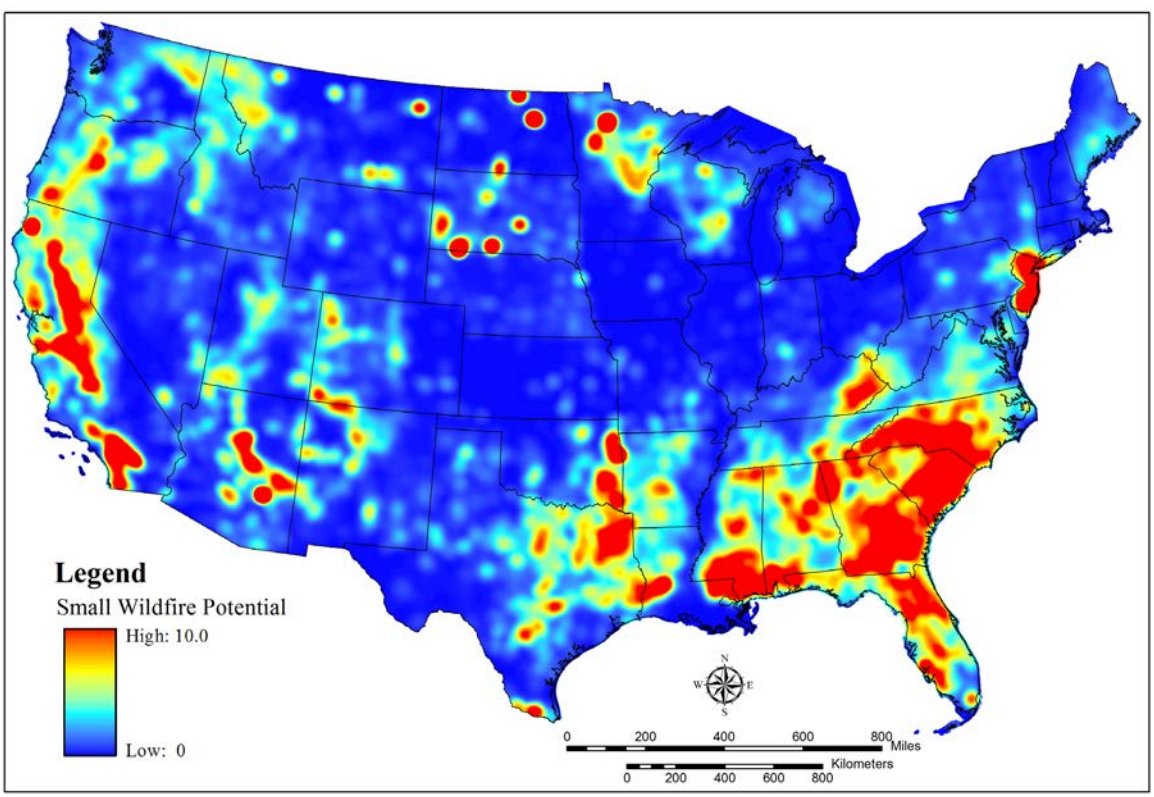

Figure 8—Map of small wildfire potential, a scaled ignition density surface for all fires less than 300 acres from 1992 to 2010. The large, rounded shapes reflect the 31.07 mi (50 km) search radius used in a kernel density function to smooth the ignition density surface.

LWFP contribution. These weights also closely approximate the relative contribution of "large" and "small" fires to total area burned.

Apply Resistance to Control Weights

Keeping in mind our objective of depicting the potential for fire that would be difficult for suppression resources to contain, we applied a final set of resistance to control (RTC) weights to the TWFP (figure 9). Based on the concept that fires are easier to contain in some fuel types than others, the fireline handbook (NWCG 2004) lists fireline production rates (ch/hr) for initial attack by hand crews for the original Anderson 13 fuel models (Anderson 1982). FPA has updated these line construction rates for the newer 40 fuel models (Scott and Burgan 2005), with the most recent update made in 2010. Using these rates to calculate an RTC weight for each of the 40 fuel models, we could then use the LANDFIRE Refresh 2008 (v1.1.0) Fire Behavior Fuel Model 40 (FBFM40) layer to apply the weights spatially to adjust the values in our TWFP layer.

To derive RTC weights from FPA's line construction rates, we first calculated the reciprocal of the rate (1/rate). This results in fuel models with a line construction rate greater than one (easier to control) getting an RTC weight less than one (table 3). When the TWFP is multiplied by these RTC weights, the index of potential in the final WFP output is therefore reduced. Conversely, fuel models with a line construction rate greater than one (harder to control) would get an RTC weight greater than one, resulting in increased WFP. After applying RTC weights based solely on this logic, however, we found that the effect on the final WFP index, particularly in fuel models with RTC weights greater than one, was too much. It was essentially giving the LANDFIRE FBFM40 too much influence on the final WFP product.

To refine the RTC weights, we made some adjustments to the weights themselves and to the way we applied them spatially. Since our main goal with these weights was to reduce the WFP values in fuel models with a higher likelihood of suppression success (for example, light grasses and shrubs, hardwood litter), we decided to only apply RTC weights that are less than one. In four timber understory and litter fuel models, we also manually adjusted the RTC weight up to one (table 3) based on our visual examinations of initial tests in ArcGIS. Lastly, to guard against potential mapping errors in the FBFM40, we incorporated the LANDFIRE EVT when applying the weights spatially. Anywhere with a conifer EVT class, we automatically set the RTC weight to one.

Produce the Final WFP Products

The product that results from the process steps above is an 885-ft (270-m) resolution raster layer, with values representing wildland fire potential on a continuous 0 to 10 scale. We apply a few further geospatial processing steps to convert it into the two final WFP products: one with continuous

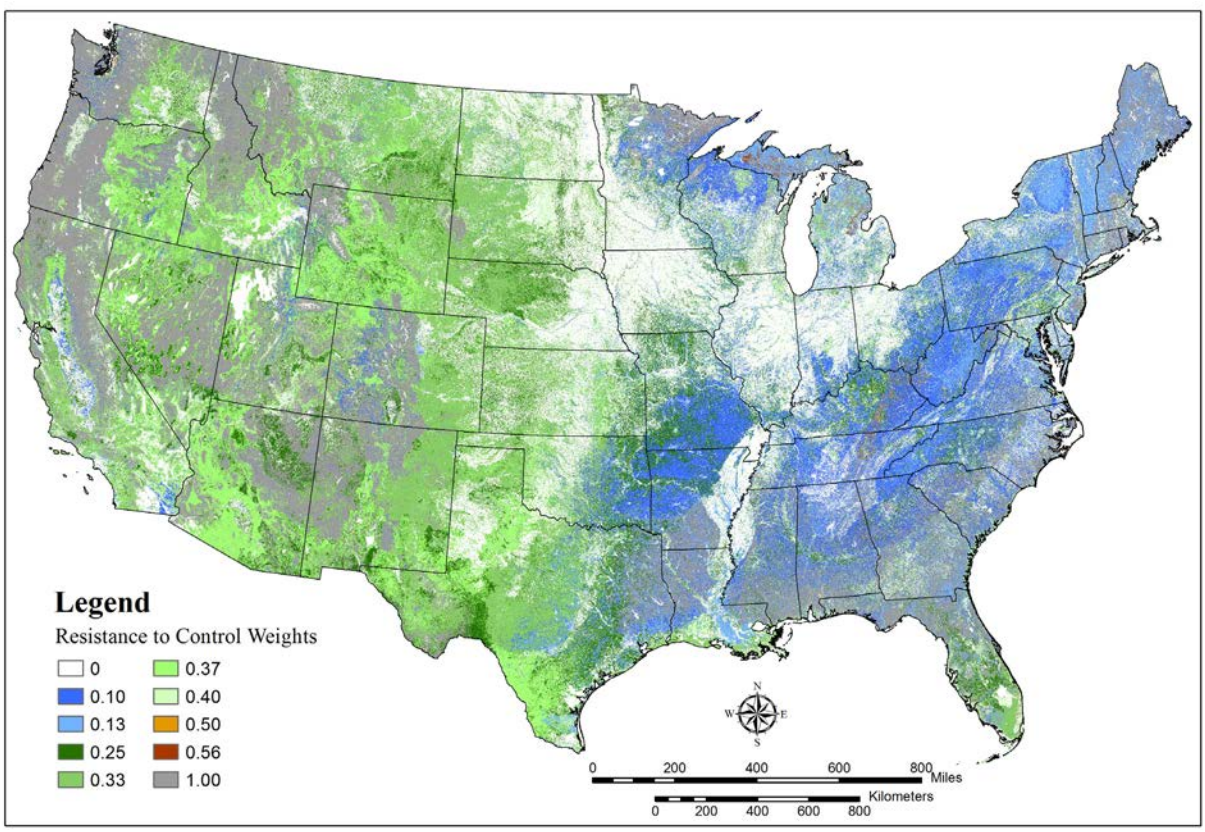

Figure 9—Map of the spatial distribution of adjusted resistance to control (RTC) weights, derived from fireline construction rates for the Scott and Burgan (2005) fuel models (see table 3).

Table 3—Resistance to control (RTC) weights for fuel models with line construction rates > 1 chain/hour.

Fuel Model	Fireline construction rate (ch/hr) [a]	Calculated RTC weight [b]	Adjusted RTC weight [c]
GR1 (101) Short, Sparse Dry Climate Grass (Grass)	4	0.25	0.25
GR2 (102) Low Load, Dry Climate Grass (Grass)	3	0.33	0.33
GR3 (103) Low Load, Very Coarse, Humid Climate Grass	2.49	0.40	0.40
GR4 (104) Moderate Load, Dry Climate Grass	2.49	0.40	0.40
GR5 (105) Low Load, Humid Climate Grass	3	0.33	0.33
GR6 (106) Moderate Load, Humid Climate Grass	2.49	0.40	0.40
GS1 (121) Low Load, Dry Climate Grass-Shrub	2.7	0.37	0.37
GS2 (122) Moderate Load, Dry Climate Grass-Shrub	2.7	0.37	0.37
GS3 (123) Moderate Load, Humid Climate Grass-Shrub	2.7	0.37	0.37
TU1 (161) Low Load Dry Climate Timber-Grass-Shrub (Hardwood)	10	0.10	0.10
TU2 (162) Moderate Load, Humid Climate Timber-Shrub	1.8	0.56	0.56
TL2 (182) Low Load Broadleaf Litter	8	0.13	0.13
TL6 (186) Moderate Load Broadleaf Litter	10	0.10	0.10
TL9 (189) Very High Load Broadleaf Litter	2	0.50	0.50
TU1 (161) Low Load Dry Climate Timber-Grass-Shrub (Conifer)	2	0.50	1.00
TL1 (181) Low Load Compact Conifer Litter	2	0.50	1.00
TL3 (183) Moderate Load Conifer Litter	1.8	0.56	1.00
TL8 (188) Long-Needle Litter	2	0.50	1.00

[a] Published by FPA 4/27/10
[b] Calculated as: (1 / Fireline construction rate)
[c] Some weights manually adjusted based on visual examination of tests in ArcGIS.

integer values on a 0 to 100,000 scale, and another that is classified into five WFP classes. To create the first of these, we multiply the original 0 to 10 floating point values by 10,000, then round to the nearest integer. This preserves four decimals of precision in the original output, but converts values to integer format, which makes the file size of the resulting raster layer much smaller and more manageable. This is the Continuous WFP product (figure 10).

We evaluated a number of ways to classify the Continuous WFP into the following five WFP classes: very low, low, moderate, high, and very high. The values in the Continuous WFP are heavily skewed toward lower values, with a long tail extending out to very high values (figure 11a). Because of this distribution, we found it helpful to visualize the distribution on a natural log scale (figure 11b), and pursue class breaks based on percentiles. Conceptually, we started with the idea that land managers have limited resources for strategic fire management efforts such as fuels treatment and positioning of suppression assets, and need to be able to focus those efforts where they are most needed. Therefore, our goal was to derive a classification that placed most of the landscape into very low, low, and moderate WFP classes and constrained the high and very high WFP classes to the upper tail of the distribution, thus highlighting the areas of greatest concern for management. We classified the Continuous WFP using a variety of percentile breaks (table 4), each time evaluating the resulting map visually in ArcGIS and tabularly with a summary of acres in each WFP class. Ultimately, we determined the following percentile breaks best met our objectives: very low to low at 44th percentile; low to moderate at 67th percentile; moderate to high at 84th percentile; high to very high at 96th percentile (table 4, trial 4). The logic behind these class breaks was:

- $^2/_3$ of total area should be in the very low or low WFP classes
  - of that, $^2/_3$ is in very low and $^1/_3$ is in low
- the remaining $^1/_3$ of total area has moderate, high, and very high WFP
  - of that, ½ is in the moderate class
  - the remaining ½ (of the upper $^1/_3$) is divided as follows:
    - $^2/_3$ is in the high class
    - $^1/_3$ is in the very high class (see inset in figure 12).

The final step in processing the Classified WFP was to add in water and other non-burnable land cover types. To do this, we used the LANDFIRE FBFM40 layer and selected the water class (NB8) and all non-burnable fuel models (NB1—urban or suburban development; NB2—snow/ice; NB3—agricultural field, maintained in non-burnable condition; and NB9—bare ground).

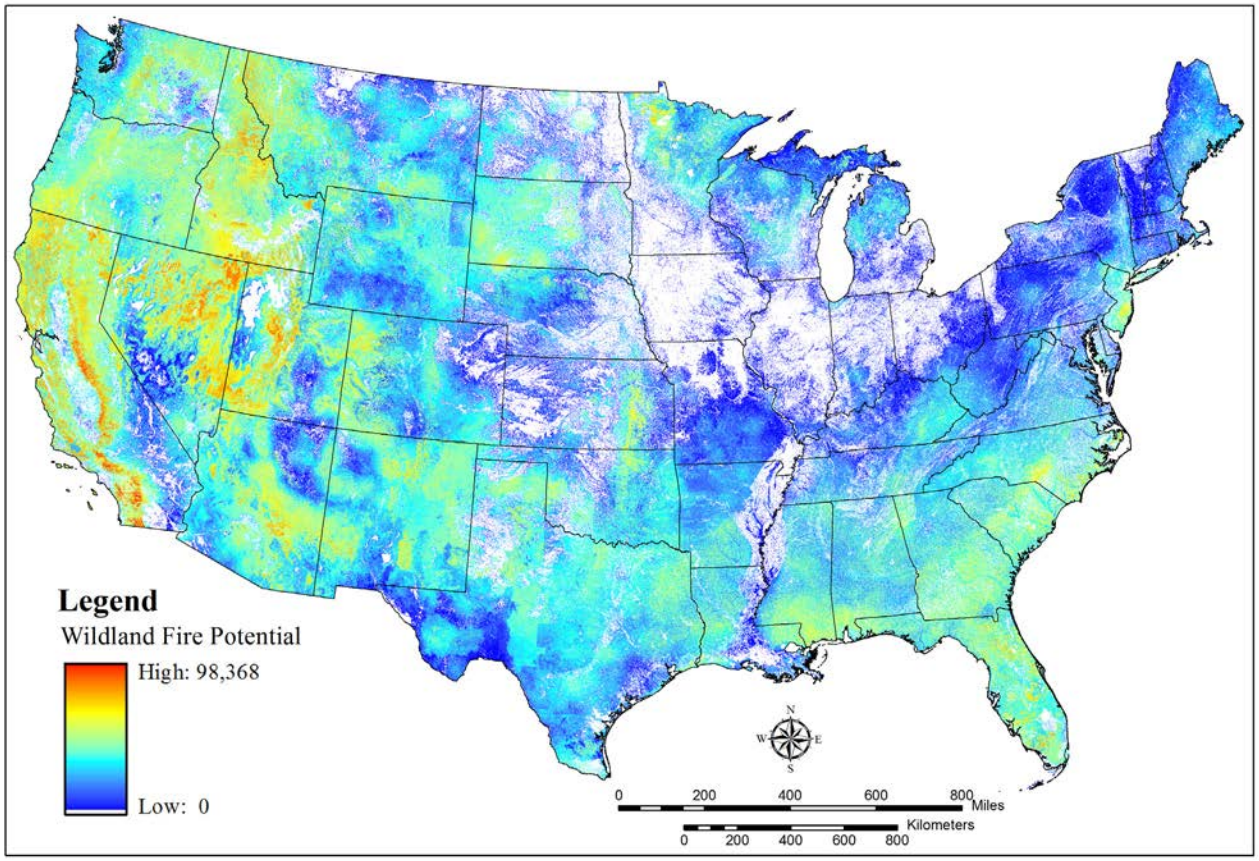

Figure 10—Map of the continuous WFP index. Values are displayed here using a 32-class geometrical interval classification (ESRI 2011) to maximize visual differentiation of values, given the strongly skewed distribution.

Data Products

The continuous WFP index has values that range from zero (primarily developed, agricultural, and unvegetated areas where the modeled burn probability was zero) to 98,368 (figure 10). The distribution of continuous WFP values is very positively skewed, with over 95 percent of values less than 2,000 (figure 11a). Spatially, the highest WFP values are most heavily concentrated in the eastern foothills of the Sierra Nevada Mountains, as well as the transverse and peninsular ranges, in California; and in the mountain ranges of northern and eastern Nevada and central and southeastern Utah. High WFP values are also scattered throughout other western states, as well as a few locations in the upper Midwest (northern Minnesota) and Southeast (Florida).

The classified WFP product provides a simplified and more interpretable view of relative wildland fire potential, with its five classes ranging from very low to very high potential (figure 12). The high and very high WFP classes, which represent the long upper tail of the continuous WFP distribution, are most abundant in the mountains of California, Nevada, Idaho, and other western states, but 22 states have a total of over 1,000,000 acres (most over 2,000,000 acres) in these two WFP classes combined (table 5). Notable areas outside the mountainous west with areas of high and very high WFP include pine forests throughout the Gulf and Atlantic Coastal Plain, the Pine Barrens in New Jersey, tallgrass prairie in the Flint Hills of Kansas, and northern boreal forests in northern Minnesota (figure 12).

Notably, the percentage of total area in each of the mapped WFP classes does not match exactly with the percentile values used to assign classes (table 6). The very high WFP class accounts for approximately 4 percent of the total (compared to an expected 5 percent, using a 95th percentile threshold), while the high and very high classes combined account for approximately 12 percent (compared to an expected 16 percent). These discrepancies are the result of adding in the non-burnable and water classes after evaluating the percentile breaks in the continuous WFP index. Additionally, the proportions of mapped area in different WFP classes on National Forest System (NFS) and Department of Interior (DOI) lands are quite different from proportions on all lands (table 6). The moderate, high, and very high classes are proportionally more abundant on NFS lands, while the very low and non-burnable classes are much more prevalent when considering all lands.

We completed development of the continuous and classified WFP products in late 2012, and made them available online in February 2013. Visitors to the WFP website (http://www.firelab.org/project/wildland-fire-potential) can download the raster geospatial data for either the

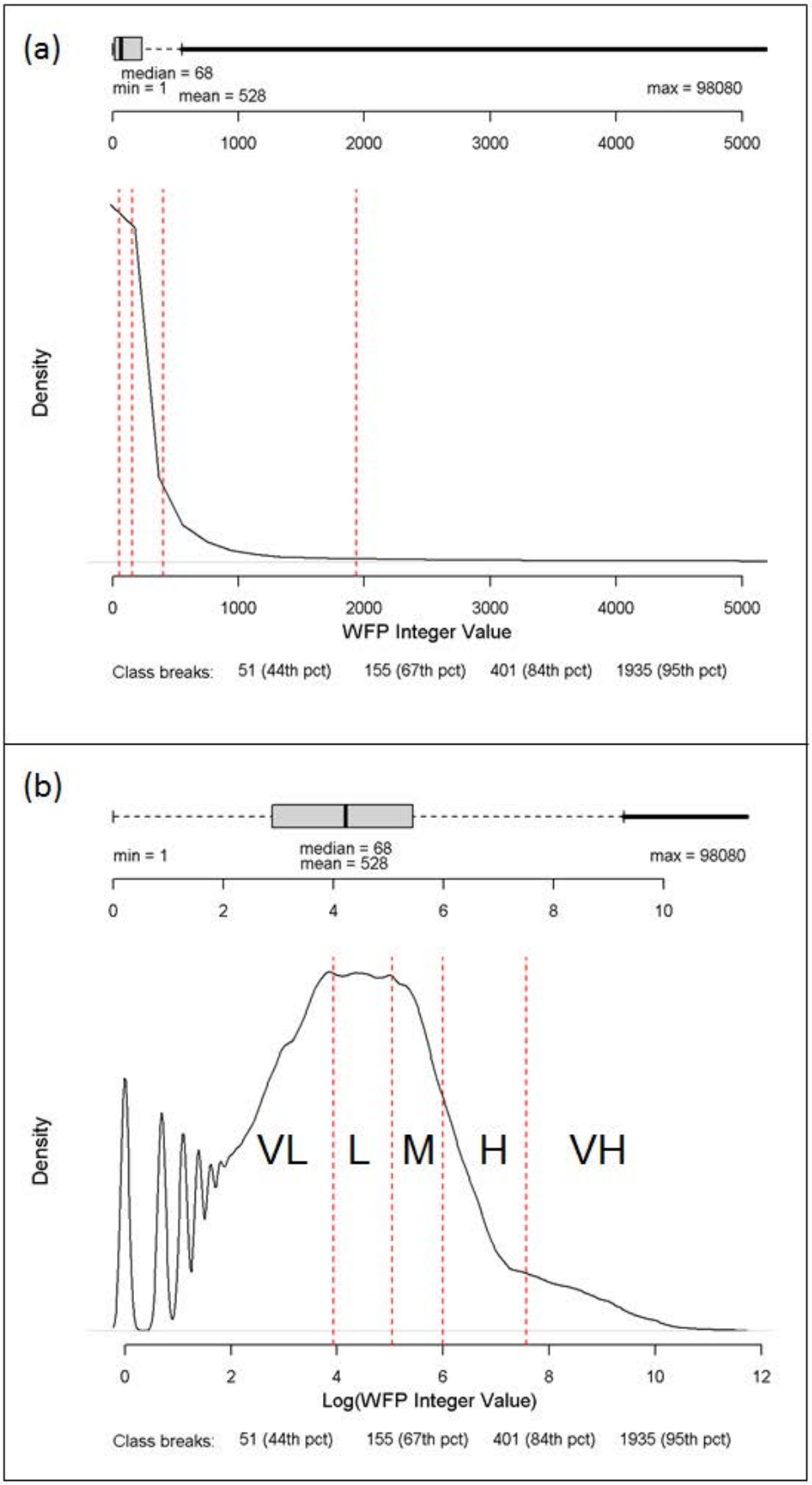

Figure 11—Boxplots and probability density curves (histograms) of continuous integer WFP values: (a) on the original measurement scale, and (b) on a natural log scale. Values in (a) are strongly skewed toward the lower end of the range, with over 95% of values less than 2,000. The upper tail in (a) is truncated at 5,000 for the purposes of this figure, but the full distribution extends to more than 98,000. Log-transformed values in (b) are much more normally-distributed. Plots shown here are from a sample of 10,000,000 pixels from the CONUS map. The shaded box in the box plots depicts the inter-quartile range and the vertical black hash mark is the median. Dashed red lines on the histograms show class breaks used in creating the classified WFP map. Integer WFP values for class breaks along with corresponding percentiles are given along the bottom.

Table 4—Different percentiles and corresponding integer WFP values tested for determining class breaks for the Classified WFP. The selected trial is highlighted.

	Very Low to Low		Low to Moderate		Moderate to High		High to Very High	
Trial	percentile	value	percentile	value	percentile	value	percentile	value
1	33	29	66	148	90	697	97	3848
2	33	29	66	148	85	433	95	1935
3	50	68	75	232	88	562	96	2658
4	44	51	67	156	84	401	95	1935
5	44	51	67	156	89	623	96	2658
6	23	16	67	156	93	1123	99	9668

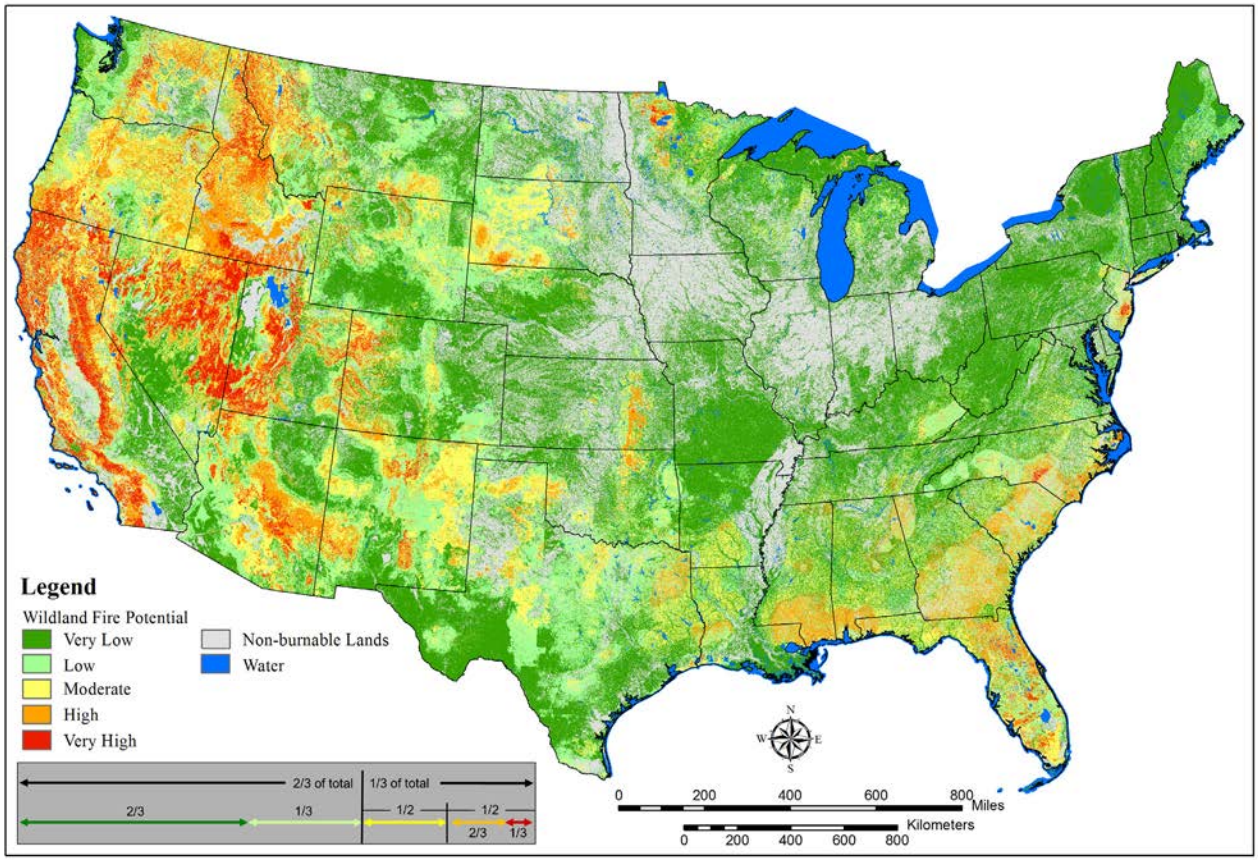

Figure 12—The classified Wildland Fire Potential map. Non-burnable areas on the map are from non-burnable fuel models in the LANDFIRE 2008 40-fuel-model layer, and may in some cases actually include agricultural lands capable of burning. The box inset in the lower left visually depicts the logic used to partition continuous WFP values into the five classes.

continuous or classified WFP products. Map graphics, spatial metadata, and other descriptive information are also available. The classified WFP raster data are also available as a map service from Environmental Systems Research Institute (ESRI) through their ArcGIS online website (ESRI 2013a), and can be viewed interactively on ESRI's Wildfire Public Information Map (ESRI 2013b).

Intended Uses and Applications of the WFP

The WFP map is a raster geospatial product that is intended to be used in analyses of wildfire risk or prioritization of fuels management needs at very large landscapes (millions of acres). On its own, WFP is not an explicit map of wildfire

Table 5—Area in the high and very high WFP classes, sorted in descending order by state, for the 23 states with over 1,000,000 acres in those two WFP classes.

		WFP Area (Millions of Acres) [a]		
Rank	**State**	**High**	**Very High**	**Sum**
1	California	14.18	21.19	35.37
2	Nevada	13.54	13.95	27.49
3	Idaho	17.23	7.64	24.87
4	Oregon	12.69	3.44	16.12
5	Utah	7.72	7.82	15.54
6	Arizona	10.85	3.10	13.96
7	Montana	6.49	3.97	10.46
8	Florida	7.52	1.73	9.25
9	Georgia	8.78	0.11	8.88
10	New Mexico	6.57	1.73	8.31
11	Washington	5.36	1.78	7.14
12	Colorado	5.30	1.58	6.88
13	Texas	4.96	0.24	5.20
14	Mississippi	5.05	0.08	5.13
15	South Carolina	4.91	0.05	4.96
16	North Carolina	4.06	0.38	4.45
17	Alabama	3.10	0.02	3.12
18	Wyoming	2.28	0.76	3.04
19	Minnesota	2.27	0.61	2.89
20	South Dakota	2.51	0.18	2.69
21	Oklahoma	2.24	0.11	2.35
22	Louisiana	1.95	0.01	1.96
23	Kansas	1.92	0.02	1.94

[a] Area is given in millions of acres, based on counts of 270 m pixels (each approximately 18 acres).

Table 6—Relative area in different WFP classes for US National Forest System lands, Department of Interior lands, and all lands in CONUS.

	National Forest System Lands			Department of Interior Lands [a]			All Lands	
WFP Class	**Area [b]**	**Percent**	**Percent of All Lands**	**Area [b]**	**Percent**	**Percent of All Lands**	**Area [b]**	**Percent**
Very Low	34.60	20%	2%	75.02	27%	4%	661.60	33%
Low	30.49	18%	2%	58.26	21%	3%	324.50	16%
Moderate	41.50	24%	2%	49.67	18%	2%	238.13	12%
High	35.26	21%	2%	38.84	14%	2%	154.85	8%
Very High	22.98	13%	1%	22.66	8%	1%	70.98	4%
High + Very High	58.24	34%	3%	61.50	22%	3%	225.82	12%
Non-burnable	4.86	3%	0%	27.42	10%	1%	442.19	22%
Water	0.66	0%	0%	2.55	1%	0%	102.99	5%
Total	170.36	100%	9%	274.42	100%	14%	1,923.22	100%

[a] Department of Interior Lands include: Bureau of Indian Affairs, Bureau of Land Management, Bureau of Reclamation, National Park Service, and US Fish and Wildlife Service.
[b] Area is given in millions of acres, based on counts of 270 m pixels (each approximately 18 acres).

threat or risk, but when paired with spatial data depicting appropriate HVRAs, it can spatially approximate relative wildfire risk to those specific resources and assets. However, this would only be appropriate for HVRAs where our weighting scheme for suppression difficulty is similar enough to the expected fire effects to serve as a proxy HVRA response function. In other words, WFP as a risk product is only suitable for HVRAs without any possible beneficial effects of fire, and where losses increase steeply with increasing fire intensity. Specifically, human communities that include built structures, infrastructure assets such as powerlines, and habitat areas for certain fire-sensitive species are examples of HVRAs that have this type of wildfire response function (Thompson and others 2013a). It is therefore critical to stress that using WFP as a stand-alone risk map across multiple HVRAs will tend to overestimate losses, and completely ignore beneficial fire.

The primary intended use of the WFP map, however, is for identifying priority areas for hazardous fuels treatments from a broad, national- to regional-scale perspective. The classified WFP product, in particular, allows for relatively quick identification of the land area within different geographic units (States, Forest Service regions, individual National Forests) with fuels that could present problems for wildfire suppression efforts or certain HVRAs under wildfire conditions. A manager or decision maker can quickly evaluate, therefore, the relative scope of fuels management work required in different geographic areas, and make informed decisions about allocation of funding and resources. Further, with the addition of spatial data depicting particular HVRAs or high-priority management concerns, these types of evaluations can be tailored to reflect agency fuels management priorities.

An example of Forest Service use of the WFP map to date is the identification of the total area nationally, and among Forest Service regions, at high priority for fuels treatment based on three goals from the National Cohesive Wildland Fire Management Strategy: 1) fire-adapted communities, 2) resilient landscapes, and 3) safe, effective fire response (WFLC 2014). From the WFP map alone, we can identify that roughly 58.24 million acres (34 percent of NFS lands) have either high or very high WFP, and could be considered as candidate areas for treatment. Of those, however, the highest priority acres are those where fuels treatments can achieve one or more of the Cohesive Strategy goals and are operationally feasible. Therefore, we incorporated several additional spatial datasets into our analysis:

- A spatial buffer zone around residentially developed areas, derived from a 2 km circular focal mean (moving window raster neighborhood analysis) of the national Residentially Developed Populated Areas (RDPA) dataset (Haas and others 2013). This zone reflects areas meeting both the fire-adapted communities and safe, effective fire response goals.
- High value watersheds for municipal surface drinking water supply, defined by 12-digit Hydrologic Unit Code (HUC) watersheds with a Forests to Faucets surface drinking water importance index of 70 or higher (Weidner and Todd 2011). These watersheds represent an important ecosystem service provided by Forest Service lands to neighboring human communities, and fuels treatments could help support both fire-adapted communities and resilient landscapes.
- Historic Fire Regime Groups from LANDFIRE 2008 (http://www.landfire.gov/fireregime.php), useful for identifying fire-adapted vegetation communities that experienced relatively frequent low- to mixed-severity fire historically (Fire Regime Groups I, II, and III). Treatments in these areas can help to advance the goal of resilient landscapes, as well as facilitating safe and effective response to future wildfires.
- Designated Wilderness and Roadless areas on NFS lands. As lands either congressionally (Wilderness) or administratively (Roadless) designated as places where mechanical treatment is restricted or prohibited, we removed them for consideration as high priority treatment areas (although prescribed fire could be used in either under the right circumstances).

Intersecting these spatial datasets with the classified WFP allowed us to develop categories reflecting different fuels treatment priority levels. Only considering areas within either the RDPA buffer zone or high-value watersheds, we identified the following categories:

1. High or Very High WFP, outside of Wilderness and Roadless, in Fire Regime Group I, II, or III. These are the highest priority areas (red on figures 13 and 14).
2. High or Very High WFP, outside of Wilderness and Roadless, in Fire Regime Group IV or V. These are acres where treatments might advance community or watershed protection objectives, but would be counter to the natural fire ecology of the vegetation, which would have been marked by infrequent, largely stand-replacement fire (pink on figures 13 and 14).
3. Very Low, Low, or Moderate WFP, outside of Wilderness and Roadless, in Fire Regime Group I, II, or III. These are acres that may not currently have hazardous fuels conditions, but based on the historic fire regime group they could move into high or very high WFP over time without treatments or disturbances to maintain the current condition. These are not the highest priority areas, but should be watched closely over time (yellow on figures 13 and 14).
4. All other areas that are either in Wilderness or Roadless, or have Very Low, Low, or Moderate WFP in Fire Regime Groups IV or V. At a National or regional scale, these would not be priority acres for treatment but local analysis might reach a different conclusion (green on figures 13 and 14).

Using this analysis, we identified 11.3 million acres of NFS lands in CONUS as being high priority fuels treatment areas (category 1 above). The distribution of these acres among Forest Service regions (figure 14) can help to inform managers of the relative fuels treatment workloads, and therefore guide allocation of budgets and resources. A

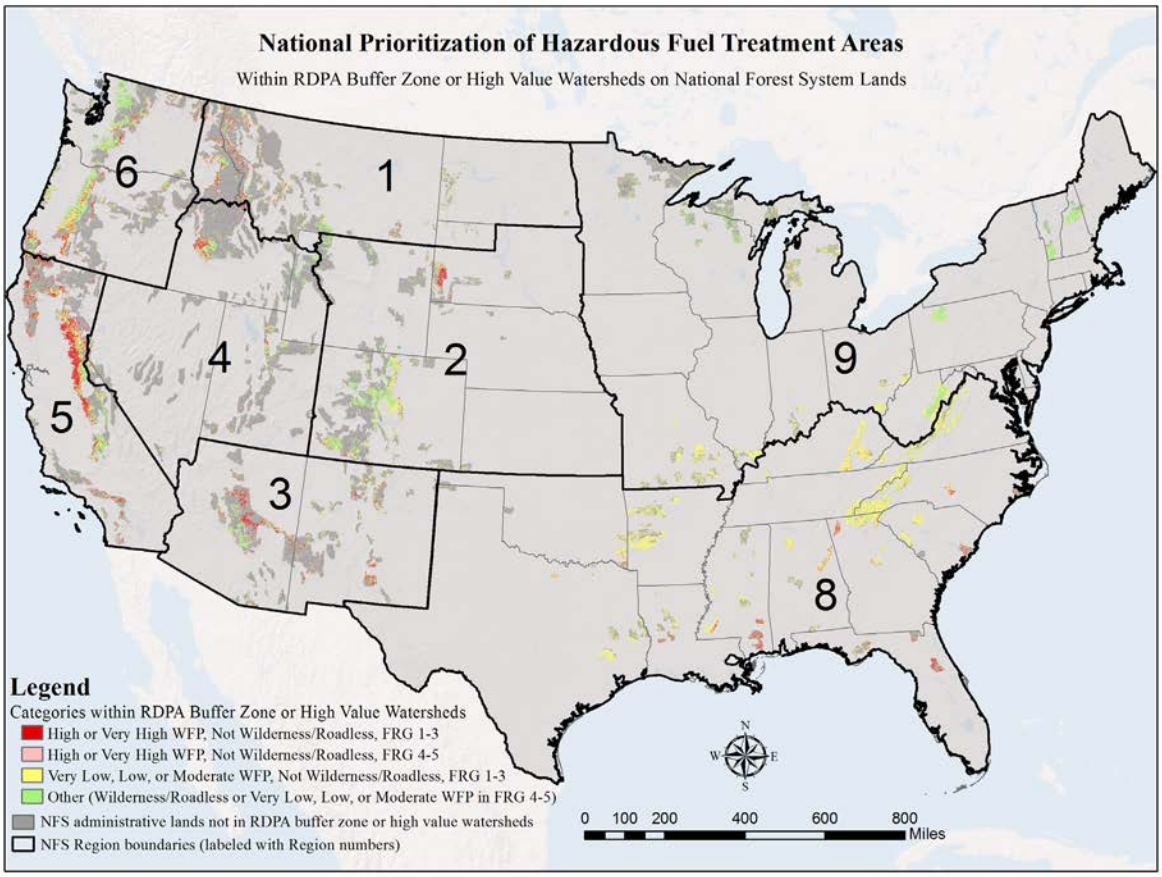

Figure 13—Map of the results from an analysis using the classified WFP along with other spatial data to conduct a national-scale prioritization of possible fuels treatment areas on National Forest System lands in the conterminous US. Based on this analysis, red areas on the map represent the highest priority and green represent the lowest priority.

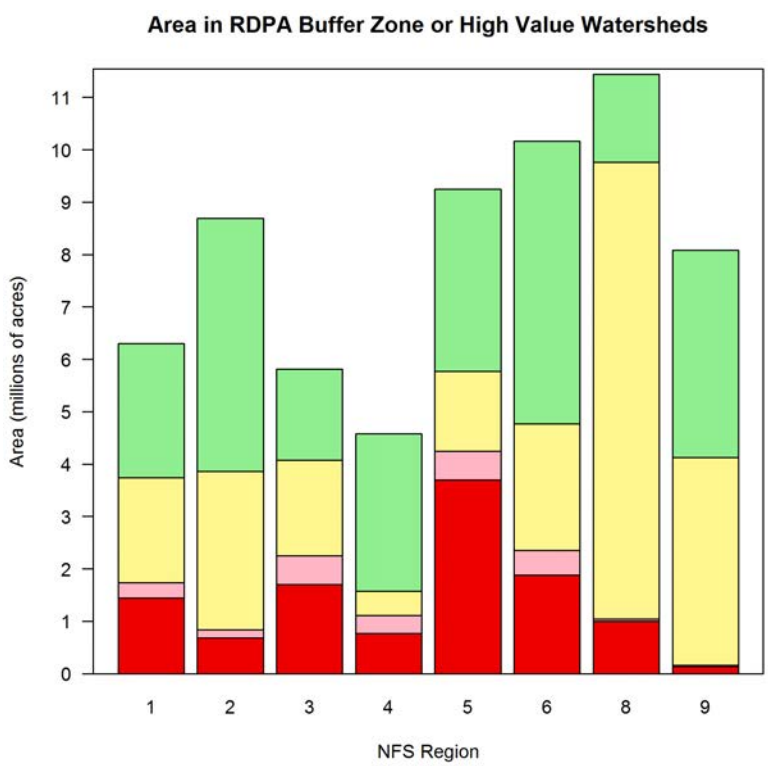

Figure 14—Land area within either residentially developed populated area (RDPA) buffer zones or high value watersheds on National Forest System lands, by Forest Service regions (x-axis). Colors in the bars correspond to map colors in figure 13, and represent land in different categories of fuels treatment priority. Red represents the highest priority areas and green represents the lowest priority for treatment.

risk-based analysis such as this, however, is just one of many factors that managers must consider in making these types of allocation decisions. Further, placement of actual treatments on the ground must be determined by local analyses, possibly using similar methods but factoring in critical local information that is too fine-scale for this type of national assessment (Calkin and others 2011).

Next Steps

The WFP map will be updated in the future as new LANDFIRE fuels and vegetation data, and subsequently national-scale wildfire simulation products, become available. The current 2012 WFP version was created with LANDFIRE 2008 data and wildfire simulation outputs generated from those data in 2012. The LANDFIRE 2010 data were released in 2013, and the latest FPA FSim runs using those data were completed in the spring of 2014. Therefore, a 2014 version of the WFP is imminent and will likely be released in the fall of 2014.

It is important to note that the WFP is not a forecast or wildfire outlook for any particular season, as it does not include any information on current or forecasted weather or fuel moisture conditions. The year associated with any version of the WFP indicates the year in which the map was produced, using the best available data at the time. In the case of the 2012 WFP, it reflects a 2008 landscape because that is the vintage of LANDFIRE data that were used in its creation. This is in contrast to the monthly and seasonal "significant wildland fire potential outlook" products produced by the Predictive Services program of the National Interagency Coordination Center and Geographic Area Coordination Centers, which are based on weather and fuel moisture forecasts.

In future versions of our map, beginning with the 2014 version, we plan to change the name from the Wildland Fire Potential (WFP) to the Wildfire Hazard Potential (WHP). By making this name change, we intend to avoid confusion between our product and the Predictive Services outlook products, and also to align better with standard wildland fire and risk assessment terminology (NWCG 2014, Scott and others 2013). The estimates of burn probability and intensity from FSim represent simulations of *wildfires*, as opposed to the more generic term *wildland fire*, and the integration of probability and intensity reflects the *hazard* posed by wildfires. Thus, we also feel that Wildfire Hazard Potential will be more descriptive of what the map really depicts.

Lastly, despite the temptation to compare subsequent versions of the WFP to indicate changes in fuels conditions across the landscape, we must caution against doing this. As mentioned previously, there have been significant changes in data quality, wildfire simulation methods, and WFP mapping methods between previous 2007 and 2010 WFP versions and the current 2012 version. While the mapping and modeling methodologies are stabilizing somewhat, we still anticipate some minor changes in future versions. Development of wildfire simulation outputs and subsequent products like the WFP map is an evolving science, and will continue to change as our knowledge advances.

Acknowledgments

The current wildland fire potential product has benefitted from the contributions of many individuals. For their critical contributions of wildfire simulation products and the wildfire risk assessment framework upon which this work rests, we particularly thank Mark Finney, Karen Short, and Matt Thompson of the USDA Forest Service, Rocky Mountain Research Station, and Joe Scott with Pyrologix LLC. Chuck McHugh (USDA Forest Service, Rocky Mountain Research Station) and Karin Riley (formerly Systems for Environmental Management) also provided valuable input during development of earlier WFP versions. We are grateful to Matt Thompson, Karen Short, and one anonymous reviewer for their thoughtful comments on earlier versions of this manuscript. This work was supported by the USDA Forest Service, Fire and Aviation Management through the Rocky Mountain Research Station, Fire Modeling Institute.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

An Analysis of Large Chaparral Fires in San Diego County, California

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Abstract—*San Diego County, California, holds the records for the largest area burned and greatest number of structures destroyed in California. This paper analyzes 102 years of fire history, population growth, and weather records from 1910 through 2012 to examine the factors that are driving the wildfire system. Annual area burned is compared with precipitation during the winter preceding the summer–fall fire season and with a five-year running average precipitation. All fires over 4 000 ha from 1950 through 2012 are examined for fuel age at the section of origin, fuel type, and weather, including the presence or absence of foehn winds. The burning characteristics between chaparral and Coastal sage scrub are examined. Annual precipitation was found to have no relationship to the annual area burned. Population increased over 50 times but mean area burned showed no statistical increase. Young chaparral (>20 years)age was shown to constrain the spread or wildfire while coastal sage scrub showed less resistance to fire at any age. Old age chaparral was significant of large wild fires.*

Keywords: *chaparral, conflagration, fire behavior, fire history, fuel age*

Introduction

San Diego County, California USA, holds many dubious records in the history of California wildfires, including the largest fire by area and greatest number of structures destroyed in a single fire (Cedar Fire 2003; 110 579 ha or 273 250 acres; 4 847 structures). Unfortunately, wildland fire policy is heavily influenced by anecdotal evidence and "common sense." Annually, the press is filled with predictions of a severe fire season. Yet not all fire seasons are severe. Not all drought years or years with strong foehn-type winds result in destructive fires. Some observers blame changing climate for large fires, but are climate and large fires related in southern California? In this paper, I attempt to answer that question by analyzing 102 years of fire history and weather records from 1910 through 2012 to examine the factors that drive the chaparral wildfire regime.

I compared the annual area burned with precipitation occurring during the water year preceding the summer-fall fire season and also with a five-year running average water year precipitation. All fires over 4 000 ha from 1950 through 2012 were examined for fuel age near the fire's origin, fuel type at that location, and weather including the presence or absence of foehn winds. The alignment of the topography of San Diego County with normal sea breeze and foehn winds may also help explain the spread of some large fires.

Objectives

The objectives of this project are to: 1) determine if young chaparral has constrained the spread of wildfires based on the historical database of the California Department of Forestry and Fire Protection (FRAP 2012); 2) quantify the relationship of annual precipitation to summer fire season severity; 3) investigate the relation of increasing human population density to anthropogenic area burned; and 4) analyze the similarities and differences between shrubland fuels.

Materials and Methods

Study Area: San Diego County

San Diego County, California, is the most southwestern county in the United States. It is bordered by Mexico to the south, Imperial County to the east, Riverside and Orange Counties to the north, and the Pacific Ocean to the west. Elevation ranges from sea level to over 1990 m (6 500 feet) along the peninsular range in the eastern county before dropping to below 200 m (600 feet) in the eastern desert. The climate is Mediterranean, with warm dry summers and moist cool winters. Mornings in spring and summer are characterized by a strong marine, atmospheric boundary layer along the coast that usually dissipates by late morning. Climate zones are as follows:

- **Maritime**. Lands generally less than 150 m (500 ft) elevation, within 13 km (8 mi) of the coast, dominated by ocean conditions, moderate temperatures and coastal fog.
- **Coastal plain.** Lands 13 to 50 km (8 to 30 mi) from the coast with less maritime influence and increasing diurnal and seasonal temperatures.
- **Transitional.** Also called the inland valleys and foothills with elevations up to 1200 m (4 000 ft) and diurnal and seasonal temperatures greater than the coastal plain.
- **Interior or Mountain.** Much diminished marine influence, air is warm and dry in summer with poor overnight

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Table 1—Generalized Vegetation Cover Type.

Cover Type	Hectares	Acres	Percent
Chaparral	341 847	844 692	55
Coastal Sage Scrub	115 657	285 785	19
Coniferous Forest	6 273	15 500	1
Grasses	79 959	197 576	13
Mixed Conifer/Hardwood Woodland	17 858	44 127	3
Oak Woodland	58 810	145 318	9
TOTAL	620 404	1 532 997	100

(California Land Cover Mapping and Monitoring Program. 1997)

humidity recovery, winter snows, and the marine layer is rare in summer.

- **Desert.** Extreme temperatures, strong winds, and dry air.

The county is divided into three general zones; the coastal plain, inland mountains, and desert. Northeast/southwest trending rivers drain the mountains to the coast. The county is seismically active with two major active faults, the Elsinore and the San Jacinto in the mountain regions, and the San Andreas near the Salton Sea, east of the county.

Native vegetation (excluding desert) covers 620 404 ha (1 533 050 acres) or 55 percent of the total county. Of that area, shrublands comprise about three quarters of all burnable lands (74% - 457 503 ha or 1 130 514 acres) (Table 1).

History

The area presently called San Diego County has been inhabited by humans for over 10 000 years. At the time of European contact, numerous tribes lived, hunted and gathered here including the Kumeyaay in the south, the Luiseño at the north coast and the Cahuilla and Cupeño in northern inland and desert portions. These Native Americans hunted small game, gathered acorns and seeds, fished, and used fire to manage the lands. While it is debatable how much the Native American contributed to the state of the vegetation at the point of European contact, it is safe to say that they did cause frequent fire ignitions that likely had a major impact on the vegetation patterns (Biswell 1974; Anderson 2006; Stewart 2002; Lightfoot 2009). The Governor's proclamation in 1793 is illustrative:

> *"With attention to the widespread damage which results...I see myself required to have the foresight to prohibit...all kinds of burning, not only in the vicinity of the towns, but even at the most remote distances... Therefore I order...to take whatever measures they may consider requisite and necessary to uproot this very harmful practice of setting fire to pasture lands...and in case some burning occurs, they are to try immediately to...stop the fire, or failing that, to direct it into another direction which may result in less damage... "*
>
> Given in Santa Barbara, May 31, 1793.
>
> Don Jose Joaquin de Arrillaga, captain of cavalry, interim governor and inspector comandante of Upper and Lower California (Arrillaga 1793).

The arrival of the Spanish brought many changes to San Diego. European annual grasses and forbs replaced many of the native herbs and forbs. Cattle and sheep grazed the pastures, roads and farms acted as firebreaks, and Indians were removed to reservations (Wade 2009). Fire exclusion became the norm and in 1910, the Forest Service, followed by the California Division of Forestry, began active fire suppression. Simultaneously, burning by ranchers to increase grass production was halted. The changes in the chaparral and forest ecosystem were gradual. Likely, the mosaic of uneven aged fuels initially acted to retard the growth of fires. By the 1920s, large fires were becoming common (FRAP 2012).

Precipitation

Monthly precipitation records are available for the San Diego's Lindbergh Field dating back to 1850. For this study, precipitation data were converted from calendar years to water years (October 1 through September 30) (WRCC 2014). Precipitation occurs in the winter, usually beginning in late October through April, and falling as rain except in the mountains above 1200 m (4000 ft) (Figure 1). Monsoon type summer thunderstorms occur mostly in the mountains and deserts but occasionally spread to the coast. Rainfall is highly variable. The annual average for the period 1910-2012 recorded at Lindbergh Field, San Diego, was 257 mm (10.12 in) with a maximum of 636 mm (25.04 in), minimum 84 mm (3.31 in), and standard deviation of 106 mm (4.17 in). Average annual precipitation was 250 mm (9.84 in) on the coastal plain, 400 mm (15.75 in) in the inland valleys, 575 mm (22.64 in) in the interior, 920 mm (36.22 in) on the higher mountains, and 1100 mm (43.31 in) on south facing Palomar Mountain (SanGIS/SANDAG 2004).

Precipitation records are available from 1948 through 2006 for Campo, CA (WRCC 2014a) and Lake Cuyamaca Dam (WRCC 2014b). Simple linear regression showed a strong relationship between Lindbergh, Campo ($R^2 = 0.16$, $P = 0.0018$), and Cuyamaca Dam ($R^2 = 0.21$, $P = 0.0003$).

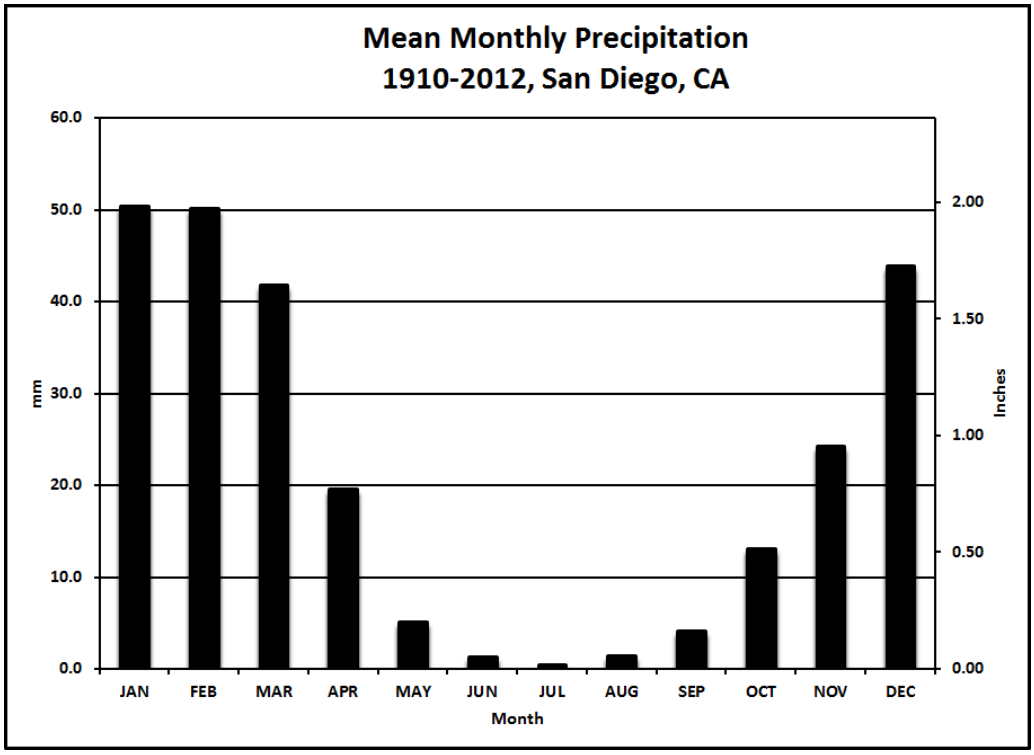

Figure 1—Annual Precipitation at San Diego Airport (Lindbergh Field).

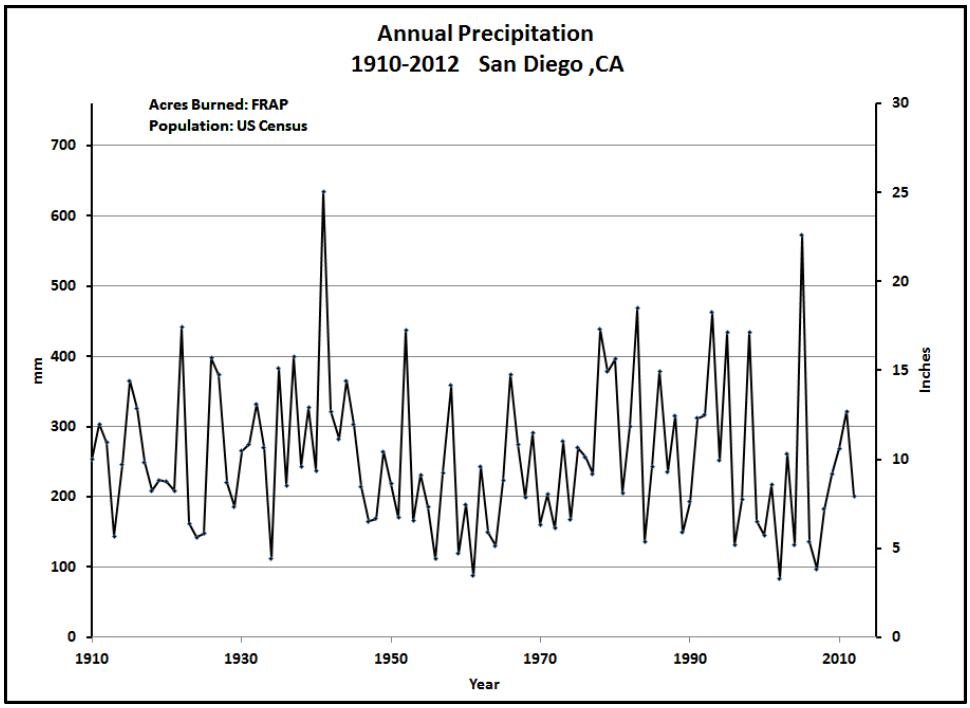

Figure 2—Mean precipitation = 256.8 mm (10.11 inches).

Thus, data from Lindbergh Field can be used as a surrogate for determining wet or dry years for the entire county's burnable areas (Figure 2).

Fire Weather

Large fires occur generally during foehn (Santa Ana) wind events or during Pacific High heat waves. Santa Ana winds, caused by high pressure in the Great Basin, may occur in southern California during the fall, winter, and spring. They do not generally occur in July, August and early September (Figure3) (Countryman 1974; Raphael 2003; Minnich and Chou 1997). Due to compressional heating of air as it descends over the mountains toward the coast, Santa Ana winds are generally hot and dry. However, regression analysis of the number of Santa Ana events (mean = 20; P = 0.666) or the duration of the events (mean 1.5 days; P = 0.195) shows no correlation with annual area burned.

Table 1 –*Number of Santa Ana periods by months southern California 1951-60*

Month	Frequency	Average days
September	11	4.4
October	19	4.5
November	26	5.0
December	18	3.7
January	7	1.7
February	10	1.9
March	17	2.5
April	8	1.8
May	7	1.4
June	4	4.5
July	2	2.5
August	0	0

Figure 3—Santa Ana wind frequency by month from Countryman 1974.

Table 2—Area Burned by Primary Fire Spread Driver.

Spread type	Area Burned		Percent
	Hectares	Acres	
Fuel	92 750	229 181	17
NE wind	256 871	634 718	48
Wind Maxima	14 273	35 267	3
Wind/Fuel	169 142	417 944	32
Total	533 035	1 317 110	100

Another weather pattern that heightens fire danger in San Diego County is the summer heat wave, which is caused by an area of high pressure over the western United States resulting in high temperatures, low humidity and unstable air (Schroeder and Buck 1970).

Monsoonal moisture from the Gulf of California can produce dry lightning that can ignite more fires than suppression forces can hold during initial attack. Lightning fires tend to be in remote, roadless areas that increase the complexity of successful initial attack. Low level wind maxima (low level jet) winds were responsible for large fire spreads on August 22, 1969 (Ryan and others 1971) (Table 2).

For our purposes in this analysis, fires over 4 000 ha since 1950 were classified as to fuel driven, wind driven, or both. Fuel driven may, in actuality, mean "not wind driven" as topography may play a large role and in some cases fuel driven is synonymous with plume dominated fires. The wind/fuel class was added for fires after 2003 when the first day of burning was foehn wind driven followed by three hot dry days of prevailing southwesterly winds. The Cedar Fire of 2003 first spread to the west, then winds reversed. The heel of the fire became the head and spread fire to the east until it reached the 2002 Pines burn and halted (Johnson, 2003).

Population Growth

Some have suggested that the increase in population is responsible for the alleged increase in area burned. Since 1910, the population of San Diego County has increased 50 times. Annual area burned shows no statistically significant increase (Figure 4).

Vegetation

Over 600 000 ha (1.5 million acres) of native vegetation covers San Diego County east of the urbanized area and west of the desert. Fingers of vegetation extend into the developed areas as riparian areas and open space. Approximately 70% of the eastern county is owned by the public and administered by the Cleveland National Forest, US Bureau of Land Management, US Fish and Wildlife Service, California Department of Fish and Wildlife, California State Parks, San Diego County Parks, and others. The majority of these public lands are managed for environmental, open space, and recreational use (SanGIS 2013).

The predominant vegetation type is chaparral, followed by soft chaparral or coastal sage scrub (CSS). While they are both shrub-type plant communities and have been considered together by some, they are distinctly different in their burning characteristics (Keeley 2005). The time since last fire needed for chaparral and CSS to become capable of propagating fire is significantly different. CSS shrubs are contiguous from the ground to the tops of the crowns and burn similar to grass. Chaparral shrubs have a distinct crown with fine litter on the ground. Chaparral burns in a continuous crown fire but as burning conditions moderate, fire will drop to the ground and stop spreading.

Healthy CSS communities can grow back in 5 to 10 years, usually interspersed with grass, and can be reburned after five years of post-fire growth. (Figures 5 and 6). That is not the case with chaparral. Young chaparral commonly does not grow with an understory of grass, its young leaves are relatively moist, and there is little to no fine dead fuel on the plant. In the absence of high winds and very low humidity, young chaparral (<20 years) will not carry fire. (Figure 7) As chaparral ages, the amount of fine dead fuel on the shrub increases, which increases flammability (Figure 8) (Hanes 1980; Green 1981; Ottmar and others 2000).

Many analyses of fire history treat fire as a binary system—an area either burns or it doesn't burn. Chaparral burns with varying spread rates and intensities that are related to the age of the vegetation and the current weather. Young chaparral (<20 years) constrains fire spread except during periods of very strong winds with low humidity (Green 1981). Minnich and Chou (1997) found that "Fires burning in old growth tend to cease spreading when they move into adjoining younger stands for lack of fuel."

Fire spread rate is a function of the foliage and fine fuels while heavier fuels contribute to fire intensity (Andersen 1982). Ottmar and others (2000) showed that the ratio of live to dead fuel biomass on 14 year old coastal sage scrub was similar to 30 year old stands. The live to dead fuel mass for young chaparral was about 3:1, while old chaparral was 1:1 (Table 3).

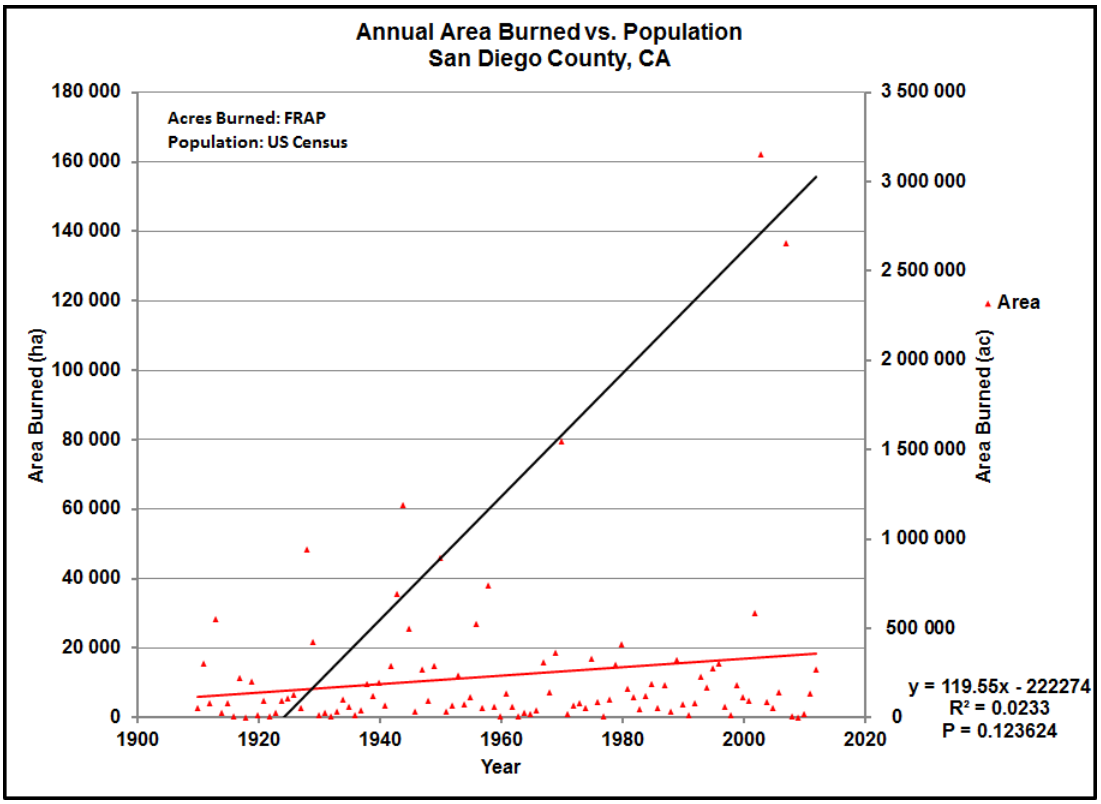

Figure 4—Significant growth in population compared to a non-significant growth in area burned.

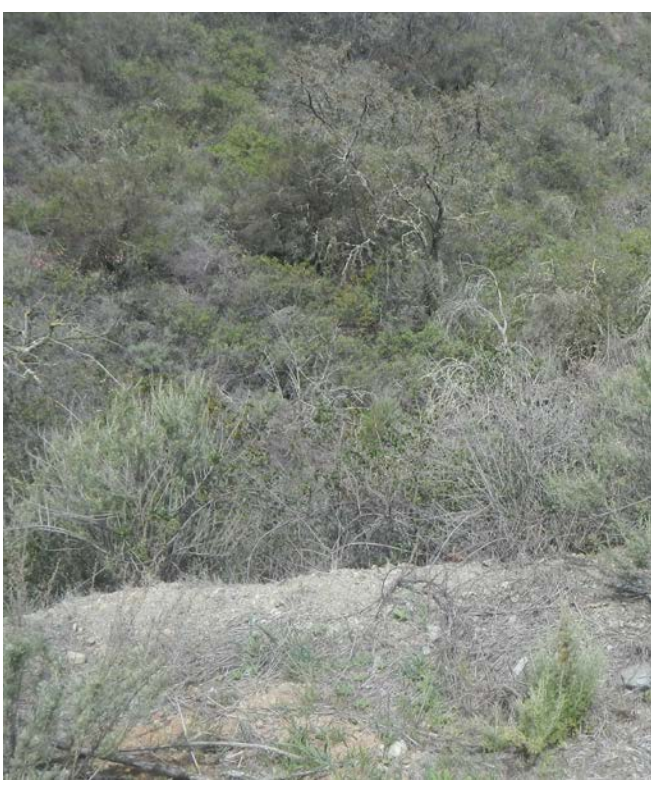

Figure 5—Young coastal sage scrub (7 years).

Fuel Age of Large Fires

The area of origin of thirty three fires over 4 000 ha (10 000 acres) during the period 1950 through 2012 was obtained from a master's thesis used by the County of San Diego to compile early fire history maps (Krausmann 1981). The type of the fuel at the origin was obtained from historic fire perimeters provided by FRAP. Some fire origins were in Riverside County for fires that burned into northern San Diego County. Four fires with ambiguous origins were not included in the study. Twenty fires had no previous fire history recorded and were logged as "greater than." (FRAP 2014).

Results and Discussion

Precipitation

Regression analysis was applied to estimate acres burned as a function of precipitation during the winter preceding the fire season. Because some have suggested that the wildfire area burned is a function of rainfall two years prior, or that long-term drought may increase area burned, regression analysis was applied to both one and two years prior to fire year. No relationship was found. Annual rainfall vs. area burned: $R^2 = 0.023$, $P = 0.227$, preceding year annual precipitation: $R^2 = 0.0014$, $P = 0.563$, and five year running average precipitation: $R^2 = .003$, $P = 0.951$.

A similar analysis was completed for Santa Barbara County and the Santa Monica Mountains. Results were

Figure 6—Old coastal sage scrub (30 plus years). Pole is 5 ft. (1.5 m).

Figure 7—Young chamise seven years since last fire. Parent plant skeleton suggest future growth size. Shovel for scale.

similar: Santa Barbara County: $R^2 = 0.0003$, $P = 0.812$; Santa Monica Mountains: $R^2 = 0.016$, $P = 0.307$.

Vegetation Age and Fire Spread

Four examples illustrate young age chaparral constraining the spread of wildfires.

The Pine Hills fire

At approximately 0600 on October 30, 1967 strong Santa Ana winds blew down a power line east of the community of Pine Hills (1 340 m or 4 400 ft), near Julian, CA during a typical foehn wind event in San Diego with strong (~15m s^{-1} or 30 m h^{-1}) dry winds out of the northeast, relative humidity in single digits, and hot daytime temperatures. The fire spread rapidly through two youth camps, skirted the south end of the community of Pine Hills and destroyed one residence. It crossed Boulder Creek Road and entered the steep, rugged, and road-less Cedar creek drainage area (Schroeder 1968).

Two hours after the Pine Hills fire started, another fire broke out near the Ramona Airport (425 m or 1 400 feet), 26 km (16 miles) west of the Pine Hills fire. In spite of being within a mile of an air tanker base, the fire escaped initial attack and spread rapidly through grass and old chaparral, climbed the eastern slopes of 882 m (2 900 feet) high Mt. Woodson, then headed downslope towards the community of Poway (Figure 9).

The Woodson Fire eventually blackened 12 060 ha (29 800 acres), destroyed 29 houses, and resulted in the first countywide mobilization of municipal firefighting resources for a wildland fire. The Pine Hills Fire was officially contained three days later after burning 2 870 ha (7 090 acres) (Figure 10).

Why did the Woodson fire burn four times the area as the Pine Hills fire?

Wind? Both fires were pushed by strong Santa Ana winds. The higher elevations tended to have longer duration of stronger winds than did lower elevations due to the effect of the afternoon sea breezes.

Temperature? Dry adiabatic compression rates would indicate about 6 °C higher temperatures at Ramona compared to Julian, but this difference is not significant to fire spread according to the Rothermel model (Rothermel 1972).

Access for firefighting? The Pine Hills fires burned into an area inaccessible to engines and too steep for dozers. The Woodson fire burned through the flat Ramona valley and down into Poway, a suburban community with ranch style homes, avocado groves, and a well-developed road network.

Figure 8—Over 100 year old scrub oak (*Quercus* sp.), ca. 25% alive. Trekking pole for scale.

Table 3—Vegetation Biomass—Coastal Sage Scrub and Chaparral.

		Loading (tons/ac) by size class (in) (live/dead)				
Coastal Sage Scrub						
14 years (Ch 02)		**Foliage**	**≤ 0.25 in**	**0.26–1.0 in**	**1.1–3.0 in**	**Total**
	Artemisia californica	0.1 (0.1/—)	0.4 (0.3/0.1)	0.1 (0.1/0.0)	0.0 (0.0/0.0)	0.6 (0.5/0.1)
	Encelia californica	0.0 (0.0/—)	0.5 (0.3/0.2)	0.1 (0.1/0.0)	0.0 (0.0/0.0)	0.6 (0.4/0.2)
	Eriogonum cinereum	0.3 (0.3/—)	1.4 (0.4/1.0)	0.1 (0.1/0.0)	0.0 (0.0/0.0)	1.8 (0.8/1.0)
	Salvia leucophylla	0.3 (0.3/—)	3.1 (2.0/1.1)	1.5 (1.3/0.2)	0.0 (0.0/0.0)	4.9 (3.6/1.3)
	Total	0.7 (0.7/—)	**5.4 (3.0/2.4)**	**1.8 (1.6/0.2)**	0.0 (0.0/0.0)	7.9 (5.3/2.6)
30 years (Ch 01)	**Species**					
	Artemisia californica	0.4 (0.4/—)	2.5 (1.2/1.3)	1.2 (0.8/0.4)	0.1 (0.1/0.0)	4.2 (2.5/1.7)
	Encelia californica	0.0 (0.0/—)	0.1 (0.1/0.0)	0.0 (0.0/0.0)	0.0 (0.0/0.0)	0.1 (0.1/0.0)
	Hazardia squarrosa	0.0 (0.0/—)	0.1 (0.1/0.0)	0.0 (0.0/0.0)	0.0 (0.0/0.0)	0.1 (0.1/0.0)
	Salvia leucophylla	0.2 (0.2/—)	0.8 (0.4/0.4)	0.4 (0.3/0.1)	0.1 (0.1/0.0)	1.5 (1.0/0.5)
	Salvia mellifera	0.2 (0.2/—)	0.3 (0.2/0.1)	0.3 (0.3/0.0)	0.0 (0.0/0.0)	0.8 (0.7/0.1)
	Total	0.8 (0.8/—)	**3.8 (2.0/1.8)**	**1.9 (1.4/0.5)**	0.2 (0.2/0.0)	6.7 (4.4/2.3)
Chaparral						
13 years (Ch 08)	**Species**					
	Adenostoma fasciculatum	2.6 (2.6/—)	3.4 (2.6/0.8)	5.1 (3.9/1.2)	0.2 (0.2/0.0)	11.3 (9.3/2.0)
	Arctostaphylos glandulosa	0.8 (0.8/—)	0.5 (0.4/0.1)	0.9 (0.6/0.3)	0.0 (0.0/0.0)	2.2 (1.8/0.4)
	Ceanothus crassifolius	0.0 (na/—)	0.0 (na/na)	0.0 (na/na)	0.0 (na/na)	tr (na/na)
	Total	3.4 (3.4/—)	**3.9 (3.0/0.9)**	**6.0 (4.5/1.5)**	0.2 (0.2/0.0)	13.5 (11.1/2.4)
55 years (Ch 09)	*Adenostoma fasciculatum*	1.0 (1.0/—)	3.3 (1.8/1.5)	4.8 (3.1/1.7)	4.8 (4.8/0.0)	13.9 (10.7/3.2)
	Arctostaphylos glandulosa	0.4 (0.4/—)	0.6 (0.2/0.4)	1.4 (1.0/0.4)	1.3 (1.3/0.0)	3.7 (2.9/0.8)
	Total	1.4 (1.4/—)	**3.9 (2.0/1.9)**	**6.2 (4.1/2.1)**	6.1 (6.1/0.0)	17.6 (13.6/4.0)

From Ottmar and others 2000.

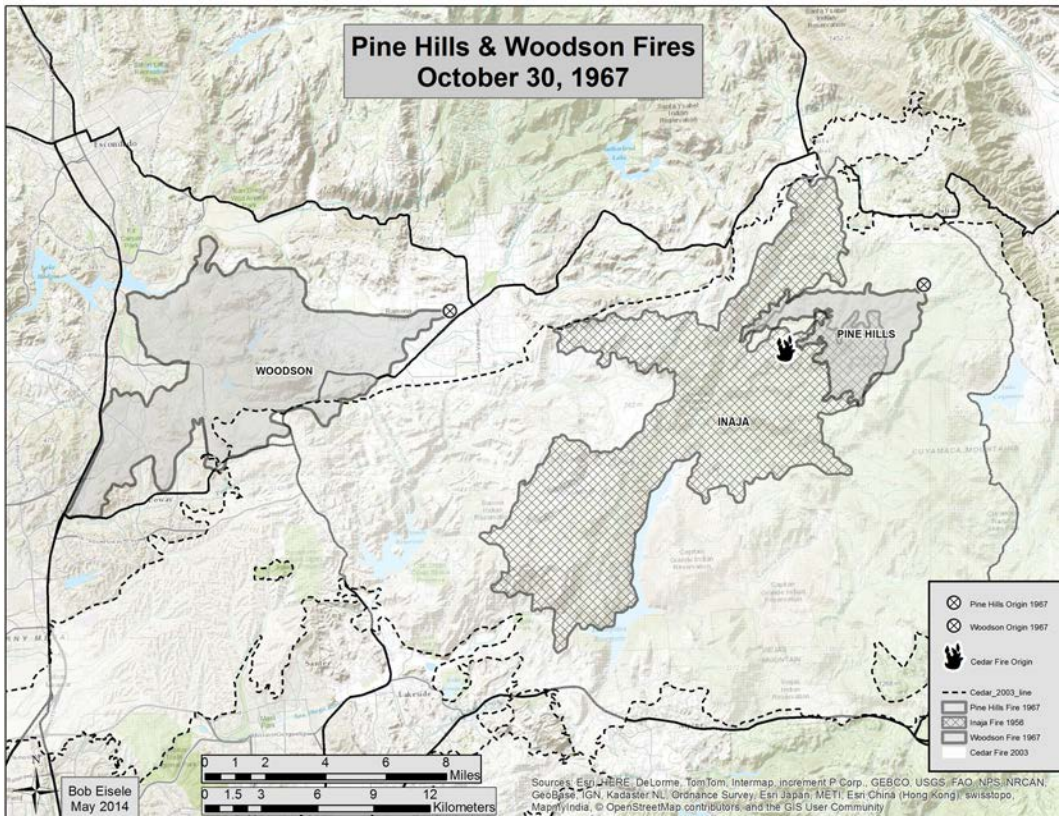

Figure 9—1967 Pine Hills and Woodson fires showing 1956 Inaja Fire.

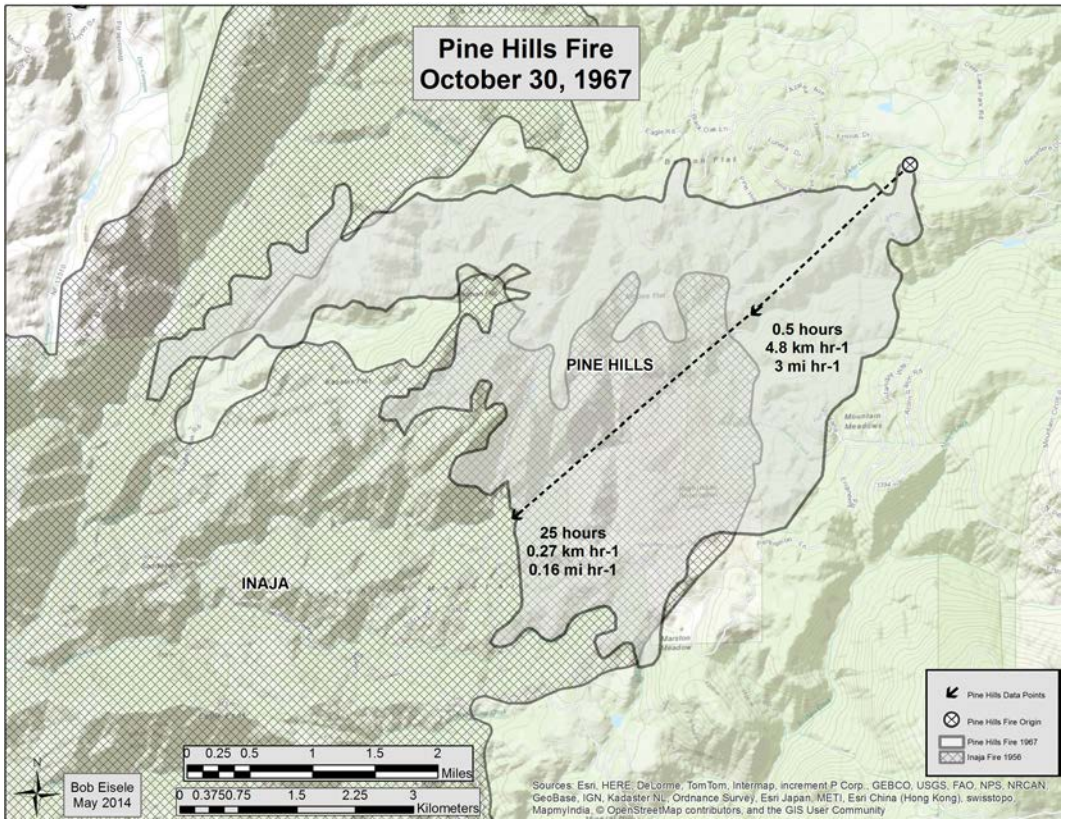

Figure 10—Estimated spread rates of the Pine Hills Fire.

Fuel age? The Pine Hills fire burned into the older Inaja Fire area of 1956. The Inaja Fire burned in 28-year-old fuels, under similar conditions, from Boulder Creek Road to Lakeside, some 22 km (14 miles) to the southwest. An aerial news photo taken on the afternoon of October 31, 1967, after the northeast winds had ended, shows the Pine Hills fire creeping downhill on southwest facing slopes of the San Diego River. The Woodson fire burned through chaparral that had last burned in 1913 (54 years previously) and stopped in 23-year old vegetation last burned in 1944.

The Cedar and Witch fires

The October 26, 2003 Cedar Fire (Figure 11) burned 110 578 ha (273 245 acres), killed 15 people, destroyed 2 232 homes and cost $27 million to extinguish (CDF. 2003). The Cedar Fire started under similar conditions and only 8 km (5 mi) from the origin of the Pine Hills Fire and 5 km (3 mi) from the Inaja Fire origin. All fuels near the origin were over 40 years old and no significant tracts of younger fuels were positioned to impede the fire's progress.

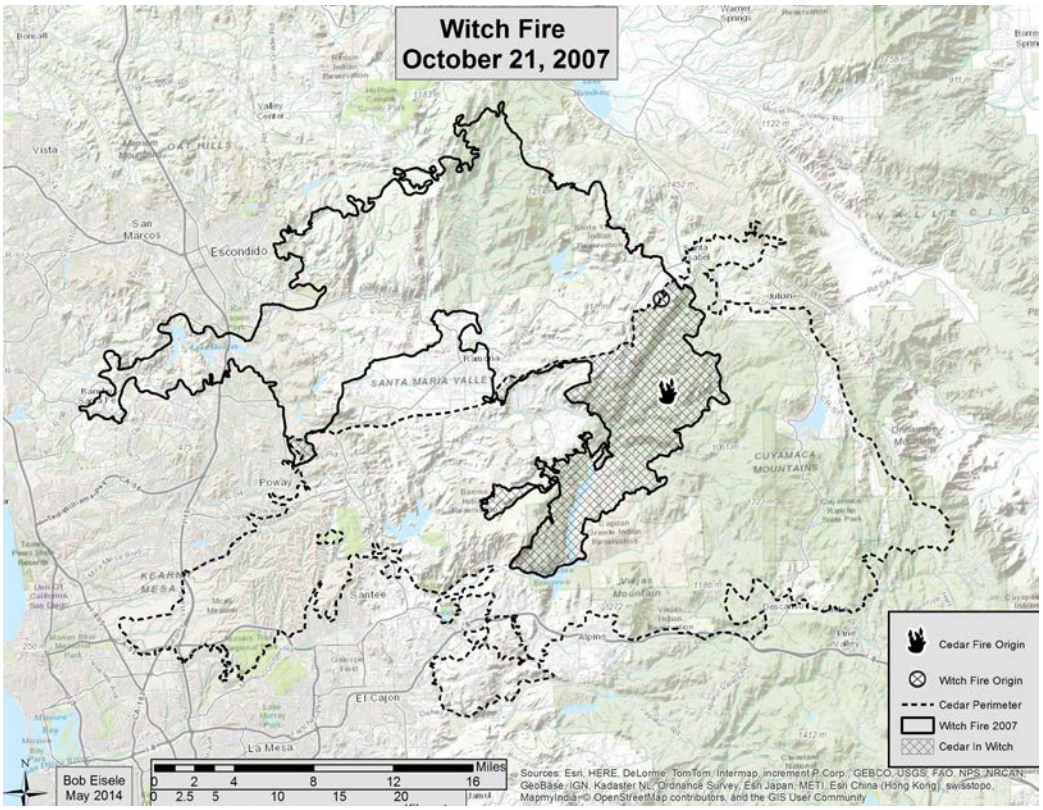

Figure 11—2007 Witch fire showing area 2003 Cedar reburn.

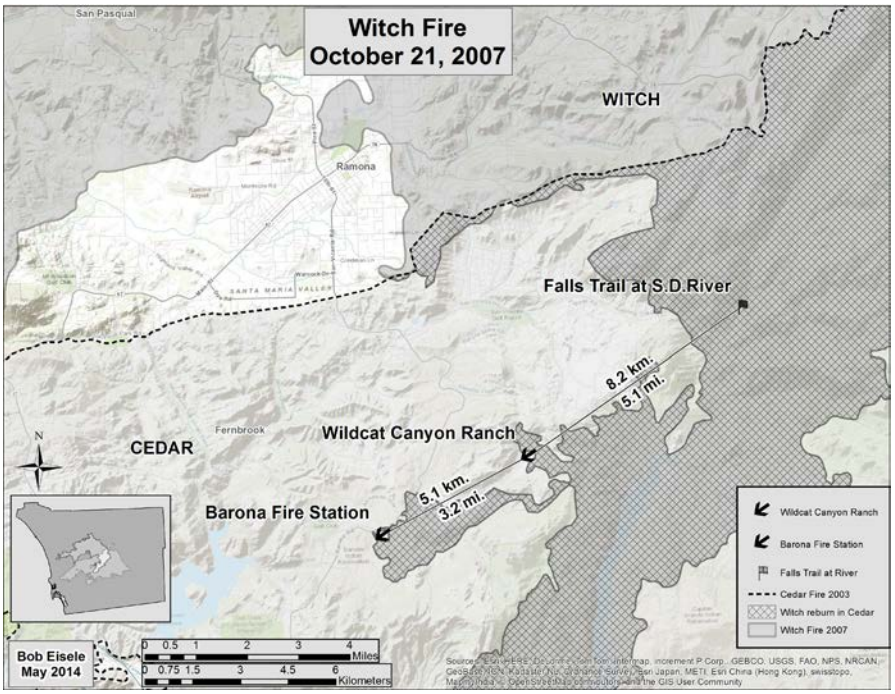

Figure 12—Spread rates of Cedar and Witch over three points.

In October of 2007 the Witch Fire (Figure 12), driven by strong north east to east winds, burned over 65 000 ha (160 000 acres) of San Diego County. 16 400 ha (40 500 acres) of the total were within the 2003 Cedar Fire (FRAP 2012). Little suppression action was taken in the four year old chaparral (Hawkins 2008). General fire arrival times were obtained at three points common to both the Cedar and Witch fires. The first point was the intersection of the Cedar Creek Falls trail with the San Diego River (Reece, personal communication). The second landmark was at the ranch house of the Wildcat Ranch on Featherstone Road (Ranch Foreman, personal communication). The third was the Barona Fire Station (Kremensky, personal communication).

The Cedar Fire traveled the 13.2 km (8.2 miles) in four hours at an average rate of 3.3 km h^{-1} (2 mi h^{-1}). The Witch Fire covered the same distance in 33 hours at an average rate of 0.4 km h^{-1} (2 mi h^{-1}). Firefighters stopped the progress of the fire at 0300 hours on October 23, 2007. At the time, the Goose Valley Remote Automatic Weather Station (RAWS) recorded air temperature of 24 °C (75 °F), relative humidity of 9%, wind from the east northeast at 8 m s^{-1} (18 mi h^{-1}), gusting to 17.4 m s^{-1} (39 mi h^{-1}). (Figure13)

Fire spread halted on the remainder of the four year old fuel portion of the Witch Fire when the wind stopped and the weather moderated. Most of the perimeter was never lined. Similar fire behavior was observed where the Witch Fire contacted the 1993 Guejito, the 1990 Paint, and the 1997 Del Dios fires.

Figure 13—Chaparral within the burned area of the Cedar and Witch fires.

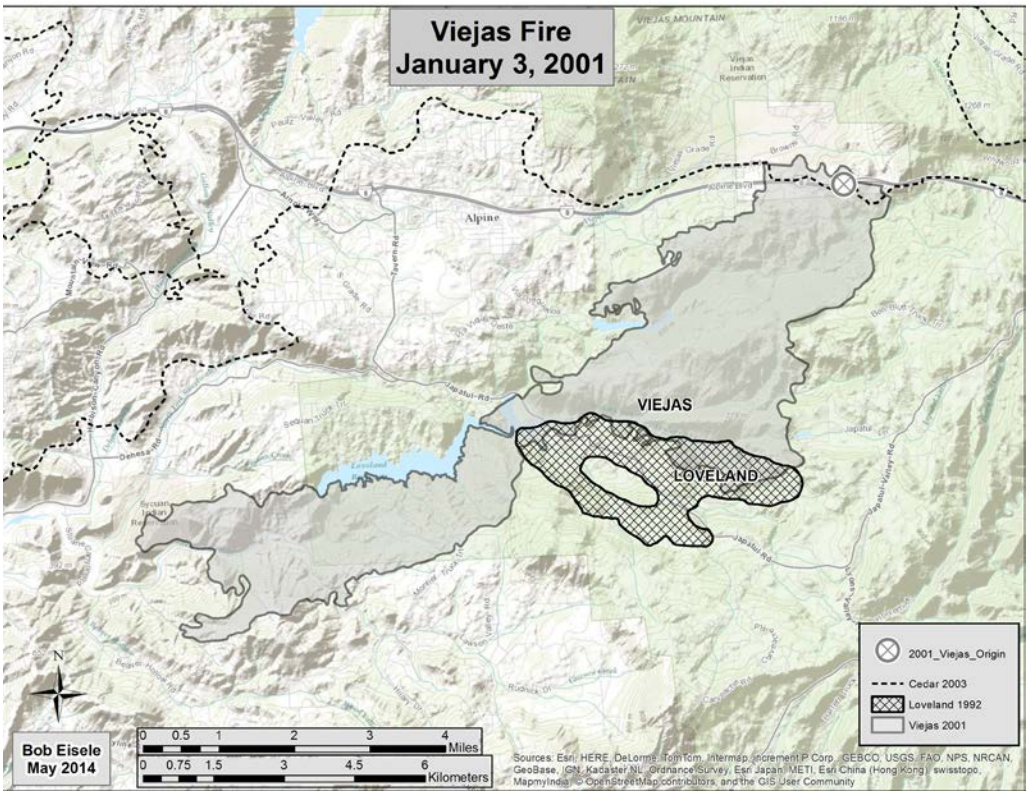

Figure 14—2001 Viejas Fire constrained by the 1992 Japatul Fire. Note 2003 Cedar constrained by Viejas (near origin).

The Viejas fire

In the early morning of January 3, 2001, the Viejas Fire (Figure 14) started in the center median of Interstate 8, about 8 km (5 mi) east of Alpine, CA. Pushed by strong Santa Ana winds, the fire skirted the eastern edge of Alpine, ran down to the Japatual Valley and climbed toward Jamul. The area had last burned in the Laguna fire of 1970 (31 years previously). The progress of the fire was slowed where it encountered the 1992 Loveland burn. Fire fighters were able to keep the fire from crossing Japatual Valley Road except west of the Loveland burn which is older fuel.

The McCoy fire

Sunday, October 21, 2007 was the first day of the 2007 "Fire Siege." The Harris fire started at 0930 and the Witch fire began at 1230. At 2330 that night, the McCoy fire started on the west side of Cuyamaca Peak along Boulder Creek Road. Fire units responded and determined it was too dangerous to attempt suppression action due to extreme winds and darkness (Truitt, personal communication). When fire crews returned at daylight, the fire was out, having consumed 143 ha (353 acres) of young chaparral and two homes. The area had last been burned in the 2003 Cedar Fire, and the young vegetation would not carry fire, even during such extreme conditions. Recently, a newly installed weather station at Sill Hill less than 1 km (0.6 miles) from the McCoy Fire recorded a Santa Ana wind gust of (45 m s^{-1} or 101 m h^{-1}), possibly the highest gust ever recorded for San Diego County. Thus, the area of the McCoy Fire was likely to have sustained very high winds throughout the night of October 21-22, 2007.

Fire Return Interval Departure (FRID)

The calculated FRID (Eisele 2011) for San Diego County is similar to that obtained by FRID for the USDA Forest Service, Pacific Southwest Region (FRID 2012). A major difference between studies is identifying areas that have never burned or are not burnable. Some may be pastures that are annually grazed, others are agriculture lands, some are too sparsely vegetated to burn, and so forth. The basic picture is the same. Only three percent of County's wildlands have burned more frequently than at the expected fire return interval. Fifty-six percent have burned once or not at all in the past 100 years (Table 4).

A closer inspection of the data suggests that the majority of the area that is burned frequently is associated with more flammable CSS or annual grasslands generally found at lower elevations or comprises south and west facing slopes that have a naturally shorter fire return interval (Westman 1982; Green 1981).

Fuel Age of Large Fires

The mean age of the fuel at the section of origin for fires over 4 000 ha was greater than 68.6 years. The minimum age was 26 years and the maximum was >102 years (Appendix A).

Conclusions

Two factors appear to be significant in explaining the present fire regime in the chaparral of San Diego County. First, the age of the vegetation affects the intensity and spread rate of the fire. Young fuel is receptive to suppression actions while old vegetation is very resistant to fire control efforts. An unintended consequence of fire suppression is the shifting of the fire season from moderate summertime weather to conditions with extreme foehn winds in the fall (Countryman 1974). Area burned under low and moderate intensity fires during the summer season are underrepresented in the current fire regime (Minnich and Chou 1997).

For a fire to become large there must be a successful ignition in old chaparral (greater than twenty years since last

Table 4—Fire Return Interval Departure.

Times burned	Area Burned		Percent	Category	Percent
	Hectares	Acres			Summed
0	146 148	361 127	23	Below expected interval range	56
1	208 332	514 782	33	Below expected interval range	
2	144 572	357 233	23	Within expected interval range	
3	84 914	209 820	13	Within expected interval range	42
4	36 388	89 915	6	Within expected interval range	
5	12 806	31 643	2	Above expected interval range	3
6	3 896	9 627	1	Above expected interval range	
7	780	1 928	0	Above expected interval range	
8	50	124	0	Above expected interval range	
9	6	15	0	Above expected interval range	
	637 893	1 576 212	100	Totals	

Table from: FRID. "Region 5 - Geospatial Data." *Region 5 - Geospatial Data*.

fire), moderate to severe fire weather, and a large expanse of old vegetation ("running room") that is devoid of barriers such as younger age class fuels, urbanized areas, large lakes, deserts, oceans, and so forth. Old fuels and high winds often combine to produce fire intensities and spread rates that overwhelm the initial fire-suppression forces. "The energy of flame lines is several orders of magnitude greater than the energy expended to put them out, and this overwhelms the ability of fire fighting forces to protect property and resources" (Minnich and Sanchez-Vizcaino 1999). The fire history database is replete with examples of young age class fuels constraining fire spread, even under extreme burning conditions. This has been recognized by Philpot 1971, Hanes 1971, Countryman 1974, Biswell 1974, Green 1981, Minnich and Chou 1997, and others.

The second factor is randomness. Ignitions happen by chance. Many extreme fire days pass uneventfully, while similar periods result in multiple large fires (fire sieges). There is no statistical relationship between large fire years and drought. Spending effort on predicting fire season severity is not fruitful for chaparral. Educating the public and the policy makers on the likelihood of random rare events with very severe outcomes should be a priority. Believing that all ignitions are preventable and that large fires are inevitable are equally unsupported by science. Ignitions are random. All severe wind events are finite. Young fuels reduce the rate of fire spread, even under extreme conditions, and stop spread when weather conditions abate as during the Witch/Cedar reburn in 2003 and during the Pine Hill/Inaja reburn in 1967. If fuel management on a landscape scale is not embraced, large destructive fires are inevitable (Countryman 1974).

Perhaps a lesson can be learned from the disastrous fires that destroyed American cities in the 19th and early 20th centuries. The conflagration problem was not solved with more fire engines or prevention efforts– instead the fuel was modified. Wooden construction was banned in favor of fire resistant concrete and steel. (Wermiel 2000). So too, we must look to the fuels to mitigate the destructive wildland fires in San Diego.

Acknowledgments

We sincerely appreciate the helpful suggestions and reviews of this manuscript provided by J. Ramirez, L. Hall, P. Riggan, J. Coen, and W. Graves.

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Appendix A. Vegetation age at origin of fires over 4 000 ha (10,000 acres) 1950-2012.

Date	Year	Name	Area (ha)	Area (acres)	Last Fire	Age	Fire Type	Cause	Fuel Type	Other
10/25/2003	2003	Cedar	109 542	270 686	1956	47	Wind-Fuel	lost hunter	chaparral	Santa Ana winds subsided after 24 hours. Remaining spread was fuel and topography driven.
9/26/1970	1970	Laguna	70 481	174 162	1910	>60	Wind	power line	forest/chap.	No Prior History
10/21/2007	2007	Witch	65 587	162 070	1910	>97	Wind	power line	mixed	Chaparral
10/21/2007	2007	Harris	36 716	90 728	1910	>97	Wind	campfire	chaparral	No Prior History
12/14/1958	1958	Stewart	27 561	68 106	1910	>48	Wind	shooting	chaparral	Started in Riverside County
7/29/2002	2002	Pines	24 965	61 691	1910	>92	Fuel	aircraft	conifers	Much of the initial area of the fire burned in 1943 (59 yrs.)
10/26/2003	2003	Paradise	22 883	56 546	1925	78	Wind-Fuel	human	sage scrub	Section has some 1996, 1925, and NFH
10/23/2007	2007	Poomacha	19 996	49 411	1910	>97	Wind	structure fire	grass	Grass-800' to NFH Chaparral
11/24/1956	1956	Inaja	18 859	46 599	1910	>46	Wind	juvenile	mixed	No Prior History
10/26/2003	2003	Otay/Mine	18 103	44 734	1910	>93	Wind	unk	scrub/chap.	No Prior History
10/30/1967	1967	Woodson	11 769	29 083	1913	54	Wind	misc.	grass/chap.	Started in grassland. Spread to 1913 chaparral
8/22/1969	1969	Walker Basin	7 896	19 513	1910	>59	Wind	unk	chaparral	Nearby fire in 1950; stopped a 1979 fire
7/16/2003	2003	Coyote	7 569	18 705	1910	>93	Fuel	lightning	chaparral	Assume county line origin - all area had no fire history.
10/27/1993	1993	Guejito	7 211	17 820	1910	>83	Wind	*powerline	chaparral	*Cause may have been compost pile
7/23/2006	2006	Horse	6 749	16 678	1970	36	fuel	human	chaparral	Laguna Fire footprint
10/22/1996	1996	Otay #322	6 702	16 562	1910	>86	Wind	campfire	chaparral	
10/18/1969	1969	San Mateo	6 376	15 757	1910	>59	Wind	flare	chaparral	No Prior History
9/28/1970	1970	Boulder	5 192	12 830	1910	>60	Wind	smoking	forest/chap.	No Prior History
10/3/1987	1987	Palomar	6 305	15 580	1919	68	Fuel	power line	groves	Origin by power line
9/22/1975	1975	Tenaja	6 047	14 942	1949	26	Fuel	misc	chaparral	1919
7/11/2011	2011	Eagle	5 662	13 993	1939	72	Fuel	structure fire	chaparral	Started at night burned into 2002 Pines fire; Grass carried the fire after
6/7/1950	1950	Case Springs	5 579	13 785	1910	>40	Fuel	misc	grass/chap.	
10/18/1989	1989	Mateo	5 455	13 479	1959	30	Fuel	unk	chaparral	Estimated. start location
7/29/1989	1989	Vail	5 454	13 478	1910	>79	Fuel	unk	chaparral	
7/22/1975	1975	San Ysidro	5 192	12 829	1910	>65	Fuel	smoking	chaparral	No Prior History
7/29/2000	2000	Pechanga	4 748	11 733	1910	>90	Fuel	unk	chaparral	Agua Tibia Wilderness
8/14/2013	2012	Wilson	4 721	11 667	1910	>102	Fuel	lightning	chaparral	Vallecito Lightning Complex -No Fire History
8/14/2013	2012	Stewart	4 302	10 630	1910	>102	Fuel	lightning	chaparral	Vallecito Lightning Complex -No Fire History
1/3/2001	2001	Viejas	4 224	10 438	1970	31	Wind	smoking	sage scrub	Laguna Fire footprint

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Building Fire Behavior Analyst (FBAN) Capability and Capacity: Lessons Learned From Victoria, Australia's Bushfire Behavior Predictive Services Strategy

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Abstract—*Wildland fire managers must frequently make meaning from chaos in order to protect communities and infrastructure from the negative impacts of fire. Fire management personnel are increasingly turning to science to support their experience-based decision-making processes and to provide clear, confident leadership for communities frequently exposed to risk from wildfire. The inclusion of science into their thought processes helps these decisions to be more consistent, accurate, reliable and defendable in an environment where the risk and impact of incidents continues to increase.*

Based on a combination of personal bushfire experience and knowledge of academically reviewed scientific principles, Fire Behavior Analysts (FBANs) provide advice before and during emergencies. The FBAN role has been widely used in North America for many years but was not formally used in Victoria prior to 2006. In Victoria, the program developed rapidly and produced a cadre of highly skilled analysts whose products and services quickly become vital in everyday bushfire management for quantifying risk to communities and infrastructure.

This paper presents the history of the development of the FBAN program in Victoria along with examples of predictive services products regularly accessed during the fire danger period. In order to mature beyond its initial start-up state, fire control agencies in Victoria reviewed past successes and weaknesses and consulted with invested stakeholders in order to produce a strategic document that aims to embed predictive services into emergency management decision-making of the future.

The Bushfire Behavior Predictive Services Strategy sets out future direction under three main goals: 1) provide clear governance; 2) create a unified approach; and 3) develop fit-for-purpose and sustainable products and services. A series of ten lessons learned are also presented as reflection of this strategic analysis process to create knowledge through the translation of previous experience in support of other agencies working to build FBAN capability.

The evolution of fire behavior prediction tools and services in Victoria provides an interesting account of lessons learned, success stories and rapid innovation in response to increasing demand in the emergency sector for more consistent, accurate, reliable and defendable decisions during emergencies.

Introduction

The management and control of bushfires in the Victorian landscape involves making decisions in a complex and rapidly changing spatial and temporal environment. Today's bushfire manager must make the most of his/her background experience and combine it with a team of others' knowledge and skills to maximize the protection of life and property. However, when fire management decision making is largely based on personal experience, the result varies greatly across individuals and fire danger is estimated rather than accurately quantified. Predicting the spread and behavior of a going fire is a complicated task; however, recent advances in technology and scientific research have provided additional tools to facilitate the diverse decision-making process. Models have been designed and tested for use in predicting rates of spread, head-fire intensities, flame heights and spotting potential all of which are key behavior components on which to base operational and tactical decisions.

Recent critical analyses of devastating fires in south-eastern Australia heralded the need for improvements in bushfire behavior prediction. Specifically, the Victorian Bushfires Royal Commission (VBRC) following the Black Saturday fires of February 2009 stressed the need to "provide regular training to IMT staff, highlighting the importance of information and reinforcing the support available from specialists within the State Control Centre" (Recommendation 15, Victorian Bushfires Royal Commission 2009a). Historically, Victoria has had to

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Figure 1—Victorian FBAN Tim Wells (Country Fire Authority) with a Phoenix fire growth simulator output in the background (CFA 2012).

haphazardly draw on experts from scientific agencies during days with multiple ignitions and threatening fires. International experts were also used to fill the need for technical fire behavior advice during busy seasons.

In 2006, the need for a Fire Behavior Analyst (FBAN) role[1] was identified by Alen Slijepcevic and Liam Fogarty from the then named Department of Sustainability and Environment (DSE). This led to an agreement by multiple fire and land management agencies and a national course was designed to train in-house experts in the physical behavior of bushfire in the landscape. Since its inception, multiple personnel across all agencies have attended the courses and the state has produced a team of highly skilled technical specialists for use. The FBAN is a key link between the abilities of the scientific community to use mathematics and experimental fire data to predict the impact of fires on people and their communities (Slijepcevic and others 2008). It is their role to communicate the complicated principles to operational staff in a way that informs and improves their suite of complex decision-making activities (Figure 1).

History and Development of the FBAN Program

Southeastern Australia suffers a history of high loss of life and property related to heavy forest fuel loads and extreme fire weather (Blanchi and others 2011) (Figure 2). The capital cities of both Victoria (Melbourne eastern suburbs- 2009 Black Saturday Fires) and Australia itself (Canberra- Duffy Fires 2003) have experienced destructive fire loss in their fringes in recent history. In 2006, following successive seasons of large destructive bushfires and related inquests and inquiries, the Fire Behavior Analyst (FBAN) response role was formally initiated in the state of Victoria. Since its inception, Victoria has rapidly developed a cadre of highly skilled FBANs whose products and services have become integrated into everyday bushfire management activities by identifying and analysing risks to communities and infrastructure. Response personnel use this information to evaluate these risks and determine options to mitigate them. The Victorian FBAN program evolved quickly and on an as needed basis, making it essential that any obstacles to

Figure 2—An example of Victorian fire behaviour (photo credit: Nicolas Bauer, Department of Environment and Primary Industry).

[1] The Australasian Fire and Emergency Service Authorities Council (AFAC) defines a Fire Behaviour Anaylst (FBAN) as the "person responsible for developing fire behaviour predictions based on fire history, fuel, weather and topography" (AFAC 2012).

growth be met and overcome efficiently. The evolution of FBAN capability and capacity in Victoria offers insight for those attempting to build or review predictive services skills within their own organizations elsewhere.

Training and Recruitment

Initially when fire behavior expertise was required during a going fire in Victoria, individuals were requested from academic and research organizations as there was no state or national capability for specialized fire behavior prediction services. The arrangements were informal with limited individuals called upon to provide support only during times of urgency, which was not sustainable. Following a multi-agency workshop targeted at identifying end-user needs for scientific applications by the Bushfire Cooperative Research Center (Bushfire CRC) in Wollongong in 2006, it was deemed necessary to develop a National Fire Behavior Training Course to develop personnel with specific technical fire behavior skills. The contents of this course grew from collaboration with experts from the University of Melbourne, the Bureau of Meteorology (BOM), the Commonwealth Scientific and Industrial Research Organization (CSIRO), the University of Tasmania and the Australian Defence Force Academy (ADFA) within the University of New South Wales.

Two individuals within the former Department of Sustainability and Environment (DSE) of Victoria (now the Department of Environment and Primary Industry or DEPI) managed to establish national arrangements with lead fire behavior scientists and most land, fire and emergency agencies in 2006. With the forecast for an approaching busy fire season, DSE and the Country Fire Authority (CFA) signed an agreement with the fire management agency in British Columbia, Canada, to provide additional resources (including FBANs) if needed. The forecast for a severe fire season became reality with the Great Divide Fires which burned over a million hectares of land across more than 65 days (Smith 2007). Canadian FBANs arrived on request to assist with the fire behavior predictions, and the international FBAN cell consisting of Australian, New Zealand, Canadian and American personnel highlighted the importance of predicting fire extent and used it to raise government and community awareness of the pending mega-fire (Figure 3). The estimates of impact potential supported strategy setting including construction of fireguard, back-burning and the deployment of national and international support.

The operational review of the previous season's Great Divide Fires supported the growing need for specialized fire behavior expertise (Smith 2007). The debrief concluded that a requirement for fire behavior specialists existed,

Figure 3—An original Victorian FBAN, Andy Ackland installs a portable weather station during the 2006/2007 Ensay fires.

with a primary need at the incident management team (IMT) level to communicate likely fire spread under forecast conditions. The need was also recognized at the state level to provide a strategic overview of potential fire spread and impact across all districts. In a timely manner, the first nationally recognised FBAN training course was attended by individuals from all across southeastern Australia in July of 2007.

The program continued to grow through the 2007/2008 season with a total of four courses delivered with sixty-two attendees across twelve different agencies. During this time, Australian FBANs were deployed to fires in Tasmania, Victoria and South Australia. They demonstrated the value of their expertise by providing predictions to support fire control decisions that significantly reduced the potential area burnt as well as providing early warnings to communities about to be affected. FBANs were even eventually requested by Canadian fire control agencies with four individuals sent over to assist with the busy fire season in British Columbia. Canadian fire officials were impressed with the quality of FBAN services and the speed with which skills had been developed and the program matured.

Early Operational Impacts

Pre-season fire risk assessment for the 2008/2009 fire season provided warnings for the onset of a catastrophic fire season. Melbourne's urban fringe was identified as a particular risk zone related to the lack of spring rainfall and long-term drought effects. An FBAN team was initiated by Alen Slijepcevic, Assistant Chief Fire Officer Capability, and worked at producing a range of predictive and risk communications tools as the conditions continued to build and support a serious fire risk. When the Black Saturday fires broke out in early February 2009 (Victorian Bushfires Royal Commission 2009b) FBAN products and services were in place and supported critical decision-making related to resource deployment and management strategies amongst the tragic losses of life and property of the first twenty-four hours. Although the services were relatively new to most operational staff, the available FBAN resources were used heavily to produce estimates of impact zones[2] along with escaped fire scenarios which contributed to management of this complex event (Gibos 2013a).

As the 2010 fire season approached, Victoria prepared its trained cadre of FBANs through a mentoring program in which trainees were tutored by fire behavior scientists from local universities and research agencies, as well as by visiting American and Canadian FBANs. Across the following years, FBANs continued to prove their value by their performance during deployments to other states as well as their contributions to the control of several large fires in Victoria including the 2011 Tostaree Fire, the 2013 Aberfeldy Fire and the 2013 Alpine Fires (Kelsy Gibos, personal observation 2011 to 2013).

History reveals that although developed somewhat haphazardly and to meet emergent demand, FBAN products and services in Victoria have proven to be invaluable in incident management decision-making. Operational personnel on the fireline and those on IMTs continue to seek support from FBANs and are requesting services and products at an increasing rate.

Examples of Victorian FBAN Products and Services

FBANs in Victoria produce a range of products and services in order to communicate the risk of bushfire. The first product developed in Victoria was based on a paper from Canada by Beck and others (2002) which outlined simple graphs that could be calculated and displayed in relation to diurnal head-fire intensity and then related firefighter safety. Since then, predictive services products have been developed across all preparedness and response activities. FBANs in Victoria make use of a multitude of tools to make these predictions including a range of fire spread models in various fuel types, gridded forecast weather data, ground observations, fire spread modelling software and smoke modelling (Gibos 2013a).

Preparedness products

FBANs create products in advance of going fires to support preparedness planning and prepositioning of resources. In Victoria, FBANs regularly produce spatial renderings of bushfire hazard by calculating head-fire intensity, in kilowatts per metre (kW/m), and elapsed time in minutes (min) required for the fire to grow to 5.0 hectares (ha) in size (Figure 4).

The head-fire intensity map uses a rate of spread model based on the broad fuel type group (dry or wet forest, grassland, heath, etc.) and the fine fuel load from a spatial fuel layer (including the effects of burn history) along with the gridded forecast weather to produce a spatial illustration of variation in intensity across the state. Intensity can be linked to ease of suppression and resource allocation (Alexander and Cole 1995); as intensity approaches 4,000 kW/m, the upper limits of direct attack using ground crews is approached (intermittent crown fire behavior can be expected). Fire intensities greater than 10,000 kW/m represent 'explosive' fire conditions with rapid rates of spread, continuous crowning activity, fire whirls and convective fire spread. The head-fire intensity map represents the magnitude of the destructive potential of a fire and the likelihood of suppression success; the elapsed time (min) to reach 5.0 ha in size map also represents and element of suppression difficulty by indicating how fast a fire is likely to expand. The use of predicted area burnt helps to indicate to fire managers how quickly their suppression resources must mobilise before the fire approaches an equilibrium rate of spread and may become more difficult to suppress, with 5.0 ha being an agency agreed upon assumption across Victoria's fuel types. Each map product is produced in hourly steps six days in advance so managers can review variations over time and determine the duration

[2] In Victoria, an impact zone refers to areas expected to be impacted by smoke and ember attack.

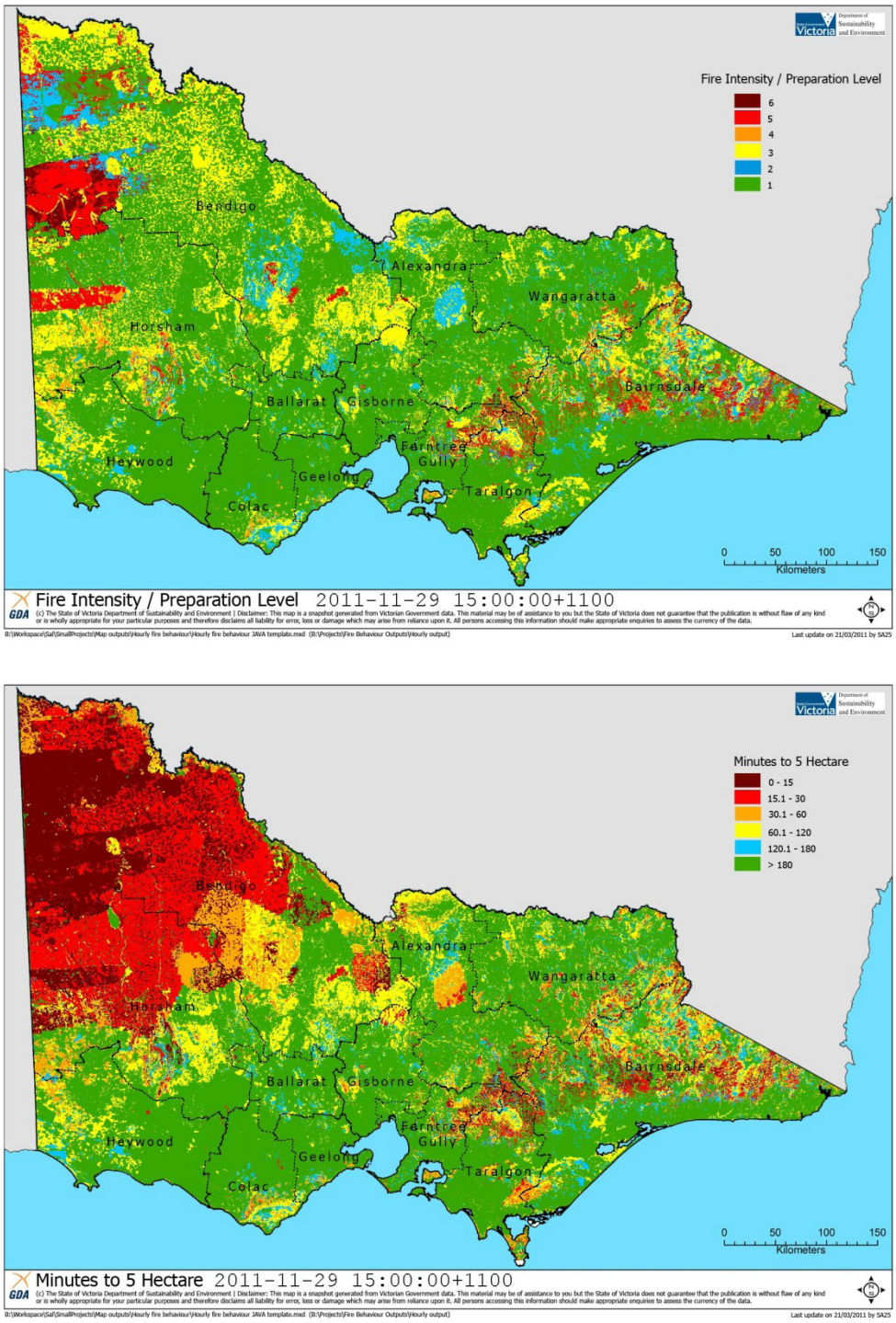

Figure 4—a) Head-fire intensity map for 1500 hrs for the state of Victoria, Australia. Fire intensity Level 1 corresponds to 0–500 kW/m, Level 2 to 501–1,000 kW/m, Level 3 to 1,001–5,000 kW/m, Level 4 to 5,001–10,000 kW/m, Level 5 to 10,001–30,000 kW/m and Level 6 to 30,001–200,000 kW/m. b) Map showing the estimated minutes it will take for a fire to reach 5.0 hectares in size for the state of Victoria.

and magnitude of the threat. Fire management personnel can use these two products together to inform decisions on the location and configuration of resource positioning and allocation. The elapsed time to 5.0 ha in size map (Figure 4) indicates areas with rapid rates of spread across the Bendigo district of Victoria (center of the map); however, after referencing the head-fire intensity map it shows those areas are likely within a suppressible limit by direct attack. So these areas will escalate quickly in fire size, but the flame heights and intensities should be controllable by hand crews. In this case, the maps indicate that quick turn-out times and smart tactical manoeuvers may assist firefighters in controlling the fire. In another example, the fire may be slow moving (longer time to grow to 5.0 ha) but the fuel load and dryness may support a high intensity fire that it would be difficult for ground crews to approach and air support may be required. Fire behavior based preparedness products make it simpler to compare hazard across districts. Quantification of fire behavior can be paralleled across all climatic and fuel conditions. This makes it easier for fire fighters and incident

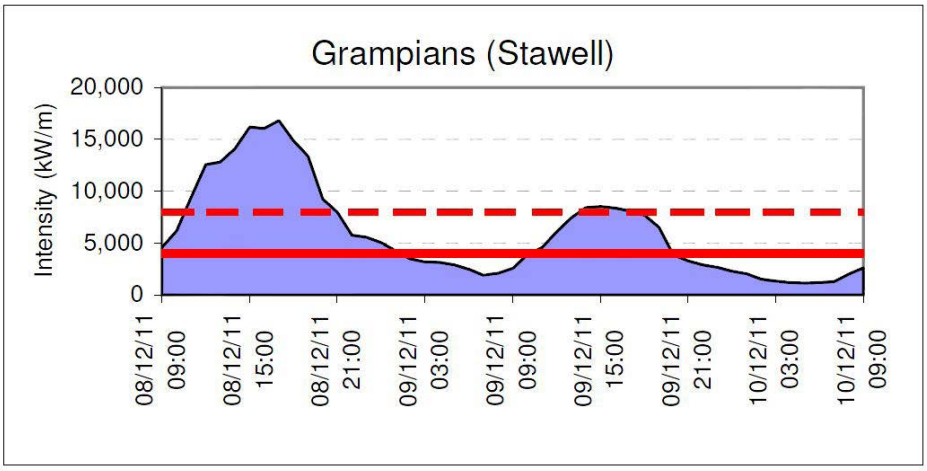

Figure 5—a) An example of the daily fire behaviour estimates (also known as "camel hump" diagrams) produced by FBANs in Victoria. The image shows a collection of state-wide predictions of head-fire intensity across a two day prediction period. b) Close up of a "camel hump" diagram showing head-fire intensity (kW/m) across a two day period for the Grampians district. The solid red line indicates the agreed threshold for direct attack (4,000 kW/m) and the dashed red line indicates potential for crown fire activity in this district's designated fuel type. The diurnal trend in fire behaviour is important for tactical decision making as well as firefighter safety.

management staff deployed intrastate to communicate and understand local fire risks and conditions.

A series of graphs colloquially referred to as "camel-hump" diagrams are created daily during the operational fire season to demonstrate the variation in fire behavior outputs across the prediction or burning period. Information on fire behavior characteristics such as rate of spread and head-fire intensity provide fire management personnel with additional information about damage potential and the success of frontal attack in adding to that determined from fire weather indices. Communicated information on fire behavior potential can provide the on-the-ground firefighter and general public with an improved state of situational awareness; forecasting where the fire will be and whether it is likely to be suppressible provides information about potentially dangerous situations that could occur during the forecast period.

The daily produced fire behavior estimates show forecasted head-fire intensity in forested areas across two days for each district in the state (Figure 5). The predictions are

made using gridded forecast weather produced that morning and calculated for an established fire (considered greater than 10 ha in size) that is burning in a standard fuel type (i.e., unburned for at least 20 years) assigned for each region. The graphic includes agency agreed upon estimated thresholds for crowning as well as frontal attack[3]. Direct suppression of a fire is assumed difficult when the fire intensity exceeds 4,000 kW/m as suppression tactics may only be successful early on in the development of the fire (Alexander and Cole 1995). For the duration of the period when the potential head-fire intensity exceeds 4,000 kW/m, direct fire suppression will be limited to the flanks and back of the fire. While indirect fire suppression tactics may be employed, it is unlikely that backburning will be successful during the period. It is expected that when there is no period of time overnight where the head-fire intensity is predicted to drop below 4,000 kW/m, a going fire is likely to become very large over the next 24 hours.

If the head-fire intensity is forecasted to be above the agreed upon frontal attack threshold (refer to Footnote 3) of 4,000 kW/m, an additional page of graphics provides details about key fire behavior variables for each district (Figure 6).The duration (number of hours) that the intensity is above the threshold in the next 24 hours is represented by a number in a black box as well as the percentage filled of a rectangle. The average perimeter growth rate (km/h) is also included and if that value exceeds 2 km/h it is coloured red to emphasize the estimated potential for greater loss. The maximum rate of spread (km/h) in the next 24 hours is also shown, with values greater than 1.5 km/h emphasized as a useful threshold recognized by firefighters on the ground.

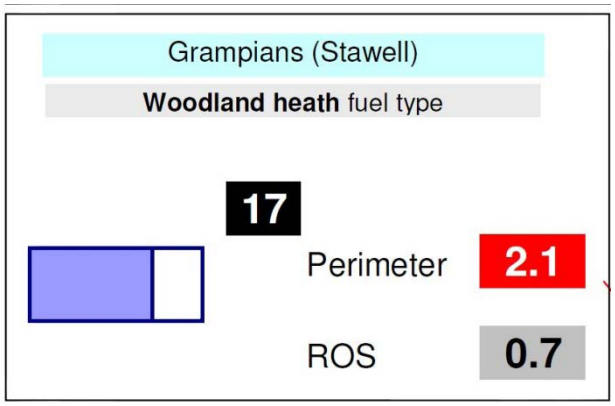

Figure 6—An example of an additional visual aid provided with the daily fire behaviour estimates (Figure 2). This image shows the hours of today that the head-fire intensity is predicted to be above 4,000 kW/m in a black box with white text. This is represented visually by the blue bar on the left. The estimated perimeter rate of spread (km/h) and forward rate of spread (km/h) are given on the right.

The daily fire behavior estimates also include a seven day forecast of forest and grassland Fire Danger Index (FDI) (Cheney and others 1998, McArthur 1962, Noble and others 1980) (Figure 7). The FDIs are calculated using gridded weather data[4] and the grassland values using curing percentages based on the Day 0 curing map provided by CFA (Country Fire Authority 2014). A red line in the diagram represents agency designated "severe" FDI levels which result in high levels of suppression difficulty except for very early in the development of a fire or in very low fuels.

A similar product showing head-fire intensity and upcoming forecasted fire danger is also produced during the prescribed burning periods during the year. FBANs can use these tools to better recognize upcoming windows of opportunity that would generally support prescribed burn objectives. All of the above products can also be personally adjusted by the FBAN; some practicing FBANs produce the "camel hump" diagrams specific to their area of responsibility to focus in from the coarseness of the state-wide resolution.

Response products

During a going fire, the role of an FBAN in Victoria is to provide analysis and advice through the Planning Section of the IMT to the State Controller, the Chief Officers and other government executives about the medium and longer term potential fire spread, risk and priorities, operational options, resource requirements and potential fire impact zones. In addition to this, FBANs can also provide advice about potential planned burning strategies and options including back-burning and burning out operations. The FBAN must also inform the State Duty Officer and Planning Officer within the relevant emergency coordination centre about strategic risks and priorities for communication to strategic Regional Coordination level, IMTs and the general public via the Information Unit.

FBANs produce a large menu of items during a going fire. There are standard products produced immediately following a reported ignition as well as the ability to cater the products specifically to the incident upon request (Table 1). There are two main product types that FBANs can develop during a going fire (Slijepcevic and others 2008). The first is a series of maps indicating potential fire impact zones. The maps indicate all areas that will be possibly affected by fire or ember attack in the defined forecast period. The information includes a 'use-by' date and time, and the map often includes an indication of the area beyond the current projection where

[3] The thresholds chosen for head-fire intensity in the diagrams are based on research data in fuel types different from that in Victoria (Alexander and Cole 1995), but were deemed acceptable by agency managers due to a lack of similar research in Australian fuel types. Using a single value of head-fire intensity across multiple fuel types and conditions is not ideal; a firefighter or fire manager must still combine their experience and "gut feel" along with the mathematical determination of measures such as intensity. These values are meant to provide a rough "rank" or "heads-up" to flag conditions that could be potentially dangerous and difficult for crews on the fireground, and are not meant to be used in isolation. One must calibrate their experience to the science and personally decide when the measure is effective and what conditions might cause it to be inaccurate.

[4] Similar to all forecasts, the accuracy of the gridded weather products decreases as one moves forward from Day 0. Caution must be used when using a seven day outlook; the graph is meant to highlight "spike" weather days and indicate upward or downward trends. The absolute values calculated seven days out will be limited by the accuracy of the weather prediction models.

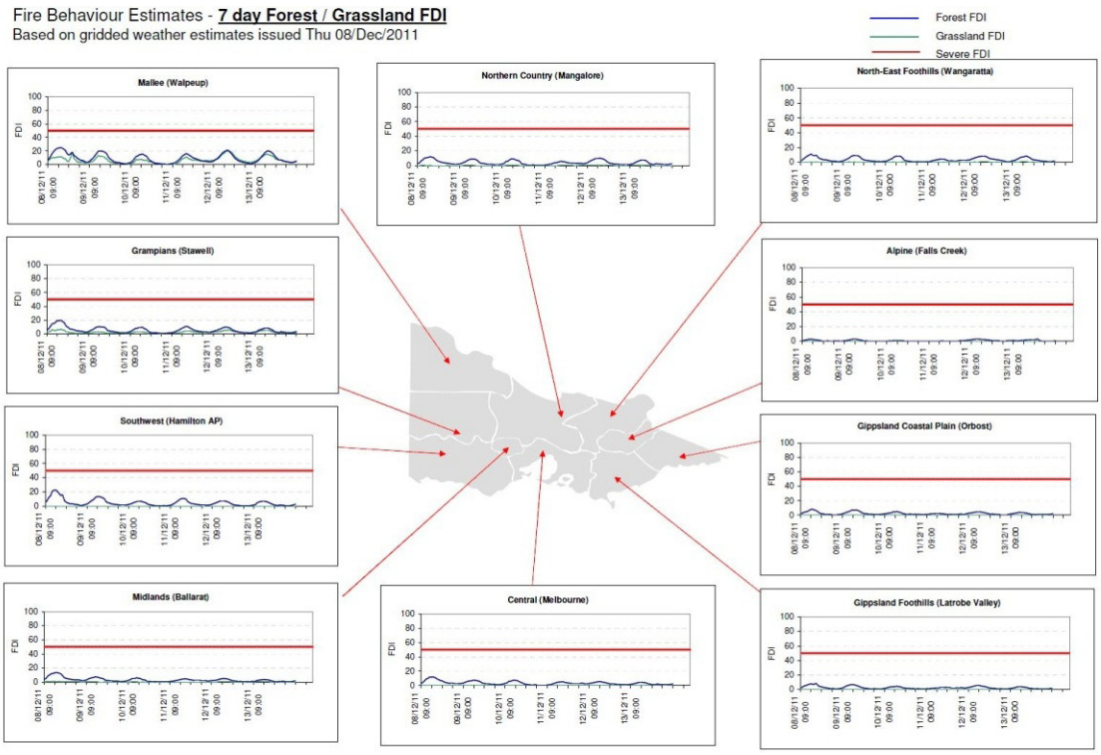

Figure 7—Seven day Forest Fire Danger Index (FFDI) in blue and Grassland Fire Danger Index (GFDI) in green forecast based on gridded weather. The red line represents the agency agreed upon threshold for severe levels of FDI.

Table 1—Activities to be conducted by FBANS in Victoria during a fire incident.

Category	Detail
Data gathering	Develop fire weather profiles for fire area based on spot weather forecasts and weather models for up to seven days ahead
	Assimilate fire history, fuel and topographic information in the fire area
	Analyse fire intelligence from situation reports, linescans and satellite hotspot data
Fire behaviour prediction	Prepare best estimate fire spread and growth predictions for areas where fire activity is likely. Predictions are to be typically based on daily growth to midnight but shorter time intervals may be used if necessary
	Prepare a map of the potential fire impact zone to show the possible extent of the fire, spotfires and burning embers within a specified period
Strategic planning	Provide advice on efficiency of fire suppression strategies including backburning and methods of direct attack
	Indentify aspects of incident management that require post-incident improvement
Safety and warnings	Issue safety warnings of severe potential fire behaviour or fire weather to the operations officer and incident controller
	Monitor fire and weather to assess if or when fire danger is likely to suddenly increase

future potential impact areas may be located. These maps show a general overview of the predicted impact area which is useful for providing warnings to inform the public about the impending fire potential.

The second is a fire spread prediction. It represents the best estimate of the fire spread at specified times across the forecast period; the prediction can span from six hours to six days. The predictions are adjusted as new weather information solidifies and fire intelligence is gathered from the fireline. These predictions are accompanied by a detailed report and are best used for internal strategic planning.

Originally, FBAN fire behavior predictions were only done by hand (Figure 8). Fire spread isochrones (i.e., contours of fire perimeter mapped as occurring at the same time) were drawn based on calculations from the McArthur Forest Fire Danger Meter (McArthur 1967) and the CSIRO Grassland Spread Meter (Cheney 1998). These maps included up-to-date weather information direct from BOM

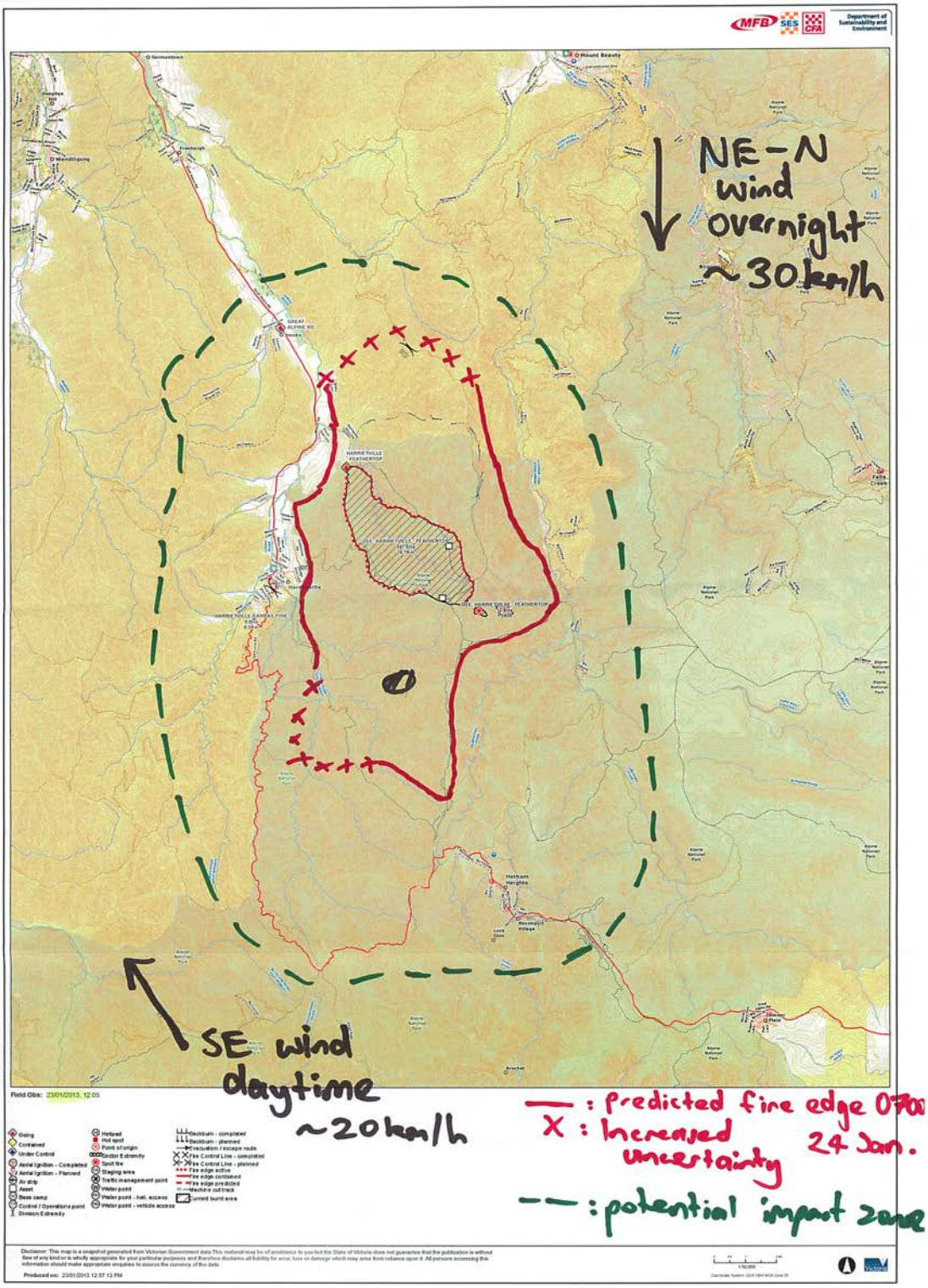

Figure 8—Rough hand drawn prediction map created for a going fire in northeastern Victoria.

and areas of potential ember impact. These maps are still regularly produced today, but can also be supplemented by computer generated fire growth prediction maps.

The introduction and use of the Phoenix fire growth modelling software (Tolhurst and others 2008) allowed FBANs to quickly produce graphically represented views of fire spread and behavior that are more easily viewed and analysed in various formats. Phoenix is a dynamic fire growth simulator that runs in a computerised environment where it can respond to changes in fuel, weather and topography as the fire moves across the landscape (Figure 9). It contains various underlying simplifying assumptions. Phoenix incorporates models to characterize spotting and ember storms, fuel accumulation curves for Victorian fuel types, a fuel moisture function across space and time as well as a function for including the effects of suppression.

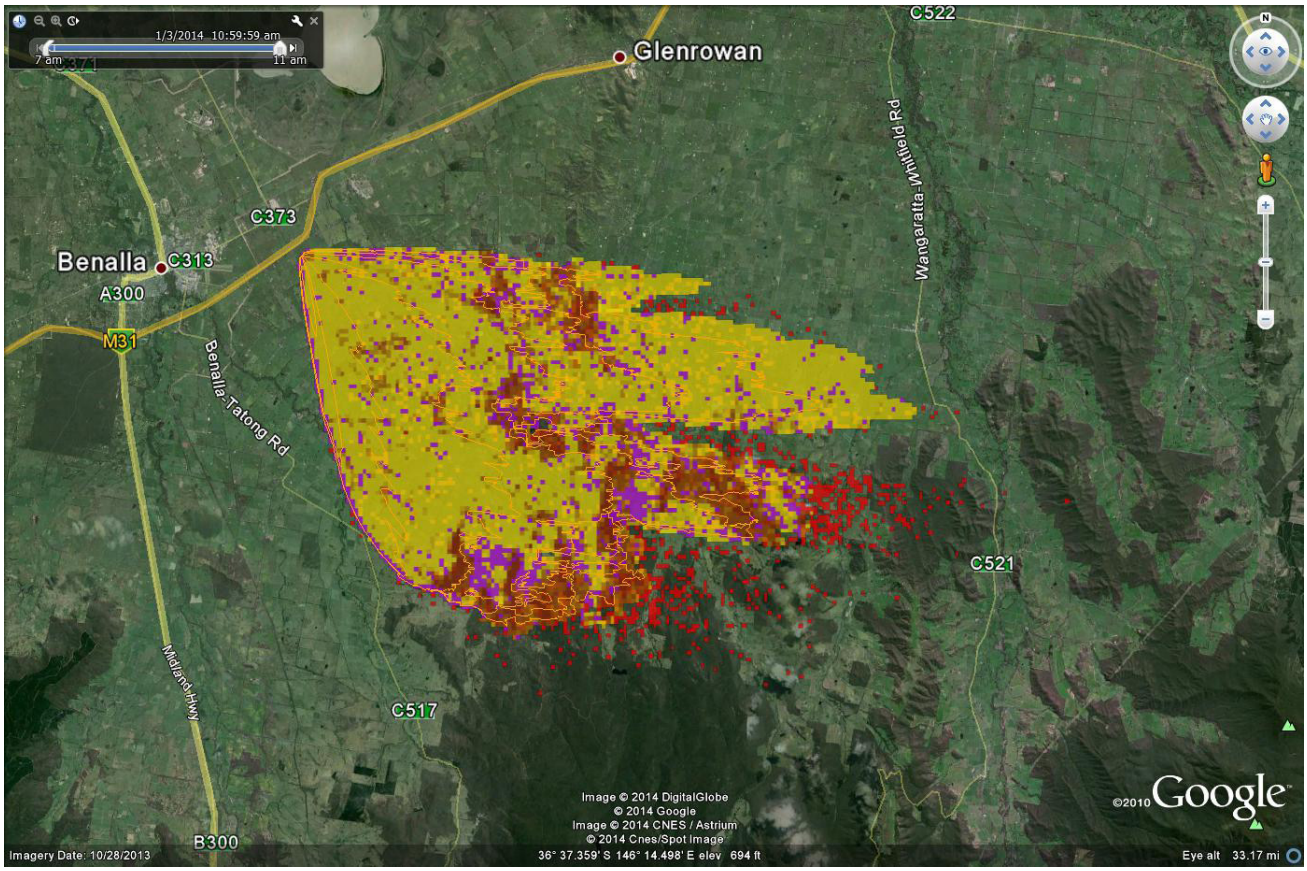

Figure 9—Fire behaviour prediction created by the Phoenix fire growth simulator shown in Google Earth. The orange lines indicate fire spread isochrones. The red to orange color ramp indicates flame height increasing from yellow to orange to red. The purple squares indicate prediction of self-extinguishment. The red squares indicate spotting activity.

Phoenix RapidFire is an automated version of the Phoenix fire growth simulator that is used to produce quick initial predictions based on an ignition point. As soon as a fire is detected and reported, Phoenix RapidFire produces a six hour fire growth prediction and loads it to a universally accessible internet platform known as FireWeb. The prediction uses the forecast gridded weather and state-wide fuel type layer. All personnel with appropriate access can view the predictions once they have been uploaded. FBANs can open the predictions and check their validity by reviewing local weather information and any fireline observations about fire behavior and fuel condition.

Embedding Predictive Services Into Emergency Management Decision Making

The advance of Victoria's FBAN program has to be largely credited to a few key individuals and a lot of formally unrecognized personal time and commitment. As a result, in 2013, it was acknowledged that these previous arrangements were not sustainable and that the state needed a strategy to deal with some of the resulting symptoms of the hurried developments led to the FBAN program in the first place. Initiated by the Country Fire Authority (CFA) in mid-2013, the Bushfire Behavior Predictive Services Strategy (BBPSS) was developed by an operational FBAN in consultation with FBAN peers as well as incident and emergency managers from various emergency response agencies (Gibos 2013b). The multi-agency strategy combined experiences from previous fire seasons with stakeholder preference to produce a series of long term goals and interventions for the state.

Embedding predictive services into emergency management decision-making requires lasting change to provide for a sustainable, trusted and innovative predictive service model in Victoria. To support the FBAN program into the future, the end-user agencies will need to change the way they make decisions regarding workforce planning, technological research and the delivery of predictive services.

The BBPSS contains a range of initiatives under three goals:

1. **Clear governance** for bushfire predictive services and the FBAN role through the introduction of a new model to lead the management and development of the program into the future.
2. **Unified approach** through the development of common standards to improve consistency.

3. **Fit-for-purpose and sustainable resources, products and services** that are delivered efficiently and are designed to meet the collective changing needs of fire agencies and communities.

The state will seek to institute clear accountability for the sustainability of bushfire predictive services through the establishment of a new governance framework to set priorities and oversee joint planning and investment, and to ensure state capability and capacity is development and maintained. A single, authorized and central point of governance will allow for the setting of common goals and standards whilst still providing agencies with the flexibility to meet the particular requirements of their business. The proposed governance model promotes a hierarchy for decision-making focussed on common standards related to people, technology and processes.

The strategy also stresses the need to drive interoperability, improve performance and reduce duplication through the development of a predictive services model that is focused on achieving common standards for people, technology and process with support from agency participation. Agencies share many common goals and needs and the specialized nature of bushfire predictive services, which means that a more unified approach will benefit emergency managers and agencies. Instituting a series of common standards related to accreditation, certification and role specification will work to secure and improve the quality of FBAN human resources. The state must assign authority to prioritize and coordinate maintenance and improvement to existing technology platforms along with providing common control for data management and feedback reporting systems. Developing a forecast doctrine process will ensure that uncertainty and model accuracy are communicated appropriately to end-users. The key to implementing these standards will be in educating emergency managers to facilitate uptake and adoption of these products and services in line with individual policies and operations.

The third goal within the BBPSS outlines the need to keep pace with the changing needs of the community and fire managers in order to ensure that resourcing, products and services are all secure, reliable, adaptable and benchmarked against good practice. FBANs must be able to operate across the incident, regional and state-wide levels and withstand a constantly changing physical, political and economic environment. The agencies must clearly identify their priorities and objectives for evolving predictive service capability and capacity. Bushfire behavior predictive services must also keep pace with technological and scientific advances in order to remain current and relevant. This means that agencies must look to the future and plan for changes in FBAN workforce requirements as well as maximise investment in research and development to achieve shared objectives. Encouraging innovation and excellence in the predictive services field will help to ensure that predictive services are meeting the shifting needs of emergency managers.

The BBPSS was completed in December 2013 and implementation across the state has begun. The strategy provides an implementation plan to help achieve the identified goals across the next five years. Recently, the strategy has been reviewed by national research bodies and it is intended that it will be used to help guide the development of a national FBAN and predictive services approach for Australia.

Lessons Learned

The BBPSS in Victoria was informed by an intensive stakeholder engagement analysis. Operational personnel from various management levels and locations across the state were interviewed and surveyed in relation to their preferences and previous experience with FBANs and predictive service outputs. Functioning FBANs were also engaged in a workshop using a strengths, weaknesses, opportunities and threats (SWOT) analysis in order to evaluate the predictive services program.

From these interactions and across the development of the BBPSS, ten simple targets became emergently important in relation to forming and maintaining effective capability and capacity for specialized fire behavior prediction. They are:

1. **Quality over quantity:** Nominate personalities and backgrounds who are most likely to succeed and carry forward knowledge gained from training. Investing time into specific individuals will produce the best results.
2. **Maintain flexibility**: Be ready to adapt to the changing emergency response environment. Updates to technology, shifting demographics and increasingly complex fire behavior must be regularly addressed.
3. **Measure success**: Gain support from those who do not interact with the role directly by quantifying the impact of including predictive science in decision-making. Science can support positive reporting (e.g., area saved instead of lost, contribution of prescribed burning to forest fire control, etc.).
4. **Good governance**: Identify a program champion(s) whose role it is to strive for identified strategic goals, to maintain training schedules, to facilitate new product development and to update overhead staff of ongoing advancements.
5. **Fit for purpose**: Build FBAN products and services to suit end-user needs. Consultation with those on the fireline will ensure outputs are adapted easily and are well used in the field.
6. **Skills maintenance**: Allocate FBANs enough time annually to maintain their skills and to keep up-to-date on advances in the research and modeling realm. This IMT role requires substantial time additional to that allocated to regular duties.
7. **Technical support**: Deal with technical support issues as soon as they arise. Although FBANs are trained to function entirely separate from modern technology, certain tools assist their ability to provide timely advice especially when there are multiple ignitions to triage.
8. **Unified front**: Keep products standardized for delivery across all involved fire control agencies. Uniform prod-

ucts will help decisions be more consistent, accurate, reliable and defendable under scrutiny.

9. **End-user education:** Continually educate those who regularly use and interpret FBAN products. New products and services should be accompanied by a form of technical transfer outlining intended uses and applications.
10. **Urgency:** Build FBAN capability and capacity with the future in mind. Increasing public expectation and rising risk of liability means that fire management decisions must be defendable and accountable. Do not get caught undersupplied.

Applications and Conclusion

The development of the Victorian predictive services capability is truly a story of learning by doing. It is a strong example of the power of a few committed individuals and the strength of scientifically based decision support tools. By reflecting on the outcome of the SWOT analysis, learning becomes a process whereby knowledge is created through the transformation of experience (Healey and Jenkins 2000).

The key lessons from the Victorian experience as described in this paper indicate that in order to build new capability in an organization, it is important to have champions high enough in the hierarchy to be able to continue promoting and investing in the development of a new service. There must be an individual capable of explaining and frequently providing proof of the value of the new capability to those decision-makers with the power to promote or cull the program.

The agencies involved also need a number of individuals who are willing to learn and be flexible enough while exploring new options and optimal solutions. There needs to be a willingness to persevere even when new capability is not understood within the organization and individuals must continue to educate end-users until those new products and services become business as usual. A lack of recognition tends to plague early generations of new capability, but case studies and evidence of ongoing adoption and success can fuel recruitment of additional willing individuals.

Given the above, it is clear that training alone will not deliver appropriate results when implementing the strategic plan. The Victorian fire agencies have adopted the "10:20:70 model" for capability development (Figure 10) (Slijepcevic and others 2012). This is borrowed from Lombardo and Eichinger (1987) who explain the learning process as:

- 10% gained from courses that provide specific material to support knowledge and tools for a leadership toolbox;
- 20% acquired from others from coaching, feedback, mentoring and reviewing lessons learned; and
- 70% attained on-the-job through practice, simulations and actually doing the job.

In closing, the history of the advancement of the FBAN capability in Victoria demonstrates the highs and lows of developing a program on an as needed basis using experience-based learning to guide the evolution of a program. Collecting lessons learned from past experience and engaging end-users in the thinking for a future approach has helped to produce an adaptable and easily adoptable series of strategic interventions; these actions will guide the program forward and allow it to flex through anticipated changes in the emergency management environment while providing objectives on which to evaluate ongoing success.

For Further Information

The process as described in this paper produced a series of four documents that are available upon request from the authors. They include:

1. "*History of the Development of Fire Behavior Analysts in Victoria"* provides a full history of Victoria's FBANs along with case studies of their work.
2. "*Initial stakeholder analysis report"* summarises extensive stakeholder consultation undertaken to capture future

Figure 10—The 10:20:70 model (adapted from Lombardo and Eichinger 1987) which emphasises the value of on-the-job training versus coursework and coaching programs.

expectations of both practicing FBANs and incident management personnel.

3. "*Predictive Services Strategy discussion paper"* presents key themes identified in the background document and initial stakeholder analysis. It is paired with a stakeholder survey.
4. "*Embedding predictive services in emergency management decision-making- Victoria's Predictive Services Strategy"* is the final document which pulls together solutions and strategic interventions for issues identified in the first three documents.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Influence of Landscape Gradients in Wilderness Management and Spatial Climate on Fire Severity in the Northern Rockies USA, 1984 to 2010

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Abstract—*Management activities, applied over broad scales, can potentially affect attributes of fire regimes including fire severity. Wilderness landscapes provide a natural laboratory for exploring effects of management because in some federally designated wilderness areas the burning of naturally ignited fires is promoted. In order to better understand the contribution of fire management activities to fire effects, we examined patterns of severity across a management gradient defined by wilderness—non-wilderness boundaries in a northern Rocky Mountain study region. We identified a significant positive effect of the management gradient on severity for the time period 1984 to 2010, but the magnitude and direction of effects varied from year to year. However, the influence of management on severity was subsumed by the influence of spatial climate. Our findings represent an important step in constructing predictive models of severity with changes in both climate and fire management practices.*

Introduction

Understanding the contribution of management policies and practices to emerging attributes of fire regimes is increasingly important, given the broad scales at which fire suppression, prescribed burning, vegetation management and other strategies continue to be applied. A primary example is found in some federally designated wilderness areas in the western U.S., where management policies have encouraged so-called "natural burning," that is, allowing lightning-ignited fires to burn with little human interference (Parsons and others 1986). The likelihood that fires will burn of their own accord in wilderness is increased because the practice is favored by policy; in addition, natural burning is favored in wilderness during times when suppression in non-wilderness areas takes higher priority, or when remoteness prevents timely and effective suppression response. However, natural burning policies are not applied uniformly across wilderness areas; the need to protect property and respect management policies on adjacent lands plays an important role in deciding when and where fires are allowed to burn in wilderness (Kelson and Lilieholm 1999; Karieva and others 2007).

In a previous study, we found indications that the distribution of fire sizes, and in particular, the predominance of the largest fires, was influenced by differences in management along a non-wilderness—wilderness continuum (Haire and others 2013). Based on analysis of contemporary fire size distributions (1984 to 2007), the magnitude and direction of change along the wilderness gradient varied among three study regions. Results for the northern Rockies study region were particularly striking: conditions favorable to large fire events increased dramatically toward wilderness interiors.

If large fire events are apparently influenced by wilderness management context, what about the ecological changes resulting from those fires? Several recent projects have examined the dynamics of severity with re-burning that has occurred within wilderness areas in recent decades (Holden and others 2010; van Wagtendonk and others 2012; Parks and others 2014b). These studies suggested that previously burned areas moderate the severity of subsequent fire. Importantly, however, outcomes can vary in relation to several factors including climate and weather conditions, vegetation type, time-interval since fire, and effects of the previous fire. Following on the findings of these studies, we derived two research hypotheses which we tested in a northern Rockies study region across a wilderness gradient (figure 1).

H_1: Fire severity varies primarily in relation to management and fire history. Burning practices in wilderness contribute to the heterogeneity of fuels in such a way that limits imposed on severity at local scales (e.g., Parks and others 2014b) will be apparent at the regional scale of our study.

H_2: Variability in spatial climate is the primary driver of severity at regional scales through its effects on fire season length, vegetation type, productivity, and fuels. These patterns are more important than management in determining trends in severity; effects of management are superimposed on this basic template.

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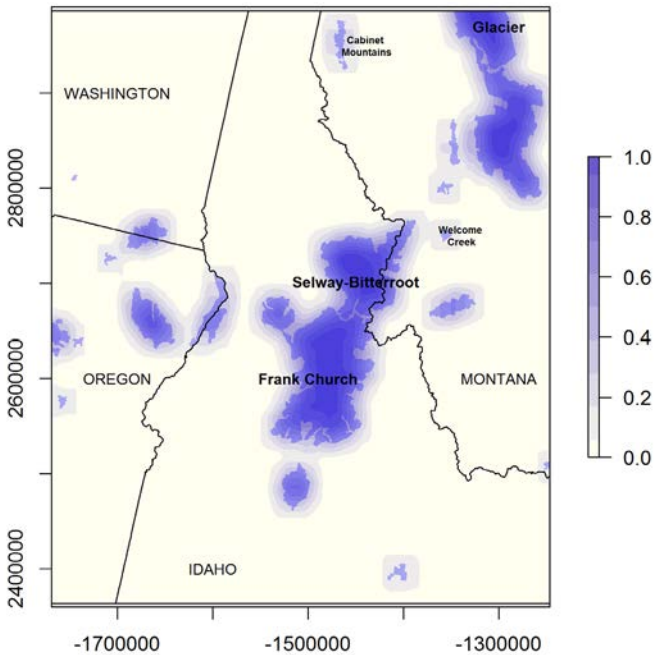

Figure 1—The northern Rockies study area included several wilderness areas (dark blue shading; those mentioned in the text are labeled, as is Glacier National Park). Legend colors represent the wilderness gradient (WG) which formed the basis of our study design.

Methods

Study Region

The study region includes several northern Rockies wilderness areas and their surrounding landscapes (figure 1). Regional-fire years in the northern Rockies are associated with broad scale synoptic climate (Baker 2003; Heyerdahl and others 2008; Morgan and others 2008). Infrequent high-pressure blocking systems promote extremely dry regional climate patterns (Romme and Despain 1989; Bessie and Johnson 1995) and may respond to global climate anomalies (Baker 2003).

Ecosystem characteristics vary across the region with elevation. Higher elevation forest species include whitebark pine (*Pinus albicaulis*), lodgepole pine (*P. contorta*), subalpine fir (*Abies lasiocarpa*), grand fir (*A. grandis*), and Engelmann spruce (*Picea engelmannii*); ponderosa pine (*P. ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*) are present at middle elevations (Rollins and others 2002; Morgan and others 2008). In wetter climates, including areas of the Cabinet Mountains Wilderness, western redcedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) are found in valleys with heath-shrublands inhabiting open ridges (www.wilderness.net). Upmost elevations are known for their sparsely vegetated rocky and often icy conditions.

Wilderness areas range in size, with Frank Church-River of No Return (957,820 ha) and Selway-Bitterroot (542,516 ha) located adjacent to each other, separated by the Magruder Corridor. Glacier National Park was also included as a "wilderness area" due to its large size (200,075 ha) and fire management history which includes allowance of natural burning. Some relatively smaller wilderness areas are scattered on the surrounding landscape, for example, Welcome Creek (11,385 ha). Wilderness areas are surrounded by publicly owned lands managed for multiple uses including livestock grazing, timber harvest, and recreation (www.nationalmap.gov), and also abut parcels of private land.

Sampling Design

We sampled fire severity data and other variables across a wilderness gradient (WG; figure 1) which was constructed using the following steps. First, we added Glacier National Park to a base map of wilderness boundaries (www.nationalmap.gov). Then, we derived a gridded map (400 m cell size) of wilderness/non-wilderness (assigned values of 1/0 respectively), based on the wilderness (plus one Park) boundaries. Next, we applied a uniformly weighted kernel within ~130,000 ha moving windows across the region. Variations in the shape and size of the wilderness areas resulted in a continuous gradient of values ($0 < x < 1$; figure 1). The WG achieved its maximum value (1) in interior portions of large wilderness areas, and the minimum value (0) in areas farthest outside wilderness boundaries. The WG surface matched the projection of all other spatial datasets used in the study (i.e., severity and climate data; Albers Equal Area Projection, North American Datum of 1983). All spatial and tabular data analyses were accomplished in R (R Core Team 2014).

Neighborhood Severity Models

We used burn severity data for 1984 to 2010 (Differenced Normalized Burn Ratio, ΔNBR; www.mtbs.gov) to develop a response variable for the analysis. Recognizing that new burn severity metrics continue to be developed and tested for their utility (Parks and others 2014a), we judged ΔNBR appropriate to our need for a continuous measure of landscape change. Burn severity images ($n = 895$) were resampled from 30 m to 100 m cell size and a uniformly weighted kernel (7 x 7 cells/ ~50 ha) was applied to create a measure of neighborhood severity (NS; figure 2). The goal of resampling and kernel smoothing was to identify and map concentrations of similar values of burn severity at a scale that better corresponded to regional conditions in spatial climate. The kernel models were randomly sampled at a consistent density (1 point/100 ha); points were then subsampled to achieve uniform distribution across the WG ($n = 2000$). Thus, points fell primarily within and immediately adjacent to wilderness areas. Twenty of the sampled burn images were striped due to failure of the forward motion of Landsat 7 (http://landsat.usgs.gov/products_slcoffbackground.php), but we were able to obtain alternative burn images in 15 cases (JFSP project 12-1-03-19: Quantifying the effectiveness and longevity of wildland fire as a fuel treatment). Samples from the remaining five striped images were dropped from the analysis, resulting in a final sample of $n = 1979$.

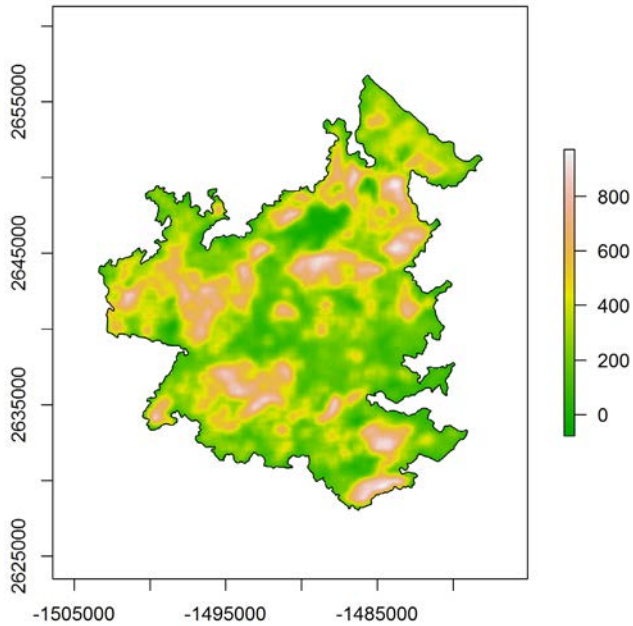

Figure 2—Neighborhood severity (NS) was modeled using burn severity images (*n* = 895). Images were smoothed by resampling from 30-m to 100-m cell size and applying a uniformly weighted kernel. The ~36,000 ha Flossie Complex (Idaho, 2000) NS model is shown here.

Spatial Climate Models

We used 19 Bioclim layers to represent variability in fuel conditions across the study region based on the assumption that ecosystem and associated fuel characteristics are strongly driven by climate. Staff at the U.S. Geological Survey, Fort Collins Science Center developed the data set employed in our study using 400 m climate normals data (1971 to 2000) which were downscaled from PRISM data (http://www.prism.oregonstate.edu/) by Climate Source, Inc. Conditions in temperature or precipitation are modeled annually (e.g., Annual Precipitation), and within time periods defined by variability at each grid cell location (e.g., Precipitation in the Driest Period). Definitions of the 19 variables are available on the WorldClim website (http://www.worldclim.org/bioclim; see also Hijmans and others 2005). All layers were sampled at the random locations (*n* = 1979) and used as predictor variables in the analysis.

Analysis

We used quantile regression (Koenker 2013) to analyze patterns of severity (NS) across gradients of spatial climate (Bioclim layers) and management (WG). Compared to ordinary least squares regression, quantile regression allows a more complete picture of relationships between variables when a single rate of change based on central tendency may not adequately characterize patterns in the data (Cade and Noon 2003; Cade and others 2005). Quantile regression models have the same interpretation as ordinary least squares models, but the models can be developed for specific portions of the data distribution. For any given quantile (τ), slope coefficients represent rates of change after adjusting for the effects of the other variables in the model. At upper and lower quantiles, results can be interpreted as constraints because a majority of the sample data occurs below or above the modeled interval (τ), in contrast with other regression techniques where interpretation focuses on the mean response (Cade and Noon 2003).

The goal of our modeling process was to evaluate the effects of the WG on NS at upper τ after accounting for the effects of ecosystem and associated fuel characteristics. We were most interested in modeling upper limits to NS because constraints on higher severity would be expected under H_1; thus, we estimated rates of change of the response distribution (NS) conditional on the matrix of predictor variables (19 Bioclim variables, WG) for $\tau = 0.70$ to $\tau = 0.90$ at intervals of 0.05. We used the linear quantile regression method to estimate parameters for each τ and the rank score-based method to compute confidence intervals assuming independent but not identically distributed errors; these options are available in the quantreg package written in R (Koenker 2013).

First, we tested each predictor in a separate univariate model to identify patterns in relationships between NS and the WG and between NS and each of the 19 Bioclim variables. We then derived 1) a full model containing all Bioclim predictors found to be significant in univariate models and 2) a minimally adequate (reduced) model which contained variables found to be significant in the full model. Finally, we added WG to the reduced model, to test for its importance after taking into account effects of the Bioclim representations of ecosystem and associated fuel characteristics. A variable was considered an active constraint if the upper and lower bounds of 90 percent confidence intervals were either both greater than zero or both less than zero for the upper range of τ. We repeated the univariate WG model using data from three years which were both well represented in the data set and had a fairly even distribution of data points across the WG (1988, 2000, and 2007), to compare outcomes for these large fire years (Morgan and others 2008) with the result for all years.

We used $AIC_c(\tau)$ to compare models with spatial climate variables only (reduced model, described above), to models containing the WG as an additional predictor (reduced model + WG):

$$NS = \beta_0 + \beta_1,,,nClimate + WG + \varepsilon$$

where NS = neighborhood severity, Climate = Bioclim spatial climate variables and WG = wilderness gradient. The $AIC_c(\tau)$ is a modification of Aikake's Information Criterion for small sample size (Hurvich and Tsai 1990) that incorporates differences in coefficients of determination, that is, the weighted sum of absolute deviations minimized in estimating the τth quantile regression with *p* parameters (Cade and others 2005). We compared differences between $AIC_c(\tau)$ for the more complex models and the simplest model with a constant only (β_0) to represent model improvement with addition of parameters ($\Delta AIC_c(\tau)$ as defined in Cade and others 2005). The resulting scale of $\Delta AIC_c(\tau)$ provides a positive measure that is proportional to model fit, as well as a measure of relative improvement as variables are added to

simpler models. We calculated $\Delta AIC_c(\tau)$ across all τ (0.05 to 0.95 in increments of 0.05) to observe changes in models representing lower, middle, and upper constraints on NS while focusing on outcomes at upper τ.

As a final exploratory step we constructed a spatial model of predicted values using a set of variables selected, above, for the 75th quantile. We used the "predict" function in the raster package (Hijmans 2014) which outputs a raster object with predictions from a fitted model object. The spatial model was evaluated qualitatively for the purpose of generating ideas for research to follow.

Results

Wilderness management context had a marked influence on fire effects at the regional scale of the study, based on consideration of the wilderness gradient alone. We identified a gradual, positive constraint on NS at upper quantiles (τ = 0.70 to τ = 0.90) wherein severity increased along the WG (figure 3). However, the direction and magnitude of effects varied when viewed in different time frames (figure 4). Patterns of NS in 1988 showed a steep, negative upper limit indicating *decreased* severity along the WG. In 2000, however, no significant trends were evident, and in 2007, an *increasing* trend in NS was seen across the WG at upper τ.

Gradients in spatial climate, represented in Bioclim variables, were major contributors to patterns of severity across the region from 1984 to 2010. Specifically, all significant predictors worked to increase NS at the upper range of the data distribution (table 1). Among the seven Bioclim variables which were significant in univariate models, Precipitation in the Wettest Period, Precipitation in the Driest Period, and Precipitation in the Coldest Quarter emerged as important, positive predictors of NS in multiple regression models (table 1, Models 2 and 3). The contribution of WG to trends in severity became insignificant when considered in combination with the spatial climate gradients (table 1, Model 4).

Although the positive, upper limit to NS imposed by the WG was statistically significant in univariate models (table 1), it added relatively little information to models representing constraints across the range of lower, middle, or upper τ

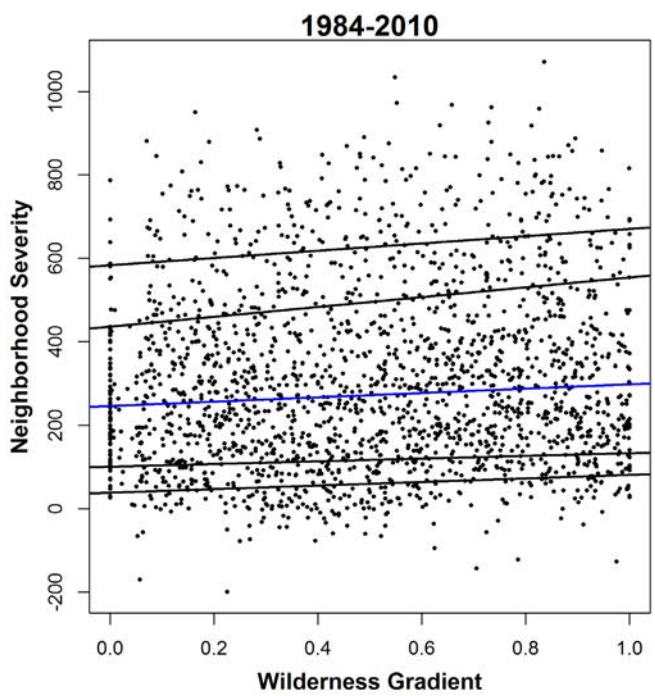

Figure 3—Plots of regression quantile model fits using fire severity data for all years, where *y* = neighborhood severity (NS) and *x* = wilderness gradient (WG). The black lines represent regression quantile fits for τ = 0.10, 0.20, 0.80, 0.90; the blue line is the median fit (τ = 0.50), and data points are shown as black points. Neighborhood severity increased gradually but significantly at upper quantiles, indicating increasing magnitude of fire effects along the wilderness gradient.

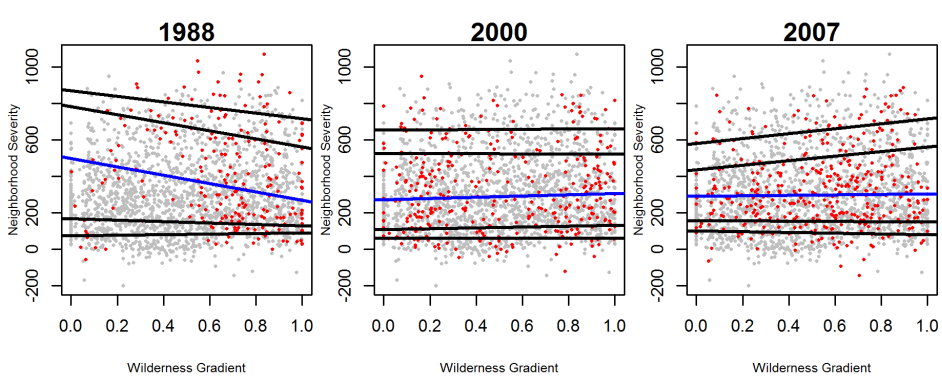

Figure 4—Plots of regression quantile model fits, as in Figure 3, but using fire severity data for 1988, 2000, and 2007 (show as red dots in each plot; gray dots represent data from all other years). At upper quantiles, a decreasing trend was observed for 1988, trends were non-significant for 2000, and neighborhood severity increased across the wilderness gradient in 2007.

Table 1—Regression results for τ = 0.70 to τ = 0.90 at intervals of 0.05 (direction of effect: +/− or non-signficant: ns). Seven out of 19 Bioclim variables and the wilderness gradient (WG) were significant predictors of neighborhood severity (NS) in univariate models (1). Results are also shown for univariate regression of NS~WG by year. Three of the seven Bioclim predictors retained importance in a full multivariate model (2), but only Precipitation in the Driest Period held its influence in a reduced model (3). After adding WG to the reduced model, Precipitation in the Driest Period and Precipitation in the Coldest Quarter were positive predictors, but WG was not important (4). Significance was determined by tests of 90 percent confidence intervals.

Model	Ann. PPT	PPT Wettest Period	PPT Driest Period	PPT Wettest Quarter	PPT Driest Quarter	PPT Warmest Quarter	PPT Coldest Quarter	WG 1984-2010	WG 1988	WG 2000	WG 2007
1. Univariate	+	+	+	+	+	+	+	+	−	ns	+
2. Multiple regression (full)	ns	+	+	ns	ns	ns	+				
3. Multiple regression (reduced)		ns	+				ns				
4. Multiple regression (reduced) + WG		ns	+				+	ns			

(figure 5). Models tended to be better overall, in terms of fit and explanatory power, at the highest values of τ, indicating that landscape gradients included in the models became operative at the upper range of severity.

Predicted patterns of severity at its upper limits were highly variable across wilderness landscapes. Some of the highest predicted values, and steepest gradients in NS, occurred higher along the WG, that is, in wilderness interiors (e.g., in the Frank Church–River of No Return and Glacier; see figure 1); however, a wide range of values were observed across the study region and relative to location across the WG (figure 6).

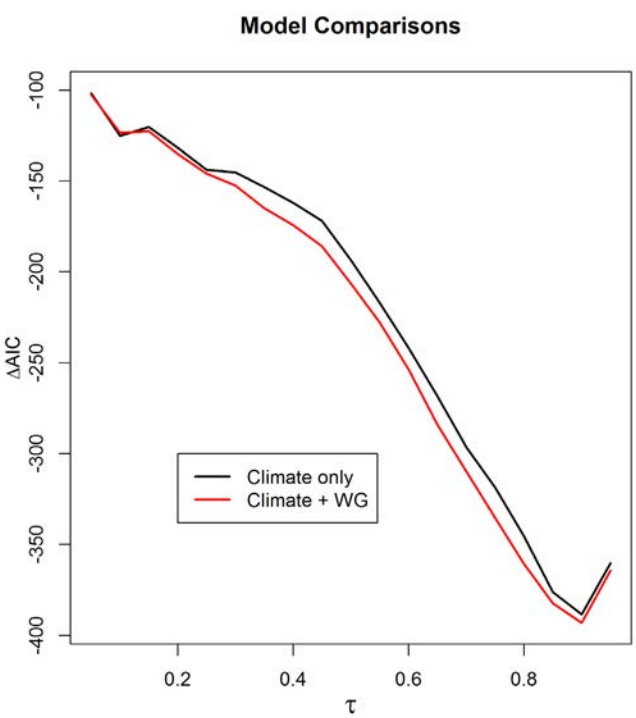

Figure 5—Differences between AIC_c (τ) (*y*-axis) for the more complex models and the simplest model (β_0) were plotted across τ (*x*-axis) to represent model improvement with addition of parameters. Larger absolute values of $\Delta AIC_c(\tau)$ also signal better model fit. The models included three Bioclim precipitation variables before and after adding the wilderness gradient (WG). Model fit improved across quantiles, but the WG added very little to models at lower, middle, or upper τ.

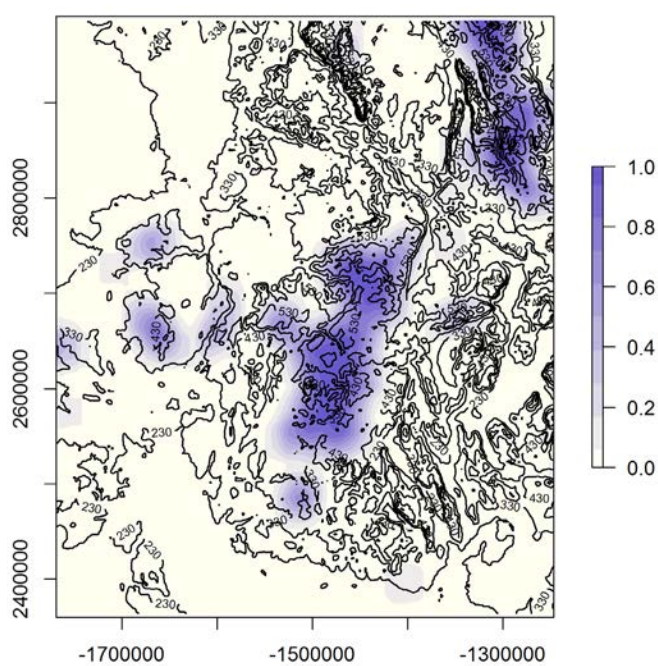

Figure 6—Spatial prediction for the neighborhood severity (NS) gradient (black contour lines) at upper limits of the data distribution (τ = 0.75). Two Bioclim variables were included in the model: Precipitation in the Driest Period and Precipitation in the Coldest Quarter. The wilderness gradient (WG) is shaded in the background, with wilderness interiors dark blue as in Figure 1.

Discussion

In an earlier study, the wilderness—non-wilderness gradient had a strong correspondence with the influence of large fires in structuring fire size distributions in the northern Rockies (Haire and others 2013). Our current findings indicate that the severity of fires also varies spatially in relation to the shape and size of wilderness areas which define the wilderness gradient. Although management history cannot be assumed to vary uniformly across the gradient, the coincidence of multiple factors along the gradient, including management activities, led to measurable consequences for both fire size distributions and fire severity at the regional scale of the study.

Natural burning practices which are known to affect landscape heterogeneity of fire effects at particular locations (Holden and others 2010; van Wagtendonk and others 2012; Parks and others 2014b) also influence patterns of severity at a regional scale in the northern Rockies. However, across all years of our study, rather than leading to lower severity, wilderness management was implicated in producing a gradual, but statistically meaningful positive trend in severity at locations associated with its upper range of values. It is possible that the agency of wilderness management in lessening fire effects is only quantifiable in particular years (figure 4), or that interactions between management and environment constitute primary drivers of increased severity across the study landscape.

In the northern Rockies study region, patterns of severity adhere to underlying templates which are closely related to gradients in spatial climate. Our findings reinforce the basic premise of studies which focus on patterns of burning differentiated by major ecological zones (e.g., Andison and McCleary 2014). Precipitation during specific seasons defined this template in our study region, reflecting dynamics of fuel condition and connectivity in both space and time. Wetter conditions were the predominant contributors to increased severity at locations associated with its upper range of values, and their influence subsumed the role of management in multiple regression models (table 1; figure 5).

Our results are best interpreted with consideration of other landscape attributes that can influence fire effects and are potentially confounded with the wilderness gradient. In particular, outside of wilderness, anthropogenic landscape fragmentation caused by roads and other human structures, as well as land use practices such as agriculture, livestock grazing, and timber harvest can alter fuel type, condition, and continuity (Parisien and Moritz 2009; Shinneman and others 2010). In contrast, fragmentation in wilderness areas is more often defined by natural boundaries that modulate fire spread and intensity including rock, ice, and topographic variability. These landscape attributes may affect our ability to accurately detect changes in severity along the management gradient at regional scales.

Concern regarding climate change has led to strong interest in predictive models which utilize spatial climate data. These spatial models require establishment of a functional relationship between climate variability and a process of interest, often species presence or abundance (Elith and Leathwick 2009). Our work represents a successful first step in the modeling process for fire severity and, with further development, could ultimately provide predictions under future climate scenarios.

For example, steep gradients in severity were predicted relative to management boundaries in some places (figure 6). Examining changes in these gradients under different climate scenarios could be useful in understanding the role of more static landscape properties (e.g., management boundaries and topography) compared to dynamic shifts in the composition and arrangement of ecosystems. More robust models would be achieved through inclusion of additional environmental data, further exploration and quantification of scales of importance in pattern-process relationships, and assessment of predictive performance and model uncertainty. Resulting insights into the dynamics of fire effects across space and time could provide useful perspectives for managers and conservationists alike.

Acknowledgments

We gratefully acknowledge L. Holsinger for providing alternative burn severity imagery for some fires, E. Plunkett who wrote and assisted in implementing R code for kernel functions, and the GIS-RS Team at USGS Fort Collins Science Center who produced and distributed the Bioclim data. Thanks go to J. Coop and B. Harvey for constructive manuscript reviews. The project was funded by the USFS Rocky Mountain Research Station, Study Number 12-JV-11221636-138.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Mapping Landscape Fire Frequency for Fire Regime Condition Class

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Abstract—*Fire Regime Condition Class (FRCC) is a departure index that compares the current amounts of the different vegetation succession classes, fire frequency, and fire severity to historic reference conditions. FRCC assessments have been widely used for evaluating ecosystem status in many areas of the U.S. in reports such as land use plans, fire management plans, project plans, burn plans, and agency reporting.*

The FRCC Mapping Tool ($FRCC_{MT}$) spatially models FRCC within a Geographic Information System (GIS). Succession classes are available as a spatial input to the $FRCC_{MT}$ from LANDFIRE. The FRCC fire severity spatial input can be generated with the Wildland Fire Assessment Tool (WFAT) which utilizes spatial inputs from LANDFIRE along with weather inputs which are readily available from the Remote Automated Weather Stations (RAWS) Climate Archive at www.raws.dri.edu. At this time, no models have been developed which enable the generation of fire frequency at a spatial scale similar to that of succession class and fire severity.

This research develops and evaluates methods and data which enable users to create spatial fire frequency inputs to the $FRCC_{MT}$. Fire frequency data being analyzed for inclusion in such a model include LANDFIRE disturbance maps, Monitoring Trends in Burn Severity maps, and local fire history maps. Fire frequency methods and results are presented for case studies of user-specified time periods. We conclude that these methods could be implemented to provide a software tool which can utilize the previously mentioned datasets to produce spatial frequency data which can be utilized as inputs for mapping of FRCC. Additionally, we propose additional metrics which can assist with development of management plans for mitigating severe frequency departure and returning project areas to a state which more closely resembles reference conditions.

Introduction

The precursors to the Fire Regime Condition Class (FRCC) concept have been in existence since the 1990s as indicators of landscape ecological condition and resilience to disturbance (Hann and others 1998; Hann and Bunnell 2001). FRCC was developed as a standardized national approach during the late 1990s. FRCC is a departure index that compares the current amounts of the different vegetation succession classes, fire frequency, and fire severity to historic reference conditions. FRCC assessments have been widely used for evaluating ecosystem status in many areas of the U.S. in reports such as land and fire management plans, National Environmental Policy Documents, project plans, burn plans, and agency accomplishments. FRCC requires a variety of data inputs including the amounts of different succession classes within biophysical settings, estimates of time period fire frequency and severity and associated reference values for historical within the analysis area extent.

The FRCC Mapping Tool ($FRCC_{MT}$) has been developed under the sponsorship of the USDA Forest Service and USDI Fire Management Agencies. The Wildland Fire Management Research Development and Applications (WFMRD&A) unit, an inter-agency team, manages the development and applications of this tool and many other wildland fire and fuels decision support tools. The $FRCC_{MT}$ spatially models FRCC within a Geographic Information System (GIS). Succession classes (SClass) are available as a spatial input to the $FRCC_{MT}$ from LANDFIRE. The FRCC fire severity spatial input can be generated from the WFMRD&A Wildland Fire Assessment Tool (WFAT) which utilizes spatial inputs from LANDFIRE along with fire weather inputs which are readily available. At this time, no models have been developed which enable the modeling of fire frequency at a spatial scale similar to that of succession class and fire severity. The only method for determining current fire frequency spatially as an input for the $FRCC_{MT}$ relies on using expert opinion as an input for the Fire Frequency and Severity Editor (FFSE) which is included as part of the $FRCC_{MT}$.

Fire frequency is defined as the fire occurrence or rate, such as the average time interval between successive fires, or the number of fires within a specific period of time (McPherson and others 1990; Agee 1993). The FRCC Guidebook specifically defines fire frequency and the associated term mean fire return interval as the average number of years between fires for representative stands (Barrett and others 2010). Fire frequency is an important ecological and resilience measure because fire is a keystone process in most ecosystems, even

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

in rare-interval systems (Keane and others 2002). It is important as an ecological measure as the interval between fires determines the subsequent species of plants that may occur, the amount and structure of re-growth, and the amount and kinds of fuel accumulation (Wright and Bailey 1982). These in turn determine, for the next fire occurrence, its probability of ignition and type of fire. Fire frequency is an important factor in measuring resilience as it can determine both the next kind of fire disturbance as well as the ability of the ecosystem to return to its prior functions (Denslow 1985; Holling 1973).

This research develops and evaluates methods and data which would enable users to create spatial fire frequency inputs to the $FRCC_{MT}$ at a similar scale as SClass and fire severity. Fire frequency data being analyzed for inclusion in such a model include LANDFIRE disturbance maps, Monitoring Trends in Burn Severity (MTBS) maps, and local fire history maps. Fire frequency methods and results are presented for case studies of user-specified time periods including a set of historic sub-periods based on the dataset that best captures the fire history within the post-reference period. The goal of this research is to develop a methodology for the determination of fire frequency which could be implemented to provide a software tool. This tool will utilize the previously mentioned datasets to produce spatial frequency data which can be utilized as the fire frequency input to the $FRCC_{MT}$ for mapping of FRCC outputs.

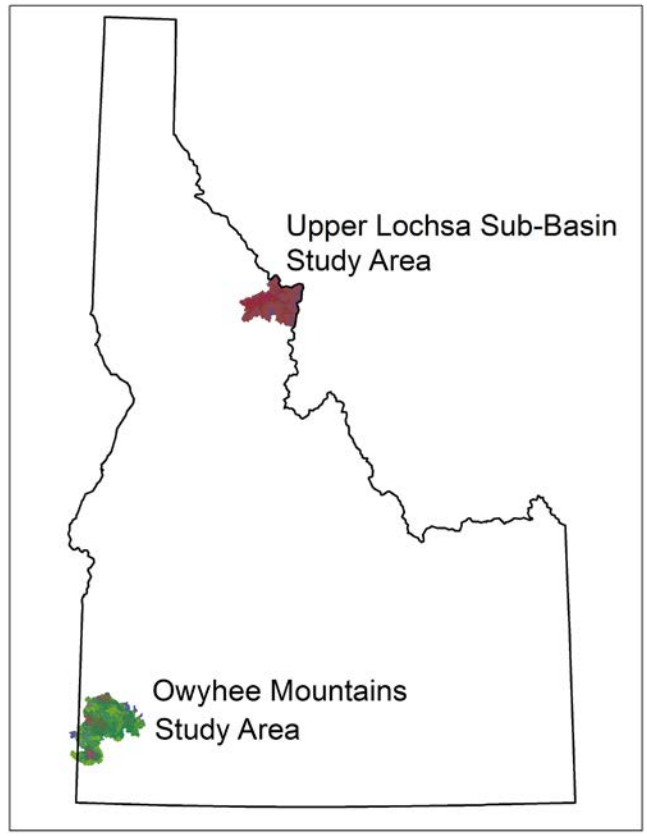

Figure 1—The upper Lochsa River subbasin in northern Idaho is a mountainous region containing subalpine and mountain mesic forests and woodlands. The upper Lochsa subbasin is in the Clearwater National Forest in northern Idaho. The Owyhee Mountains in southwest Idaho consist primarily of xeric montane sagebrush steppe. Most lands in the Owyhee Mountains are administered by the BLM's Owyhee Field Office.

Fire History Data Sources

When calculating wildland fire frequency for Fire Regime Condition Class, the method that users currently have available is to utilize the Frequency and Severity Editor (FFSE) in the $FRCC_{MT}$. The FFSE allows a user to assign current estimates of fire frequency by Biophysical Setting, creating a Fire Frequency raster which the $FRCC_{MT}$ can utilize as a spatial input. When using the Frequency and Severity Editor, the preferred data source for a study area is a fire atlas of the local management unit. Basing estimates on a fire atlas is more defensible than other data sources, such as fire history field observations and formal fire history research (Jones and Ryan 2012).

Spatial fire history data can come from a variety of sources depending on what historical data is available. Fire history from the later part of the 20th century and the 21st century can be obtained from sources that utilize remotely sensed data. The Monitoring Trends in Burn Severity (MTBS) program has spatially documented large wildland fires that have occurred beginning in 1984. The LANDFIRE project has produced disturbance layers that include both wildland fire and prescribed fires since 1999. In order to obtain spatial fire history data prior to the start of the MTBS records in 1984, it is necessary to rely on digitized fire history atlases which are maintained by some land management units. These historic atlases will contain the perimeters of fires which have occurred. In order to utilize historic atlases, they have to first be digitized into an electronic format which facilitates their use with a geographic information system (GIS).

The case studies of the data and methods included two study areas in Idaho. One study area was the upper Lochsa River subbasin in north Idaho, a region consisting primarily of subalpine and mountain mesic forests and woodlands. The other study area was in the Owyhee Mountains in southern Idaho, an area which by contrast is primarily xeric montane sagebrush steppe. The location of both study areas is shown in figure 1.

LANDFIRE Disturbance Data

The LANDFIRE Disturbance data are a set of digital spatial datasets which provide temporal and spatial information related to change to wildland vegetation and fuels across the United States caused by management activities and natural disturbances. Disturbance data were developed using Landsat satellite imagery, local agency-derived disturbance polygons, and other ancillary data (LANDFIRE 2014). These data include attributes which are associated with disturbance year and disturbance type, including both wildland fire and prescribed fire. The LANDFIRE Disturbance data starts with disturbances that occurred in 1999. As of the year of this analysis, 2014, the dataset includes disturbances that occurred through 2010.

The LANDFIRE Disturbance dataset consists of a set of rasters in ArcGRID format, each of which shows at 30-meter resolution the spatial extent of disturbances for a given year. These disturbances include wildland and prescribed fire, mortality due to insect and disease, and harvesting and thinning. In addition, the data indicates the conversion of wildland into housing, commercial and industrial building sites. The LANDFIRE Disturbance rasters can be downloaded from the LANDFIRE website at www.landfire.gov.

Monitoring Trends in Burn Severity

Monitoring Trends in Burn Severity is a project which maps the burn perimeters of fires across all lands of the United States. MTBS datasets developed by the USDA Forest Service Remote Sensing Application Center show data for each large wildland fire in the United States recorded in federal and state fire incident databases. Determination of the perimeter of each of these fires is accomplished by utilizing a differentiated Normalized Burn Ratio between pre-fire and post-fire Landsat satellite scenes containing each of the fires (MTBS 2014).

Perimeters of wildland fires exceeding 1000 acres in the western U.S. and 500 acres in the eastern U.S. are represented as polygon features in a shapefile. The national MTBS shapefile contains attributes of interest including fire year, size in acres, and fire ID. Fire year will be of most interest while calculating fire frequency in that the year the fire burned will allow us to temporally partition the fires based on when they occur, identifying which fires occurred during the period for which we do not have LANDFIRE Disturbance data. The nationwide MTBS shapefile containing all large wildland fires can be downloaded from the MTBS website at www.mtbs.gov.

Local Fire History Atlas

The third data source that is often available is a local fire history atlas. Local land managers will typically have some sort of history of what fires have burned within their jurisdiction. Historic information about early fires has often been obtained by digitizing hand-drawn maps. More recently, policy has directed that this information be reported in incident reports which over time have facilitated the inclusion of fire perimeter data, often in an electronic form. These fire perimeters may have been collected by traversing the perimeter of a fire with a GPS, or utilization of remote sensing technology. Typically this historic fire history data is stored in vector format as polygon features in a shapefile. The temporal extent of local data will vary by unit based on what historical data was recorded and has been retained.

Fire atlases are available for both study areas. The fire atlas data from the Clearwater National Forest for the upper Lochsa subbasin includes fire history from 1907 through 2011. The fire atlas data from the BLM for the Owyhee spans from 1962 through 2011. In comparing fire data from local fire history atlases against perimeters recorded in MTBS and LANDFIRE, it was found that the local fire history atlases tended to under-report fires, especially smaller fires.

Fire Frequency Methodology

Once MTBS, LANDFIRE, and fire atlas data have been collected for determining fire frequency, those data layers can be coalesced into a single dataset from which fire frequency can be calculated. This process consists of the following steps:

1. Each of the input datasets was converted into Fire Occurrence rasters which do not overlap temporally. Both the MTBS and local fire history datasets were vector-based polygons, so methods followed a similar process. The LANDFIRE disturbance rasters required a separate process for creating an associated Fire Occurrence raster.
2. The Fire Occurrence raster from each dataset was then conjoined into a single Fire Occurrence raster.
3. Fire frequency, using the FRCC definition, was then generated from the Fire Occurrence raster.

Conversion of Fire Polygons to a Fire Occurrence Raster

To include either an MTBS or fire atlas shapefile containing fire perimeters, that shapefile must first be converted into a Fire Occurrence raster. This raster indicates how many times each pixel has burned.

When converting either the MTBS or fire atlas polygon shapefile to a Fire Occurrence raster, data sets were identified for each given sub-period. Once those date ranges have been identified, only fire perimeters within the sub-period were retained. LANDFIRE Disturbance layers were used for fires from 1999 through 2010. MTBS data was extracted from fire seasons from 1984 through 1998, which was prior to the availability of LANDFIRE data. The fire atlas from the Clearwater National Forest contains fire history for the upper Lochsa study area, recording fire polygons dating back to 1907, allowing the extraction of fire atlas polygons from 1907 through 1983. The fire atlas from the Idaho BLM which includes the Owyhee study area contains fire history data dating back to 1960, allowing utilization of fire atlas polygons from that fire history sub-period.

Conversion of polygons to a raster

Conversion of fire perimeter polygons into a Fire Occurrence raster was accomplished by taking the geometric intersection of the polygons from which a resulting raster indicates how many fire polygons were co-located with each intersection polygon. This can be with the following steps:

1. Obtain the geometric intersection of the fire perimeter polygons. It is assumed that all areas within the fire perimeter polygons were burned. Taking the geometric intersection will produce a polygon layer which contains segmented fire polygons where all the area within a given polygon will have burned the same number of times. For example, assume there are two overlapping fire perimeter polygons corresponding to the A fire and the B fire. This would result in 3 polygons, one polygon containing area within the A fire but not within the B fire, denoted A\B, another polygon

containing the area burned by the B fire but not by the A fire, denoted B\A and the intersection of the two fires, denoted A ∩ B.

2. Create a centroid for each segmented polygon resulting from the geometric intersection.
3. Identify how many fire perimeters each of the centroids are located within.
4. Copy the centroid attributes back to their associated segmented fire polygons.
5. Convert the shapefile with the segmented fire polygons into a Fire Occurrence raster.
6. Set the pixels in the Fire Occurrence raster to 0 where fire did not occur.

The resulting Fire Occurrence raster will show the spatial distribution of fire occurrence in the study area during that fire history sub-period. Each pixel will be annotated with how many times that pixel has burned.

Conversion of LANDFIRE Disturbance Rasters into a Fire Occurrence Raster

LANDFIRE Disturbance rasters contained a spatial record of the disturbance types including both wildland fire and prescribed fire. Each LANDFIRE Disturbance raster contained the disturbances of a given year. The fire records were extracted from each of the LANDFIRE Disturbance rasters and then conjoined into a single Fire Occurrence raster.

Extraction of fires from LANDFIRE Disturbance rasters

Extracting the spatial record of fire disturbances from a LANDFIRE Disturbance raster was accomplished by reclassifying the raster for fire associated disturbance types. This process was employed on each of the LANDFIRE Disturbance rasters within the set of rasters which cover the fire history sub-period. Extraction of fire disturbances from a LANDFIRE Disturbance raster can be accomplished with the following steps:

1. Export the raster attribute table to a database.
2. Add a "FIRE" column to the table, setting the column based on whether the value in the *DIST_TYPE* column for a row contains the word "fire."
3. Join the database table back to the raster so the FIRE attribute is included in the raster's attribute table.
4. Reclassify the raster to create a Fire Occurrence raster from the LANDFIRE Disturbance raster, resulting in a binary raster showing burned and unburned pixels.

The resulting annual Fire Occurrence rasters showed the spatial distribution of fire occurrence in the study area for the year represented by the corresponding LANDFIRE Disturbance raster.

Conjoining the LANDFIRE annual Fire Occurrence rasters into a single Fire Occurrence raster

A single Fire Occurrence raster was created which represents fire occurrence for the LANDFIRE historic sub-period. The set of annual Fire Occurrence rasters which were derived from the LANDFIRE Disturbance rasters were conjoined into a single Fire Occurrence raster using a map algebraic add. This Fire Occurrence raster corresponds to the LANDFIRE Disturbance rasters for 1999 through 2010.

Conjoining the LANDFIRE, MTBS and Fire Atlas Fire Occurrence Rasters

A single Fire Occurrence raster was created from the Fire Occurrence rasters that were derived from the LANDFIRE Disturbance, MTBS and Fire Atlas by conjoining the three rasters utilizing a map algebraic add. The resulting Fire Occurrence raster showed fire history for the entire fire history period where each pixel of the raster contains an integer value that indicates how many times that pixel burned. The Fire Occurrence raster for the upper Lochsa subbasin is shown in figure 2.

Calculate Frequency from Fire Occurrence

Once the Fire Occurrence raster was created for the complete fire history period, a Fire Frequency raster was derived. In this process, there were additional intermediate rasters that were generated.

Creation of the Fire Frequency raster from the Fire Occurrence raster involved normalizing the Fire Occurrence raster by landscape and for the Biophysical Setting (BpS). The BpS layer was downloaded from LANDFIRE and represented a relatively uniform environment for categorizing vegetation and fire regime. Intermediate fire frequency metrics were calculated for the combination of landscape and BpS.

Normalization of Fire Occurrence by landscape and BpS

For analysis of FRCC, the $FRCC_{MT}$ utilized two spatial inputs for stratifying the study area. The study areas were delineated via a landscape level to allow for a spatial extent of the FRCC analysis to an assessment area which contained a spatial extent of sufficient size to allow for variability in the vegetation and fire regimes. Watershed hierarchies were used to delineate landscapes to achieve this outcome. Study areas were also stratified within the watershed hierarchy by using BpS. These Hydrologic Units (HUC) layer were downloaded from the USDA Natural Resources Conservation Service's Geospatial Data Gateway at datagateway.nrcs.usda.gov. The Fire Occurrence data, stratified by watershed hierarchy and BpS were then combined, producing a single spatial dataset representing Fire Occurrence within landscape and BpS.

Calculation of intermediate metrics

The attribute table of the combined watershed/BpS/Fire Occurrence raster was exported to a database. This database was then queried to derive the intermediate fire frequency metrics, which were calculated for each BpS within each watershed. These calculations were conducted with the following steps:

1. BpS Size (BS) was the pixel count for each BpS within each watershed.

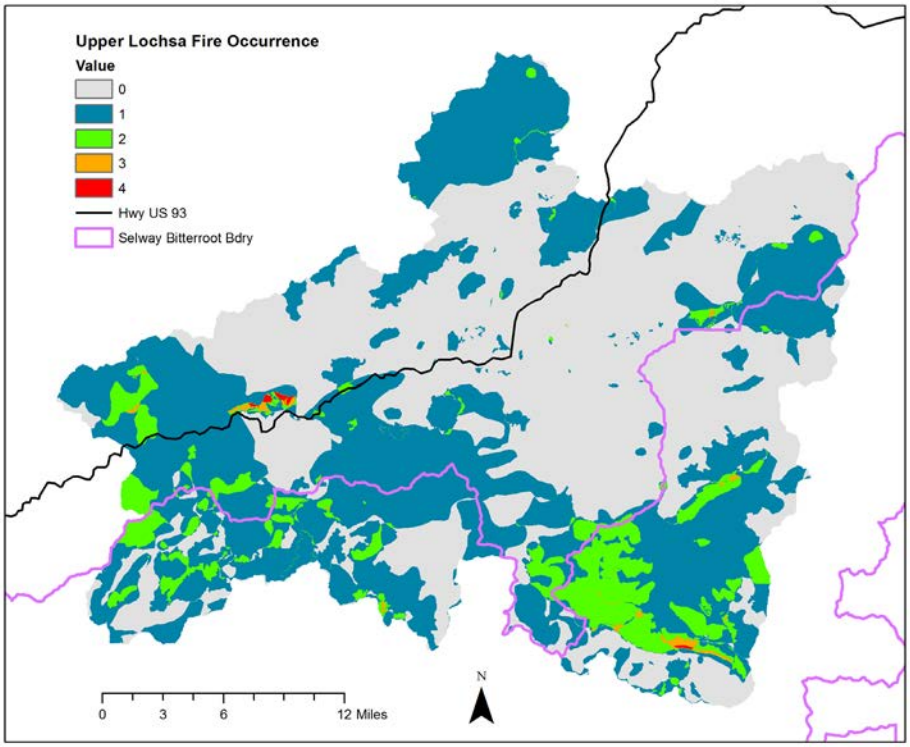

Figure 2—Fire Occurrence raster for the upper Lochsa subbasin for the fire history period from 1907 through 2010. Highway US 93 and the wilderness boundary are shown for reference.

2. Area Burned (AB) was the total number times pixels burned within this BpS/watershed. This calculation took into account that the fire occurrence for a given pixel may have burned more than once.
3. Mean Annual Burned (MAB) was equal to Area Burned divided by the length of the Fire History Period (FHPL).
4. Mean Fire Interval (MFI) is defined as the average number of years between fires. This refers to a grand mean for a BpS within a watershed (Barrett and others 2010). MFI was calculated utilizing BpS Size, Length of the Fire History Period and Mean Area Burned. This relationship was expressed as MFI = BS * FHPL / MAB.
5. Frequency is distinguished from Mean Fire Interval in that MFI only takes into account the spatial fire occurrence data originating from the sources of fire history data mentioned earlier. By contrast, Fire Frequency also considers reference fire regime (Barrett and others 2010). In BpS types which typically experienced relatively frequent fires during the reference period prior to European settlement, but currently are experiencing infrequent fire during the fire history period; frequency was set to the Fire History Period Length (FHPL). For BpS types that experienced less frequent fire during the historic reference period prior to European settlement, a lack of fire during the fire history period would result in setting Fire Frequency to the reference fire frequency which was modeled for that BpS.

This relationship of Fire Frequency to MFI can be expressed with the following expression:

If MFI is less than reference fire frequency or MFI is less than FHPL

Set Frequency to MFI

Else

Set Frequency to the maximum of reference fire frequency and FHPL

Reclassify landscape/BpS to create Fire Frequency raster

The Frequency attribute from the database was joined to a combined raster of the watershed and BpS. The layer was then reclassified to produce a fire frequency that was averaged over each BpS within each watershed for the fire history period. This Fire Frequency raster (figure 3) was then used as the Current Fire Frequency spatial input to the $FRCC_{MT}$. In addition to the Current Frequency raster, rasters based on other intermediate metrics which resulted from the frequency calculation, such as Mean Annual Burned could also be generated.

Comparison of Data Sources

In analyzing the upper Lochsa study area, we also compared data from LANDFIRE and MTBS against the local fire atlas data for the overlapping sub-period of the fire history period. This was done to compare local data with LANDFIRE and MTBS approaches. Additionally, we compared these datasets to point-based fire data derived from fire incident reports which was provided by the Clearwater National Forest.

Comparison of MTBS/LANDFIRE Data to the Local Fire Atlas

For the purpose of this comparison, we looked at fire history data from 1984 through 2010, which corresponds to the fire history sub-period for which we have fire history available through a combination of the MTBS and LANDFIRE projects. In selecting data from the MTBS and LANDFIRE projects, LANDFIRE Disturbance layers

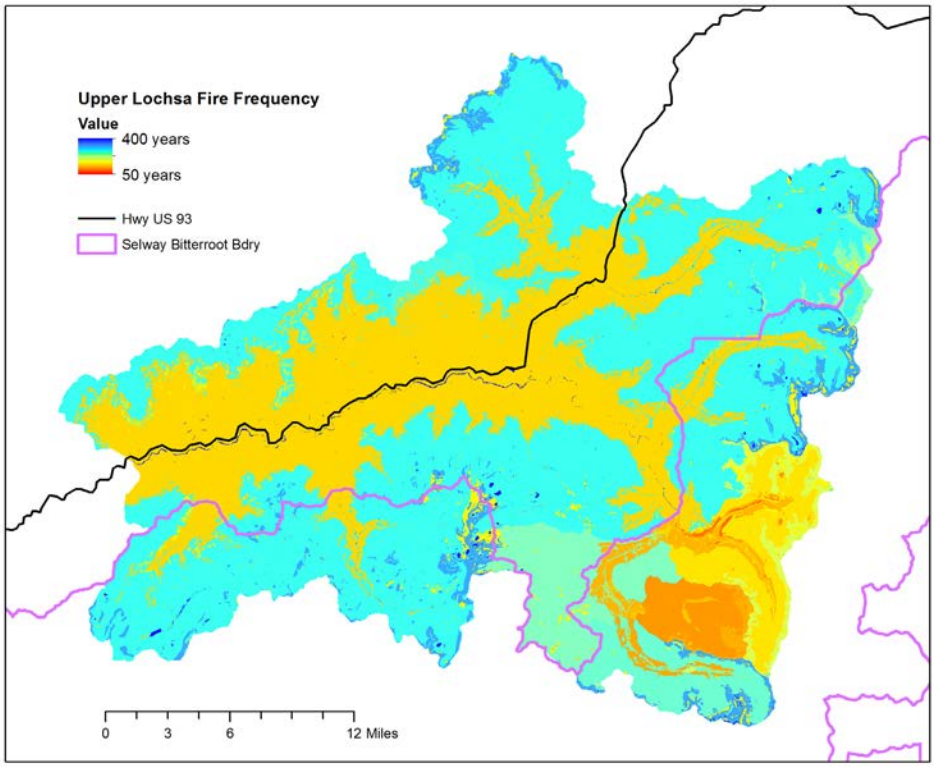

Figure 3—Fire Frequency raster for the upper Lochsa subbasin for the fire history period from 1907 through 2010. This raster can be utilized as the Current Fire Frequency spatial input for assessing FRCC with the FRCC Mapping Tool.

were used from 1999 through 2010 and MTBS perimeters were used from 1984 through 1998.

In comparing the area burned between the MTBS/LANDFIRE and the local fire atlas, data from MTBS/LANDFIRE was found to report very similar total acres burned to the acreage reported from the fire atlas for that period. Both, the LANDFIRE/MTBS data and the local fire atlas data indicated about 108,000 acres burned. However, the MTBS/LANDFIRE data indicated that a substantial area had burned more than once; about 2000 acres for MTBS/LANDFIRE versus about 1000 acres from the fire atlas. A visual inspection of both datasets show a higher fire occurrence in the portion of the study area within the portion of the upper Lochsa subbasin which lies within the Selway-Bitterroot Wilderness.

Comparison of Spatial Fire History Data to Point-Based Data

In addition to these fire history data sources, we also looked at a point-based fire history shapefile provided by the Clearwater National Forest which was attributed with date, size class, and acres burned. The point-based fire history data was analyzed for the same fire history sub-period (1984-2010) within the study area. The point-based dataset was found to contain 13 percent more acres burned than recorded by the LANDFIRE/MTBS dataset. MTBS data does not contain record of fires where less than 1000 acres burned. This could account for a significant portion of the difference between acres burned between the two datasets.

Comparison of Frequency from Fire History versus Frequency and Severity Editor

Currently the only method for determining current fire frequency spatially as an input for the $FRCC_{MT}$ relies on using expert opinion as an input to the Fire Frequency and Severity Editor (FFSE) component of the $FRCC_{MT}$. This tool allows the user to specify a single current frequency for each BpS, from which the tool will create a frequency raster. The disadvantage of this approach is that the BpS is assigned the same frequency in all landscapes across the study area. A comparison of the Frequency raster generated from the MTBS/LANDFIRE period for the upper Lochsa sub-basin as compared to the Frequency raster generated from the editor indicates that this may not be a valid methodology. As indicated in table 1, there is considerable variability in the MTBS/LANDFIRE fire frequency across BpS's between watersheds in the study area. This variability is not surprising considering that part of the study area lies within the Selway-Bitterroot Wilderness Area where management policy emphasizes allowing fire to play its natural role as compared to the rest of the study area which is affected by different management policies.

Management Implications

After the Frequency raster was created using this methodology, the $FRCC_{MT}$ was run using the Frequency raster as its Current Fire Frequency spatial input. The $FRCC_{MT}$ produced a Frequency Departure output raster which was used

Table 1—Comparison of Frequency within Biophysical Settings (BpS)'s between landscapes across the upper Lochsa subbasin, as mapped in Figure 3.

BPS	Name	Size (acres)	Minimum Frequency (years)	Maximum Frequency (years)
1010451	Ponderosa Pine-Douglas Fir	8677	24	28
1010452	Western Larch-Douglas Fir	4912	25	40
1010453	Grand Fir-Douglas Fir-Beargrass	48744	21	69
1010460	Whitebark Pine	26579	26	161
1010471	Grand Fir-Douglas Fir-Western Red Cedar-3	72441	26	80
1010550	Engelman Spruce-Subalpine Fir-4	7920	27	133
1010560	Engelman Spruce-Subalpine Fir-4	275157	25	172
1011400	Green Needlegrass-Idaho Fescue-4	424	24	150
1011590	Black Cottonwood-Narrowleaf Willow-3	8529	28	50
1011600	Black Cottonwood-Narrowleaf Willow-3	413	28	80
1011610	Engelman Spruce-Ladyfern-5	267	19	400
1011660	Douglas Fir-Ninebark-3	469	26	31

to calculate Regime Departure and Condition Class. Based on the Frequency Departure, we then could evaluate which BpS's were departed from their Reference Frequency for each of the watersheds.

Based on the frequency departure by BpS and watershed, we hypothesized that a plan could be developed to respond to departures caused by a lack of fire or too much fire. One method tested identified how much more of a BpS needs to be burned in a landscape by comparing the Burned Area metric against how many acres needed to be burned within an upcoming planning period to restore a BpS to the amount of burning indicated by the historical fire regime. For example, we assumed that the objective is to restore the BpS to a burn rate which would be within 33 percent of the historical reference frequency (RefFreq) over the next 10 years. We referred to the 33 percent variance from the historical frequency as a Condition Class Factor (ccFactor). The acreage that would need to be burned in order to achieve this objective was referred to as Planned Area Burned (pAB) which is calculated with the following equation:

$$pAB = (ccFactor(BS * (FHPL + PPL)) - cAB)/RefFreq$$

where cAB is the area that has already burned in the BpS during the current fire history period and PPL is the planning period length.

Once we identified the planned Area Burned, we used that as input to the metrics used to calculate planned MFI and planned Fire Frequency at the end of the planning period. The results indicated that the Planned Fire Frequency raster for the upper Lochsa study area could be mapped (figure 4). This

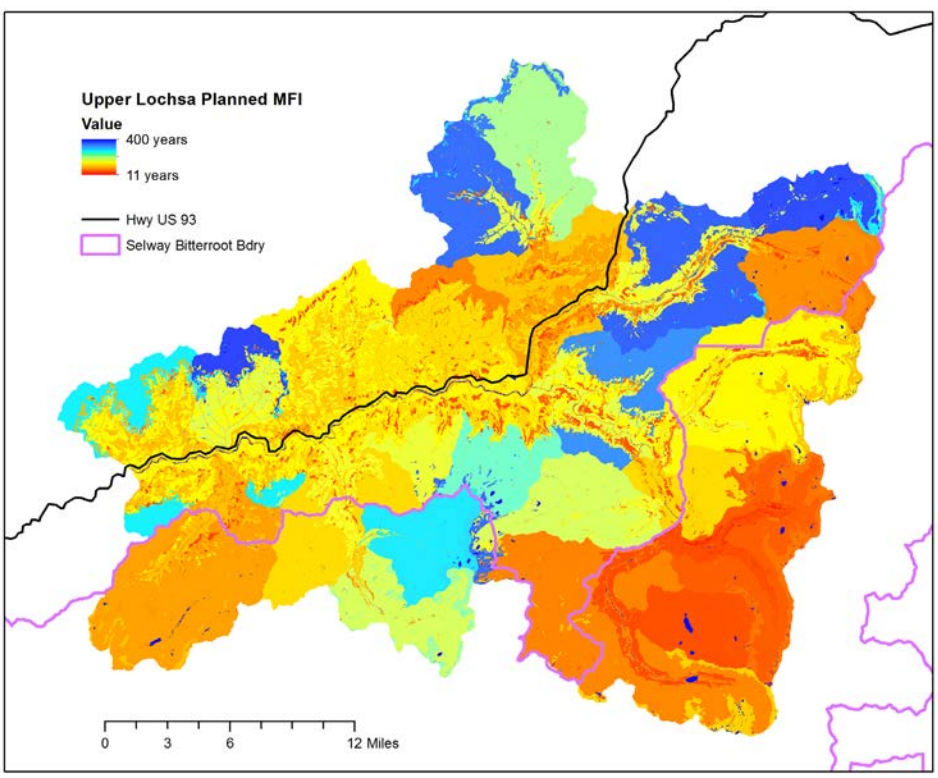

Figure 4—Planned Mean Fire Interval raster for the upper Lochsa subbasin. This MFI raster assumes that the acreage indicated by the Planned Area Burned is successfully burned in order to achieve the objective of returning the BpS to within 33 percent of the acreage that would have been burned under reference conditions during the current fire history period.

planned Fire Frequency can then be used as an input to the $FRCC_{MT}$ to determine the Frequency Departure for the BpS at the end of the planning period.

Conclusion

Fire history data were coalesced from multiple fire history sources with different formats covering different time periods in order to calculate Frequency for a specified time subperiods or averaged for the whole period.

Fire frequency and departure were found to be very useful measures for evaluating the ecological condition and resilience of the fire regime. Using this approach with data readily available we calculated a frequency ecological condition class that can be used independently or as an input to the Regime or FRCC calculations. Condition classes 2 and 3, associated with high departures from historical reference values, would have high potential to have lost or vulnerability to loss of key ecological values, such as native structures and composition and natural disturbance regimes and watershed processes.

We also tested use of the fire frequency data to calculate if fire is trending towards too much fire or lack of fire in comparison to the historical reference frequency. We consider this to be an important metric for evaluation of ecosystem resilience. This Mean Fire Interval Percent Difference (MFIPD) was calculated as follows:

```
If MFI < Reference Frequency
    MFIPD = (1 - [MFI / RefFreq ] ) * 100
Else
    MFIPD = -1 * ((1 – [RefFreq / MFI] ) * 100 )
```

A positive MFIPD indicated that fire was abundant (in other words, there is too much fire). A negative MFIPD indicated that fire was deficient (in other words, there is not enough fire). An MFIPD raster for the upper Lochsa sub-basin is shown in figure 5. Values determining fire to be too abundant would indicate a lack of resilience as plant species would not have time for adequate succession or growth and development to achieve a complete cycle of functioning processes. In contrast, values portraying a deficiency of fire indicate a lack of resilience for return of fire-adapted species that are time or fire disturbance type dependent.

The results from this study indicate that use of the $FRCC_{MT}$ Fire Frequency and Severity Editor may be much too coarse for useful management interpretations. The data in the upper Lochsa study area indicated that there was far too much variability in fire occurrence between watersheds to assume a single value would accurately reflect the current fire frequency for a BpS across all watersheds.

We found that small fires can substantially impact the Frequency within a BpS within a watershed. Analysis of the upper Lochsa data showed that exclusion of small fires from the historical record may have accounted for a loss of spatial record for over fifteen percent of the acres burned. This loss of historical fire extent is especially important as small fires accounted for a greater spatial distribution of fire across the study area than was found for large fires. This tendency to under-report small fires has been reported in other studies as a common problem with local fire history atlases (Morgan 2014).

Results from the upper Lochsa study area indicate that a large wildland fire or many small fires can enable managers to approach reference Mean Fire Interval for a BpS/watershed

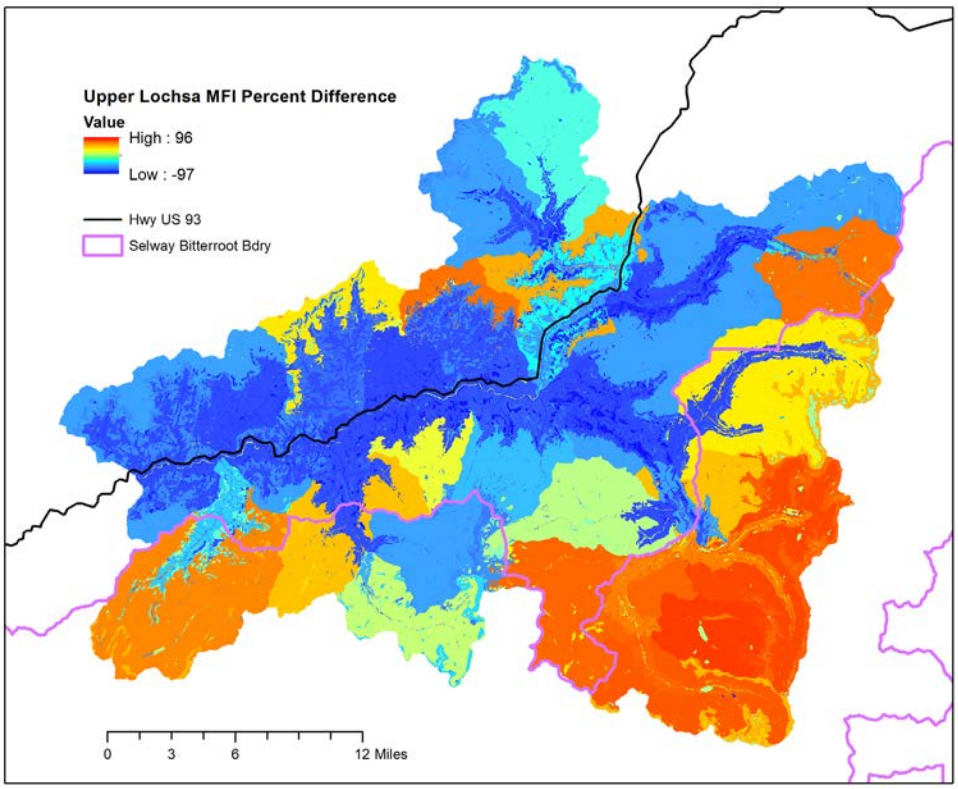

Figure 5—Mean Return Interval Departure raster for the upper Lochsa sub-basin. This MFID raster indicates how abundant or deficient fire is within a BpS. Negative MFID indicates fire deficiency (not enough fire), positive MFID indicates abundance.

where fire occurrence has been in deficit. The large fires allowed to burn in the Selway-Bitterroot Wilderness Area (in the southeast corner of the study area) had a dramatic effect on increasing Fire Occurrence and as a result reduced Frequency Departure. Managing for additional fire activity over the next 10 years could increase this positive impact on Fire Frequency Departure and thus improve the overall Fire Regime Condition Class.

The methodology employed to spatially integrate the data sources and calculate fire frequency was complex. This process would be error prone if performed manually due to the numerous geoprocessing steps and calculations performed. Thus, it would be impractical for the majority of the analysts to manually perform the steps to map current frequency and departure. In order to provide efficient and confident results these methodologies should be automated. A large number of layers were downloaded and analyzed as inputs to calculate FRCC with the $FRCC_{MT}$. Our analysis for generating a fire frequency input for the $FRCC_{MT}$ required the downloading of 13 layers from LANDFIRE and MTBS. Creating a Severity input raster using WFAT required downloading 9 layers. The $FRCC_{MT}$ required the Landscape, BpS and SClass layers be downloaded. Consequently, the complete analysis of all inputs and outputs for mapping FRCC required a total of 25 data layers. We recommend implementing these methodologies as a web application along with migrating the rest of the $FRCC_{MT}$ and the WFAT. Hosting the tools on the web would facilitate updates to the data inputs and methodologies, increase efficiency of downloading LANDFIRE data, and ensure users adequate computing resources for calculating vegetation, fire frequency, and fire severity departures and condition along with the composite FRCC.

In summary, we conclude with the following three points.

1. Recent historic and current fire frequency data generated from MTBS, LANDFIRE, and local fire atlases allowed implementation of the FRCC Guidebook methods for mapping fire frequency at equivalent scales as currently available for vegetation and fire severity inputs.
2. The recent historic and current fire frequency maps were highly useful in evaluating ecological condition, resilience to disturbance, and building of scenarios to achieve fire and fuel management objectives.
3. Downloading, analysis, and modification of FRCC input data to produce reliable outputs was a complex process. Integration of this process into a web-based decision support system would substantially increase efficiency, and application of these important ecological measures within the fire, fuels, and vegetation management community.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

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Ecological Fire Use for Ecological Fire Management: Managing Large Wildfires by Design

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Abstract—*Past fire exclusion policies and fire suppression actions have led to a historic "fire deficit" on public wildlands. These sociocultural actions have led to unprecedented environmental changes that have created conditions conducive to more frequent large-scale wildfires. Politicians, the newsmedia, and agency officials portray large wildland fires as catastrophes and unnatural disasters, but these fires could actually provide fire managers unique opportunities to recover fire-dependent species and restore fire-adapted ecosystems that have been adversely affected by the fire deficit. This paper will describe a vision of utilizing wildland fires in a way that holistically synthesizes the principles and practices of prescribed burning, suppression firing operations, and wildland fire use as part of a land stewardship philosophy to be called Ecological Fire Management (EFM). Under EFM, preplanned ecosystem restoration goals will guide management actions—including suppression actions—on every large wildfire. However, suppression will be redefined from its current frame of "aggressively fighting" to limit large fire size, to one of "actively managing" to mitigate uncharacteristic fire severity. Fire use will be a major tool in EFM, actively applied to steer, slow down, or speed up rather than simply stop fire spread. With increased fire use for ecological restoration goals, future wildfires may become large by managerial design.*

Introduction

Every year the newsmedia blares sensationalist stories about "wildfires burning out of control" somewhere in the United States (KHBS/KHOG TV). This has become an acceptable, almost hackneyed, media frame that never seems to lose its dramatic appeal, and rarely gets critically examined by journalists who attempt to outdo each other with hyperbolic stories about so-called "megafires" or "the worst fire season ever." Journalists typically focus on scenes showing the most extreme fire behavior like crown fires or homes fully engulfed in flames, or focus on areas with the most severe fire effects like fire-killed trees or "moonscapes" that often result from burned clearcut timber plantations. Readers or viewers of these news stories are left with the false impression that every acre of a wildfire burned catastrophically, and if not for the heroic efforts of brave firefighters, the size of the catastrophe would have been even greater. This overused media frame promoting hype and hysteria of wildfire events is contributing to a widespread belief among the public that all large wildfires are unnatural and entirely destructive events, and that we suffer from an over-abundance of wildfire.

In some ecosystems large wildfires were a natural part of the historic fire regime, There is accumulating scientific evidence that large wildfires and megafires are becoming more frequent in the western U.S. (Dennison and others 2014; Littell and other 2009; Westerling and others 2006). Depending on the given region, the increasing size of wildfires can be attributed to the following factors: (1) the effects of ongoing climate change that are producing weather and fuel conditions more conducive to ease of wildfire ignition; (2) rapid fire spread and/or extreme fire behavior; (3) sprawling housing development in fire-prone rural areas that produce more human-caused ignitions and/or divert firefighters away from managing fires in wildlands to prioritize structure protection; and (4) the accumulation of excess fuel loads resulting from past logging, grazing, and firefighting actions and fire exclusion policies.

Although some wildfires are getting bigger in size, there is an oft-stated assumption that they are also getting hotter, i.e., more severe in effects. Indeed, there is healthy scientific debate and conflicting evidence concerning increasing fire severity. Some studies conclude that the frequency and extent of high-severity fire is increasing in some regions (Miller and Safford 2012), while other studies claim that there is no demonstrated increase in severity (USDA Forest Service 2012). In ecosystems that are characterized by infrequent fire return intervals and high-severity fire regimes, severe fire effects may still be within their historic range of variability. In ecosystems with frequent fire return intervals and low-severity fire regimes, recent large wildfires do appear to be uncharacteristically large or severe. However, some fire history studies reveal that, in the pre-settlement era, some low-severity fire regimes had some extremely large-scale wildfire events that included patches of high-severity fire, so questions remain whether or not recent large-scale or high-severity fires are truly "uncharacteristic" events in these ecosystems (Odion and others 2014; Williams and Baker 2012). Regardless, when the scale of wildfire phenomena is limited to the last few decades, the trend is clear that the frequency of large wildfires and the number of acres burned by the largest wildfires is increasing dramatically.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Decades of sensationalist media coverage coupled with Smokey Bear anti-fire propaganda have conditioned most people to fear and loath wildfires, and there is almost unquestioning support by the public and elected officials for any or all efforts to prevent or suppress wildfires. Understandably, when flames encroach upon homes and communities, people want firefighters to put those blazes dead out. Paradoxically the fear of fire extends ever outward into the hinterlands so even when fires burn in remote wildlands or designated wilderness areas far away from human communities, there still exists a popular desire to aggressively suppress those fires. In fact, the U.S. Forest Service (USFS) boasts that it is successful in suppressing 98% of all wildfire ignitions during initial attack operations (Tidwell 2014). This success rate further contributes to the perception that large wildfires are unnatural events. Ironically, successful initial attack fire suppression is a primary factor contributing to the growing frequency of large-scale wildfires that burn through areas that would have burned if not for prior suppression efforts. Dead and live fuels continue to accumulate in the absence of fire increasing the intensity of the next fire incident. Agencies have acknowledged that past fire suppression has contributed to excess hazardous fuel loads that feed larger wildfires, but there is nothing "past" about this. Systematic fire suppression is still ongoing, and the still-rare but increasing frequency of large-scale, long-duration, uncontrollable wildfires are entirely natural outcomes of fighting fires near and far from human communities.

The Minority View: The Land Needs More Fire

Despite the widespread belief among the public, politicians, and the press that there is an overabundance of wildfire on the landscape, fire ecologists hold a minority viewpoint that in actuality many fire-adapted ecosystems and fire-dependent species have been adversely altered or are in decline due to a lack of fire. In fact, just in terms of total acres, there is an historic fire deficit of burned acres that has accumulated since the industrial area and in particular over the most recent 60 years (Leenhouts 1998). Table 1 reveals the dramatic decrease in burned acres in the U.S. since the 1940s. According to one study, in the eleven western states of the U.S., the amount of acres that needs to burn to maintain historical fire regimes, compared to the amount that actually burns, comes to a deficit averaging 10 to 12 million acres per year (Medler 2006). This fire deficit continues to grow every year with each wildfire that is contained at the smallest size feasible by fire suppression crews. The annual fire deficit could be reduced over time if the fire-fighting agencies would stop suppressing nearly all fires and allow more fires, especially those in remote settings, to spread larger and burn longer. Even if that were to happen, natural ignitions alone probably would not provide sufficient amounts or the right kinds of fire to recover from the huge fire deficit that has grown to date. Consequently, many fire ecologists believe that, for the sake of ecological restoration and biodiversity preservation, it will require active fire reintroduction on a landscape scale. This is currently impractical politically given the public's perception that we have too much rather than too little fire on the land.

Table 1—Average number of wildfires and acres burned by decade in the U.S.

Years	Average number of fires	Average acres burned
1919-1929	97,599	26,004,567
1930-1939	167,277	39,143,195
1940-1949	162,050	22,919,898
1950-1959	125,946	9,415,796
1960-1969	119,772	4,571,255
1970-1979	115,112	3,194,421
1980-1989	163,329	4,236,229
1990-1999	106,306	3,647,597
2000-2009	70,771	6,612,363

Source: National Interagency Fire Center

There is another contrarian viewpoint that is gaining more credence among fire ecologists: the number of "acres burned" is the wrong metric for analyzing the effects of wildfire or the effectiveness of fire management. Given current attitudes, a large wildfire is seen as a natural disaster, while a fire that is kept small due to aggressive suppression efforts is considered a management success. But is a large wildfire that reduces accumulated dead fuels, rejuvenates wildlife habitat, and regenerates fire-dependent species a "natural disaster" or "catastrophe"? Is a small fire that required extensive money, crews, toxic chemicals, and heavy equipment to keep it small a "management success" in terms of ecological land stewardship? An emerging vision of land stewardship that I call Ecological Fire Management (EFM) advocates that the proper focus of fire managers should be mitigating extreme fire behavior and uncharacteristic severity, not limiting fire size. Managers should be addressing what Pyne (1995) calls the "maldistribution" of fire: too much of the wrong kinds of fire burning in the wrong places and conditions, and too little of the right kinds of fire burning in the right places and conditions. In this new perspective, managers must combine the tasks and missions of fire prevention and fire promotion, fire suppression and fire restoration, and a qualitative assessment of ecological integrity should become the new measure for management success rather than the quantity of acres burned or ignitions successfully attacked.

Even though the newsmedia typically portrays wildfires as "catastrophic," in fact, most large fires burn with a range of severities resulting in a landscape "fire mosaic." High-severity fire is generally a smaller proportion of the total acres burned in large wildfires compared to moderate and low severity areas, and there can be significant unburned islands located within wildfire perimeters that are often overlooked in mapping efforts (Kolden and others 2012; Kolden 2010; Kolden and Weisberg 2007). Even incidents of rapid fire spread or large fire "runs" rarely uniformly burn with high severity, rather, they burn unevenly leaving a mosaic of effects (Donovan and others 2014). Regardless, the

dominant cultural bias against wildfires is especially strong in its antipathy to high-severity fire. However, from an ecological standpoint, high-severity fire is not necessarily bad or undesirable given that many species depend on it for various habitat needs including natural regeneration.

Despite or because of the historic fire deficit, there is accumulating scientific evidence that large wildfires are becoming more frequent under the influence of ongoing climate change, an abundance of surface and ladder fuels, and human communities sprawling into fire-prone environments. Even though large wildfires are becoming more frequent, they are still relatively rare events due to the agencies' success rate with initial attack fire suppression. Much more fire on the landscape is needed to restore fire-adapted ecosystems, preserve fire-dependent species, and protect rural communities located in fire-prone places. As an alternative to the dominant cultural and management view of large wildland fires as a problem, they could be reframed as a possible solution to a number of land management challenges. The key will be for fire managers to de-emphasize the significance of fire size, and focus instead on more critical issues such as fire severity and whether the severity level is likely to be beneficial to ecosystem integrity, natural resource values, and other social values for the particular region, fire regime, and ecotype of any given wildfire.

Future wildfires that destroy property or harm people may legitimately be viewed as disasters, but in the emerging vision of EFM, future megafires that burn within the historical range of variability for fire severity may be used as opportunities for landscape-level fuels reduction and ecosystem restoration. Toward that vision, agencies will be actively managing wildfires in backcountry and wilderness areas in ways that mitigate uncharacteristic fire behavior or effects, and maximize the social, ecological, and resource benefits of the burns. In so doing, managers will be using large fires intentionally—by design and with desire—to achieve land management goals for ecological restoration and community protection.

Evolution of Fire Use Terminology

Fire use has been a wildfire management technique for several decades, with one of its first applications by the U.S. Forest Service on the Bad Luck Creek Fire in the Selway-Bitterroot Wilderness Area as part of the White Cap Fire Plan in 1972 (Mutch, unpublished data). The practice has undergone several name changes over the years. The first term for fire use was "prescribed natural fires" (PNFs) and was a fairly descriptive label for using lightning ignitions for prescribed burning. Early practitioners had a philosophy that restricted management actions mainly to monitoring the natural spread of PNFs, particularly in designated wilderness areas. The ideal PNF in their view was a fire that "started and stopped on its own, with minimal management interventions" (Campbell, personal communication). In fact, if fire behavior or spread threatened to exceed managers' prescriptions, then the only way to take management actions on the fire was to declare it a wildfire and then commit to total suppression. Unfortunately, PNFs were dubbed with the phrase, "let it burn," and this passive non-interventionist approach to fire use generated opposition by the public and most agency line officers. This opposition had the effect of making PNFs rarely authorized, and only viable in the largest, most remote areas of designated wilderness or national parks. PNFs were even more restricted following the 1988 Yellowstone Fires (Parsons and Landres 1998).

With the creation of the 1995 Federal Wildland Fire Management Policy, official fire management terminology went through a significant revision, and PNF was replaced by the term, "Wildland Fire Use for Resource Benefits" (WFURBs, sometimes called "furbees" by firefighters) that was later shortened to "Wildland Fire Use" (WFU, pronounced "woo-foo" by fire crews). WFU was elevated from a fire management tactic to become a strategy that defined its own kind of wildland fire that was distinct from wildfire which, by definition, had to be totally suppressed. In practice, WFUs allowed more management actions to keep fire spread or behavior within prescribed parameters, but in 2003 the Bush Administration issued new guidance for implementation of the Federal Wildland Fire Policy that had the effect of inhibiting authorization of WFU even more.

At the outset of the Obama Administration in 2009, new guidance for implementing federal fire policy was issued again, and this time it was made explicit that multiple objectives such as protection and restoration could be combined on a single fire. Thus, crews could implement both fire suppression and fire use actions on different portions or different times on the same wildfire. This was a remarkably progressive policy change that greatly facilitates a shift to ecological fire management and restorationist fire use, but part of this policy change involved the National Wildfire Coordinating Committee eliminating the term "wildland fire use" from the official glossary of fire management, leaving only two kinds of wildland fire: prescribed fire and wildfire. The reason behind the glossary change by the NWCG was that they did not want managers to view fire use as a type of fire (e.g., "Fire Use fires"), but rather, as a tactic or tool to be considered on any wildfire. The intention was to expand opportunities for fire use as much as possible, but given the cultural baggage of a century of demonizing and attacking wildfire, most of the public and politicians believe wildfires are something to fear and fight, never to "use." Consequently, wildland fire use continues to be rarely authorized or applied, and when it is applied, fire managers prefer to euphemistically call it "managed fire for multiple objectives" in an attempt to avoid controversy over the term fire use.

The Three Kinds of Fire Use

In the goal to encourage more use of wildfires to achieve fire reintroduction and ecosystem restoration goals, it is important to rearticulate fire use as something besides or beyond a passive "let it burn" approach. This is important to gain more public support and line officer approval for it,

but also to maximize its potential usefulness in fire management. One way to do this is to recognize and integrate all three kinds of fire use that are already widely practiced as the staples of fire management methodology: prescribed fire use, suppression fire use, and wildland fire use. The public understands and largely accepts the first two kinds, and from that basis, can come to support the third kind of fire use that, in my opinion, should be renamed as ecological fire use and become the primary focus if not major means of implementing wildland fire management on federal lands.

Prescribed Fire Use

Prescribed fire is the most preferred form of fire use for managers because it offers them the most control over desired fire behavior and fire effects. However, paradoxically a number of social, administrative, and fiscal factors make this most desirable form the least utilized of all. First, there is opposition to prescribed burning from people who fail to understand the necessity and inevitability of fire in fire-adapted ecosystems, and believe that we can and should prevent all forest fires. Second, there is the ever-present risk that controlled burns may escape or exceed their prescriptions, and become uncontrolled wildfires. Indeed, there have been huge wildfire disasters that were initiated by escaped prescribed fires. It only takes one of these accidents to end a manager's career in fire, and set back a local burn program for years. Barely one percent of all prescribed fires escape, and of these, just a fraction cause any property damage or human casualties; nevertheless, these are the fires that make the headlines and get burned into the public's psyche, reinforcing other contemporary political themes about government incompetence or mismanagement. The perceived risk of escaped fires has become greater given the sprawl of homes into wildlands. The other 99 percent of prescribed fires that are safely and successfully implemented largely go unreported and unacknowledged.

Smoke emissions are becoming a key constraint on the use of prescribed fire due to air quality regulations that unfairly lump smoke from burning for fuels reduction or ecosystem restoration in the same category as "agricultural" burning of farming or logging wastes. Indeed, prescribed fire use must compete with agricultural and industrial burners for smoke allowances, and even when these are within legal limits, smoke from controlled burns can trigger public nuisance complaints that can provoke air regulators into shutting down the burns. However, along with the fire deficit there has been an historic "smoke deficit" from wildfires! One study concluded that ten times more landscape should be burning annually, consuming eight times more biomass, and producing seven times more smoke emissions (Leenhouts 1998). Nevertheless, the effect of the wildfire smoke deficit has been masked by the air pollutants emitted from urban, industrial, and agricultural sources. Unlike the largely invisible emissions from auto tailpipes or industrial smokestacks, the smoke plume from a prescribed burn is a visible target for public complaints and the ire of air regulators.

Lastly, funds for prescribed burning and other fuels treatments must come from budgets that are fixed by annual appropriations, and are getting smaller due to Congressional budget cuts to federal agencies. Wildfire suppression enjoys near limitless funding through large budgets, "fire transfers" from other non-suppression accounts, and emergency supplemental appropriations. At the time of this writing there are bills in both houses of Congress that would allow wildfire suppression to access FEMA disaster funds, too. But funding for prescribed fire use that would mitigate some of the damages and costs of wildfires is becoming more limited each year. For all the above reasons and more, even though prescribed burning is the most preferred kind of fire use from the standpoint of managers, it is the least utilized and most unlikely means of implementing the vast scale of burning needed to reduce fuels, restore ecosystems, and recover landscapes from the historic fire deficit.

Suppression Fire Use

Fire use is commonly considered the opposite tactic from fire suppression, but in fact, fire is used extensively if not systematically in wildfire suppression, especially on large wildfires. Indeed, suppression firing operations implement a longstanding practice of "fighting fire with fire." The two forms of suppression fire use are called backfires and burnouts. Backfires are largely uncontrolled high-intensity fires ignited to eliminate all burnable fuels in advance of wildfires, and to apply force to change the direction of wildfire spread. They are normally ignited in conditions or locations that cause high-severity effects. On steep slopes or rugged terrain with dense fuels and severe fire weather conditions, backfiring is often the safest method for firefighters to attempt wildfire containment. Burnouts, on the other hand, are typically low-intensity fires ignited adjacent to fire containment lines, and are intended to eliminate surface fuels and therefore strengthen the firelines. Burnouts are ignited on almost every fire of any significant size as a routine practice. In recent years large-scale backfires and burnouts have started resembling each other, creating a hybridized firing operation dubbed "backburning" by the newsmedia. Most people do not associate fire-lighting with fire fighting, but suppression fire use is arguably occurring on a scale that far exceeds any other kind of fire use, thus, challenging the conventional assumption that fire suppression equates with fire exclusion. It is an open question whether extensive backburning is a cause or consequence of large-scale wildfires.

The dominant objective of wildfire suppression is to contain fire spread—to keep fires as small as feasible and limit the number of acres burned. The great paradox of suppression firing operations is that they objectively spread fire and add to the number of acres burned while at the same time they are intended to limit even greater potential spread and size of a wildfire. There has been no systematic tracking of suppression firing locations, so the size or severity of these fires individually or cumulatively is currently unknown. Anecdotally, though, two case studies revealed that suppression fire use was conducted on a very large scale, such as the

1999 Megram and the 2002 Biscuit fires that were the largest (and most expensive) wildfires in the U.S. during those years. Backfires and burnouts were ignited considerable distances away from the wildfires' edges, adding tens of thousands of acres cumulatively to each wildfire's perimeter, and much of this acreage also burned with high severity (Ingalsbee, unpublished paper; Ambrose, unpublished data).

Given the need to reintroduce fire on a landscape scale, the fact that suppression fire use is partly accomplishing this goal should be celebrated, however, it is not known if the places, patterns, sizes and severities of firing operations are ecologically appropriate, or instead are creating uncharacteristic fire effects. Again, suppression actions generally have one objective in mind—to contain fire spread—and the ecological effects of firefighting actions have until recently rarely been considered in suppression operational planning. But speculating that backburning is the dominant form of human-caused fire reintroduction, there is an urgent need for systematic research and critical analysis of the ecological effects of suppression fire use. In those incidents where backburns are ignited in places or conditions certain to cause large high-severity patches, it begs the questions: is that a desirable outcome, and if so, how does that constitute "suppression" of a wildfire?

Because backfires are uncontrolled high-intensity blazes, they used to be ignited as a kind of last resort when conditions did not permit safe or effective fireline containment, but it appears that backfiring is becoming more prevalent, especially on large wildfires or fire complexes with indirect attack strategies. Sometimes backfires can literally backfire on crews by changing direction and failing to merge with the main wildfire, and thus, its own separate wildfire, or by vastly increasing the intensity or rate of spread of the main wildfire. Some notorious examples include the 2000 Cerro Grande fire that started as a prescribed burn slopover that was eventually contained at 30 acres, but then when crews ignited a large burnout, the fire surged out of the area and eventually spread across 44,000 acres, destroying hundreds of homes in Los Alamos, New Mexico in the process. On the 2009 Station Fire, backfires helped save homes in the community of La Crescenta, but two firefighters were killed while fleeing a backfire they ignited and burned back toward them. Backfires and burnouts thus may represent a greater risk of adverse impacts on firefighters and ecosystems than are commonly perceived, but without systematic tracking or long-term monitoring or analysis, the overall effects of backburns are currently unknown.

There is inherent risk in managing fire, and even the most carefully planned and implemented prescribed burn has the potential to escape control given the dynamics of fire and all the environmental variables that influence its behavior. Backburns, on the other hand, are by definition emergency actions that enjoy the "suppression exemption" from many laws and regulations governing normal agency operations. They are ignited with minimal planning, no prior environmental impact analysis, and often under less than ideal conditions for controlling fire behavior or effects. However, there is a double standard when it comes to the professional and public consequences of escaped prescribed fire use versus uncontrolled suppression fire use: managers face formal reviews, negative sanctions, and are publicly vilified as incompetents for the former, but are unquestioned and even heralded as heroes for the latter. This double-standard creates additional disincentives for prescribed burning, while making suppression firing almost risk-free with barely any legal, regulatory, or fiscal limits on its use, even when backfires damage private property (Backfire 2000 v. U.S. 2006). It is easy to understand, therefore, why suppression firing may be the dominant form of fire use today. While it might be getting fire on the ground and helping to compensate for some of the fire deficit, if it is creating uncharacteristic patch sizes, patterns, or locations of high-severity fire, then it would be further contributing to Pyne's concept of the maldistribution of fire.

Ecological Fire Use

Progressive fire managers have been implementing fire use for ecosystem restoration and resource benefit objectives for several decades. It has been called many names and acronyms over the years, most recently it has been called "wildland fire use" but may soon be called "managed wildfire." Fire use specifically for ecosystem restoration purposes is currently the rarest form because it suffers from a few misperceptions and overly restrictive management regulations that constrain opportunities and options to apply it. This paper argues that wildland fire use needs to be re-envisioned and re-articulated as an active form of ecological fire management that should become a principal way that fire management is defined and practiced in the future. For that reason, I propose that we start calling it "ecological fire use."

There are a number of institutional biases against ecological fire use that explain its rarity. First, the agency imposes several extra planning requirements and restrictions upon fire use for resource benefits, especially compared to suppression fire use that has almost no prior restrictions placed upon it. Ecological fire use is not permitted unless an approved Fire Management Plan and Forest Plan authorizes it. However, many National Forests have forest plans that are outdated, and have obsolete or non-existent fire management plans. This functions as a form of prior restraint that prevents fire use from being considered as an option at all. Second, many "old-school" foresters view wildfire as a threat to natural resources, especially commodity timber values, and thus exclude fire use from most "General Forest" areas committed to multiple-use resource management. Third, State forestry agencies have suppression-only policies, and some in federal agencies fear that they might face legal or financial liability if their fire use actions on federal lands spread wildfires onto State or private lands.

These institutional biases stem from a misperception shared by much of the public that views fire use narrowly and simplistically as "let it burn," a passive or laissez faire approach that seems almost "anti-management" in its essence. In a recent survey measuring homeowners' attitudes about wildfire and fire management in Central Oregon, researchers

came to a surprising finding: people opposed fire use more than they opposed wildfire! Examining the survey questions explained the basis for this attitude: the concept of wildfire was defined in a way that assumed it would automatically be suppressed while fire use was defined as "let burn" (Olsen 2014, 2012). Despite the insistence of Fire Use managers that monitoring is a kind of management action, most of the public and too many agency officials believe that wildland fire use really means "unmanaged" wildfire. Consequently, this kind of fire use is the rarest management response because when a wildfire ignites the public demands that land managers do something to control it.

In contrast to the view of ecological fire use as a passive, hands-off response, it needs to be rearticulated as a hands-on fire management tactic and a proactive strategy for reintroducing fire, reducing fuels, and restoring ecosystems. Many progressive land managers have used such tactics and strategies for years, but it's time to enhance the practice and promote it. As a strategy, ecological fire use would employ all of the tools and techniques of fire management to manage wildfire spread in ways that serve pre-planned ecosystem restoration goals. Instead of contain and control strategies with tactics that aim to stop fire spread, more confinement strategies and related tactics could be used to start and steer fires into areas that planners want to burn, and away from areas like human communities that should not burn. Fewer fires would be suppressed with perimeter control strategies in favor of point or zonal protection strategies that would allow wildfires to grow larger and burn longer. Utilizing the best available technology for monitoring, mapping, and modeling fire spread, fire crews might be asked to slow down fire spread one day but then speed it up the next, depending on changes in current and expected conditions, in order to accomplish desired fire behavior and effects. Management actions would occur on strategic locations deemed the safest, most effective, least damaging places to take action, and crews would likely do much more firing and much less fireline cutting than they currently do. In essence, crews would be utilizing wildfire ignitions as triggers for managing, applying, and using fire in an active, hands-on approach to reintroducing fire on a landscape scale.

Ecological Fire Use as the Means For Implementing Wildland Fire Management

In this future vision of ecological fire use, "let it burn" will be rearticulated as "make it burn," and wildfires will be managed to become large-scale by design, both in the sense that behavior and effects will be prescribed with preplanning, and in the sense that fire patterns and perimeters will be larger by desire. Natural ignitions will start the process, but management ignitions and other actions will sustain wildland fire events and processes as long as conditions permit the accomplishment of ecological restoration goals. The goal of this redefinition and greatly expanded application of fire use is ultimately to support safer, more ethically and ecologically sound fire management. This may take some protracted messaging campaign to persuade the public, the press, elected and administrative officials about fire ecology and the necessity, inevitability, and desirability of large wildfires burning on the landscape. This campaign could be challenging, but not impossible, if the other two forms of fire use that already enjoy public acceptance—prescribed and suppression fire use—are incorporated into the new definition of ecological fire use. In fact, the three kinds will essentially be holistically synthesized into one form with one simple term: fire use. Ecological goals will be considered on every wildfire incident and in every management action, and fire will be used as much as possible to fulfill both protection and restoration objectives.

At the same time that fire use is redefined and rearticulated, fire suppression will need to be re-conceptualized, ending its single-objective focus on limiting wildfire spread to keep fire size small, and more concerned with mitigating uncharacteristic fire intensity or severity. In the context of unfolding climate change that will likely make future conditions more prone to extreme fire behavior or severe fire effects across broad regions, this may require fire managers to take a long-range view and permit wildfires to burn at higher intensities in the short-term in order to mitigate fuel conditions for future wildfires. Employing more fire use will also allow agencies to be more flexible, strategic, and selective in where they dispatch scarce or costly suppression resources. Overcoming the historic fire deficit and preparing landscapes for future climate change will require getting as much ecologically appropriate fire on the ground as soon as possible, so fire use will continue to be a major suppression tool. But again, suppressing fire severity, not limiting fire size, will be done for the sake of pre-planned ecological restoration goals, not out of generalized fear of fire, or as a default mode of risk-adverse managers compensating for a lack of prior fire planning.

The Ecological Fire Management Vision

The words that agencies use matter in terms of conveying to the public what is or should be happening on the ground, and also to guide management actions in the first place. The traditional suppression-centric focus of federal fire management has been dominated by the pervasive use of military metaphors, e.g., "fire fighting," and these kinds of words and the mindsets that they impose will need to be changed to reflect a new restorationist mission and ecological ethos. For example, instead of fighting against fire, crews will be working with fire; instead of conducting initial "attack," crews will be taking initial action, instead of preventing large wildfires, crews may actually be promoting them! The mission of fire management will be redefined from mainly fire fighting to one resembling fire guiding. Given the qualitative change in mission and terminology used to explain new pro-fire use policies and

practices, it would be anachronistic to call crews "fire fighters." Consequently, a term like fire rangers might be a more accurate if not more inspiring identity for crews doing Ecological Fire Management. In a future restorationist paradigm, fire "control" efforts will be newly applied to fire use rather than suppression actions; indeed, suppression itself will be redefined and practiced in a new way: mitigating uncharacteristic fire severity not containing fire spread or limiting fire size.

Although incidents might not have been called "fire use for ecological restoration" and the policy was not called "Ecological Fire Management," a good argument could be made that these were the unspoken objectives and underlying philosophy of progressive fire managers over the last 40 years, beginning with the pioneering work of wilderness fire managers implementing Prescribed Natural Fires, to the recently terminated Fire Use Modules and Fire Use Management Teams. Indeed, anecdotal examples can be culled from past incidents to bring concrete working models to bear on the seemingly abstract, "pyrotopian" visions of ecological fire use and EFM described in this paper. Progress toward that vision is happening slowly but surely. Consideration of resource benefits is gradually becoming more systematized in suppression operational plans as part of the Wildland Fire Decision Support System (WFDSS). A broader range of management strategies are being employed on most large fires, from full suppression on one end of the spectrum through point/zone protection, confinement, and monitoring actions on the other end. Fire managers are taking more advantage of the flexibility of the Federal Wildland Fire Policy to manage fires for simultaneous multiple objectives such as community protection, resource benefits, and ecosystem restoration. This is all progress worth celebrating.

Indirect suppression strategies that "back off and burn out" for the sake of firefighter safety are likely significantly expanding the number of acres burned, so the accumulated fire deficit may be incrementally shrinking through increased suppression fire use. The public seems to accept large-scale backburning when it is implemented reactively in a state of emergency, but the task ahead is to build public support for its use as a pre-planned proactive method for managing wildfires not as crises or potential catastrophes, but as opportunities for sustainable land stewardship. As a public education strategy needed to build more stakeholder support for restorationist fire use in ecological fire management, it is important to clearly call it what it is and fully explain what the many roles and benefits of fire use are to achieving the multiple objectives of promoting firefighter safety, ensuring ethical and economical use of taxpayer resources, protecting rural communities, and restoring fire-adapted ecosystems. Given the assumption that large wildfires are natural, essential, inevitable phenomena, and will become more so in the future as climate change continues to affect our pyrogenic planet, the wildland fire community must embrace and articulate the role and benefits of ecological fire use in managing large wildfires safely, ethically, and ecologically by design.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Assessing Three Fuel Classification Systems and Their Maps Using Forest Inventory and Analysis (FIA) Surface Fuel Measurements

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Abstract—*Fuel classifications are integral tools in fire management and planning because they are used as inputs to fire behavior and effects simulation models. Fuel Loading Models (FLMs) and Fuel Characteristic Classification System (FCCSs) fuelbeds are the most popular classifications used throughout wildland fire science and management, but they have yet to be thoroughly evaluated with field data. In this study, we used a large dataset of Forest Inventory and Analysis (FIA) surface fuel estimates (n = 13,138) to create a new fuel classification called Fuel Type Groups (FTGs) from FIA forest type groups, and then keyed an FLM, FCCS, and FTG class to each FIA plot based on fuel loadings and stand conditions. We then compared FIA sampled loadings to the keyed class loading values for four surface fuel components (duff, litter, fine woody debris, coarse woody debris) and to mapped FLM, FCCS, and FTG class loading values from spatial fuel products. We found poor performances (R^2<0.30) for most fuel component loadings in all three classifications that, in turn, contributed to poor mapping accuracies. The main reason for the poor performances is the high variability of the four fuel component loadings within classification categories and the inherent scale of this variability does not seem to match the FIA measurement scale or LANDFIRE mapping scale.*

Introduction

It is difficult and problematic for many managers to sample wildland fuels for a project area or wildfire so fuel classifications were created to simplify the input of fuelbed characteristics into the fire behavior and effects software packages used extensively in fire management (Burgan, 1987; Keane, 2013). Wildland fuels are the dead and live biomass available for fire ignition and combustion (Albini,1976; Sandberg and others 2001). In most fuel classifications, fuel particles are stratified into unique categories called fuel components (Table 1), such as duff, litter, and shrubs, and each component is assigned attributes based on the input requirements of fire software applications (e.g., Anderson, 1982; Arroyo and others 2008; Deeming and others 1977). There are many fuel component attributes, such as heat content, mineral content, and density, but the most commonly used attribute across most fire management applications is fuel loading or the biomass per unit area (Brown and Bevins, 1986; Harmon and others 1986; Pyne and others 1996). Fuel loads are required as inputs to nearly all fire applications (Burgan, 1987; Krivtsov and others 2009), and they are also important for the quantification of carbon inventories (de Groot and others 2007), site productivity (Neary and others 1999), and wildlife habitat (Ucitel and others 2003).

Two fuel loading classifications are commonly used in fire management applications to predict fire effects such as smoke, soil heating, and tree mortality. Fuel Loading Models (FLMs) identify fuel classes designed specifically for predicting unique fire effects (Lutes and others 2009). The Fuel Characteristic Classification System (FCCS) (Ottmar and others 2007; Riccardi and others 2007a, 2007b) was developed to provide managers with a conceptual framework to construct fuelbeds that describe biomass across both surface and canopy fuel components. We also created a new Fuel Type Group (FTG) classification based on the forest type groups of the Forest Inventory and Analysis (FIA) program for simulating emissions from fires across the US by summarizing fuel component loadings from FIA plots by the 20 classes in the forest type group classification (Ruefenacht and others 2008). Each of these classifications is different in that they were built using uniquely different approaches (Keane 2012). None of these classifications have been formally tested for performance and accuracy.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Table 1—Descriptions of commonly used surface fuel components.

General Fuel Type	Fuel Component	Common Name	Size	Description
Downed Dead Woody	1 hour woody	Twigs	<1 cm (0.25 inch) diameter	Detached small woody fuel particles on the ground
	10 hour woody	Branches	1-2.5 cm (0.25-1.0 inch) diameter	Detached small woody fuel particles on the ground
	100 hour woody	Large Branches	2.5-7.6 cm (1-3 inch) diameter	Detached small woody fuel particles on the ground
	1000 hour woody	Logs, Coarse woody debris (CWD)	7.6+ cm (3+ inch) diameter	Detached small woody fuel particles on the ground
	Fine woody debris (FWD)	Twigs, branches, and large branches	0-7.6 cm (0-3 inch) diameter	Combined 1, 10, 100hr fuel loadings
Duff	Duff	Duff	All sizes	Partially decomposed biomass whose origins cannot be determined
Litter	Litter	Litter	All sizes excluding woody	Freshly fallen non-woody material which includes leaves, cones, pollen cones,
Total	All fuels	Total surface fuel load (TSFL)	All surface fuels	All material on the ground

Both the FLM and FCCS classifications were mapped at 30 m pixel resolution to describe fuel loadings across the contiguous United States in the National LANDFIRE Project (Reeves and others 2009; Rollins, 2009) and the FTG classification was mapped to forest type groups at 250 m resolution using the Remote Sensing Applications Center (RSAC) FIA forest type group mapping effort (Ruefenacht and others 2008). The LANDFIRE FLM and FCCS maps are used extensively in fire management planning projects, such as prioritizing, designing, and implementing fuel treatment projects (Reynolds and others 2009). Yet, despite their widespread use, these three fuel classification maps have not been thoroughly assessed for accuracy and precision at fine scales (plot-level) because of a lack of extensive ground data (Reeves and others 2009).

Recently, the Forest Inventory and Analysis (FIA) program made available an extensive set of surface fuel data for forested areas for several states in the western United States consisting of georeferenced plot measurements of the surface fuel component loadings. In this study, we used the extensive FIA surface fuels data for the western US to evaluate the performance of the FLM, FCCS, and FTG classifications and then to estimate the accuracy and precision of the LANDFIRE FLM and FCCS geospatial maps and the FTG map developed from the RSAC forest type group layer (see Keane and others 2013). This study was intended to provide context and background for those who plan on using FLMs, FCCSs, and FTGs in the field, and those who plan on using the FLM and FCCS LANDFIRE maps and FTG RSAC-based maps in their fire management activities.

FLMs

The FLMs of Lutes and others (2009) were created using field-collected fuel loading data from 4000+ plots located across the contiguous United States that were then used as inputs to FOFEM to simulate smoke emissions and soil heating. The simulation results for all 4000+ plots were clustered to identify unique "effects groups", then a comprehensive key based on loading was created using regression tree analysis to objectively identify the classification category for a field-assessed observations. As a result, this classification integrated the resolution of the fire effects models into the FLM classification design and used easily obtained field measures in the field key. This direct, top-down approach partitions variation in the field data to reduce redundancy and produce an effective classification that can be used in the field. Fuel loading values were assigned to each FLM as the median fuel loading across all plots in that class (Keane and others 2013). There are 27 FLMs, which are mutually exclusive by design, yet intended to coarsely represent the range of surface fuel conditions encountered across the contiguous United States (Sikkink and others 2009). FLMs can be used as inventory techniques to quantify fuel characteristics (Sikkink and others 2009); as classifications of unique fuel types to facilitate communication between managers, scientists, and other professionals (Sandberg and others 2001); and, most importantly, as map units in fuel mapping efforts (Reeves and others 2009). There were insufficient data for some FLM classes and the FLM analysis was missing critical data from several major US fuelbeds that were unsampled at the time of FLM development, such as non-forest rangelands and rare forest types (Lutes and others 2009).

FCCS

The FCCS uses a bottom-up approach for quantifying unique fuelbeds and associated fuelbed categories and subcategories (Ottmar and others 2007). In this flexible classification, fuelbeds are added into FCCS as they are identified and perhaps measured by managers, scientists, and resources specialists to account for succession, management, and disturbance history for local, regional, or national applications (Berg, 2007); new fuel conditions are sampled in the field and these data become a new fuelbed in the FCCS (Riccardi and others 2007a). The FCCS also contains its own surface fire spread model adapted from Rothermel (1972) to simulate surface fire behavior using FCCS fuelbed data (Sandberg and others 2001).

A national fuelbed database within the FCCS, compiled from published and unpublished literature, fuels photo series, fuels data sets, and expert opinion, was created to represent a particular scale of interest. This set of national fuelbeds is referred to as FCCSs in this paper and it was intended to represent broad vegetation types and change agents (e.g., wildfire, insects and disease) throughout the contiguous United States. They are mapped at regional and national scales (McKenzie and others 2007), but for site-specific applications, such as prescribed burn planning, the FCCS fuelbed should be customized with local field data. FCCS fuelbeds are datasets that represent the physical characteristics of a diverse set of wildland fuels from canopy characteristics (e.g., percent cover and height of trees) to surface fuels (e.g., percent cover and depth of duff). Because fuel loadings are calculated from input fuelbed characteristics and FCCS fuelbeds were developed to represent the structure and composition of wildland fuels, there is likely high "redundancy" in the fuel loading values between FCCS classes. Moreover, FCCSs were developed to be used as map categories because of their fine scale application.

FTG

We used the recently available FIA fuels data to assemble a new fuel classification system to develop fire emission inventories and eventually predict real-time emissions (Urbanski and others 2011). The Fuels Type Group (FTG) classification was built by summarizing fuelbed component loadings by FIA forest type groups using the new FIA fuels data. We created the FTG classification by extracting the forest type group variable for each FIA plot (Arner and others 2003) and computing the mean loading for each fuel component for each forest type group using the keyed FIA fuels data. FTG classes were given the same name as the corresponding forest type group. We included this new classification in our analysis to represent those fuel classifications that are based on vegetation types (Keane and others 2001) and to evaluate the performance of a classification that was created using the same data as was used for the comparison (i.e., best case scenario). However, FTGs are summarized to vegetation types (FTGs) and it has been shown that fuels are rarely correlated to vegetation composition (Brown and Bevins, 1986; Keane and others 2012b).

Classification Maps

FLMs were mapped by the LANDFIRE project using the following protocol: (1) available FIA fuels plots were keyed to an FLM value using the Sikkink and others (2009) key; (2) FIA plots and their assigned FLMs were matched to combinations of existing vegetation type, existing vegetation cover, and existing vegetation height; and (3) an FLM class was systematically assigned to each pixel using a cross-walk approach where all possible pixels were assigned an FLM by vegetation type/cover/height hierarchical combinations. Because there were few data to assign an FLM to all combinations, pixels were assigned an FLM by using more general vegetation type/cover, or type/height combinations, and finally by a broad existing vegetation type group classification (Reeves and others 2009). Approximately 75% of the FIA plots used in this study were also used by LANDFIRE to assign FLMs to LANDFIRE classification class combinations.

FCCS fuelbeds were mapped by the LANDFIRE project based on the existing vegetation type classification (McKenzie and others 2012). For certain vegetation types, multiple FCCS were available that reflected certain seral stages of the vegetation, and, in these cases, cover and height values were used to assign separate FCCS fuelbeds. Post-disturbance vegetation types were assigned a "custom" set of FCCS fuelbeds because there were few post-disturbance FCCS fuelbeds (Reeves and others 2009).

Scientists at the USDA Forest Service RSAC and FIA mapped forest type groups for the conterminous U.S. and Alaska with a spatial resolution of 250 m and an overall accuracy of 64% for the western U.S. (Ruefenacht and others 2008; http://fsgeodata.fs.fed.us). In the western conterminous U.S., 17 forest type groups were mapped with an area >10,000 ha; however, 12 forest type groups account for 98.6% of total mapped forest area. Ten forest type groups comprised 99% of forest burned area in the western conterminous U.S. from 2003–2010 (MTBS, 2012). These 10 groups included 9 of the 10 most commonly mapped groups. We assigned the FTG summarized loadings to each forest type group to create the FTG map.

Methods

In summary, we compiled a surface fuels dataset from the FIA database by selecting specific FIA plots that met our evaluation criteria as described below. We then keyed the FLM, FCCS, and FTG classes for each selected FIA plot from the sampled fuels and vegetation data. And, for each FIA plot location, we determined the mapped FLM, FCCS, and FTG by taking the value of a single pixel at the FIA plot location; we found a single pixel worked better than any average of surrounding pixels (Keane and others 2013). We then compared the FIA-keyed FTG, FLM and FCCS values

to the mapped values, and more importantly, we compared the FIA-measured loadings of the four fuel components to loadings of the mapped FLM, FCCS, and FTG classes. We used a combination of contingency table, regression, and accuracy assessment statistical techniques to compare results. We compared FIA loadings to median FLM and mean FTG values because most management applications use these values to simulate fire effects.

This paper will confine its discussion to loading or the dry weight biomass of fuel per unit area (kg m^{-2}) of four major surface fuel components: litter, duff, fine woody debris (FWD; particles 0-7.6 cm diameter), and coarse woody debris (CWD, particles7.6+ cm diameter; also called logs or 1000 hr fuels) (Table 1). While shrub and herb components are included in the FLM and FCCS classifications, only cover and height were sampled at the FIA plots for these components so they weren't included in this study. We combined 1, 10, and 100 hr downed woody fuel loadings into one FWD loading because of the low and highly variable loadings for each of the individual fine woody components (Table 1).

FIA Sampling and Data Compilation

The study area includes eight states in the western United States, covering the Pacific Northwest and Interior West FIA regions (Figure 1). The scope was limited to states where FIA fuels data were available, which included Arizona, California, Colorado, Idaho, Montana, Oregon, Utah and Washington. No FIA fuels data were available at the time of analysis for Wyoming, Nevada and New Mexico.

The FIA program applies a three-phase sampling design covering all ownerships across the USA using a hexagonal grid with approximately one permanent plot per 2,428 ha (Bechtold and Patterson 2005). Phase 1 sampling is designed to reduce variance of population estimates through stratification based on remotely sensed forest cover at plot locations. Only forested land is included in the inventory and it is defined as areas at least 10 percent stocked with tree species, or land formerly having such tree cover and not currently developed for a non-forest use, at least 4,000 m^2 in size, and at least 36.6 m wide (Bechtold and Patterson 2005). Phase 2 sampling refers to the detailed measurements made at each plot location. Inventory plots consist of four 7.32-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with subplot 1 in the center and subplots 2, 3, and 4 at azimuths of 0, 120, and 240 degrees, respectively, from the center of subplot 1 (USDA Forest Service 2007, Woodall and others 2010). The plot footprint, defined as the minimum circle enclosing all four subplots, is approximately 6000 m^2. Phase 3 sampling is done on a $1/16^{th}$ subset of the Phase 2 plots and includes additional measurements associated with forest health such as tree crown condition, soil conditions, lichen community composition, understory vegetation, and down woody material (Bechtold and Patterson, 2005; Woodall and Monleon, 2008; Woodall and others 2011).

Fuel sampling protocols are summarized in Keane and others (2012). Woody fuels were tallied by particle diameter size classes commonly used by fire management and fire behavior computer programs (Table 1). Measurement protocols included planar intersect transect sampling for FWD

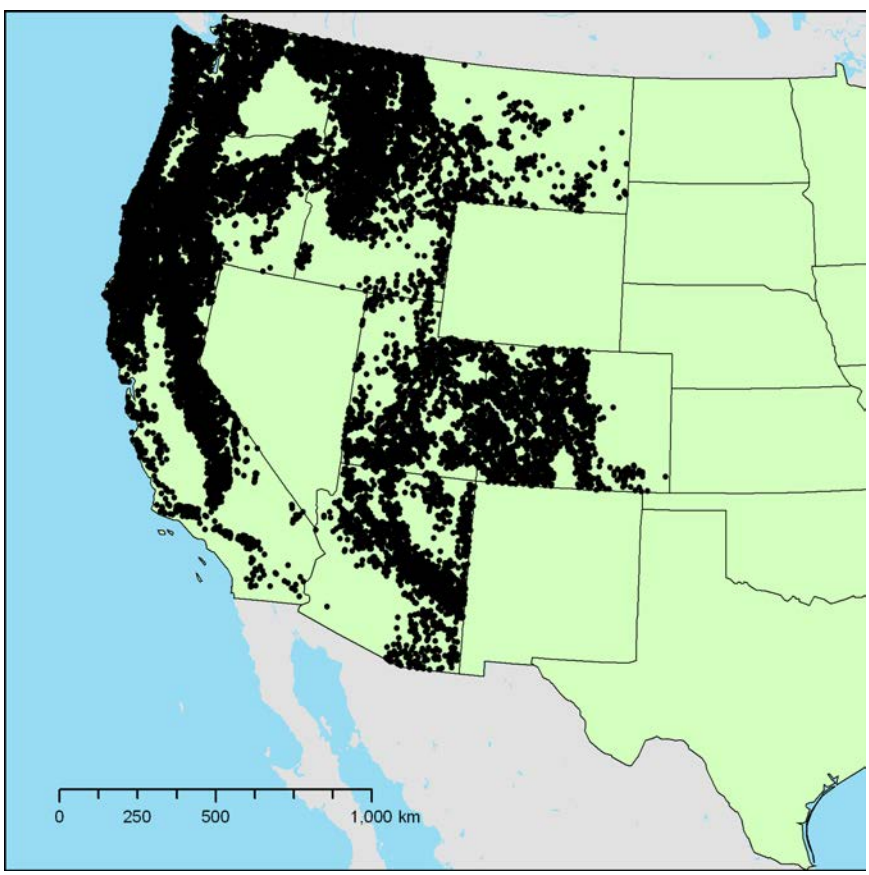


Figure 1—The approximate FIA plot locations for all plots used in this study.

and CWD, and systematic point sampling for duff and litter depths (Brown, 1974; Woodall and others 2010). Biomass estimates of CWD, FWD, litter, and duff were calculated using estimators detailed in Woodall and Monleon (2008).

We used plots from the Pacific Northwest and Interior West FIA regions measured during 2001-2009 that had fuel loading data available and a single forest condition class described across all four subplots. We overlaid the plot locations on the LANDFIRE disturbance layers for 1999-2008 to identify plots that were disturbed after the plot measurement date and omitted disturbed plots since they likely would not represent conditions depicted on the circa 2008 LANDFIRE fuel maps. We used a total of 13,138 FIA plots to evaluate the FCCS and FLM classifications and maps (Figure 1).

Keying Fuel Classification from FIA Data

The Sikkink and others (2009) key was used to identify most appropriate FLM class for each FIA plot from the loadings of duff, litter, logs, and FWD. All FIA plots were successfully keyed to a forested FLM. Because FLMs characterize a large range of fuels, median loading values were used for each of the four components in our comparisons.

LANDFIRE refresh mapping rule sets provided by Smail and others (2012) were used to assign an FCCS type to a FIA plot using vegetation type, vegetation cover, and vegetation height by LANDFIRE mapping zone. Additionally, these rule sets accounted for disturbance, severity, and time since last disturbance. We assigned 10,471 of the 13,138 plots an FCCS category; the other 2,667 were removed because the FIA plot characteristics didn't match an available rule set, often because vegetation cover was less than 10%. Once an FCCS was assigned to an FIA plot, we derived measurements of the four fuel component loadings using a lookup table provided by Prichard and others (2012).

FTGs were already keyed to FIA plots based on the RSAC FIA forest type group classification (Arner and others 2003). Every FIA plot has an assigned FTG value and this value was matched to the FTG values (Keane and others 2013). There is some inherent bias because the FTGs fuel classification was created with the same data used for this assessment, but we thought the results would be informative and useful to fire management since it represented a best-case scenario for accuracy.

We extracted the mapped FLM, FCCS, and FTG values by overlaying FIA plot locations on the LANDFIRE Refresh 2008 and RSAC forest type group data layers. We selected the classification class by taking the pixel value for each plot location. The RSAC forest type group has a pixel resolution of 250 m, comparable to the resolution of the FIA plot footprint; the FTG assessment used the RSAC map pixel in which each FIA plot was located

Analysis

To assess performance of FLM and FCCS classifications, we compared surface fuel loading values for each of the four components and for the total surface fuel loading (TSFL) for the keyed classification class with the corresponding fuel loading measurements from FIA data. For FLMs, we compared median fuel loadings for each fuel components and TSFL for the FLM class keyed from the FIA data with the measured loadings from that FIA plot. Using univariate regression analysis, we computed measures of model accuracy (R^2, slope, and intercept) by regressing measured FIA loadings with keyed FLM median fuel loadings, and using error analysis, we computed measures of uncertainty (root mean squared error-RMSE, bias as a percent). We repeated this procedure for FCCS and FTGs, and for the smoke emissions predictions. For FCCSs, we compared each of FIA-keyed FCCS fuelbed loadings (see http://www.fs.fed.us/pnw/fera/fccs/) to the FIA measured surface fuels loadings for the same fuel components. For FTGs, we compared the average loadings for the fuel components in each FTG class with the FIA loading measurements. We also compared the keyed FLM and FCCS component loadings using the same statistical tests to evaluate if they correlate with each other. To evaluate classification performance, we compared fuel component means for all classification classes to FIA loadings for those classes with 50 or more keyed FIA plots (20 FLM models, 31 FCCS models, and 12 FTG models) using three statistical tests (percentile bootstrap, Welch, Wilcox). We included TSFL in some of the analysis to evaluate if differences in performance and mapping were due to the stratification of fuel loadings by component.

To assess LANDFIRE and FTG fuel map accuracy, we used contingency analysis to test for dependence of mapped classification on the field-based FIA classification. We summarized relationships with a contingency table analysis and tested for statistical significance using chi square tests. We also estimated the K_{hat} statistic for each accuracy assessment to adjust for unequal observations in each mapped category. We analyzed the predictive power of the mapped values for the FIA values to represent loadings (how well are FIA data represented by the mapped fuel classification loadings) using methods similar to those used for the classification assessment. The same regression and error analyses techniques used to evaluate classification performance were also used to compare the mapped FLM median, FCCS fuelbed loadings, and FTG mean loadings (predicted) to the FIA loading data (observed). We summarized regression and contingency statistics in both tabular and graphic formats.

Results

Classification Performance

A test of classification performance is how well the measured FIA fuel component loading values compared with the keyed FLM, FCCS and FTG class component loadings (Table 2; Figures 2-4). For FLMs, we found that FIA measured loadings compared well for duff and CWD with R^2>0.70 and slopes ranging from 0.98-1.02 (a slope of

Table 2—Comparison of the **FIA-keyed classification** class loadings for the three fuel classifications to the reference FIA-measured surface fuel component loadings using regression and error statistics. Ideally, R^2 and slopes should be close to 1.0, intercepts should be zero, % bias should be zero, and Root Mean Square Error (RMSE) should be zero. Surface fuels are described in Table 1.

Classification	Reference	Sample Size	Fuel Component	R^2	Slope	Intercept	% Bias	RMSE
Fuel Loading Models (FLM)								
FLM	FIA	13,138	Duff	0.84	1.02	0.04	4.9	1.01
			Litter	0.20	0.88	0.65	147.6	1.15
			FWD	0.16	0.62	0.16	-4.2	0.55
			CWD	0.70	0.98	0.48	40.3	1.38
			TSFL	0.77	1.00	1.12	31.0	2.45
Fuel Characteristics Classification System (FCCS)								
FCCS	FIA	10,471	Duff	0.02	0.03	1.37	-86.4	16.30
			Litter	0.04	0.24	0.71	-28.8	1.34
			FWD	0.07	0.08	0.21	-86.7	3.74
			CWD	0.11	0.12	1.02	-71.8	7.91
			TSFL	0.14	0.09	2.82	-79.3	25.77
Fuel Type Groups (FTG)								
FTG	FIA	10,472	Duff	0.27	0.27	0.74	0.06	0.92
			Litter	0.10	0.10	1.51	0.01	2.39
			FWD	0.10	0.10	0.44	0.26	0.54
			CWD	0.25	0.25	1.25	0.09	2.07
			TSFL	0.23	0.23	3.70	0.07	3.91
FLM vs FCCS								
FLM	FCCS	10,471	Duff	0.02	0.03	1.32	-87.0	1.32
			Litter	0.02	0.09	0.31	-70.7	1.45
			FWD	0.16	0.08	0.24	-85.9	3.69
			CWD	0.10	0.10	0.69	-79.6	8.25
			TSFL	0.13	0.08	1.95	-84	26.75

1.0 indicates good agreement), but there were few agreements between observed and predicted loadings for litter and FWD with computed R^2 values quite low (<0.20) and regression slopes mostly less than 0.88 indicating most loadings were under predicted (Table 2; Figure 2). In addition, intercepts were statistically ($p<0.05$) different from zero (>0.16 kg m^{-2}), the bias for litter was greater than 148% of the mean, and the RMSE values were high (>0.5 kg m^{-2}) (Figure 2).

FCCS and FTG classification performances were poorer than FLM performance with no fuel component having an R^2 value greater than 0.27 and all slopes less than 0.27 (Table 2; Figures 3,4). All FCCS fuel component loadings were under-predicted with negative bias values greater than 28% of the mean, while bias for FTGs were significantly lower (0.01-0.26%) (Figure 3). Both FCCS and FTG classifications had high RMSEs (0.54-16.3) and high intercepts (>0.44). There was no apparent relationship between keyed FLM and keyed FCCS using the FIA loadings (Table 2).

Map Accuracy

We found low map accuracies for all three fuel classifications. The LANDFIRE mapped FLM categories for the FIA plot locations matched the keyed FLM categories from the FIA data only 25% (K_{hat} = 0.098) of the time (Keane and others 2013). FLM categories with lighter fuel loadings (11-31) had the best agreement (4-67% agreement), while those FLMs with heavy log and duff loadings (classes 63-102) had poor agreement (0-19% agreement). The lightest load FLM 011 had both the highest agreement (67%) and highest number of plots (3,016), while the next most frequent FLMs (021, 031) had high plot numbers (1,847, 1,856 respectively) but low accuracies (<22%). Over 57% of the FIA plots were classified to these three classes (011, 021, 031) thus explaining the lower K_{hat} (0.098). Five FLMs (041, 062, 083, and 091, and 102) did not have any FIA plot classified correctly, probably because of their rarity on the landscape and the low number of FIA plots for these categories (635 plots). In general, omission error was greater than commission error for most FLMs.

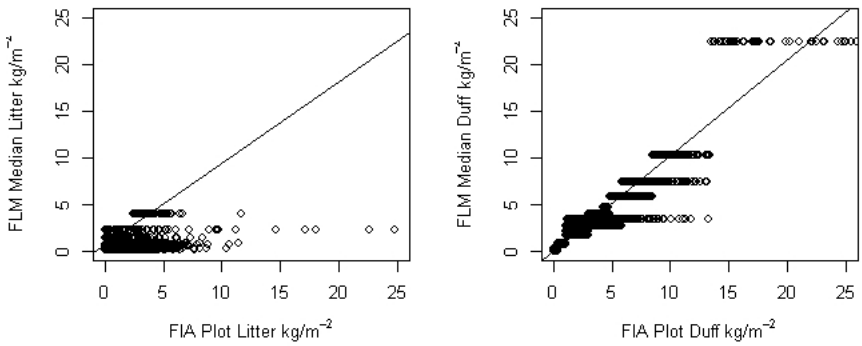
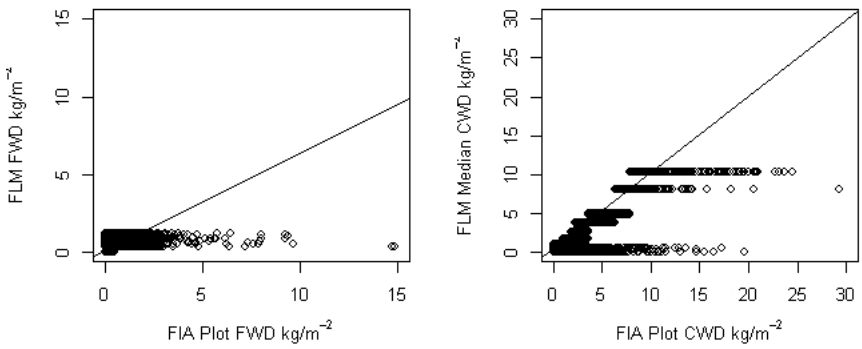


Figure 2—Relationships of measured FIA loadings to the keyed FLM median fuel loadings for FIA plots for the following fuel components (a) litter, (b) duff, (c) FWD, (d) CWD (see Table 1 for definitions of fuel components).



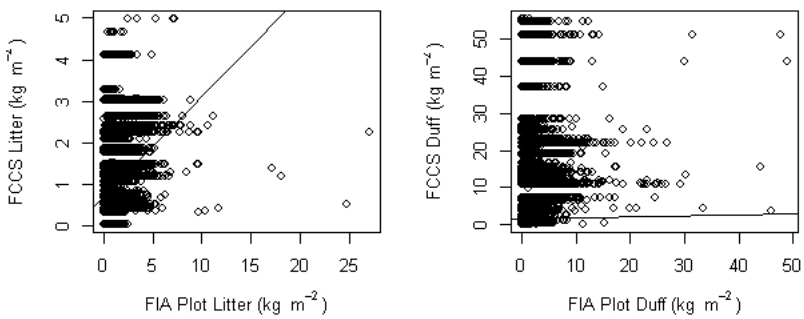
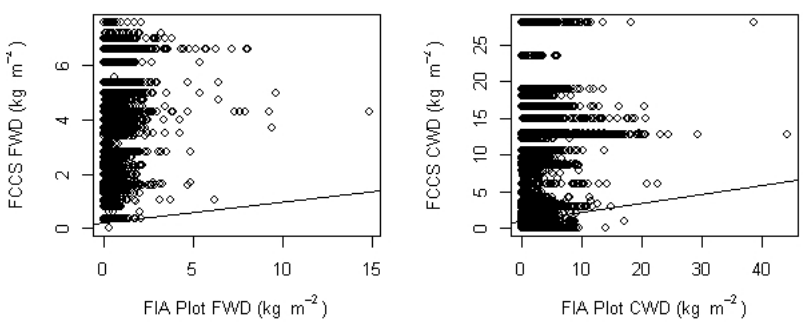


Figure 3—Relationships of measured FIA loadings to the keyed FCCS fuel loadings for the following fuel components (a) litter, (b) duff, (c) FWD, (d) CWD (see Table 1 for definitions of fuel components).



FCCS and FTG mapped class values compared better than mapped FLM classes to the FIA keyed classes (FCCS was 34% agreement, K_{hat} = 0.33 and FTG was 64% agreement, K_{hat} = 0.54). However, this was probably because the key that was used to assign FCCS classes to combinations of LANDFIRE vegetation composition and structure (cover, height) layers was also used to assign FCCS categories from FIA data and the same is true for FTGs (forest type groups were used to key FIA plots). Therefore, the FCCS 34% and FTG 64% agreements reflect the accuracy of the LANDFIRE vegetation and RSAC forest type group layers rather than the fuel maps. FCCS results were similar to FLMs in that many plots (4661 of 10470) were in few categories (20% in FCCS 4, 12% in FCCS 9, 12% in FCCS 210), and these categories had poor agreement (<25%). There were several FCCS categories that had a high number of plots (>500) and high agreement

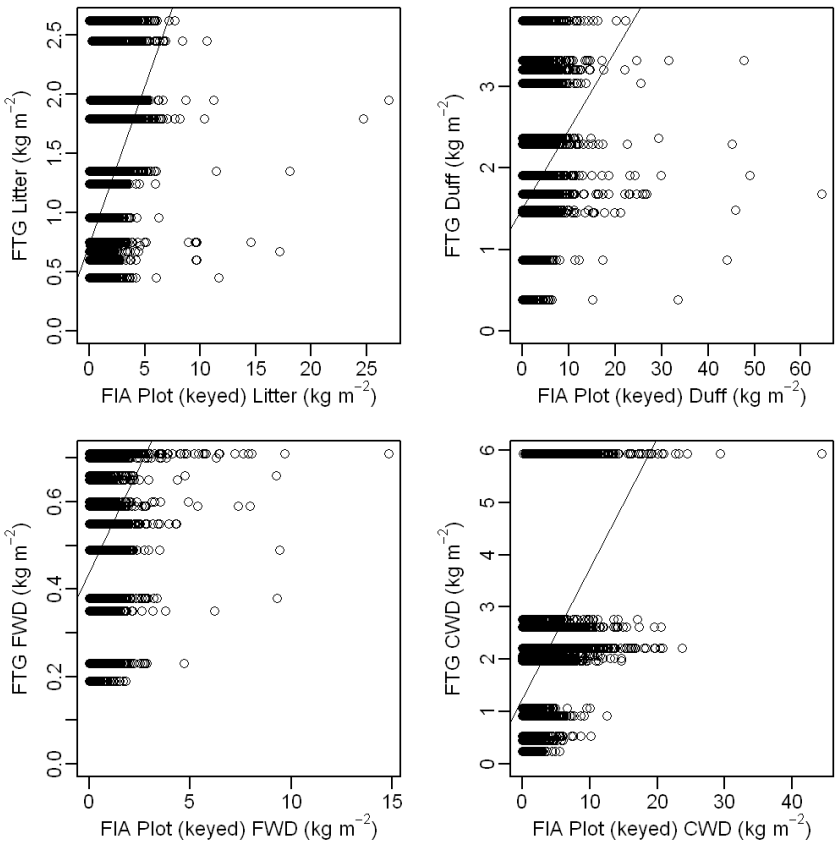


Figure 4—Relationships of measured FIA loadings to the keyed FTG fuel loadings for the following fuel components (a) litter, (b) duff, (c) FWD, (d) CWD (see Table 1 for definitions of fuel components).

including FCCS 210 (1262 plots and 67% agreement), FCCS 70 (530 plots and 63%), FCCS 21 (507 plots and 40% agreement). Interestingly, only six of the 55 mapped FCCSs did not have any FIA plots correctly mapped, and only 11 of the mapped FCCSs had less than 10 FIA plots. We did not include a FCCS and FTG contingency table because of the high number of classes (55 FCCS mapped classes).

A better measure of map accuracy is to compare measured FIA fuel loadings to the loadings of the mapped FLM, FCCS, and FTG classes. Here, results are even less promising (Table 3; Figures 5-7). Agreement between mapped FLM and FIA loadings are poor (R^2<0.1). Slopes of the regression line reveal severe under prediction for all FLM components (<0.24) (Figure 5) and FTG components (<0.20) (Figure 7), but are somewhat close to 1.0 for FCCS loadings (0.1-1.4) (Figure 6). However, bias for mapped FCCS loadings (39-811%) are much greater than FLM loadings (-73-18%) and FTG loadings (-3.5-0.89%), and RMSE values are higher for FCCS (1.46-22.54) than for FLM (0.66-3.53) and FTG (0.98-2.42) (Table 3). As expected, mapped FCCS fuelbed loadings compared poorly with mapped FLM loadings (Table 3), with R^2 ranging from 0.04-0.17 and bias greater than 436% of the mean, and errors less than 22 kg m^{-2}.

Discussion

Results from this study demonstrate the incredible difficulty in describing and mapping fuels for fire management (Keane 2013). All three classifications performed poorly which resulted in poor map accuracies. The FLM classification appeared to perform better than both FCCS and FTG classifications probably because of the duff and CWD components explained more of the variation in the FLM key than litter or FWD (Lutes and others 2009). We found a high degree of redundancy in FWD and litter fuel loadings across most classes in all classification systems (Keane and others 2013) and this redundancy probably served to make accurate quantification of classification fuel loadings difficult (Table 2; Figures 2-7). Poor classification performances for loadings (Table 2) are the major reason why the map layers have poor accuracies (FLM 25%, FCCS 34%, and FTG 64%) and poor loading comparisons. It is nearly impossible to accurately map fuel loadings when the classifications can't effectively discriminate fuel component loadings within classification classes. Even when we summed all component loadings into a total surface fuel load (TSFL), we got poor classification performances for FCCS and FTG (Table 2) and poor mapping accuracies (Table 3), indicating that the problem is not because the loading was inappropriately stratified or summarized.

Probably the most important reason why these classifications performed so poorly was the high degree of variability in fuel loading in each of the four fuel components and the interaction of this variability across spatial scales, which complicates sampling, mapping, and classification (Keane and others 2012a). The fuel classifications of FLMs, FCCSs, and FTGs best describe fuel information for small areas (a point; <5 m^2) so their accuracies will always be low unless they are applied at the finest scale of variability (probably

Table 3—Comparison of the **mapped** classification class loadings for the three fuel classifications to the reference FIA-measured surface fuel component loadings using regression and error statistics. Ideally, R^2 and slopes should be close to 1.0, intercepts should be zero, % bias should be zero, and Root Mean Square Error (RMSE) should be zero. Surface fuels are described in Table 1.

Classification	Reference	Sample Size	Fuel Component	R^2	Slope	Intercept	% Bias	RMSE
Fuel Loading Models (FLM)								
FLM	FIA	11,740	Duff	0.01	0.11	1.62	-32.7	3.53
			Litter	0.01	0.25	0.97	-73.1	1.36
			FWD	0.03	0.27	0.39	18.0	0.66
			CWD	0.07	0.29	1.46	-45.7	2.96
			TSFL	0.08	0.30	4.19	-44.2	5.79
Fuel Characteristics Classification System (FCCS)								
FCCS	FIA	10,469	Duff	0.03	0.02	1.42	811.4	22.54
			Litter	0.02	0.15	0.85	39.8	1.46
			FWD	0.04	0.05	0.33	612.1	3.80
			CWD	0.12	0.08	1.10	356.7	11.40
			TSFL	0.13	0.06	3.39	474.8	35.51
Fuel Type Groups (FTG)								
FTG	FIA	10,470	Duff	0.17	0.20	0.78	-3.52	0.98
			Litter	0.07	0.08	1.58	-2.39	2.42
			FWD	0.06	0.08	0.47	0.89	0.55
			CWD	0.18	0.20	1.44	-0.07	2.21
			TSFL	0.17	0.19	4.05	-1.47	4.07
FLM vs FCCS								
FLM	FCCS	11,738	Duff	0.04	1.28	14.50	1259.1	22.43
			Litter	0.04	0.64	1.34	436.1	1.59
			FWD	0.04	0.05	0.33	781.5	3.80
			CWD	0.11	1.47	6.70	757.4	11.84
			TSFL	0.17	2.56	21.96	939.2	36.35

1-5 m patch sizes), which is often too small for cost-effective fuel sampling and mapping. In other words, FLM, FCCS, and FTG description systems assessments are point estimates so when their application is across large spatial scales (pixel or stand), there is a higher chance that multiple classes will occur because of high spatial variability that acts at different scales for each fuel component (i.e., the variability within a pixel was so great that it overwhelmed the comparison making it difficult to assess classification accuracy). This is especially true in managed stands where slash piles, thinning techniques, and harvest methods dictate spatial variability and distribution (Domke and others 2013; Keane and others 2012b).

The top-down FLM classification showed the most promising results even though our comparison also showed a great deal of uncertainty. FLMs had good classification performance for duff and CWD but poor differentiation of FWD and litter loading (Table 2; Figure 2). The primary reason for the low FWD and litter correlation is because the FLMs were developed for identifying fuelbeds with significantly different PM2.5 emissions and soil surface temperature. By their nature, each FLM class represents a wide range of FWD and litter loading with similar emissions and surface soil temp. Another source of error was the assumption that median fuel load of the assigned FLM class accurately represented loadings for FWD and litter.

Design mismatches between LANDFIRE mapping and the FCCS classification are probably the primary reason for the low FCCS LANDFIRE map accuracies. The FCCS fuelbeds were not designed to accommodate mapping across broad and diverse land areas; FCCS was designed for stand or point-level on-site fuel description (Ottmar and others 2001). Therefore it is difficult to scale this classification across large spatial domains. The LANDFIRE FCCS fuel map was created by representing broad vegetation types mapped by satellite imagery with a standard generic FCCS fuelbed that was created for finer scale applications. For site-specific applications, fire and fuels managers would need to

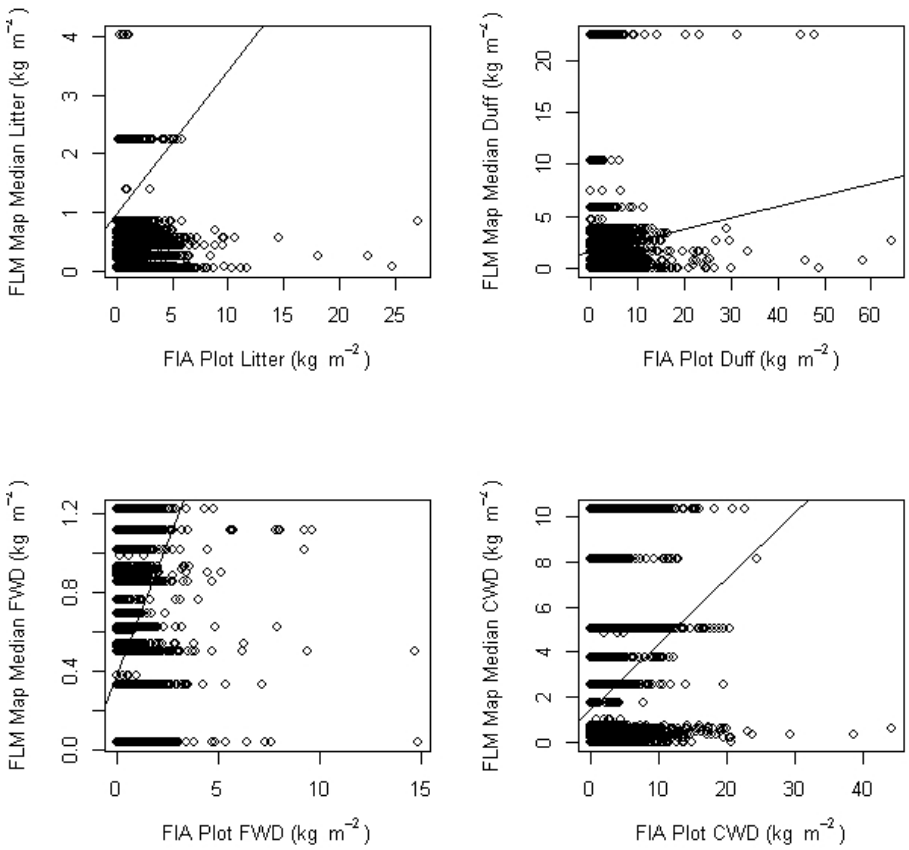


Figure 5—Relationships of measured FIA loadings to the LANDFIRE mapped FLM median fuel loadings (Table 2) for FIA plots for the following fuel components (a) litter, (b) duff, (c) FWD, (d) CWD (see Table 1 for definitions of fuel components)

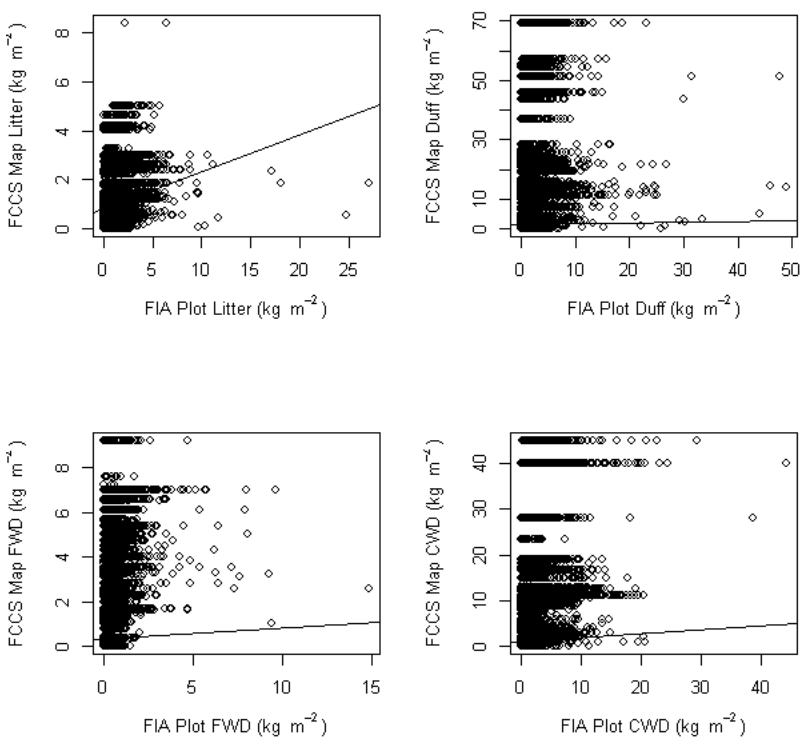


Figure 6—Relationships of measured FIA loadings to the LANDFIRE mapped FCCS fuel loadings for the following fuel components (a) litter, (b) duff, (c) FWD, (d) CWD (see Table 1 for definitions of fuel components).

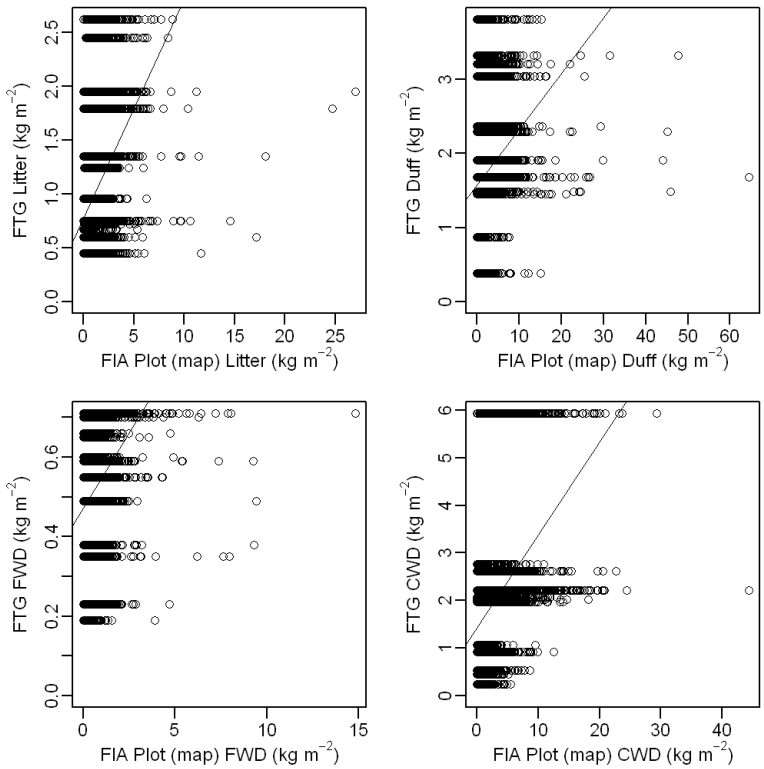


Figure 7—Relationships of measured FIA loadings to the RSAC FTG mapped FTG fuel loadings (Table 3) for the following fuel components (a) litter, (b) duff, (c) FWD, (d) CWD (see Table 1 for definitions of fuel components).

customize these generic fuelbeds by adjusting loadings using local data.

FLM and FCCS mapping accuracies for the LANDFIRE refresh 2008 products are low partly because the LANDFIRE project did not have sufficient field data available at that time to build comprehensive FLM and FCCS maps and to conduct a thorough accuracy assessment. There were few national programs that gathered comprehensive fuel loading data, even though these fuel data are critical for carbon inventories, fire management, and wildlife habitat analysis. Therefore, instead of linking fuel classifications to biophysical settings, LANDFIRE had to link FLM and FCCS classes to vegetation attributes.

There are two ways to improve these classifications. The easiest and quickest is to expand the scope and context of the current classifications to increase accuracies. We suggest that the FLM classification be redone with the new FIA fuels data, along with any other recently available fuel data sets, to refine current classes, add more classes, and improve key criteria (Lutes and others 2009). Improving the FCCS classification would involve sampling many more fuelbeds to account for the diversity of fuel conditions across the US and then refining the key criteria used to select and map FCCS fuelbeds to focus more on the fuelbed than the vegetation. FTG performance could be improved by (1) summarizing the fuels data over FIA forest types instead of groups, (2) including non-forest types, and (3) stratifying the summary of FIA loading of forest type classes by region, physiographic setting, and ownership. However, we feel that these suggested improvements may result in only minor to moderate increases in accuracy.

The more difficult but effective way to improve these classifications is to incorporate the high variability and scale of fuels, along with those processes that control fuel dynamics, into a brand new classification (Keane, 2013). This would require extensive basic research to understand fuel dynamics, explore interactions between vegetation, disturbance, and biophysical processes, and identify those processes that influence fuel attributes (Keane 2013). Then, fuel properties can be linked to those biophysical gradients that can be mapped and used in conjunction with appropriately scaled remote sensing products to map fuel loadings.

Although mapping and loading accuracies for the three classifications were low, we feel that the three fuel classifications and the LANDFIRE maps are still quite useful to most fire management applications, especially across broad scales, because they (1) depict relative differences in fuel loadings across major regions, (2) represent state-of-the-art fuel mapping technology, and (3) are the only spatial surface fuel resource available at this time. Users of this technology should account for the high uncertainty of these classifications found in this study when designing their analyses and interpreting their results. The use of FLMs for smoke emissions, for example, has a lower uncertainty than using FLMs for carbon inventories. The poor performances and low mapping accuracies indicate a real scale issue with the current fuel classifications and their associated maps in that the high variability of fuel loadings acting across multiple scales make accurate mapping of fuel loadings with current classifications difficult.

Acknowledgments

We thank the USDA Forest Inventory and Analysis program, the LANDFIRE project, and the National Fire Plan

for project support, data, and funding. Portions of this work were performed under the terms of an interagency agreement between the LANDFIRE program and the USDA Forest Service Forest Inventory and Analysis program in support of fuel load mapping in LANDFIRE. We also thank Don Long and Matt Reeves, U.S. Forest Service Rocky Mountain Research Station, for technical review.

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Creation and Implementation of a Certification System for Insurability and Fire Risk Classification for Forest Plantations

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Summary—*Currently, the Chilean insurance market sells forest fire insurance policies and agricultural weather risk policies. However, access to forest fire insurance is difficult for small and medium enterprises (SMEs), with a significant proportion (close to 50%) of forest plantations being without coverage. Indeed, the insurance market that sells forest fire insurance policies does not have an evaluation system based on known standards accepted by the market; rather, it is discretionary, with each company evaluating risk with their own specific parameters. This lack of standardization reduces access and increases costs due to uncertainty, assigning a high risk rating by default. At present, over 19,000 SMEs and more than 810,000 forested hectares are affected by difficulties in getting fire insurance policies.*

This situation is being addressed through a project funded by the Chilean Foundation for Agriculture Innovation (FIA), along with government institutions, forest companies, insurance companies, and insurance adjusters and brokers, and executed by the Chilean Forest Institute (INFOR). The proposed solution is a certification system of fire risk classification for forest plantations (named SAFOR –Sello de Asegurabilidad Forestal- as per the Spanish acronym), that will be created and implemented, allowing the SMEs to have access to the insurance market.

The system has two elements, the standard, built as a formal national norm that describes objectively how to evaluate the risk, and the certification system that will transfer the standard into the market based on an appropriate accreditation of auditors through the fulfillment of certain procedures.

The implementation of SAFOR certification is expected to have several different benefits and positive impacts, improving several indicators. Forest companies with plantations close to SMEs plantations may also benefit from a decrease in fire risk. The adoption of fire management best practices that landowners may apply to reduce the risk and therefore obtain lower insurance premiums could reduce the fire occurrence, contributing to the environment and also to the State investments, since owners of plantations established with State contribution could continue in the forest business after a fire, preserving the rural economy.

Introduction

Chile has a population of 16.6 million inhabitants, a per capita Gross Domestic Product (GDP) of US$ 18,945, a total continental area of 756,000 km^2, a forest area covering 17.3 million hectares, with 2.3 million in plantations, and total annual forest exports amounting to US$ 5,714 million (INE 2014).

Forest plantations are essential in the forest activity since they supply 98% of the timber used by the industry. Forest ownership is concentrated in two big companies that hold over 50% of the total forest plantations (Op cit.).

Fire statistics indicate a burned area of 1.2 million hectares between 1990 and 2013, with more than 137,000 fires and losses of forest assets worth more than $50 billion a year market value, plus other losses that have been estimated in 8-10 times that amount. Forest fires are caused mainly by human activities. The annual average burned area reaches an average of 49,000 ha, and the fire forest insurance market is US$ 9.1 million (CONAF 2013).The Chilean insurance market offers two products for forest plantations: initial insurance, which operates during the first three years after plantation and deals with weather damage (drought, excessive rainfall, flood, frost, hail, snow and wind), and fire for new forest plantations; and the fire insurance policies and agricultural weather risk policies. Nevertheless, it is very difficult for forest SMEs (small and medium-sized enterprises) to obtain fire insurance policies for forest plantations because the insurance market has few specialized agents in forest plantations. As little quality information is available regarding fire risk in forest plantations, agents typically assign a high risk qualification by default. This increases

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

policy costs because of the uncertainty. Therefore, the lack of standardized information, which affects over 19,000 owners and more than 810,000 hectares of plantations, poses serious barriers to forest SMEs, with important socioeconomic implications.

An ongoing project intended to solve the problem of market asymmetry affecting forest SMEs, funded by the Chilean Foundation for Agriculture Innovation (FIA) along with government institutions, forest companies, insurance companies, insurance adjusters and insurance brokers, is being implemented by the Chilean Forest Institute (INFOR), with a total budget of US$ 410,000, allocated in three years (2013 to 2016). The project is implemented by an advisory council formed by representatives of each associated member, FIA and INFOR, which contributes with and validates results and decisions.

Forest plantations, a very valuable asset for the country, are subject to multiple risks, including fire. However, a significant proportion are not covered by fire insurance, with several negative implications, especially for SMEs, whose proportion of uninsured plantations is higher than that of large companies, increasing the gap between socioeconomic stakeholders. This gap is caused by a lack of a standardized methodology, hindering assessment of fire risks by insurance companies.

A certification system of fire risk classification for forest plantations (named SAFOR as per the Spanish acronym), will be created and implemented, allowing the access of SMEs to the insurance market.

The solution has two elements. The first element is a set of standards, built as a formal national norm generated by the Chilean Standardization Institute (INN), which describes how to evaluate the risk in a methodological and objective way. The other element is the certification system, which will enable plantations to demonstrate that they meet the designated standards based on an appropriate accreditation of auditors by following certain procedures, and facilitate the commercialization process of fire insurance policies. The insurance market will adopt the certification system as a source of information to qualify fire risk associated with insurance policies. In turn, the clients will pay for the certification to break the entrance barriers by evaluating the risk. Thus, policy price should decrease and the number of SMEs insured should increase, allowing forest SMEs to hire fire insurance policies at sustainable prices, according to the forest activity. The forest fire insurance market is expected to grow as a result of the adoption of the SAFOR certification system, because it will provide reliable information for the evaluation of fire plantation risks. In addition, the following potential benefits have been identified:

-Increase of the insurance forest market size and greater competition, because new companies are expected to join the activity;

-Improvement of self-protective management, including an increased fuels management by plantations, in order to get a lower risk qualification;

-More controllable fires;

-Improved access for SMEs to the financial system and to government promotion tools/funds due to the risk reduction;

-Better information on SMEs technology and productivity;

-The forest subsidy allocated to the establishment of new forest plantations will be protected, increasing its socioeconomic profitability;

-Environmental benefits, such as reduction of impacts to soil, water and biodiversity, as well as reduced air pollution and greenhouse gases.

It should be noted that the need to evaluate risk to a level of sophistication that will meet the needs of the insurance industry reaches far beyond Chile.

Development Process

The proposed development process is organized in four phases:

1. Feasibility analysis, considering forest sector conditions, insurance market, legal requirements, technical issues to be used in the standard construction, and the potential client's willingness to pay through a contingent valuation methodology according to Hannemann (1984), Arrow and others (1993), Vásquez and others (2006) and Tietenberg (1996). Sample size was determined according to Piñeda (2004).
2. Development of a National Standard to quantify the fire risk level in forest plantations. The standard development process follows the national authority scheme, defined in the national standard 1 (NCh 1 cR2010), and considering the risk management standard (NCh-ISO 31,000).
3. Design, creation and validation of the certification system.
4. Implementation of the new certification as a pilot project.

Due to the project characteristics, special importance has been given to joint public-private collaboration because of its potential to expand and its long-term sustainability.

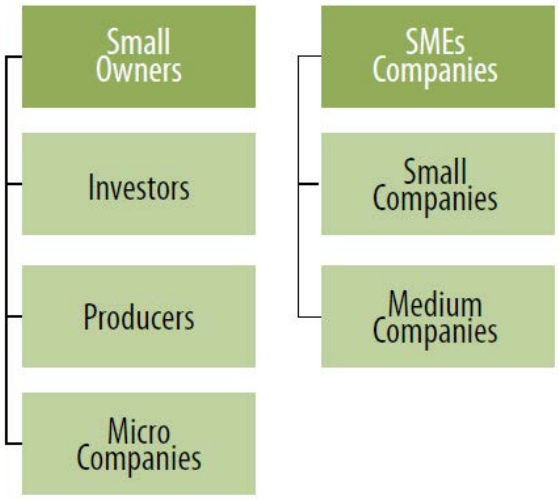

Figure 1—Demand target market segmentation.

Among the main stakeholders involved are the insurance market, SMEs and small owners of different types (Figure 1) from the private sector, the Forest Institute (INFOR), Forest Service (CONAF) and the Ministry of Environment from the public sector.

Results

Since the project has only recently begun to develop the standard, here we present the results for the first phase, which consists of a feasibility analysis. This feasibility study conducted and completed five different analyses: 1) forest sector and insurance market overviews, 2) legal aspects, 3) an examination of the insurance market in Chile, 4) socio-economic issues focusing on willingness to pay, and 5) forest management procedures. The main results (Loewe and Vargas 2014) are summarized below:

Forest Sector and SMEs Baseline

The study conducted by Loewe and others (2014) showed that forest plantation ownership is strongly concentrated, with two companies owning more than 50% of all plantations, distributed in four regions (72% from Maule to Los Ríos). On the other hand, SMEs plantations are concentrated from O'Higgins to Los Rios (88%) (Table 1) (INFOR 2013). However, little information on SMEs was available concerning how they are divided between SMEs and Small and Medium Owners (SMOs), being the threshold, for statistical purposes, among small and medium size owners 200 hectares.

Table 1—Area of forest plantations by owner and region.

Region	Big Companies (Hectares, %)		SMEs (Hectares, %)	
O´Higgins (VI)	7,725	7	105,039	93
Maule (VII)	247,831	55	204,971	45
Biobío (VIII)	654,496	72	252,860	28
Araucanía (XIX)	274,198	57	206,240	43
Ríos (XIV)	128,654	68	61,557	32
Lagos (X)	23,101	33	46,928	67
Total	1,336,005	60	877,595	40

Source: INFOR (2013)

Plantations of big forest companies are mostly devoted to radiata pine (77.3%) and *Eucalyptus globulus* (12.1%), whereas SMEs and SMOs have a more diversified resource (50% of radiata pine and 35.9% of *Eucalyptus globulus*).

Regarding age structure, most plantations are 0-20 years old. Age structure is more spread across age segments in the big companies than in SMOs/SMEs, reflecting a lack of planning due to fragmentation by the latter.

Tenure of plantations in SMOs/SMEs at the municipality level

In O'Higgins region, four municipalities (Pichilemu, Marchigüe, Litueche and Paredones) accounted for 70% of the forest plantations that belong to SMOs, located in the regional coastal zone. In Maule region, the municipalities Cauquenes, Constitution, Curepto, San Javier and Curepto accounted for 46% of SMOs/SMEs forest plantations, also located in the coastal region (INFOR 2013).

In Bio Bio region, about 25% of forest plantations within this socioeconomic segment were concentrated in five municipalities (Quirihue, Mulchén, Los Angeles, Santa Barbara and Cobquecura), whereas in the Araucanía region, six municipalities located in the central valley (Los Sauces, Traiguen, Lumaco, Galvarino, Nueva Imperial and Angol) accounted for nearly 50% of plantations.

Finally, in Ríos region, six municipalities (La Union, Los Lagos, Corral, Valdivia, Mariquina and Paillaco) accounted for 70% of forest ownership, and in Los Lagos region, four municipalities (Fresia, Purranque, San Juan and Rio Negro) accounted for 65% of their forest patrimony at the regional level.

Fire Statistics

Fire statistics are produced annually by the National Forest Service (CONAF) from data on fire occurrence and affected area by season (from July 1st to June 30th of the following year).

From 1990 to 2013, the burned area totaled 1.2 million ha, with 137,000 individual fires, and losses of assets with a commercial value averaging over US$ 50 million per year (Table 2) (CONAF 2013). However, non-commercial losses were much more critical because of their impact on the environment and quality of life for inhabitants, both in rural and peri-urban areas of towns and cities. These impacts,

Table 2—Fire occurrence and historical national damage (1990–2013).

	Forest Service	Companies	Total
Total Fire N°	93,070	44,092	137,162
Average (N° of fires/season)	3,878	1,837	5,715
Incidence (%)	67.9	32.1	100
Total affected area (ha)	983,420	192,537	1,175,957
Average (ha/season)	40,976	8,022	48,998
Incidence (%)	83.6	16.4	100
Protected area (ha)	34,000,000	3,000,000	37,000,000
Incidence (%)	91.9	8.1	100

Source: CONAF (2013)

whose valuation is not straightforward, were estimated to be 8-10 times higher than direct losses, being US$ 400-500 million/year, not including the incalculable value of loss of human lives (Julio 2012).

On average, 49,000 ha are burnt each season, in about 5,700 events, with an average of 9 ha affected per event. Nevertheless, the range of burnt area historically varied widely, from a minimum of 10,000 ha in the 2000-2001 season to over 100,000 in the 1998-1999 season. There is no relationship between occurrence and area affected; for example, in the 2011/12 season, in Quillón about 25,000 ha were burnt only in one fire event.

The four seasons that caused the highest damage coincided with big fires, and although they are known to have been originated intentionally (simultaneous outbreaks), investigations have failed to identify culprits.

Interestingly, big forest companies had 32% of fire occurrence but only 16% of the affected area, because they control a smaller area and have detection and control systems (Op cit.).

In Chile, wildfires principally originate from anthropogenic activities and are strongly linked to attitudes of the value of the forests. If people assign a low value to the forest, they behave carelessly, negligently or recklessly; on the contrary, if they assign a high value to the system they live in, they will behave wisely. At the national level, for the period 2003-2013[1], accidents accounted for 57% of the area burned (including agricultural and forest residue prescribed fires, trash burning, neglected cigarettes and fires, transit and recreational activities, among others); intentional fires accounted for 26.8%, unknown causes, 16% and natural causes accounted only for 0.2%. Even though this is a complex reality, it has the advantage that through education human behavior related to fire and fire management can be improved.

The fire statistics of the Forest Service comprises 326 municipalities, not including geographically extreme regions. Of these, 29 concentrate over 50% of wildfires and have received prevention, control, suppression and attack budgetary allocation since the 2010/2011 season.

Forest companies focus their efforts on the basis of knowledge of physical parameters (vegetation, topography, weather and fire behavior) in order to protect their forest resources. Forest companies intend to foster their protection programs and continue increasing coordination and collaboration agreements with other companies to strengthen self-protection. Accordingly, the most relevant aspects for companies are coordination and collaboration agreements with other forest companies, early detection systems, minimization of fire spread and attack resources.

[1] Statistics from CONAF, 2013.

Legal Analysis for the Development of SAFOR Certification System in Chile

The implementation of a forest plantation insurability certification was analyzed from a legal point of view (Lobo 2014), and was found to be quite feasible as no impediments were identified in our legislation.

Given the legal nature of the insurance contract, the parties may agree to include in the insurance policies terms and conditions to quantify fire risks in forest plantations through a certification process, which could be accepted by insurance companies when deciding on issuing a given policy and when setting the premium cost.

Then the Superintendence of Securities and Insurance (SVS), based on its legal powers, will validate these new terms and conditions to be endorsed in case the amount of the annual insurance premium is lower than a stated limit in support of a transparent business for SMEs; if the parties do not comply with this obligation, they cannot use a new policy or term. If the annual insurance premium exceeds the previous amount, and the insurance beneficiary is a legal entity, the mentioned obligation is no longer valid because it will be a private agreement, with those parties being free from incorporating the certification.

This conclusion is reinforced by the general rules of the Commercial Code, whose Article 516 concerning the information that policies must contain for all kinds of insurances, states that the policy must describe "the situation of the insured property," without indicating how this statement should be expressed.

Thus, there are no legal impediments for the parties to agree that part of the condition of the insured resource is determined by a third party who technically certifies the fire risk of a forest plantation through the SAFOR standard.

The Insurance Market in Chile

The analysis performed by Forestsur (2014) includes two parts. The first part describes the structure of the insurance market in general terms, including stakeholders (insured, regulator, brokers, reinsurance, adjustors and support agencies), the regulatory environment, business practices, market dimension and insurance types, in order to explain the insurance market functioning and role in the economy of Chile. The second part describes the insurance market from the point of view of supply and specific operation for forest plantations in Chile.

General Insurance Market

An increasing trend in the industry is observed: life insurance companies have increased over time, exceeding the general insurances.

Specifically in insurances for SMOs and SMEs, there would be a disadvantage in the products offered by the insurance market (coverage), because they were not designed for a specific customer segment or size; rather, they are generic, so the insurance market can access a broad market (clients or insured) but has the disadvantage that often small potential customers face entry barriers due to business size or risk rate.

Moreover, the supply of insurances is growing, with a variety of increasingly specific interests to satisfy insured needs. In addition, there is a fairly detailed legislation on what the various stakeholders in the industry may or may not do which regulates the amount of investment, diversification, policy contract components, etc., regulated and supervised by the SVS.

The incidence analysis of the total annual premium distribution for the different insurance branches shows that fire and earthquake reach 35%, and excluding the compulsory automobile insurance, it would reach 50%; given the high variety included in "others" (theft, liability and several others), fire and earthquake branch is the most important of all general insurances.

This market will probably continue to grow during the next years, both in variety and size, i.e., increasing the number of actors, both insurance and reinsurance companies and brokers, and it will improve the offered insurances, diversifying the investment portfolio.

The insurance industry in Chile is transparent and has a stable institutional framework, governed by clear laws and regulations, which has led to a sustained increase in investment value, reaching US$ 5 billion in 2012.

This has particular positive implications for SAFOR project, because when demand is added to the insurance market, it will find a market ready for taking risks quantified by the certification. This opportunity means that forest SMOs and SMEs will gain access to this market.

Insurance market for forest plantations in Chile

In the case of forest plantations, insurance companies are classified as General Insurance Companies. In the case of forest fires coverage, even if it is a standard procedure from the point of view of the product (policy type), its value chain relies heavily on reinsurance capacity and on the analysis of the inherent risks to forest plantations. Reinsurance capacity is made up of the involved reinsurance companies that cover these risks and their financial capacity. Regarding risks, each reinsurer has defined capability coverage (coverage limits) for forest plantations in Chile, and depending on the risk analysis, a structure of coverage is set, i.e. rates, compensation limits, deductibles, and special additional coverage. Risks become insured capital, then placements and finally insurance policies.

To analyze the risks, the insurance market uses discretional procedures without standardized information; among the considered elements are plantation location, forest management and operational performance, historical fire occurrence; as well as forest neighbors' protection programs, cooperation agreements and business volume.

The main stakeholders are insurance companies, insurance brokers and sales agents, reinsurers and adjusters (SVS 2013a).

Of the total plantation area insured, amounting 1,234,190 ha, eucalyptus species represent 17%, radiata pine 81%, and only 2% correspond to other species.

The three most important regions for insured plantations are Bio Bio (52%), Araucania (22%), and Maule (15%), making a total of 89% (Table 3).

The SAFOR certification system is oriented to SMOs and SMEs, including several actors, as shown in Figure 1.

An important finding was that big forest companies have a correct administration of their fire insurance policies through catastrophic coverage, concentrating in coverage for large losses, which is logical given the substantial appreciation of their resource. Therefore, if premiums were higher, the cost would be much higher given the high self-protection costs.

It was concluded that the total insurable plantations, only in the regions of O'Higgins, Maule, Bio Bio and Araucanía, exceed 1,950,000 ha, equivalent to 82% of the insurable plantations at a national level. Of these, over 1,170,000 ha are already covered, with only 18.5% belonging to SMOs and SMEs: In these four regions, 750,000 ha have not been insured, and most of that area would belong to this stakeholder segment.

The area without insurance, on which SAFOR is focusing, is located in four regions (O'Higgins, Maule, Bio Bio and Araucanía), because the insurance market has 95% of forest fire insurance policies in these regions and it is where fire hazards are higher. It has been estimated that in those regions there are 15,700 forest owners, 400 being SMEs and the remaining ones, SMOs (SVS 2011).

Regarding the estimated business volume, a conservative scenario that considers incorporating 30% of this potential area in 5 years would represent a real increase for the insurance forest market of 20%, which is relevant for a general insurance market that grows annually at a rate of 6 to 7%.

Table 3—Insured plantation area by region and insurance company.

	Region										
Insurance Company	**IV**	**XIII**	**VI**	**VII**	**VIII**	**IX**	**XIV**	**X**	**XI**	**XII**	**Area (ha)**
Magallanes	75	98	3,515	33,072	35,613	11,149	1,566	2,342	514		87,944
Mapfre		521	1,626	1,741	7,138	654	251				11,931
Penta		50	1,548	8,11	21,134	7,02	25,294	835			63,991
RSA (SMEs)			679	12,088	30,208	19,116	1,713	454		7	64,265
RSA (Big companies)			63,796	135,31	550,538	236,688	10,167	9,561			1,006,060
Insured plantation area (ha)	75	669	71,164	190,321	644,631	274,627	38,991	13,192	514	7	1,234,191
Region weight (%)	0	0	6	15	52	22	3	1	0	0	100

Source: Elaborated with information from the Superintendence of Securities and Insurance (SVS)

Socioeconomic Analysis and Willingness to Pay for SAFOR Certification

Forest fires are currently a very important concern given the occurrence of large disasters in the country in recent years, which have affected forest plantations and surrounding communities, causing irreversible damage to the heritage of many Chilean families, and also to companies that support many families. In this scenario, given the externalities that directly affect people's welfare, a study was conducted to assess the willingness to pay for SAFOR certification by potential users (SMOs and SMEs). The study was performed by García (2014) in two stages: first, surveys were conducted among SMOs and SMEs to gather data on their socioeconomic characteristics, perception of forest fire risks, reasons for not buying fire insurance policies, as well as to explore their interest in SAFOR certification. Second, the survey results were analyzed using the contingent valuation methodology to assess the willingness to pay for the new certification.

This methodology evaluates the possible willingness to pay for SAFOR certification as a private concept that depends on the income of potential users, considering that it would remove entry barriers through an objective risk assessment, reducing existing asymmetries in the current market.

The model simulates through surveys and hypothetical scenarios a market for an asset or group of assets for which no market exists. This method is used to estimate changes in welfare of people, especially when these changes involve goods or services that do not have a price. One case applied to prescribed fires in the wild land urban interface in Colorado (USA) was reported by Kaval and others (2007).

The methodology recommended by the National Oceanic and Atmospheric Administration (NOAA) (Arrow and others 1993) was used to design and implement the surveys and the sample size (72 surveys) was calculated for 90% confidence.

The analysis allowed us to characterize socially and economically the objective SAFOR stakeholders, who were found to be of low educational and low-income levels.

Surveys were concentrated in the municipalities of Nueva Imperial (18%), Hualañe (16%), Santa Barbara and Cauquenes (14% each) and Arauco (13%).

Regarding social characteristics, the educational level shows that 50% of forest owners have basic education level (years 1 to 8) and only 10% received university education; 5% have no formal education at all. Of all the respondents, 66% are married and 3% divorced. On average they have 2 children, and 23% have 3 children.

As per the income level, 66% earned less than US$ 330/month, 11% between US$ 331-640; 9% between US$ 641-1,090; 6% from US$ 1,091-3,630 and only 5% earned more than that amount. It should be considered that when answering income-related questions, people tend to report smaller values, leading to bias in the responses.

Concerning forest characteristics, respondents own on average 261 ha of plantations, and are concentrated in the Maule and Bio Bio regions, with the former locality being the one with the highest forest plantation area.

Of all of the owners, 65% indicated not having been affected by forest fires in the last 5 years, whereas 35% gave a positive answer, reporting an affected area ranging between 1 and 480 ha. The fire origin was diverse, including arson, controlled burns by neighbors, neglect, illegal burning, electric lines, etc. Roughly 20% of the total area surveyed was affected by a fire.

Regarding damage caused by fire, 88% of the respondents declared to be aware of it and, only 9% were not, showing that although they know about fire damage, they do not use this type of insurance.

The analysis of fire insurance showed that only 7% of respondents have an insurance policy, indicating the existence of buying barriers; among the mentioned reasons for not hiring are high costs (35%) and ignorance (22%); only 3% consider that the fire risk probability in their property is low.

Of all the respondents, 85% saw value in buying a policy and only 15% did not. Potential customers were willing to pay for a fire insurance policy US$ 5.5-12.7/ha/year (74%), 12.7-25.5/ha/year (4%), 25.5-42/ha/year (4%); only 3% would pay a higher amount.

Interestingly, 74% did not request a quotation from an insurance company, despite the importance given to buying a policy. Therefore, it is inferred that they ignore the requirements for accessing an insurance policy; in fact, 78% of the respondents declared not being aware about the requirements for buying a fire insurance policy.

Regarding the SAFOR certification, 59% of the respondents would get it, whereas 38% are not interested and 3% did not answer.

The willingness to pay for the certification declared in 50% of cases ranged between US$ 1.3-3.3/ha/year; 15% would pay US$ 3.3-4.2/ha/year; 23% would pay US$ 4.2-6.5/ha/year; 8% would pay US$ 6.5-9.8; and 4% over US$ 9.8.

The results of the contingent valuation analysis, using the Probit model (Pucutay 2002) (Table 4), to determine the willingness to pay for the certification, corrected for the relevant variables and salary, indicated an average willingness to pay of US$ 5.1/ha/year. Considering that the average price for fire insurance is currently US$ 36/ha/year, the certification would correspond to 14%.

The significant variables that affect the decision to buy the certification correspond to region of residence (especially Bio Bio and Maule), marital status (especially married), and the interest in buying insurance policies. The willingness to pay is strongly positively correlated to the total plantation area.

Although some of the respondents did not have the necessary education to use insurance policies, they showed interest in improving their conditions and having access to both certification and fire insurance policies.

Technical aspects related to forest management

Forest management planning provides a framework to establish priorities, set objectives and devise strategies to deal with risks (Day and Pérez 2013). Several aspects related to forest management and fires were addressed by Pinilla (2014). Every year the country is affected by forest fires that consume large areas of native forests and plantations; therefore, once a fire starts, much of the efforts are focused on losing the smallest area possible. In the case of forest plantations, the significant area planted with radiata pine and several

Table 4. Contingent valuation results through Probit model application

ξ	Coeff.	Std. Err.	z	P>z	95% Conf.	Interval	
β_o	-10.2336	6.3628	-1.6100	0.1080	-22.7045	2.2373	
β_1 (Bio Bio region)	4.6831	2.7814	1.6800	0.0920	-0.7683	10.1345	
β_2 (Maule region)	7.0493	2.7047	2.6100	0.0090	1.7482	12.3504	
α_2 (marital status)	-2.3498	1.2508	-1.8800	0.0600	-4.8013	0.1017	
θ_3 (interest in buying fire policy)	7.1935	3.4821	2.0700	0.0390	0.3688	14.0183	

Source: Estimations made from survey information

eucalyptus species create a scenario where the probability of fire occurrence is affected by a number of factors. Whenever a forest fire occurs, a serious problem arises that affects forest resources, infrastructure, services, ecosystems, as well as, and most importantly, loss of lives. In addition, forest fires cause the release of greenhouse gases, potentially increasing the negative effects of climate change.

Due to the anthropogenic origin of fires, either unintentional, through carelessness or negligence, or directly intentional, all prevention measures and early control are based on silvicultural and community actions, and recently, on increasing the penalties for the ones guilty of causing forest fires.

Therefore, efforts to mitigate damages and losses from forest fires in plantations include community awareness campaigns, education, preventive actions, availability of human and technical resources, and joint collaboration between institutions, forest companies and owners (Urzúa and Cáceres 2011).

This scenario has led to consider that, in general, higher forest fire risk areas are associated with roads and nearby population centers, recreational zones and areas where agricultural and forest activities are developed. This is associated with the chance of fire, as determined by the presence and activity of agents of ignition, known as fire hazard (CIFFC 2013).

The amount of fuels associated with forest management is very important. The occurrence likelihood and factors involved in the generation of a wildfire largely determine the fire insurance price, the investments made in forest plantations protection and the expected returns. Insurers then need elements to decide premiums for selling fire insurances.

This demonstrates the need for information and analysis of the main factors that are necessary to describe objectively the risk of fire in a forest plantation to be protected.

There are multiple forest and environmental factors that can be used to explain fire occurrence and spread; however, many of these are difficult to quantify, estimate or model, especially those related to environment, climate, topography and vegetation, as well as the relationships among them, which limit their usefulness as elements when insurance companies model or estimate these risks.

In this scenario, there are some forest or environmental factors that are more objective when determining whether to consider them as wildfire risk descriptors.

Among the most frequently mentioned silviculture factors at a national and international level are forest composition (species, age, distribution, land use planning), presence of agricultural activities, existence of forest operation planning (establishment, management, harvesting), early prevention and attack plans, fuel management, existence of perimeter firebreaks as well as the implementation of Best Management Practices (BMP) (INFOR 2006).

Other factors to be considered as part of the setting are nearby towns, topography and climate, as well as land management elements and protection used by associations, forest companies and local government.

It is concluded that the proper fuel biomass management through silviculture reduces wildfire probability when focusing on the definition and assessment of risk areas, minimizing damage at the local, personal, environmental and economic levels. Through forestry practices it is possible to reduce the number of fires and their magnitude, preventing erosion and enhancing soil protection, water movement, wildlife, etc., and if the fire has already started, to limit the associated damage (Peña and others 2004).

In this context, *Preventive Forestry* was defined with the aim of reducing the threat of and vulnerability to forest fires, seeking to reduce the number of fires, and more importantly, their size. It integrates all protective measures to achieve this objective by implementing a plantation management oriented to minimize this type of damage.

Accordingly, in 2006, the USDA noted that the decrease in stand density, understory and surface fuel loads are factors that explain historical fire rates. Hence, the efforts to prevent damage and losses in plantations aim at including measures related to firebreak use, decreasing horizontal and vertical fuel continuity, prevention measures in harvest or thinning areas, fuel management, proper zoning and management of plantations, among others, that contribute to the reduction of wildfire likelihood, minimizing losses and supporting actions for a rapid extinction if it occurs.

WWF (2013) recommends identifying critical points and most vulnerable forests, and designing specific fire prevention plans. These plans should aim, among other objectives, to:

- Refine urban uses in the forest, reducing the urban-wildland interface.
- Require that local actors located in forest areas develop and implement prevention and defense plans against fires, including selective vegetation control and access control protocols.

Regarding investigations to predict fire behavior, location and intensity in real time and the possible effects and consequences on forest resources, infrastructure and security, significant efforts have been made, concluding that more information is required to reduce model uncertainty, and that

modeling is complex, involving significant uncertainty (Taylor and others 2013).

Therefore, forest management factors should be included in the development of the proposed insurability certification system, which associated with a new Chilean standard will lead to an objective forest fire risk classification. This classification will be recognized by insurance companies, which would take into account the risk level when determining fire insurance premiums.

In order to develop the standard, different factors have been identified. Below are some of those factors grouped by category, according to their characteristic of risk, hazard, or fire control which are analyzed as potential contributors to fire risk:

1. *Forest Risk*, including history of past fires, intentionality level, proximity to main roads, proximity to population and/or recreational centers, electric lines and high risk adjacent focusses.
2. *Hazards*, including those that will likely determine the fire development and behavior once already started, such as vegetation fuel model (considering silviculture practices), slope and weather parameters.
3. Firefighting organization and prevention measures, including firebreaks, fuel treatments, owned available protection resources, distance to specialized firefighter teams, distance to big enterprises plantations and agriculture activity in or close to the property.

Based on these factors a fire risk index will be built considering the national situation and other information such as that reported by Schneider and others (2008) based on relative greenness; by Alexander and De Groot (1988) based on weather information; by Koetz and others (2008) and Hawkes and others (1995) based on fuel types and properties; by Rodríguez and Silva and others (2012) based on economic vulnerability; and by Holecy and Hanewinkel (2006) based on a forest insurance model.

Conclusions

Based on several studies, the feasibility analysis concluded that:

1. Forest plantations are a highly valuable resource for the country, and are subjected to multiple risks, with fires among the most important. Over 50% of forest plantations are not covered by fire insurances, with potentially negative implications, especially for SMOs and SMEs, in which the proportion of non-insured plantations is higher, increasing the existing gaps between the sectorial stakeholders.
2. The legal analysis did not identify administrative or legal restrictions that could affect the development of the proposed certification system in Chile.
3. The industry of insurance market in Chile is transparent and framed within a stable institution system, ruled by clear laws and procedures. This is particularly positive for the project because the increasing demand will find a prepared insurance market ready to deal with the certified risks. This means allowing forest small owners and SMEs to gain access to the market, which is also an attractive business opportunity.
4. The insurance companies lack a standardized methodology for evaluating the occurrence of forest fires risk, which is a market disadvantage.
5. The potential insurance business is significant even in a conservative scenario, with an estimated increase of 20% for the market, which is relevant in the general insurance market that grows by 6-7% annually.
6. There is agreement both in national and international standards about the parameters that can be used as indicators of forest fire prevention and that therefore can be used for generating the risk evaluation standard.
7. From the risk point of view, there are non-controllable factors, such as climate and vegetation, but also controllable factors that can be used as technical parameters in risk evaluation.
8. Several studies have identified important technical and commercial gaps that affect the project beneficiary sector; that information turns out to be relevant for the future implementation and adoption of the SAFOR brand certification.
9. The socioeconomic analysis performed through a Contingent Valuation analysis indicated, with a 90% confidence level, that although 88% of SMEs are aware about the fire risk in their plantations, an important proportion does not buy insurance policies. However, 74% of them declare to be interested in contracting insurances, and 59% is willing to pay for the certification on average US$ 5.1/ha/year when corrected by salary level. Variables that resulted in significant differences were: (1) legal status (married); (2) region (higher in regions with greater forest plantation areas, especially Maule and Bio Bio); (3) interest for buying fire insurance policies.
10. Forest SMEs will need to build partnership relations to buy fire insurances in order to protect their heritage, to articulate networks of state support and to develop agreements of detection, firefighting and suppression systems.

The performed feasibility analysis validated the initial assumptions and at the same time recommended the national standard development, currently under construction. Once officially registered, the certification system will be created, validated and implemented to transfer the standard into the insurance market.

The analysis also indicated the existence of elements that provide the opportunity of studying the establishment of a government subsidy, both for fire insurance and for the SAFOR certification system.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Measuring the Wildland Firefighting Safety Culture Change—An Analysis of Entrapment Rates from 1994 to 2013

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Abstract—*The tragic fatality events of the mid-1990s and subsequent studies led to a concentrated effort to increase safety in the US federal wildland firefighter community beginning in 2000. Addressing human factors (HF) as a causal agent in accidents was a major focal point for this cultural change. To examine the effectiveness of this change, we hypothesized a decline in firefighter entrapment rates after implementation. Seasonal data on entrapment numbers and exposure amounts were collected on a national level for federal and non-federal wildland firefighting agencies for the years 1994-2013. The rate of wildfire entrapments (number/1000 person-hours fire line exposure) was estimated using generalized linear mixed models. Since program inception in 2000, rate ratio estimates indicate a 72 percent reduction in entrapment rates for federal wildland firefighters after controlling for variation in acres burned, number of fires and exposure time compared to pre-2000. A similar 46 percent reduction in entrapment rates was estimated for non-federal firefighters. Other non-HF changes such as improved weather forecasting may account for some of this reduction. We recommend continuation of the HF focus as a significant contributor increasing safety in the firefighting culture.*

Introduction

The 1994 US wildland fire season tragically resulted in the deaths of 34 firefighters, 14 in the South Canyon Fire in Colorado. Subsequent agency investigations identified an aspect of firefighting poorly understood by the wildland firefighting culture—the role that human factors (HF) played in the outcomes of these tragic events (Putnam 1995). HF are generally regarded as the social and psychological dimensions potentially leading to human error in decision-making, particularly in risky and dynamic situations. These dimensions of decision-making include the interacting roles of crew and personal dynamics, leadership, risk-taking, stress and communication on the fire ground. Comparatively, the physical and biological processes, such as fire behavior and spread, were relatively well known compared to the HF aspects of firefighting. These events and investigations provided an incentive to better understand the HF connection at individual, crew and organizational behavior levels—a top-to-bottom examination of human error in accident causes.

Once the magnitude of role HF played in firefighter safety became apparent, the National Wildfire Coordinating Group (NWCG) authorized the Wildland Firefighter Safety Awareness Study (WFSAS) in cooperation with the TriData Corporation. This three-phase study (TriData 1996a, 1996b, 1998) identified the agencies' cultural and organizational traits having a negative effect on firefighter safety and suggested changes. The WFSAS became a blueprint for cultural change within the federal wildland firefighting agencies with some 86 goals and over 200 recommendations, of which the majority were HF related. Foremost was the goal simply stated "to become a self-learning, self-correcting, high reliability organization."

The NWCG is a consortium of five agencies responsible for fire management on federal wildlands: U.S. Forest Service (USFS), Bureau of Land Management (BLM), Fish and Wildlife Service (FWS), National Park Service (NPS) and Bureau of Indian Affairs (BIA) and it began implementing a large number of the WFSAS recommendations beginning with the 2000 fire season. One recommendation implemented was the Human Factors/Leadership (HF/L) training series (the L-series courses) and is largely recognized as the flagship for the cultural change. Six courses were designed to provide a new skill set for firefighters relating to the human dynamics of firefighting. The first course of the series, Human Factors in the Wildland Fire Service (L-180), is now required to obtain a 'red card' (certification) allowing a firefighter to work on the fire line.

Also in 2000 a method of non-punitive reporting, SAFENET, was implemented allowing frontline federal firefighters to document unsafe situations (http://safenet.nifc.gov [January, 2014]). In 2002, the Wildland Fire Lessons Learned Center (LLC) began operations to improve safety, advance organizational learning and share knowledge across all wildland fire organizations (http://wildfirelessons.net). Numerous conference and workshop proceedings have been held that document what the agencies have done to improve the safety culture within the federal wildland firefighting community from a HF/L perspective. Tangentially to the WFSAS study,

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

the USFS began 'entrapment avoidance' projects in 1999 (Dreissen and others 2005).

Omodei and others (2005) identified HF as the primary cause in approximately 80 percent of wildland fire accidents and near misses. Larson and others (2007) provide a summary of HF in the wildland fire culture. But little documentation exists quantifying any success or progress for this cultural overhaul. In Phase II of the WFSAS, TriData suggested annual citizen and firefighter surveys, anecdotes, interviews and trained observers as methods to measure periodic progress. Survey and interview methodologies were used by most authors including Dreissen and others (2005), McDonald and Shadow (2005), Wright (2009), Black and others (2012), Jahn (2012), and McBride and Black (2012). These studies largely show that perceptions of the safety culture has improved, with some variation between agencies, and by position/seniority of the individuals interviewed. Quantitative analyses of injury rates or other measures of safety that document the impact of the WFSAS changes are few. McDonald and Shadow's study used surveys to compare trends in attitude ratings along several organizational and HF dimensions from 1998-2004. They intended to document the effect of the L-series course start-up, comparing before and after measures, although no statistical analysis was reported. Using only USFS data, Saveland and Pupulidy (2009) found higher injury rates in 2007 compared to 1998 for all operations including fire. Britton (2010) used logistic and negative binomial regression to relate firefighter injury rates to fire-level factors for 2003 to 2007 Department of Interior (DOI) large fires. This study further examined job assignment and injury mechanism in relation to the nature and severity of the injury.

In this observational study, we model firefighter entrapment rates separately for federal and non-federal firefighters before and after implementation of the WFSAS study's findings. The research hypothesis is that entrapment rates from 2000 to 2013 should be less than the rates from pre-2000 if the cultural change has had the desired effect. Also, we hypothesize that any decrease in entrapment rates should be greater on federal fires compared to non-federal fires. In the models, we control for seasonal variation in acres burned and fire numbers.

Entrapment rates are only one measure of the federal wildland fire community's efforts to improve safety. Other measures such as vehicle accidents, fatalities, injuries and time-loss reports could (and should) be used in an overall evaluation of program change. But the need to reduce firefighter entrapment was the catalyst for the change and is the focus of this analysis.

Methods

Data

The NWCG Glossary of Wildland Fire Terminology (2012) defines entrapment and burnover as:

Entrapment: A situation where personnel are unexpectedly caught in a fire behavior related, life threatening position where planned escape routes or safety zones are absent, inadequate, or compromised. An entrapment may or may not include deployment of a fire shelter for its intended purpose. These situations may or may not result in injury. They include "near misses."

Burnover: An event in which a fire moves through a location or overtakes personnel or equipment where there is no opportunity to utilize escape routes and safety zones, often resulting in personal injury or equipment damage.

Entrapment**,** for this study, will be used to describe these two events. However, *entrapment rate* is a count per exposure unit. For this study, we used person-days of work by fire line personnel exposed to entrapment as the exposure measure. Overhead, command staff and aviation resources committed to a fire were excluded. Entrapment rates were modeled separately for federal and non-federal wildland fires using generalized linear mixed model (GLMM) methods.

Information available online through the National Interagency Fire Center (NIFC) (www.nifc.gov*)* provided most of data. National entrapment statistics for the years 1994 to 2013 are found in the NWCG's Safety and Health Working Team's annual report known as the "Safety Gram" (http://www.nwcg.gov/branches/pre/rmc/safety-grams.htm [January, 2014]). Statistics for acres burned and number of fires are available from the National Incident Management Situation Report (SIT) (http://www.nifc.gov/nicc/ [March, 2014]).

Estimates of fire line exposure are not part of any data collection process used by NIFC. However, from 1994 to the present, the SIT report provides an estimate of the resources used on fires greater than 100 acres for timber fuel models and greater than 200 acres for grass/brush fuel models. Resources listed as total personnel, crews, and engines were used to estimate an exposure indicator of person-days for fire line personnel. The SIT report is released at least weekly during the off-season and daily during Preparedness Levels greater than 1 by the Predictive Services Intelligence Section of National Interagency Coordinating Center in Boise, ID. A full description of the SIT Report contents can be found online at http://www.predictiveservices.nifc.gov/intelligence/Reading_the_Situation_Report.pdf.

Candidate variables and attributes are displayed in table 1. All values were recorded per season and are national totals, separated by federal and non-federal incidents. Three distinct fire season periods are identified: Season 1 (SEA) is defined as January through May, Season 2 as June through August and Season 3 as September through December. Person-days of exposure (PD) indicates the amount of time fire fighters are exposed to entrapment situations—the number of person-days on the fire line engaged in suppression activities for large fires. The timeframe (1994 to 2013) was split into two mutually exclusive periods. ERA_0 includes the years 1994 to 1999 and ERA_1 covers 2000 to 2013 to coincide with cultural change implementation. Acres burned (AC) and fire numbers (FI) are seasonal totals as reported to NIFC through the eleven Geographical Area Coordinating Centers (GACC).

We randomly sampled 10 SIT reports for each season for each year and counted the number of crews and engines

Table 1—Candidate variables, measures and data sources.

Variable	Units/Scaling	Type	Data Source
Entrapments, EN	Number	Dependent	Safety Gram
Exposure Indicator, PD	Person-days (x10^3)	Off-set (dependent)	SIT Reports
Season, SEA	Categorical (1 = Spring, 2 = Summer, 3 = Fall)	Independent, random	
ERA	Categorical (0 for years 1994 to 1999 and 1 for years 2000 to 2013)	Independent, fixed	
Total Acres, AC	Number (x10^5)	Independent, fixed	SIT and Annual Reports
Total Fires, FI	Number (x10^3)	Independent, fixed	SIT and Annual Reports

reported on new incidents. Assuming 20-person crews and 5-person engines provided an estimate of personnel on the fire line. We compared the fire line personnel estimate to the total personnel reported on new incidents and adjusted this estimate (usually a reduction) if needed. The seasonal average fire line personnel per day was then multiplied by the number of days for each season to obtain an exposure indicator of person-days for large fire suppression work. Resources assigned to non-fire incidents were not counted.

For each calendar year, cumulative acres burned and fire numbers are recorded in the SIT reports for federal and non-federal fires. We used the year-to-date totals for May 31, August 31 and the end of the year to generate seasonal totals. Data collection was completed in February 2014. Some variables were scaled as shown in table 1 to avoid leading or trailing zeros in the data and estimated coefficients.

Statistical modeling

Seasonal entrapment rate (EN_i) was computed as number of entrapments per 1000 person-days exposure

$$EN_i = \frac{Entrapments}{Exposure\ Indicator} = \frac{EN_i}{PD_i} \qquad (1)$$

We consider this dependent variable as count data expressed as a rate and fit a GLMM with Poisson errors. The log function is the natural link function so the basic model is

$$\ln(EN_i) = \ln(PED_i) + \boldsymbol{x}_i^T \boldsymbol{\beta} \qquad (2)$$

where the design matrix $\boldsymbol{x}$ contains the independent variables from Table 1 and any interaction and polynomial terms. $\boldsymbol{\beta}$ is a vector of coefficients to be estimated and the $\ln(PD_i)$ is the offset term.

Repeated measures issues may arise because the SEA may be considered as three measures of entrapments within one year. Conceptually, a busy fire year could have higher entrapment rates for all three seasons. Incorporating SEA as a random effect in a generalized linear mixed model accounts for any potential serial correlation (Crawley 2013) and the inherent seasonal variation in wildland firefighting.

The model expressed in equation 2 was estimated for federal and non-federal entrapment rates. Residual plots were used to verify statistical assumptions for the models. Polynomial terms of the explanatory variables were used to check for non-linearity and improvement in the residual plots. Model fitting was done using the glmer function in the lme4 package (Bates and others 2014) of R (R Core Team 2014).

Results

Table 2 presents summary statistics for the variables grouped by *ERA* and *SEA* separately for federal and non-federal fires. Comparing the two time periods of interest we see the mean entrapment count decreased in ERA_1 for all seasons for federal fires but increased for non-federal fires for the spring and summer seasons. Except for federal fires occurring in the fall, the average fire line exposure (*PD*) and acres burned (*AC*) increased substantially for ERA_1. The average number of fires (*FI*) changed little between the two time periods with a slight decrease for non-federal fires in all seasons.

Figure 1 for federal fires and figure 2 for non-federal fires are time series plots showing the seasonal variation and trend lines for *AC* and *FI*. Both figures show the trend for increasing acres burned and fewer numbers of fires for the time period studied. Comparing the two figures, seasonal variation has a considerably stronger cyclical component in the federal data with definite and regular peaks during the summer season at every third data point. The seasonal means for federal fires in table 2 shows substantially larger means for all variables in the summer season. For non-federal fires *EN*, *PD* and *AC* averages have the largest means in the summer season but the average *FI* is larger in the spring.

Modeling

Statistical modeling results are presented in table 3. All variables are significant in both the federal and non-federal models. No significant improvement in the AIC statistic or residual plots was achieved by incorporating interaction or polynomial terms into the models.

Rate ratios are the usual interpretation of the coefficient estimates and are found as the antilog of the estimate. A one-unit change in the explanatory variable results in a multiplicative effect on entrapment rate, assuming the remaining variables are constant. For this study, the variable *ERA* is of main interest. By construction it is a binary (0,1) variable so the coefficient expressed as a rate ratio gives the percent change in *EN* associated with *ERA*. Interpretation of the federal model rate ratio, 0.2793, means that the entrapment rate

Table 2—Summary statistics for variables grouped by *SEA* and *ERA*[a] for federal and non-federal fires.

	Season		Entrapments EN(count)		Exposure PD(x10^3)		Acres burned AC(x10^5)		Number of Fires FI(x10^3)	
	SEA	Statistic	ERA_0	ERA_1	ERA_0	ERA_1	ERA_0	ERA_1	ERA_0	ERA_1
Federal	Spring	Mean	9.0	1.9	24.8	33.9	1.42	2.54	3.32	3.59
		sd	19.6	2.0	21.6	22.0	0.82	1.41	0.22	0.55
		Median	1.5	1.5	15.5	35.7	1.13	2.11	3.34	3.55
	Summer	Mean	39.8	13.1	250.4	287.7	18.39	30.95	10.71	9.86
		sd	46.3	12.9	153.2	165.1	10.56	15.02	2.54	1.93
		Median	21.5	8.5	231.5	341.9	19.29	30.48	9.95	9.07
	Fall	Mean	3.8	1.6	137.1	105.2	3.80	5.91	3.55	3.54
		sd	5.7	3.1	150.9	85.7	3.05	3.46	1.07	0.80
		Median	1.0	0	82.5	90.3	2.94	5.28	3.56	3.56
Non-federal	Spring	Mean	2.7	4.8	7.1	40.0	6.00	8.49	33.14	26.74
		sd	2.9	4.5	1.7	30.4	3.08	7.62	11.35	7.58
		Median	1.5	3.5	6.9	37.9	4.61	5.96	32.03	25.76
	Summer	Mean	10.3	15.6	121.8	269.5	5.78	14.07	16.47	16.18
		sd	11.0	13.3	60.5	210.4	2.30	6.60	5.36	5.94
		Median	6.0	12.0	123.0	208.8	5.77	13.76	16.44	13.93
	Fall	Mean	4.2	4.1	74.2	120.4	2.83	5.85	15.94	14.72
		sd	5.5	5.7	46.4	112.2	1.66	3.12	4.20	5.13
		Median	2.5	3.0	51.8	86.9	2.53	5.26	16.59	15.38

[a]*ERA* is coded 0 for years 1994 to 1999, n = 18; and coded 1 for years 2000 to 2013, n = 42.

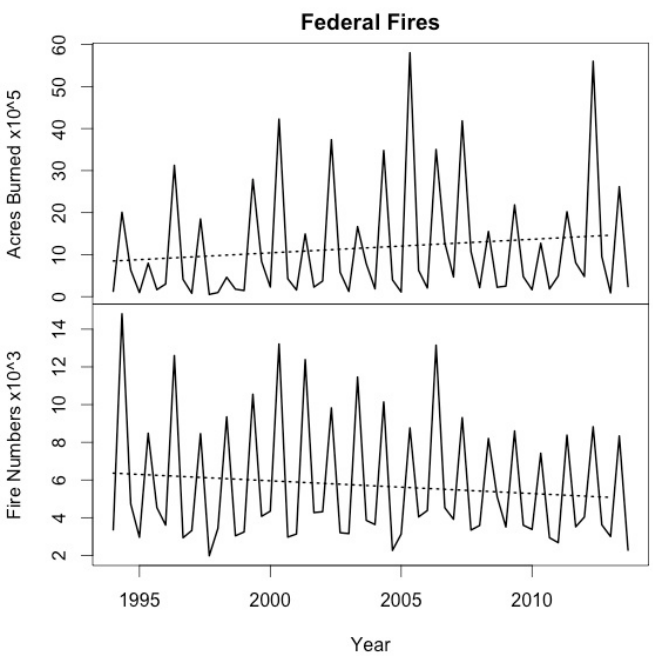

Figure 1—Seasonal time series plots of acres burned and fire numbers for federal agencies. The dashed line represents a simple linear trend line. The y-axis measures are seasonal, not annual values.

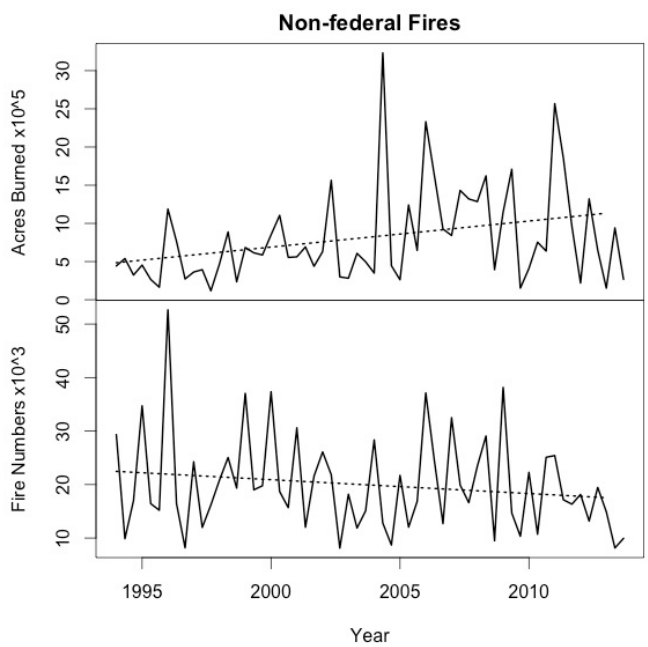

Figure 2—Seasonal time series plots of acres burned and fire numbers for non-federal agencies. The dashed line represents a simple linear trend line. The y-axis measures are seasonal, not annual values.

for ERA_1 is about 28 percent of the rate for ERA_0, a 72 percent reduction in entrapment rates. In the non-federal model the entrapment rate for ERA_1 is about 54 percent of that for ERA_0, a 46 percent reduction. The continuous variable rate ratios are similarly interpreted. For example, in the federal model, a 100,000-acre (one unit) increase in *AC* increases the entrapment rate by $e^{0.03188} = 1.0324$, times, about a 3.24 percent increase in entrapment rate.

For both models the algebraic signs for the *ERA*, *AC* and *FI* coefficients agree with the summary statistics in table 2. At first glance, the negative sign for *FI* in the non-federal model seems curious, in that it would imply a higher entrapment rate for fewer fires. Indeed, this is what the data show—smaller number of fires but a larger number of entrapments for ERA_1 for non-federal fires compared to ERA_0.

Table 3—Estimated coefficients, statistics and rate ratios.

Variable	Estimate, β	SE	P-value	Rate Ratio = e^{β}
	Federal Agencies Model, AIC = 417.4			
Intercept[a]	-3.73952	0.7461	<0.0001	
ERA	-1.27536	0.1047	<0.0001	0.2793
AC	0.03188	0.004855	<0.0001	1.0324
FI	0.19005	0.0240	<0.0001	1.2093
SEA	Random effect, Variance = 1.551			
	Non-federal Agencies Model, AIC = 693.1			
Intercept[b]	-1.42779	0.4913	0.0037	
ERA	-0.62496	0.1281	<0.0001	0.5353
AC	0.024859	0.008442	0.0032	1.0252
FI	-0.04770	0.008805	<0.0001	0.9534
SEA	Random effect, Variance = 0.6343			

[a] Incorporating the seasonal random effect into the intercept term gives the prediction coefficients of -2.0207, -4.9245 and -4.2555 for the federal agencies model.

[b] Incorporating the seasonal random effect into the intercept term gives the prediction coefficients of -0.3557, -1.7242 and -2.1900 for the non-federal agencies model.

Figure 3 shows time series plots of the model fit using the prediction coefficients and the observed values. The federal model predictions follow the observed values fairly well frequently matching the seasonal peaks associated with the summer season. For the non-federal model the fit is not quite as good.

Discussion and Conclusions

In 2000, the US federal agencies responsible for wildland fire implemented a top-to-bottom effort to improve the firefighter safety culture. This effort at cultural shift centered on addressing the HF role in decision-making in risky and dynamic situations. Other efforts in this shift included improved local weather forecasting, risk reduction through assignment turndown protocols and changes in tactics to decrease fire line exposure such as increased use of aerial suppression and departure from full perimeter control. Reducing firefighter fatalities and injuries spurred these changes after some significant entrapment and fatality events in the 1990s.

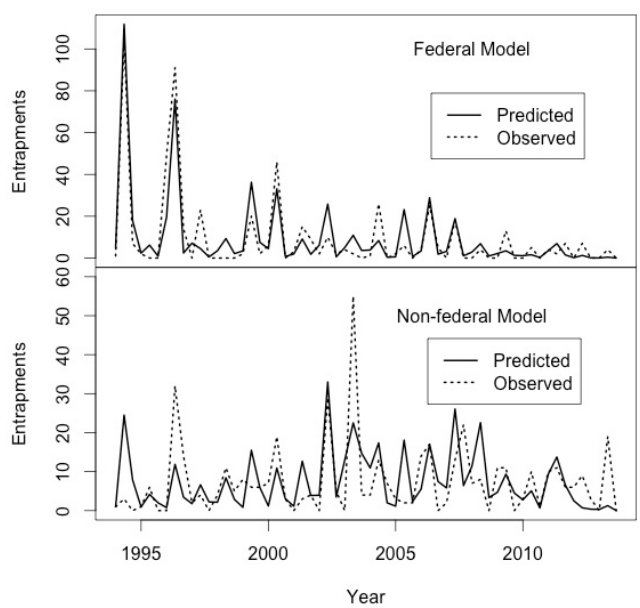

Figure 3—Time series plots of seasonal model predictions and observed values. Note the scale differences between the two y-axes.

We have found that firefighter entrapment rates measured as the number of entrapments per 1000 person-days of fire line exposure appear to have decreased significantly since 2000 after accounting for the seasonal variation in acres burned and number of fires. The entrapment rate reduction is more dramatic for federal fires than for non-federal fires, 72 percent compared to 46 percent. This is an observational study and not a causal study so we cannot say that the cultural shift "caused" the entrapment rate reduction. This study only shows that the reduction in entrapment rates is associated with the safety culture shift.

Non-federal entrapment rates do not serve as a control or comparison group for the federal rates. Most non-federal agencies cooperate with federal agencies, particularly in training and large campaign fires, and so are exposed to the changes and influences occurring in the federal culture. The 46 percent reduction in non-federal entrapments is possibly due to a spillover effect in these cooperative efforts. The poorer fit of the non-federal model compared to the federal model most likely results from the smaller *SEA* random effect and thus a larger residual error. This is also shown in the lack of a strong seasonal pattern as shown in figure 2 compared to the federal data in figure 1.

The exposure indicator we used, *PD*, is somewhat problematic. Ideally this measure would be the actual number of hours spent by personnel on the fire line and exposed to entrapment situations. This measure does not exist as far as we know. Our estimate is based on a random sampling of the number of crews and engines assigned to fires in the SIT report. The data for these reported fires represent resource assignments for only about three percent of the total number of active fires across the nation. However NIFC intelligence estimates that 85 to 90 percent of the nation's firefighting resources is captured in the SIT reports (Kari Boyd-Peak, personal communication). We feel our estimate reflects the exposure risk experienced by fire line personnel over the study time period and consider it an exposure indicator rather than a direct measure of exposure.

We conclude that the safety culture shift within the federal wildland firefighting community largely implemented post-1999 is associated with a significant reduction in the probability of entrapments on a national basis. Further, there appears to be a spillover effect in entrapment reductions to non-federal agencies. These reductions in entrapment probabilities are estimated after accounting for the seasonal variation in acres burned and number of fires.

Further investigations using quantitative measures are needed to monitor, refine and expand the estimates of the safety culture change. This culture change is not static but a dynamic and continuous process. Do vehicle, machinery, ATVs, aviation and medical incidents show similar trends? Would separate estimates for each GACC show geographic areas of the nation with high levels of achievement for others

to emulate? Are the L-series courses delivered in a timely and efficient manner? These questions, and others, are consistent with the goal of becoming self-learning, self-correcting, high reliability organizations.

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Acknowledgments

A Technical Fire Management student project by Adam Hernandez provided the impetus for this paper. The authors would like to thank the anonymous reviewers and Mary Kenady, Reid Kenady and Stew Pickford for helpful reviews of earlier drafts. We thank Shawn W. Baker, Sam Marouk and Van Arroyo for initial input and suggestions for this project.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Strategic Operations Planning—It's Not Just for Wilderness!
How the Strategic Operations Planner Can Help

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Abstract—*The Strategic Operational Planner (SOPL) wildland fire management position was created in the United States in 2009 to reflect updated terminology. SOPL merges the former Fire Use Manager positions (FUM1 and FUM2) and is now an established position within the Incident Command System. Traditionally, the FUM positions and the SOPL have been used on incidents managed for resource benefit, wildland fire use, and on long-duration events. The use of the SOPL to develop a strategic operational plan on "suppression" strategy wildfires is fairly new, thus, creating some confusion about the position's future roles and responsibilities in incident management. Our intent with this paper and associated poster is to illustrate how the SOPL position can provide value to incident management teams and the agency administrator in the development of strategic operational plans that achieve desired management goals and objectives for an individual incident.*

Introduction

The Strategic Operational Planner (SOPL) evolved from the former Fire Use Manager positions (FUM1, 2) within the Incident Command System (ICS), which were merged to reflect updates made in wildland fire management terminology (NWCG 2010). The SOPL is an established position within the Incident Command System. Required experience includes qualification as a Prescribed Fire Burn Boss Type 2 (RXB2) and Division/Group Supervisor (DIVS) (NWCG 2012). Advanced Fire Management Applications (S-482) is required training, with Fire Program Management (M-581) as suggested training (NWCG 2012).

The SOPL provides information to fire managers that can be used to determine appropriate actions to accomplish desired objectives for an incident as well as assisting in the development of relative and extended risk assessments and management actions, which enable achievement of established objectives associated with an incident.

A series of YouTube videos were developed through the Wildland Fire Lessons Learned Center to describe the evolution and development of the SOPL position. These short videos may be of interest as back-ground material regarding the SOPL position and the use of the SOPL in wildland fire management operations.

- In this first video Tom Zimmerman, former Program Manager for the Wildland Fire Management Research, Development and Application (WFM RD&A) program describes the evolution of the Strategic Operational Planner position from earlier positions in the prescribed fire program.

  http://www.youtube.com/watch?v=1GXkOeQUmU0
- In this second video, Zimmerman discusses how the SOPL position fits into the Wildland Fire Decision Support System (WFDSS) process and into the overall direction of wildland fire management.

  http://www.youtube.com/watch?v=_uOpv9Xlc68
- Tim Sexton, the Fire Use Program Manager for the U.S. Forest Service when this video was made, and current Program Manager for the WFM RD&A, explains the evolution of the Strategic Operational Planner position and how a SOPL can help fire managers and decision makers develop a long-term plan to achieve their objectives on a wildfire incident.

  http://www.youtube.com/watch?v=d9fn9Hj0K0o

The Strategic Operations Planner (SOPL) Position

The primary role of the SOPL is to provide decision support to the local Agency Administrator and Incident Commander to help ensure that actions taken on a wildfire will achieve incident objectives and are consistent with the local agency's Land Management Plan (LMP), Resource Management Plan (RMP), Fire Management Plan (FMP), or other documents providing guidance and direction for land and resource management in a designated area, as well as Federal wildland fire management policy (Taber and others 2013).

The SOPL's responsibilities include:

1. Analyze incident objectives and incident requirements (for example, are they clear? Are they consistent? Do they conflict with LMP, RMP, and FMP?)
2. Conduct assessments to quantify risks and identify uncertainties in managing wildfires

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

3. Develop a Course of Action for the incident. The course of action typically focuses 3 days out or further and is an overall plan describing the selected strategies and management actions intended to meet incident objectives and requirements based on current and expected conditions for the incident. The course of action may address some or all of the following; cultural assets, threatened and endangered species habitat, and utility infrastructures values that may be negatively and positively impacted by the wildfire. The SOPL facilitates the incorporation of the course of action into the Incident Action Plan (IAP)
4. Provide advice, support, and recommendations to the agency administrator and Incident Commander, and often serve as a liaison or bridge between the local agency and the incident management team/organization
5. Manage the implementation of an incident decision.

Decision-Making Levels

The SOPL is familiar with incident-level risk management and the decision-making levels that affect wildland fire management: Strategic, Planning, Operational, and Time-Sensitive (Taber and others 2013), and how they relate to strategic operational planning (figure 1).

Each level of decision making tiers to the levels above and below it (Taber and others 2013). The SOPL can provide an overall perspective on the incident—by looking at the incident from these decision making levels. For example, a*re decisions made at the strategic level consistent with decisions made at the operational level?* The SOPL can provide the overall perspective and serve as the bridge between these levels of decision making.

The SOPL is challenged to look at the different decision making levels to ensure that each is consistent with the others and that there is a strong tie to Leader's Intent (NWCG 2007). The SOPL focuses on how decisions made at the strategic level are interwoven between the planning and operational levels. The SOPL must effectively communicate challenges and opportunities with the various decision makers connected with an incident if the decisions made at the strategic level are to be successfully implemented.

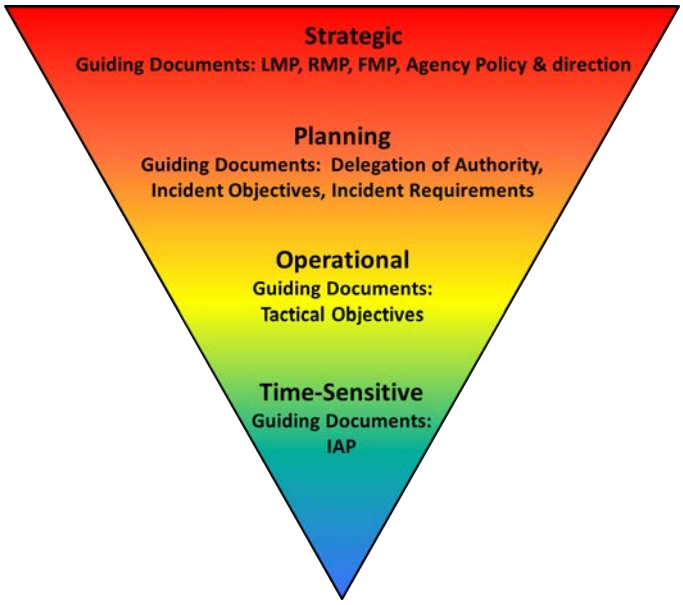

Figure 1—Four decision-making environments that affect wildland fire management.

Incident Objectives and Incident Requirements

The SOPL, working with the agency administrator, develops incident objectives and incident requirements that reflect the agency administrator's intent to achieve desired outcomes and avoid undesirable consequences. These are developed tiering off of agency policy and strategic objectives and management requirements found in the unit's Land and Resource Management Plans, and Fire Management Plans.

Incident objectives help explain the agency administrator's intent for the incident. The incident objectives and incident requirements are determined by the agency administrator and often communicated in the Delegation of Authority to the incident management team. The SOPL can provide advice and recommendations to the agency administrator and incident management team that help accurately reflect the land management objectives and requirements for jurisdictions and landowners within the planning area.

Incident objectives offer site specific guidance and direction necessary for the selection of appropriate strategy(s) and the tactical direction of resources on an incident (NWCG 2014). Management requirements usually have a legal basis, are required by policy, directives, standards and specifications, or they define the methods that must be used or avoided to meet strategic objectives (NWCG 2014). The intent of the incident objectives and incident requirements are to provide more detailed information specific to the area of the fire than the overarching strategic objectives and management requirements from the land, resource, or fire management plans for the unit(s) affected by the incident.

The SOPL compares incident objectives and incident requirements from the respective agency's decision documents (for example, RMP, LRMP, FMP), the Delegation of Authority, and Incident Action Plan to determine and ensure consistency between the various decision-making levels. The SOPL coordinates with all jurisdictional agencies and landowners to ensure that all needs have been identified. The SOPL reviews incident objectives and incident requirements to help develop the course of action, risk assessments (relative and extended), and Management Action Points(MAPs). Working with the agency administrator, the SOPL should make recommendations as appropriate to clarify objectives, establish priority of objectives and requirements, examine concerns related to objectives, and discuss options for resolving any conflicting objectives or requirements.

SOPL Interactions

The SOPL will need to interact not only with the agency administrator but also members of the incident management team and other specialists such as a Long-term Fire

Analyst (LTAN) or Fire Behavior Analyst (FBAN), and a GIS Specialist. The level of involvement and interaction will be determined by the complexity of the incident. Here we describe some of the interactions a SOPL may have with various individuals.

SOPL and the Agency administrator—The relationships between the local agency administrators and the SOPL are critical. The agency administrator is the most important person the SOPL works with to develop the incident decision.

The SOPL is a unique position because the position may be assigned to an incident management team/organization, yet it serves as an advocate for the agency administrator, making sure their needs are being met. The SOPL is the intermediary between the agency administrator, Incident Commander, and the incident management team/organization. The SOPL is the advocate for the agency administrator working with the team to ensure that their Leader's Intent is being implemented in the Course of Action and MAPs. The SOPL works with the agency administrator to assist in development of incident objectives and incident requirements, course of action, MAPs, Relative and Extended Risk Assessments and the Organizational Needs Assessment. The SOPL should always obtain feedback and consensus from the agency administrator as work progresses.

The SOPL should have regular communication with the agency administrator, keeping them abreast of changes and status of the incident, focusing on activities involving the incident decision.

SOPL and the Incident Management Team—Depending on the incident, the incident activity and complexity, the SOPL will interact with multiple positions in the Command and General Staff. The SOPL position resides within the Planning Section and in a unity of command sense works for the Plans Section Chief. Initially, as the long term plan is being developed, the SOPL is working with the Operations Section Chief to develop actions and resource needs to address Course of Actions and MAPs. In the daily schedule, the SOPL interacts with the Plans Section Chief, working to ensure that the team is prepared to implement the approved Course of Action or a MAP.

SOPL and the Long-Term Fire Analyst (LTAN)—The SOPL and the LTAN work as a team in the development of the Strategic or Long Term Plan. In most cases the SOPL will be more effective when working with an LTAN who produces fire behavior, climatology, and fire effects components in support of decisions (Taber and others, 2013). This team is critical for identifying values at risk and the potential impact by fire activity (2). The LTAN works with the SOPL to model fire growth and fire spread probabilities

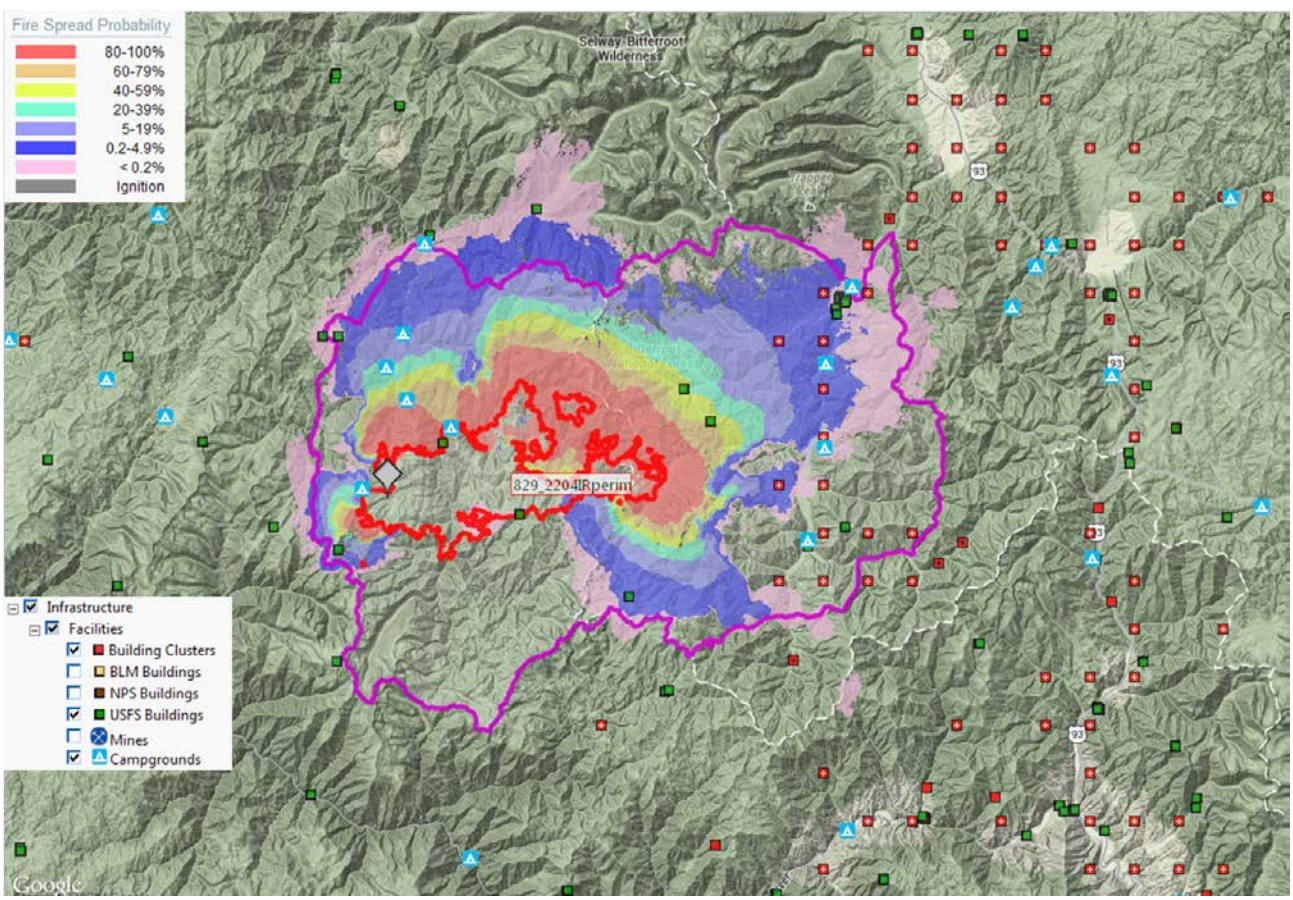

Figure 2—FSPro output from the WFDSS system is used to calculate fire spread probability and evaluate potential impacts to values of concern (campgrounds – white tents/blue background; Forest Service buildings - green squares; and US Counties/FGDC Cadastral based building clusters-red squares). The pink line delineates the planning area while the red line represents the current fire perimeter.

using a variety of models such as FSPro or the Near-term and Short-term fire behavior models within WFDSS. The outputs of these models can assist in the development and implementation of MAPs. The LTAN and SOPL work together throughout the life of the incident. They observe fire behavior and modeled outputs to provide an Operations Section Chief with projections regarding when fire may reach a MAP or other values that would require a change in strategy or tactics (figure 2).

SOPL and Wildland Fire Decision Support System (WFDSS)—The incident decision document resides in WFDSS and during the life of an incident the decision documented in WFDSS will require attention to keep it current. The SOPL position, while not specifically tasked to maintain the decision in WFDSS, can provide a point of contact to maintain the relevancy of information in the decision. As the course of action is met and management action points are either implemented or deactivated, the SOPL can update this information and capture when the actions occurred and evaluate costs associated with the actions. As an incident organization ramps up and down with fire activity and complexity, the relative risk and organization assessment should also be evaluated and revised as needed to reflect current and anticipated conditions. The SOPL position can make recommendations to assist the agency administrator.

Products

The SOPL can be involved in the development of a variety of products depending on the complexity of the individual incident. These include development of the Relative Risk or Organizational Assessments, Course of Action, establishment of MAPs, and strategic operation plans. All should be tiered to the respective agency Land Management and Fire Management Plans, and require coordination and involvement with the agency administrator and incident management team personnel. Because the level of analysis and products is so variable by incident we do not address all of the potential products that a SOPL may be involved with.

Risk Assessments—Risk assessments are simply the process of identifying values and analyzing the probability that they may be impacted by some type of hazard, such as wildfire (Taber and others 2013). The initial relative risk assessment may be all that is required, depending on the complexity of the incident or expected duration. This is typically accomplished by Federal agencies using the Relative Risk Assessment (RRA) process (Taber and others 2013). However, incidents which are more complex or of long-duration may necessitate detailed extended risk assessments that include not only negative impacts but the potential benefits of use of wildland fire to achieve resource objectives as outlined within the respective Land Management Plan and Fire Management Plans (USDA-USDOI 2009). Regardless of the required level of risk assessment, they both include information regarding the values, hazard and probability associated with the incident.

Course of Action—The course of action describes the selected strategy or strategies, priorities, and management actions for accomplishing the incident objectives and requirements based on current and expected conditions. The agency administrator is responsible for developing the course of action but may rely on a SOPL to assist with its development, potentially making the SOPL an integral part in the development of an incident's course of action. SOPLs work with the agency administrator to gain an understanding of their expectations, concerns and priorities. With this knowledge the SOPL works with the agency administrator, the Incident Commander, Operations, the Long-Term Fire Analyst, and others to determine strategies and priority management actions. These are then written clearly with strong Leader's Intent (NWCG 2007) so that the incident management team/organization can develop tactical plans that address the course of action. The course of action needs to be specific enough that it is meaningful but not so specific that it constrains the incident management team/organization. The course of action should help explain what needs to be done, why it is important, and how it should look when the action is completed.

The SOPL manages the course of action, evaluating that it continues to meet incident objectives and incident requirements. If the SOPL finds that it is not meeting these, then the SOPL may recommend that a new decision is needed and assist with that task.

Management Action Points—Management Action Points (MAPs) are clearly specified incident conditions that, when reached, prompt a predefined modification to existing fire management actions, or trigger the implementation of new strategies and/or tactics (figure 3).

- MAPs are generally incident-specific; some units have pre-planned MAPs for sensitive areas, or reuse MAPs from previous fires in the same area.
- If the incident conditions defined by the MAP are met, timely implementation is generally critical for successful accomplishment of the incident objectives.
- MAPs define the conditions necessary for the MAP to be implemented, the actions that should be implemented, and the general resources that are needed to be successful.
- The SOPL, working with the incident management team operations section, local resource advisors, and agency administrator develop MAPs to address specific guidance/instruction from the incident objectives and requirements and actions in the approved course of action.

Summary

During a fire, the SOPL is the advocate for the agency administrator, working with the incident management team/organization to ensure that leader's intent is being implemented on any type of wildland fire. The position is critical in the development of a variety of supporting

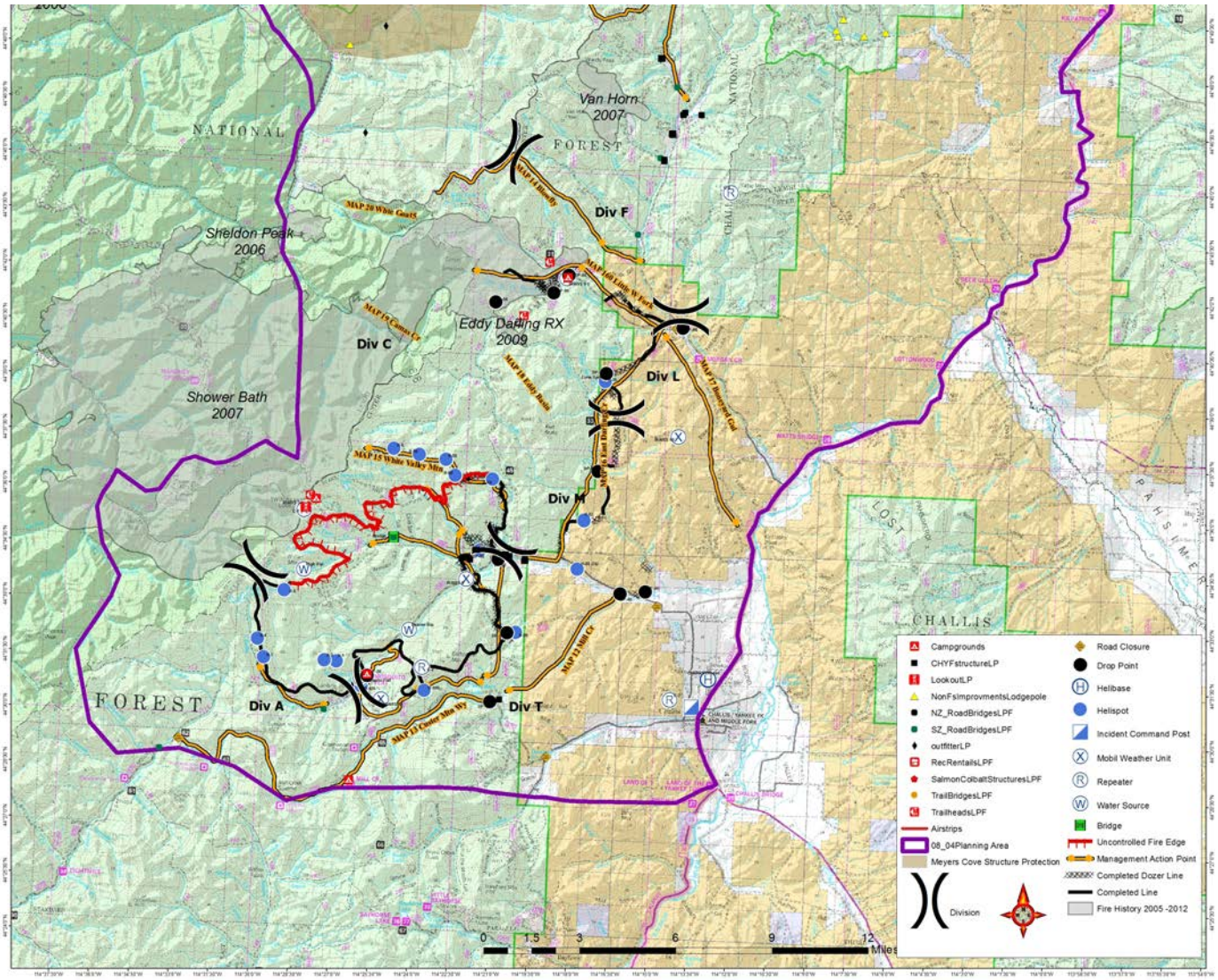

Figure 3—Example showing the Planning Area (purple line), MAPS (gold lines), and other area of concerns for the Lodgepole Fire.

documents and analysis in support of incident management goals and objectives. The use of a SOPL in managing wildland fires with a variety of objectives or of long-duration will benefit the agency administrator and incident management team/organization. As incident management teams become more familiar with the SOPL position and their expertise, knowledge, and skillset, their inclusion into fire management decision making should become less foreign in the future.

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Acknowledgments

We thank T. Opperman, E. Noonan-Wright, and an anonymous reviewer for their thoughtful and constructive comments on an earlier versions of the manuscript.

Glossary

The following sets of terms used in the paper are defined here. They are from three different sources as referenced at the end each definition.

National Wildfire Coordinating Group (NWCG). 2014. Glossary of Wildland Fire Terminology. Available at: http://www.nwcg.gov/pms/pubs/glossary/index.htm

Wildland Fire Decision Support System (WFDSS) Glossary of Terms. Available at: http://wfdss.usgs.gov/wfdss_help/542.htm

Agency Administrator—The official responsible for the management of a geographic unit or functional area. The managing officer of an agency, division thereof, or jurisdiction having statutory responsibility for incident mitigation and management. Examples: NPS Park Superintendent, BIA Agency Superintendent, USFS Forest Supervisor, BLM District Manager, FWS Refuge Man-

ager, State Forest Officer, Tribal Chairperson, Fire Chief, Police Chief. (NWCG Glossary 2014)

Course of Action—An overall plan describing the selected strategies and management actions intended to meet incident objectives and requirements based on current and expected conditions. (WFDSS Glossary)

Delegation of Authority—A statement provided to the incident commander by the agency executive delegating authority and assigning responsibility. The delegation of authority can include objectives, priorities, expectations, constraints and other considerations or guidelines as needed. Many agencies require written delegation of authority to be given to incident commanders prior to their assuming command on larger incidents. (NWCG Glossary 2014)

Fire Management Plan (FMP)—A plan that identifies and integrates all wildland fire management and related activities within the context of approved land/resource management plans. A fire management plan defines a program to manage wildland fires (wildfire and prescribed fire). The plan is supplemented by operational plans, including but not limited to preparedness plans, preplanned dispatch plans, prescribed fire burn plans, and prevention plans. Fire management plans assure that wildland fire management goals and components are coordinated. (NWCG Glossary 2014)

Incident Action Plan (IAP)—Contains objectives reflecting the overall incident strategy and specific tactical actions and supporting information for the next operational period. The plan may be oral or written. When written, the plan may have a number of attachments, including: incident objectives, organization assignment list, division assignment, incident radio communication plan, medical plan, traffic plan, safety plan, and incident map. Formerly called shift plan. (NWCG Glossary 2014)

Incident Command System (ICS)—A standardized on-scene emergency management concept specifically designed to allow its user(s) to adopt an integrated organizational structure equal to the complexity and demands of single or multiple incidents, without being hindered by jurisdictional boundaries. (NWCG Glossary 2014)

Incident Decision—Serves to document what the management decision is for a specific fire, why it was made, and how it supports the Land and Resource Management Plan objectives and requirements. (Taber and Others 2013)

Incident Objectives—Statements of guidance and direction necessary for the selection of appropriate strategy(s), and the tactical direction of resources. Incident objectives are based upon agency administrator direction and constraints. Incident objectives must be achievable and measurable, yet flexible enough to allow for strategic and tactical alternatives. (NWCG Glossary 2014)

Land Management Plan (LMP)—A document prepared with public participation and approved by an agency administrator that provides general guidance and direction for land and resource management activities for an administrative area. The LMP identifies the need for fire's role in a particular area and for a specific benefit. The objectives in the LMP provide the basis for the development of fire management objective and the fire management program in the designated area. (NWCG Glossary 2014)

Leader's Intent—A concise statement that outlines what individuals must know in order to be successful for a given assignment. The intent communicates three essential pieces of information: Task – What is the goal or objective; Purpose – Why it is to be done, and the End State – How it should look when successfully completed. (NWCG Glossary 2014)

Long Term Fire Analyst (LTAN)—LTAN is critical in predicting the potential area and extent of burning, assessing long-term risk, and validating the planning area. LTANs also predict the potential for a fire reaching certain values that may be threatened over the long term and the potential timing of a fire-ending event. (Taber and Others 2013)

Management Action Points (MAPs)—Geographic points on the ground or specific points in time where an escalation or alternative of management actions is warranted. These points are defined and the management actions to be taken are clearly described in an approved Prescribed Fire Plan. Timely implementation of the actions when the fire reaches the action point is generally critical to successful accomplishment of the objectives. Also called Trigger Points. (NWCG Glossary 2014)

Management Objectives—The objectives set forth in an approved Land Management Plan, Resource Management Plan, Fire Management Plan, or other guiding document that provide the basis for the fire management program in a designated area. The objectives identify the need for and use of fire in a particular area and for a specific benefit. Not all land management objectives are directly related to the fire management program. (WFDSS Glossary)

Organizational Needs Assessment—Are used to provide guidance on the recommended type (level) of incident management organization based on the expected difficulty of implementing the course of action, the relative risk assessment, and management concerns. (Taber and Others 2013)

Resource Management Plan (RMP)—A document prepared with public participation and approved by an agency administrator that provides general guidance and direction for land and resource management activities for an administrative area. The RMP identifies the need for fire's role in a particular area and for a specific benefit. The objectives in the RMP provide the basis for the development of fire management objective and the fire management program in the designated area. (NWCG Glossary 2014)

Relative Risk Assessment—A risk assessment is the process of identifying values and analyzing the probability that hazards may negatively impact them. In the wildfire decision making process, risk assessment is a summary of information and analyses used to evaluate each of the three components of risk: values, hazard, and probability. (Taber and Others 2013)

Strategic Operational Planner (SOPL)—A SOPL is an NWCG position skilled in applying risk assessment products to the development of complex courses of action, employing the full spectrum of fire management strategies to achieve land management objectives. SOPLs are most effective when paired with a Long-Term Fire Behavior Analyst to produce the fire behavior, climatology, and fire effects components of the risk assessment and benefit analysis. (Taber and Others 2013)

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Using Prescribed Fire to Reduce the Risk of Smoke Related Traffic Problems on I-95

Steven R. Miller, Chief, Land Management Bureau, St Johns River Water Management District

Abstract—*In many areas of the United States, prescribed burning near highways is considered too risky because of the potential for smoke to obscure the highway. In one area in Florida, prescribed fire is used to reduce the risks of smoke related impacts to Interstate 95. The St Johns River Water Management District manages over 400,000 acres of land. Seventy percent of those lands are wetlands, and nearly 200,000 acres of the wetlands are marsh ecosystems that require fire for their perpetuation. Some marsh acres are immediately adjacent to Interstate 95 near Cocoa, in Brevard County, Florida. Prior to 1993, the District had no formal wildland fire program and all wildland fire management responsibilities were abdicated to the Florida Division of Forestry. In the 1980's Florida suffered several severe droughts and associated wildfire seasons and as a result, the marshes next to I-95 supported lightning-ignited wildfires on several occasions because they were so dry that organic soils began to burn. These wildfires burned for weeks, resulting in prolonged smoke impacts to I-95, and even smoke-related vehicle accidents. In 1989, the Division of Forestry requested that the Water Management District participate in a program to use prescribed fire on a frequent basis, at least every third year, in an effort to reduce the risk of wildfires that could ignite the organic soil. It took until 1996 for the District to build a program capable of conducting a complex 4,600 acre prescribed burn using aerial ignition immediately adjacent to an Interstate Highway. Since that time, that area has been burned five additional times, and to date there have been no smoke-related accidents from either prescribed burning or wildfires. In fact, despite being subject to several severe droughts, the area has not supported a wildfire since managed fire began in 1996.*

Keywords*: Prescribed Fire, Smoke, Fire Prevention*

Introduction

When prescribed fire managers are asked to identify the factors that limit their ability to complete prescribed fires, smoke management and wildland urban interface concerns are commonly listed in the top five reasons (Melvin 2012). Headlines such as the one shown in Figure 1 paralyze many prescribed fire managers and prevent them from even considering a large burn immediately adjacent to an interstate highway. Yet, burning land adjacent to well traveled roads, such as an interstate, may actually improve public safety and reduce overall risk.

Prescribed burns conducted under specific weather conditions and desired timeframes, can reduce the risk of unplanned ignitions occurring under less desirable conditions and at less desirable times (Koehler 1993). The act of prescribing the conditions and the timing under which an area may burn offers improved public safety and reduces risk (Koehler 1993). This paper will emphasize the importance of, and the benefits offered by taking a proactive approach to fire management.

Fog causes highway pileups

I-95 MESS: Traffic comes to a standstill after a 19-car accident Saturday on Interstate 95 just north of Wickham Road near Melbourne. The pileup happened at 7:45 a.m.

Brevard accidents leave at least 15 people hurt; 45 cars involved

By Douglas Cohen and Parvetie Bryant FLORIDA TODAY

Patches of fog mixed with smoke from a suspicious wildfire caused massive pileups early Saturday on SR 528 and Interstate 95 from Cocoa to Melbourne.

Saturday marked the worst chain of accidents ever to occur on the 75 miles of interstate in Brevard County, Florida Highway Patrol troopers said. More than 45 cars were involved in 12 accidents, and at least 15 people were injured, none fatally.

"I'd say this is the worst situation I have dealt with," said Brevard sheriff's Deputy Larry Primavera, who worked accidents on the interstate from 7:30 a.m. until 3:30 p.m. "It seemed like an all-day chain reaction."

Except for a period from 10:30 a.m. to 1 p.m. when they reopened the southbound lane, FHP troopers closed both lanes of the interstate between SR 520 and Wickham Road from 7:30 a.m. until 4:30 p.m.

"There were so many accidents, we are still trying to figure out how they all happened," FHP Sgt. Pat O'Neill said as he stood at a 19-car pileup in the I-95 median north of Wickham Road.

"It was foggy north of here all the way to the Bee Line (SR 528). The visibility was only three to four feet. We're very fortunate people came out with only minor injuries."

Other troopers said the smoke and fog were so thick they could not see across the median and had to use their sirens to locate each other.

State Division of Forestry officials said they are investigating a wildfire in the St. Johns River marsh that caused the dense smoke. They would not release further details.

The major accidents occurred within half-hour intervals starting about 7:15 a.m. All occurred in low-lying areas of the interstate and other roads near bodies of water, conditions that increased the likelihood of dense fog.

First, 15 cars collided near Cocoa on SR 528 near U.S. 1. At 7:45 a.m., a 19-car pileup occurred just north of Wickham Road near Melbourne. Shortly afterward, six cars careened into

See ACCIDENTS, Next Page

Special report, 4A.

SECOND ACCIDENT: Emergency personnel help victims from a North Carolina van involved in a second Interstate 95 accident Saturday morning, about 1 mile south of Fiske Boulevard in Rockledge. Six cars were involved in the crash.

Figure 1—Headlines from the Florida Today Newspaper in Melbourne Florida from January 1, 1989. The article reports on car accidents resulting from diminished visibility from fog and smoke from a lingering wildfire in wetlands within River Lakes 8.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

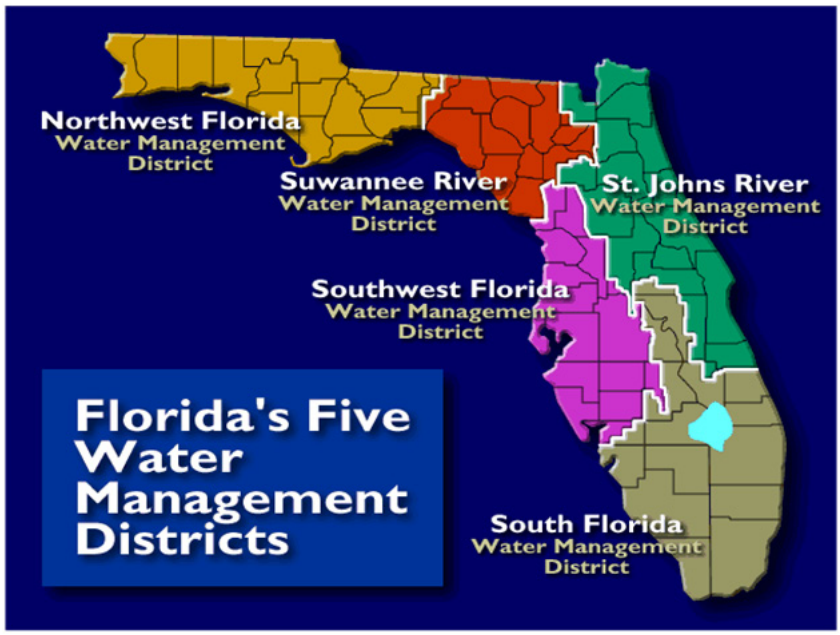

Figure 2—Map of the five Water Management Districts within the state of Florida.

The St Johns River Water Management District (the District) is located in northeast Florida (Figure 2). Its mission is to "ensure the sustainable use and protection of water resources for the benefits of the people of the District and the state of Florida."(SJRWMD 2014). To accomplish this mission, the District is expected to strike a balance in water needs by educating the public about water conservation, setting rules for water use, conducting research, collecting data, managing land, restoring and protecting water above and below the ground, and preserving natural areas. Regarding land management, Florida Statute 373.1391 states "*Lands titled to the governing boards of the districts shall be managed and maintained, to the extent practicable, in such a way as to ensure a balance between public access, general public recreational purposes, and restoration and protection of their natural state and condition.*"

Currently the District manages a multiple use program on 420,000 acres of land. An active fire management program is essential to meeting this legislative charge as this is the subject of the paper. However, that was not always the case. By the late 1980's, the District acquired 270,000 acres of land for water resource and flood control purposes. Prior to August of 1992, when the District created a Division of Land Management, it had no formal land management program, and relied heavily on other agencies for fire management. Prior to that time, fire management was primarily the responsibility of the Florida Division of Forestry, with such management limited strictly to wildfire suppression.

Seventy percent of the lands owned by the water management district are wetlands (SJRWMD 2014). Nearly 200,000 acres of wetlands are natural freshwater marshes (SJRWMD 2014). Functionally these marsh ecosystems are dependent on a regime of flooding and frequent fire (FNAI 2010, Miller 1998). In the absence of frequent fires, one fire every three to five years, marshes are invaded by woody vegetation until they eventually succeed to forested ecosystems (FNAI 2010, Miller 1998). In the absence of water, the accumulated organic matter will oxidize either slowly or rapidly through combustion (Meyers 1990).

Problem

During the late 1980's, Florida experienced several periods of drought (FSU 2014). As a result, wildfires in the District's marsh lands were frequent, and often large (Koehler 1989) Drought conditions create dry organic soils in wetland systems and ideal conditions for wildfires to grow large. Once wildfires ignite organic soil, they are likely to burn for weeks to months. Fire suppression options under these conditions are limited to securing a perimeter and waiting for either rain to flood the fire area or for complete consumption of the organic soil, thereby depriving the fire of additional fuel.

Interstate 95 is east of the many wetlands owned by the District. River Lakes Conservation Area is near I-95 (Figure 3). Several fires burning organic soils within District land during the late 1980's produced smoke for weeks (Figure 4). Because of the close proximity of the wetlands to I-95, that smoke reduced visibility for drivers using the highway, contributing to several accidents, which in turn resulted in the highway being intermittently closed for weeks at a time (Koehler 1989).

Solution

Tired of a reactive approach that included dealing with smoke impacts to I-95 for weeks at a time, John Koehler, the Orlando District Forester for the Florida Division of Forestry (now the Florida Forest Service), contacted the District and suggested a more proactive approach. He proposed to cooperatively develop a prescribed fire program that would use

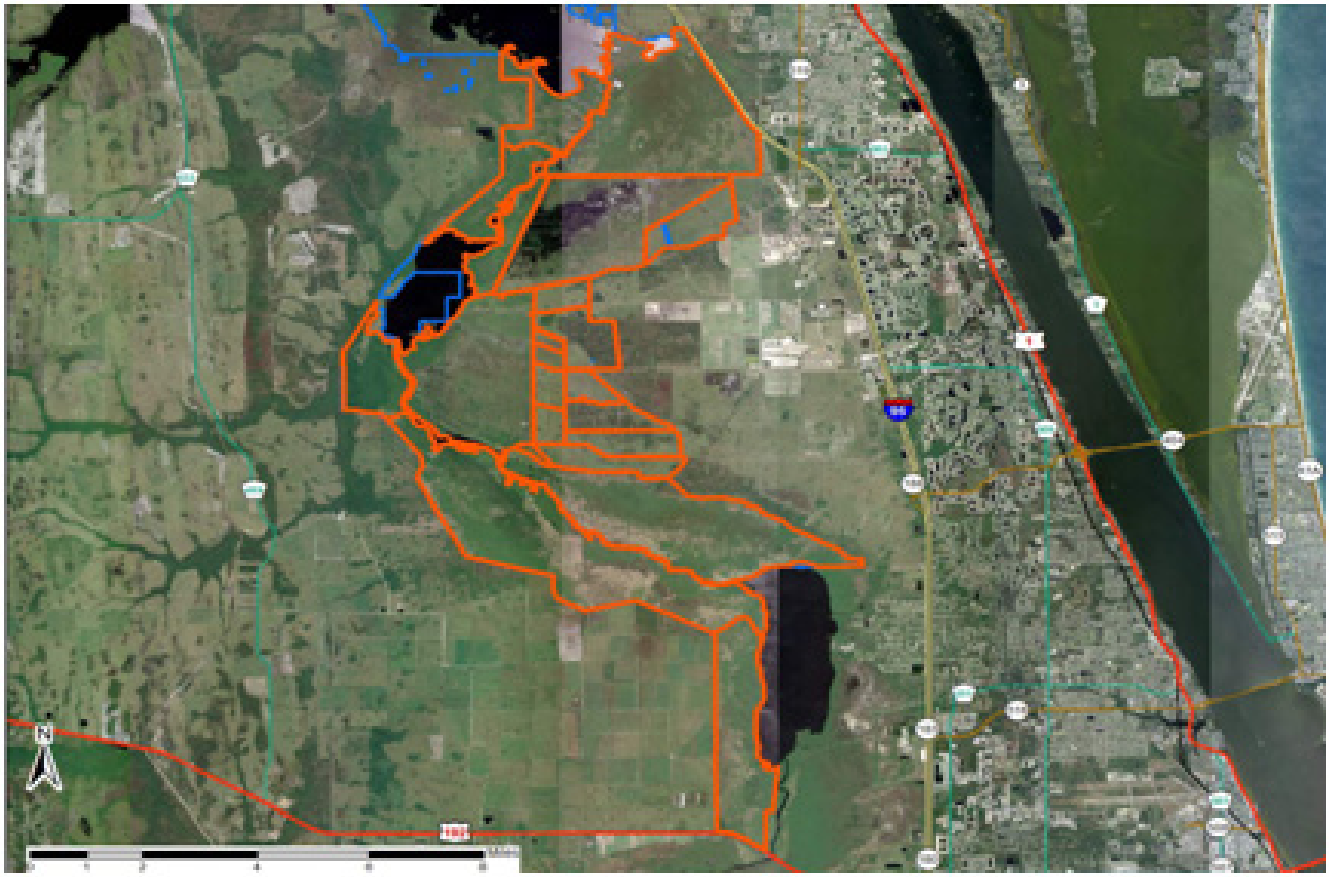

Figure 3—River Lakes Conservation Area owned by the SJRWMD and the proximity of I-95.

aerial ignition to start fires when smoke management and water level conditions were favorable. He hoped that prescribed fire would reduce the potential for wildfires to start when the soils would combust, or when smoke might impact the interstate.

Because the District had no formal Land Management program until 1992, it wasn't until 1996 that the first prescribed burn occurred as a part of Mr. Kohler's proposed plan. The River Lakes 8 burn zone became the focus of this proactive approach because it is the fire management zone

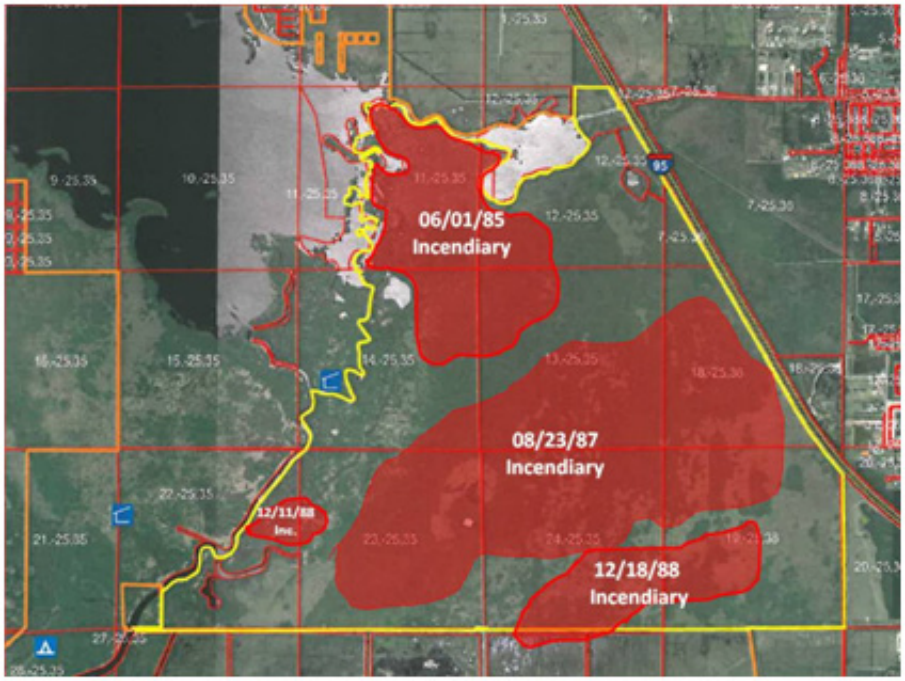

Figure 4—Map of River Lakes 8 burn zone and four wildfires that burned within the unit from 1985 through 1988. The fire ignited on 12/18/88 was the fire that resulted in the newspaper article in Figure 1.

Figure 5—The last line of aerial ignition during a prescribed burn of River Lake 8 on March 14, 2014. Image courtesy of Doug Voltolina.

closest to I-95 (Figure 3, 4). It is actually adjacent to the Interstate for nearly four miles, and wildfires burning within that zone contributed to most of the highway closures and accidents during the late 1980's.

Results

Since that first burn in 1996, River Lakes 8 has been burned seven additional times. The most recent burn was completed on March 14, of 2014 (Figure 5). During the 21-year period of prescribed burning on River Lakes 8, there have been no wildfires or any other smoke-related incidents on I-95 associated within District lands. Visual assessments indicated that, while some woody vegetation exists within the River Lakes 8 (Figure 6), marsh grasses are the dominant vegetation cover. The frequent fire return interval has provided both public safety and ecological benefits.

Figure 6—Willow within River Lakes 8 sprouting six months post burn. Note the condition of the surrounding sawgrass. At the horizon, semi trailers traveling I-95 are just barely visible.

Discussion

The keys to the success of the District's prescribed burning program have been:

1. Cooperation. Cooperation among agencies was especially important in the beginning. When the concept was new, none of the participants had conducted prescribed burns immediately adjacent to an interstate. Now, everyone knows their role. Assistance from the Florida Forest Service, Florida Highway Patrol, the National Weather Service and Brevard County Fire Rescue contributes to the safety and success of each burn.
2. Diligence. Fire managers require exacting conditions when selecting a day to burn. Because there is no way to stop a burn in River Lakes 8 once it starts, conditions must be correct. The ideal day has a wind speed greater that 10.0 miles per hour out of the northeast or east, an atmospheric dispersion index of at least 40, and water levels that at least saturate the soil.
3. Commitment. Success is not achieved by burning the zone only one time. Success results from a commitment to burn it as close to once every three years as possible.

4. Communication. Communication among the cooperators, with the neighboring landowners, and with the general public, has been critical to the success. We know efforts at communication have been successful anytime we when we can burn 4,600 acres in the urban interface, immediately adjacent to six lanes of interstate traffic and only have two telephone calls.
5. Being proactive. Too often people are convinced that taking no action is the safest approach to managing land with fire. They assume that reacting to circumstances carries less risk than taking action in the first place. The reactive approach enabled several wildfires to impact traffic safety on I-95 and resulted in several multi crashes. The proactive approach since 1993 has resulted in no wildfires, no smoke impacts to the highway, and no organic soil fires. The proactive approach has a much better record from both a pubic safety and from an ecological perspective.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Spatially Explicit Quantification of Heterogeneous Fire Effects Over Long Time Series: Patterns from Two Forest Types in the Northern U.S. Rockies

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Introduction

Within the last decade, mixed-severity fire regimes (MSFRs) have gained increasing attention in both the scientific and management communities (Arno and others 2000, Baker and others 2007, Hessburg and others 2007, Perry and others 2011, Halofsky and others 2011, Stine and others 2014). The growing influence of the MSFR model derives from several factors including: (1) recent recognition of the wide geographic breadth of mixed severity fire regimes within western North America and elsewhere, (2) a lack of basic ecological data that spans sufficient temporal and spatial scales to sufficiently describe MSFRs for many regions, (3) debate about the appropriateness of using low- and high-severity fire regime models for MSFRs and (4) uncertainty regarding the implications of the MSFR model for describing ecosystem dynamics, predicting ecosystem responses to climate change and past management, designing ecological restoration treatments, and implementing future forest management and policy.

MSFRs have been documented in low to middle elevation forests of many regions within western, and parts of eastern, North America, including a diverse array of forest types comprised of ponderosa pine, Jeffrey pine, Douglas-fir, western larch, lodgepole pine, red fir, grand fir, white fir, jack pine and other species (Heinselman 1973, Taylor and Skinner 1998, Taylor 2000, Arno and others 2000, Wright and Agee 2004, Hessburg and others 2007, Sherriff and Veblen 2007, Klenner and others 2008, Perry and others 2011, Stine and others 2014). There is substantial variation in the dynamics of MSFRs for different vegetation types, between biogeographic regions, and along climatic, topographic, and successional gradients, but this variation is not yet well understood. In general, MSFR forests are thought to contain patches created by a mixture of surface fires, and active and passive crown fires that create a fine-scale mosaic of low, moderate and high severity fire effects (Agee 1993, Taylor and Skinner 1998, Lentile and others 2005, Baker and others 2007, Hessburg and others 2007 Halofsky and others 2011). The diversity and spatial arrangement of forest structure patches are thought to be key features of MSFR forests that create landscape memory (Peterson 2002) and influence the behavior of future fires (Moritz and others 2011, Perry and others 2011, Halofsky and others 2011). However, the relative importance of low versus high severity fire effects in structuring these landscape characteristics is actively being debated (Williams and Baker 2012, Fule and others 2013, Odion and others 2014). In addition, MSFRs exhibit high variability of fire return intervals (Brown and others 1999, Sherriff and Veblen 2007, Heyerdahl and others 2012), necessitating temporally resolved records of fire occurrence.

Although substantial datasets exist for MSFR forests in some regions, such as the Colorado Front Range (Sherriff and Veblen 2007, Schoennagel and others 2011), eastern Washington and Oregon (Hessburg and others 2007, Perry and others 2011), and parts of northern California and southern Oregon (Taylor 2000, Beatty and Taylor 2001, Taylor and Skinner 2003), there is a clear need for spatially explicit, temporally resolved data on the basic fire ecology of MSFR forests in other regions. Here, we present preliminary data from a study of fire history, tree establishment, and forest structure in pure Douglas-fir (*Psuedotsuga menziesii*) forests of the Greater Yellowstone Ecosystem (GYE) and mixed conifer forests of the Northern Continental Divide Ecosystem (NCDE), two of the dominant lower-mid elevation forest types of the northern U.S. Rockies thought to exhibit MSFRs. We combine extensive networks of dendroecological data with forest structure interpretations from historical aerial photographs to describe the fire history and landscape-scale patterns of fire severity produced by fires from the years 1600–present in one watershed within each of our two study regions. In addition to providing insight on the basic fire ecology of two widespread but poorly studied forest types, these data highlight some unique aspects of MSFRs that contrast with existing perceptions of low- and high-severity fire regimes.

Background

Douglas-fir forests of the GYE are characterized by gradients of open to closed canopy stands dominated by Douglas-fir, with small amounts of Rocky Mountain juniper (*Juniperus scopulorum*) and limber pine (*Pinus flexilis*) at lower elevations and lodgepole pine (*Pinus contorta*) at higher elevations (Figure 1a,c). A limited number of fire

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

history studies exist in Douglas-fir forests of the GYE, primarily in stands at the forest-grassland ecotone, which show historically recurrent low severity fire and Douglas-fir expansion into grassland during the period of fire exclusion (Heyerdahl and others 2006, Barrett 1994, Arno and Gruell 1983). However, few studies document landscape-scale patterns of fire frequency and severity across the broader range of Douglas-fir forests.

Mixed conifer forests of the NCDE are comprised of Douglas-fir, ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), lodgepole pine, grand fir (*Abies grandis*), and occasional western white pine (*Pinus monticola*), Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) (Figure 1b,d). Numerous studies of this forest type have documented mixed severity fire effects (Arno and others 1995, Barrett and others 1991, Habeck 1990) in individual stands, but the relative importance of low and high severity fire effects and their landscape arrangement are poorly understood.

Methods

Following previously published methods (Hessburg and others 2007) we used stereo aerial photographs from the 1930s to 1950s to map forest structure across two watersheds: Six Mile Creek (21,800 acres) on the Gallatin National Forest in the GYE and Spotted Bear River (17,200 acres) on the Flathead National Forest in the NCDE (Figure 2). Forest structures were mapped across the full extent of each study area by delineating forest patches with uniform characteristics, to a minimum patch size of 4 ha. For each mapped entity, photo-interpreted structural attributes were assigned, including the percent canopy cover, cover type, and diameter class of overstory and understory canopy layers.

To characterize the age structure and disturbance history of patches in each watershed, during 2011-2013, we developed a network of 74 sample sites in a subset of patches, collectively comprising greater than 70% of each study area. These sites were spatially distributed across each watershed along topographical gradients and within different forest structural types mapped by aerial photo interpretation. At each sample site, increment cores were collected from all trees > 4 cm DBH, within fixed 0.04 ha circular plots, spaced along a transect at 50-100m, until a minimum of 40 trees were sampled. Fire history was reconstructed from a spatially distributed network of 180+ fire scar samples collected within each watershed. All increment cores and fire scars were cross-dated using master chronologies developed for each watershed using standard dendrochronological methods (Stokes and Smiley 1968). All cores used to create the master chronologies were measured to 0.001 mm and statistically crossdated using the program COFECHA (Grissino-Mayer 2001). All other increment cores and fire-scar samples were

Figure 1—Photographs depicting low (a-b) and high (c-d) density forest stands in the GYE (a, c) and NCDE (b, d).

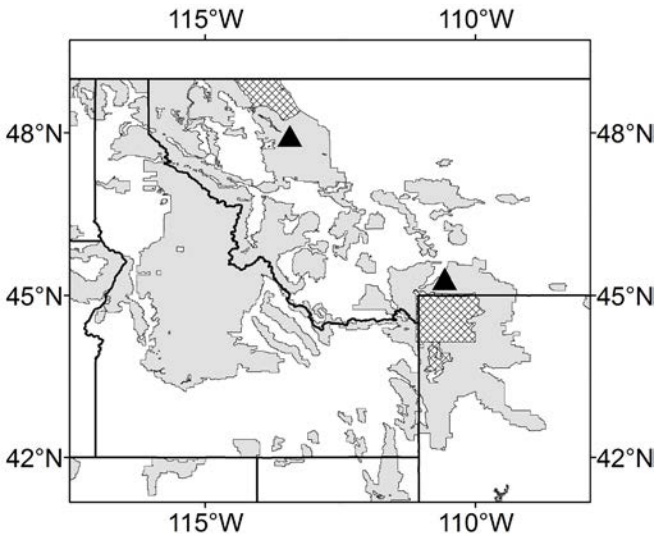

Figure 2—Map of the study region showing the study watersheds (black triangles), National Parks (crosshatched) and National Forests (grey).

crossdated using a combination of visual and statistical crossdating. Fire dates from all fire scars found within a patch were aggregated into one composite record that represented the fire history at that patch. For consistency with the aerial photo data and to minimize the influence of fire suppression on interpretations of age structure, tree establishment data were truncated at 1954, the date of the most recent aerial photograph used to map forest structures.

To determine historical fire severity, we compared the age structure of a patch with the composite fire history for that same patch to determine the percent of stand basal area (BA) that survived each fire. Similar to other studies we used the 20/70 percent threshold values of the percent BA surviving a fire to classify each fire as high, moderate, or low severity (Agee 1993, 1994, Hessburg and others 2007, Schoennagel and others 2011). To account for disturbances other than fire which might affect stand age structure, only contiguous establishment pulses following documented fires were included in the severity calculation. The time-integrated fire severity history of each patch was classified as low, mixed or high if all fires were of low severity, were a mix of low, moderate or high, or were all of high severity, respectively. According to these criteria, low severity sites are generally characterized by older, multi-cohort stands whereas high severity sites are even-aged young or old stands, depending on time since the last fire. Mixed severity sites encompass a diverse set of forest structures depending on the number of fires, the relative proportions of stand-replacing and non stand-replacing fire effects, and the time since stand-replacing fire.

Results

Forests in both regions exhibited moderate, but highly variable, stand density, with a median density of 530 trees ha^{-1} (min = 94, max = 3919) and 691 trees ha^{-1} (min = 209, max = 962) for the NCDE and GYE, respectively. Median canopy cover for both watersheds was similar, with a median

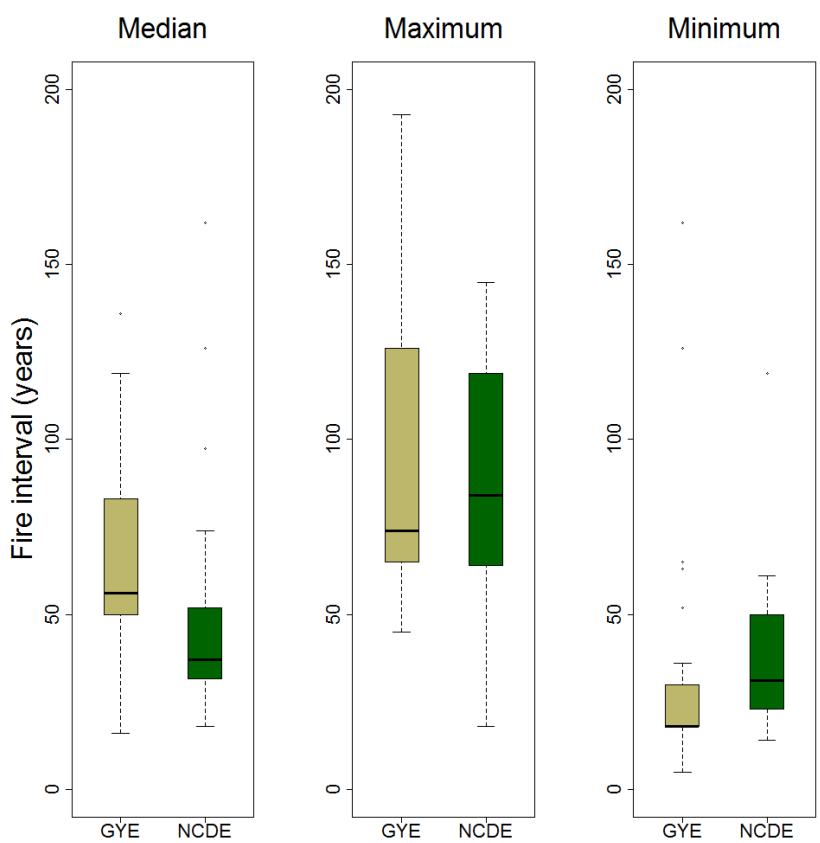

Figure 3—Boxplots of the median, maximum and minimum composite fire intervals for sites in the GYE and NCDE. Black horizontal bars within boxes represent the median, the box endpoints represent the 25th and 75th percentile values, and whiskers mark the 5th and 95th percentile values. Fire statistics were composited for all fire scars within the same patch, as defined by tree establishment patterns and forest structures identified in aerial photographs.

value of 70 percent ± 19 percent. Composite patch-level median fire intervals were 37 yr (max = 74, min = 18) and 56 yr (max = 84, min = 31) for the NCDE and the GYE, respectively (Figure 3). The age distribution of trees in both watersheds show a predominance of young trees less than 100 years old, especially in the NCDE, with greater than 80 percent of trees less than 225 years (Figure 4). Old trees greater than 225 years old are relatively rare throughout both watersheds. In both regions, forest patches were overwhelmingly classified as mixed severity (> 75 percent of sites), with no stand classified as low severity and less than 20 percent of stands classified as high severity (Figure 5).

Discussion

Relative to the mixed conifer forests of the NCDE, the Douglas-fir forests of the GYE were characterized by slightly higher median tree density, lower fire frequency and a lower percentage of high severity fire effects. However, striking similarities exist between the MSFRs in both of our study regions. Compared with forests in low severity fire regimes, where open stand conditions (stand density < 200 trees ha^{-1}) maintained by frequent fires (fire intervals of 5 to 25 yr) are common (Habeck 1990, Arno and others 1995, Williams and Baker 2012), the MSFR forests in our region were historically characterized by intermediate median stand density (> 500 trees ha^{-1}) and moderate, but highly variable, fire frequency. Forests in both study regions were dominated by mixed severity fire effects at the patch level, meaning that most patches (> 75 percent of all patches) experienced a high severity fire followed by one or more low to moderate severity fires that created multi-cohort stand structures. The other remaining 20% of stands were young forest that showed clear evidence of initiating after a high severity fire with no subsequent occurrence of low to moderate severity fire. Notably, none of the sampled stands exhibited a total absence of high severity fire or an old, low density forest structure, as would be expected in a low-severity fire regime model.

These findings suggest several unique characteristics of MSFRs that distinguish them from either low- or high-severity fire regime models, including:

- high severity fire was historically common in these MSFR forests, affecting most forest patches at some point in the last 100–300 years.
- at the patch sizes mapped in our aerial photo analysis (4 to 650+ ha), the studied MSFR forests are quite resilient to high severity fire.
- despite the widespread influence of high severity fire, the mix of stand-replacing and non stand-replacing fires experienced by most patches led to the predominance of young, multi-cohort forest patches.
- complex fire dynamics and diverse forest structures are evident in MSFRs despite moderate forest density and closed canopy forest conditions often presumed to lead primarily to high severity fire.

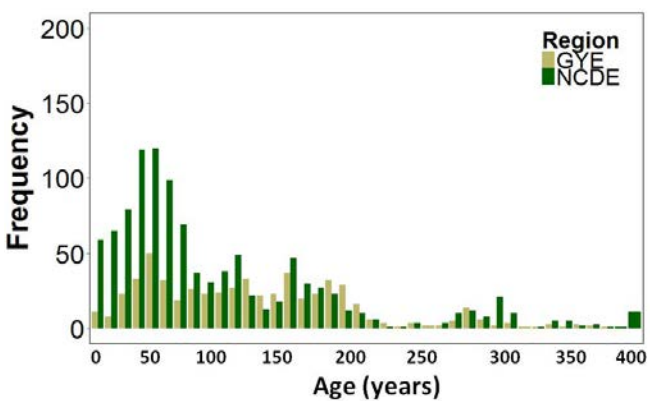

Figure 4—Age distribution of all trees sampled in the GYE and NCDE. Bars represent the frequency of ages in each 10 year bin.

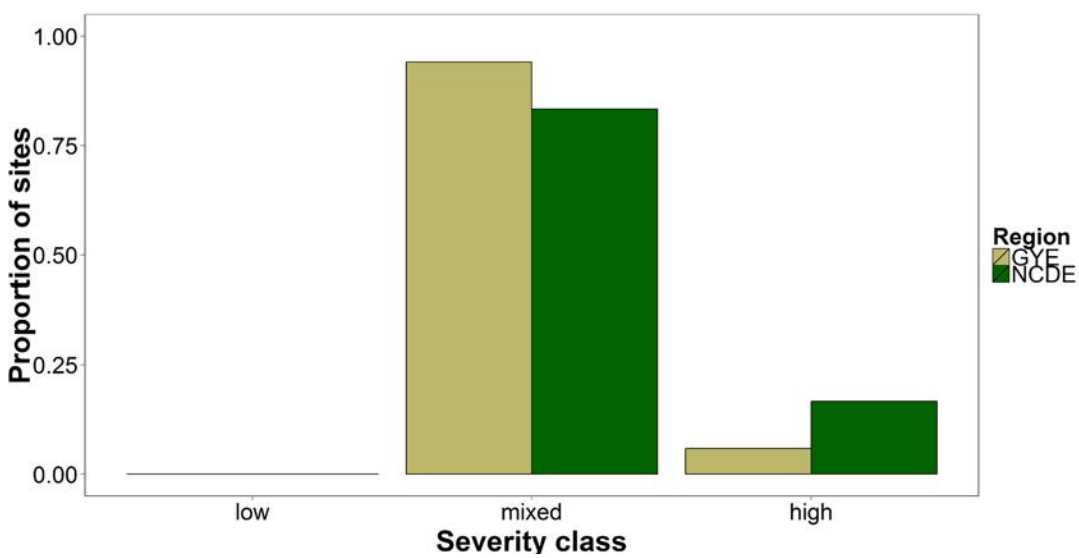

Figure 5—Proportion of sites in the GYE and NCDE classified in low, mixed, or high cumulative fire severity categories.

Consistent with previously published studies of MSFRs (Hessburg and others 2007, Sherriff and Veblen 2007, Halofsky and others 2011, Perry and others 2011, Odion and others 2014), our data support the use of a unique ecological model to describe MSFRs and to inform management in MSFR forests. Results from ongoing data analysis will expand our scope of inference to include a greater number of watersheds, assess the variability of MSFRs across topographic and climatic gradients, and examine the unique forest structural features and successional dynamics created by MSFRs.

Acknowledgments

This research was supported by the NSF Wildfire PIRE grant (award no. 0966472), an NSF Doctoral Dissertation Research Improvement grant (award no. 1302233), and the Jerry O' Neal National Park Service Student Fellowship. We thank 2 reviewers, Kerry Kemp and Brian Harvey, for helpful comments and reviews of this manuscript.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Effects of Bark Beetle Attack on Canopy Fuel Flammability and Crown Fire Potential in Lodgepole Pine and Engelmann Spruce Forests

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Abstract—*Large wildland fires in conifer forests typically involve some degree of crowning, with their initiation and propagation dependent upon several characteristics of the canopy fuels. Recent outbreaks of mountain pine beetle (*Dendroctonus ponderosae *Hopkins) in lodgepole pine (*Pinus contorta *Dougl. var.* latifolia *Engelm.) forests and spruce beetle (*Dendroctonus rufipennis *Kirby) in Engelmann spruce (*Picea engelmannii *Parry ex Engelm.) forests have affected vast areas across western and northern North America, which have subsequently produced forests containing relatively large amounts of dead or "bark beetle-altered" canopy fuel. Given that the transition to crowning represents an important threshold in terms of large fire growth and wildland firefighter safety and effectiveness, a better understanding of the potential role of bark beetle-altered foliage in altering crown fire initiation and spread is needed. This paper summarizes a recently completed research project dealing with the measurement and characterization of the changes in crown fuel flammability caused by recent bark beetle attacks and consequently the implications of these changes on crown fire potential in these affected forest types.*

Introduction

Recent epidemics of various bark beetles species in the genus *Dendroctonus* have caused widespread tree mortality in their respective conifer hosts across western North America (Meddens and others 2012). Bark beetle-caused tree mortality and its effect on both the fuels complex and potential fire behavior in affected forests, particularly in lodgepole pine forests (Fig. 1), has been a topic of much debate in recent years (Jenkins and others 2008, 2012, 2014b; Hicke and others 2012; Black and others 2013). Early research on the subject seemed to suggest a straightforward relationship where it was expected that the tree mortality and its resulting direct and indirect effects on forest structure and fuel loads would increase potential fire behavior both in the short and long term (Brown 1975; Lotan and others 1985; Schmid and Amman 1992). However, recent work has suggested a much more complicated relationship than previously thought that is dependent upon a host of site specific factors and the particular bark beetle-host system (Hicke and others 2012; Donato and others 2013). Of particular concern and the subject of most debate has been the influence of recent tree mortality on canopy fuel flammability and crown fire potential, including crown fire initiation and spread, in lodgepole pine forests.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

The work by Page (2014a) represents an attempt to quantify and clarify some of the important changes to crown fuel flammability and crown fire potential caused by bark beetle attack, so that more accurate assessments of crown fire potential can be made in the future. This research first involved a comprehensive literature review on the general topic area—i.e., the effects of bark beetle attack on fuel characteristics and fire dynamics in lodgepole pine and Engelmann spruce forests, especially as it pertains to crowning phenomena (Jenkins and others 2012, 2014a). This was in turn followed by answering four primary research questions based on the results of extensive field and lab work conducted in both lodgepole pine and Engelmann spruce dominated forests (Box 1):

- How does successful attack by mountain pine beetle in lodgepole pine and spruce beetle in Engelmann spruce trees alter the moisture content, chemistry, and flammability of foliage over time?
- How does the moisture content of dead foliage on lodgepole pine trees during the red stage of mountain pine beetle attack change diurnally?
- Can models be developed to predict the hourly change in moisture content of foliage on lodgepole pine trees during the red stage?
- What are the consequences of mountain pine beetle-caused changes to crown and canopy fuels on crown fire initiation and spread in lodgepole pine forests?

In this paper we provide a summary of the results of the analysis undertaken by Page (2014a) organized along the

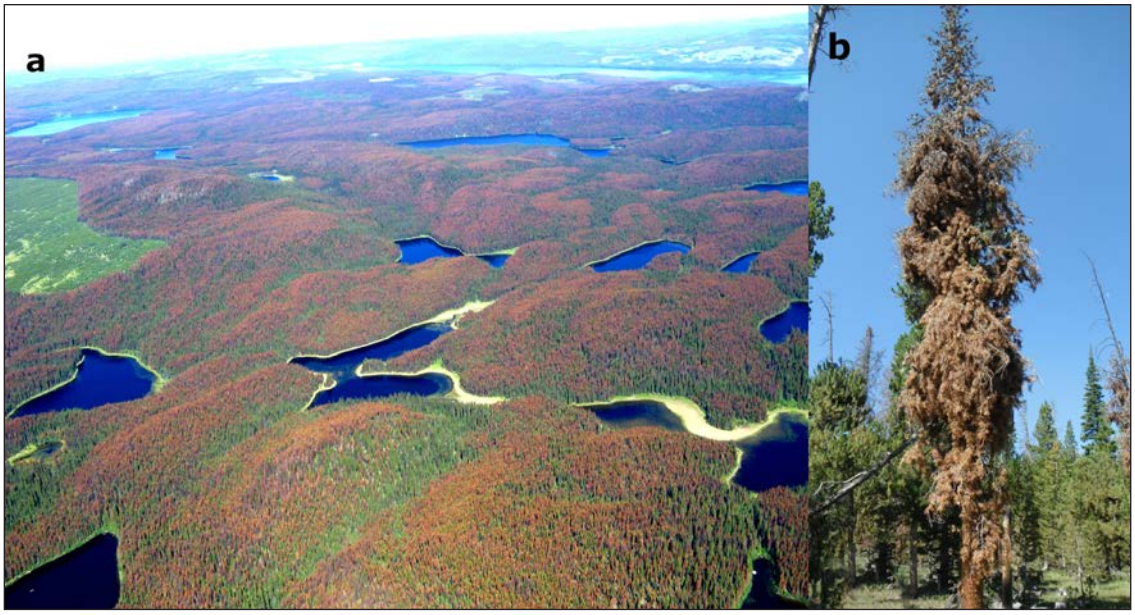

Figure 1—Lodgepole pine during the red stage of mountain pine beetle attack (a) at the landscape scale in British Columbia, Canada (from Woods and others 2010; photo by L. Maclauchlan, British Columbia Ministry of Forests and Range) and (b) at the individual tree level in northeastern Utah (photo by W.G. Page).

lines of the primary topics, namely, the seasonal changes in moisture, chemistry, and flammability of bark beetle-attacked foliage on lodgepole pine and Engelmann spruce trees (Fig. 2), the diurnal changes in moisture content of lodgepole pine foliage during the red stage of mountain pine beetle attack (Fig. 1), and the implications of those changes on crown fire initiation and spread in lodgepole pine forests. Additionally, a number of research needs and knowledge gaps are highlighted. Finally, we frame these results along with additional information about the effects of mountain pine beetle-caused tree mortality over longer time frames (i.e., during the gray and post-epidemic stages) within the context of the concept of wildfire resistance to control.

Figure 2—Engelmann spruce foliar moisture and chemistry sampling study site on the Heber-Kamas Ranger District of the Uinta-Wasatch-Cache National Forest in northern Utah (photo by W.G. Page).

For a popularized summary of the research carried out by Page (2014a), refer to the article published in *Utah Forest News* by Page (2014b). Copies of all of the articles associated with the research project and including Page (2014a) are available at: http://digitalcommons.usu.edu/barkbeetles/.

Seasonal Changes in Moisture Content, Chemistry and Flammability of Lodgepole Pine and Engelmann Spruce Foliage

The detailed results pertaining to the seasonal change in moisture content, chemistry, and flammability of foliage on bark beetle-attacked lodgepole pine and Engelmann spruce forests were presented by Page and others (2012, 2014a). The sampling of the lodgepole pine took place on the Palisades Ranger District of the Caribou-Targheee National Forest in eastern Idaho during the summer of 2011 and in Engelmann spruce on the Heber-Kamas Ranger District of the Unita-Wasatch-Cache National Forest in northern Utah during the summer of 2012. The fuel moisture sampling in lodgepole pine supplements the similar work carried out in lodgepole pine in north-central Colorado and western Montana by Jolly and others (2012).

Several similarities between the two tree species were found as well as some important differences that have implications on crown fire potential. Recently attacked lodgepole pine and Engelmann spruce foliage displayed substantial decreases in moisture content compared to un-attacked tree foliage, decreasing by a factor of 9 in lodgepole pine and 4 in Engelmann spruce foliage approximately 12 to 14 months following initial attack. Within the crowns of

Box 1. Summary of the conclusions and implications associated with the four primary research questions (from Page 2014a).

1. *How does successful attack by mountain pine beetle in lodgepole pine and spruce beetle in Engelmann spruce trees alter the moisture content, chemistry, and flammability of foliage over time?* Conclusions:

   - There are significant declines in the moisture content of foliage for both species with most of the decline occurring within 12 to 14 months after initial attack.
   - A shift in foliar chemistry occurs for both species with higher proportions of carbohydrates and crude fat in unattacked foliage and lower proportions of those compounds in foliage on attacked trees.
   - There is a significant increase in foliar flammability, particularly ignitability, due primarily to the decrease in moisture content.

   Implications: The high ignitability of foliage on attacked trees could lead to a decrease in the canopy ignition threshold in stands containing high proportions of bark beetle-altered foliage, and therefore an increase in the potential for crown fire initiation.

2. *How does the moisture content of dead foliage on lodgepole pine trees during the red stage of mountain pine beetle attack change diurnally?* Conclusions:

   - Contrary to other fine dead surface fuels like needle litter, the red foliage on mountain pine beetle-killed lodgepole pine trees does not have significant diurnal variation.
   - Existing models used to predict the hourly changes in moisture content of other fine dead fuels are inadequate.

   Implications: The high ignitability of the red foliage could extend into the overnight or early morning hours, thereby potentially lengthening the window of crown fire activity.

3. *Can models be developed to predict the hourly change in moisture content of foliage on lodgepole pine trees during the red stage?* Conclusions:

   - The red foliage does dry following a typical exponential decline thereby allowing for the development of diffusion-based bookkeeping-type system models.
   - Calibrated operational fine fuel moisture models performed as well or better than the more complicated bookkeeping-type system models.
   - Model evaluation indicated that the proposed models may be limited in geographic applicability to the Intermountain region of the western United States.

   Implication: We recommend that the calibrated operational fine fuel moisture models be used by field personnel.

4. *What are the consequences of mountain pine beetle-caused changes to crown and canopy fuels on crown fire initiation and spread in lodgepole pine forests?* Conclusions:

   - Bark beetle attack produces stands with highly heterogeneous and complex canopy fuel conditions.
   - Existing semi-empirical and empirical-based fire behavior models are inadequate for accurately assessing crown fire potential in recently attacked lodgepole pine forests.
   - Outputs from physics-based fire behavior models should be viewed with caution as these models have yet to be evaluated in conifer forests containing either live or dead canopy fuel.

   Implications: Our understanding of crown fire dynamics in recently attacked lodgepole pine forests will not substantially improve until a significant effort is made to collect field-based observations of fire behavior to either evaluate existing models or develop new ones.

individual trees, lodgepole pine foliage required a slightly longer time period to express significant decreases in moisture content compared to Engelmann spruce foliage (Fig. 2). By the end of the first fire season (October) in which the trees were initially attacked, lodgepole pine moisture content was still equivalent to the un-attacked foliage moisture content, however, the recently attacked Engelmann spruce foliage displayed patchy but significant declines in moisture content compared to un-attacked foliage. It was not until the early portion of the next fire season (i.e., spring) following the summer of initial attack that lodgepole pine foliage displayed significant declines in moisture content.

Bark beetle-induced changes to foliar chemistry for both tree species closely followed observed changes in moisture content. During the process of dry-down, the proportion of soluble carbohydrates and crude fat within the foliage decreased while the proportion composed of the structural compounds of lignin and cellulose increased. These

results were similar to those reported in litter decomposition studies where the proportion of dry matter composed of lignin was found to increase with time (e.g., Edmonds 1980). Additionally, terpenes including monoterpenes and sesquiterpenes, were found to be emitted at higher rates in recently attacked foliage on lodgepole pine but not on Engelmann spruce, however, they were found to play significant roles in needle flammability for both species.

The combined effects of the changes in moisture content and chemistry resulted in substantial increases in foliage flammability, particularly ignitability, in both tree species. Moisture content was found to be the most important variable affecting foliage flammability followed by the changes in foliar chemistry. Based on the reported results, we suggested that there may be periods of enhanced potential for surface fires to transition to crown fires in stands containing significant amounts of bark beetle-altered foliage due to a lower canopy ignition threshold compared to un-attacked stands. This enhanced potential would be most acute under more moderate fire weather and stand conditions where surface fire intensity and/or canopy base height would normally limit crown fire initiation. However, this period of enhanced crown fire initiation potential is dependent upon both the time since attack and the particular trees species, as it was found that the foliage on recently attacked Engelmann spruce only remained attached for a period of 12 to 14 months following initial colonization by the beetle, suggesting that once the needles drop to the forest floor, crown fire potential significantly decreases due to a decrease in canopy fuel density and continuity. Although, it should be noted that this outcome could be site specific as other bark beetle-affected spruce forests can retain significant vertical canopy fuel continuity in the form of small diameter branch wood after the needles have dropped to the ground (Alexander and Stam 2003; Hawkes and others 2014)

Diurnal Changes in Lodgepole Pine Foliar Moisture Content

Given the importance of fuel moisture on the ignitibility of lodgepole pine foliage as demonstrated by Page and others (2012) and Jolly and others (2012), it was important that methods be developed to predict short-term (i.e., hourly) changes in moisture content that can be used to more accurately assess crown fire potential during operational time scales. Previous research has assumed that the moisture content of mountain pine beetle-attacked lodgepole pine tree foliage during the red stage is equivalent to the moisture content of other fine dead surface fuels (e.g., Hoffman and others 2012; Schoennagel and others 2012). This assertion was partly based on the fact that most fine dead surface fuels show strong diurnal changes in moisture content as they respond to increasing atmospheric moisture during the night and lower moisture during the day (Steen 1963; Hartford and Rothermel 1991). This daily trend in moisture content usually corresponds to periods of decreased fire behavior at night and peaks in fire behavior during the afternoon.

Diurnal sampling in lodgepole pine was undertaken in the Evanston-Mountain View Ranger District of the Uinta-Wasatch-Cache National Forest in north-eastern Utah in late May and early August of 2012. The results from Page and others (2013a) showed that many of the models used to estimate fine dead fuel moisture in Australia, Canada, and the USA are inadequate for predicting the moisture content of "red and dead" lodgepole pine needle foliage (Fig. 1) due to the lack of diurnal variation, with significant under- and over-prediction biases during periods of low and high atmospheric moisture, respectively. This includes the Rothermel (1983) fine dead fuel moisture table procedure, which has been suggested as a way to estimate the moisture content of "red and dead" foliage in order to determine the probability of ignition of red attack stage trees (Hoyt and Jolly 2012).

Due to the poor predictions obtained from existing fine fuel moisture models, it was found necessary to develop and test new models or to calibrate existing models. Additional field sampling was carried out to capture a wider range of air temperature and relative humidity than observed by Page and others (2013a) in order to develop more robust models (Page and others 2015). Sampling took place on the Laramie Ranger District of the Medicine Bow-Routt National Forest in south-eastern Wyoming over the course of the summer of 2013.

Five models in total were developed and evaluated including three bookkeeping-type system models based on diffusion theory that used previously identified model forms (e.g., Catchpole and others 2001) and two calibrated operational models commonly used in the USA and Canada. All models performed well compared to the test dataset with the calibrated operational models performing as good or better than the more complicated bookkeeping-type system models. Based on these results we recommended that fire managers use the calibrated operational models to predict the moisture content of red and dead foliage on mountain pine beetle-attacked lodgepole pine due to their high accuracy and ease of use.

Crown Fire Potential in Lodgepole Pine Forests

It has previously been demonstrated that bark beetle-caused tree mortality can cause significant changes to stand structure, woody surface fuel loads, and canopy fuel loads and arrangement (Jenkins and others 2008; Hicke and others 2012). The effects of those changes on potential surface fire behavior are generally believed to be dependent upon the time since mortality, the relative concentration of fine fuel accumulation, and microclimatic changes within affected stands that can cause variations in surface fuel moisture and in-stand wind speed conditions (Jenkins and others 2008). What remains unclear however, are the possible alterations to crown fire potential as bark beetle-infested trees undergo changes in their physical and chemical characteristics as they proceed from their healthy or unattacked state to their "red" condition.

Drawing upon the results of Page and others (2012, 2013a, 2014a, 2014c) as well as other pertinent literature, Page and others (2014b) completed a critical review and digest of the literature on the subject of crown fire potential in recently attacked, mountain pine beetle-infested lodgepole pine forests during the red stage of attack. They found inconsistent results in the literature due to the use of inappropriate and/or un-validated fire behavior models based on inadequate descriptions of the mountain pine beetle-affected crown and canopy fuels. Van Wagner's (1977) crown fire initiation model, for example, in its present or some modified form is not applicable to mountain pine beetle-attacked stands because their very low foliar moisture content levels are not in aligned with the model parameterizing (Cruz and Alexander 2010).

Page and others (2014b) suggested that crown fire initiation and spread potential is higher in recently attacked forests compared to un-attacked forests and that a host of site specific factors such as outbreak severity, timing, and length could have important but as yet unknown impacts based on a set of limited fire behavior observations and re-examination of fire behavior modeling methodology. Due to the limitations of current fire behavior models and lack of quality data we propose that further advances in our understanding of crown fire potential in recently attacked forests will only be possible if a substantial effort is undertaken to document wildfires, prescribed fires, and/or conduct experimental fires.

Addressing Future Research Needs and Knowledge Gaps

As described by Page and others (2014b), the study of crown fire potential in recently attacked, bark beetle-infested stands will not be able to substantially progress until wildfire observations and/or experimental fires can be used to quantify several important fire behavior metrics, including, rate of spread, fireline intensity, fuel consumption, flame front residence time, and burn-out time under a variety of weather and stand conditions. Ideally, stands with varying amounts and proportions of bark beetle-altered foliage, distributed spatially in arrangements from random to highly clustered would be subjected to fire in order to quantify the relative impact of both the amount of red foliage and its spatial distribution. This would allow wildland firefighters to identify and rank the relative hazard of stands, in terms of crowning potential, containing the variety of mortality levels and spatial arrangements that are found naturally in forested landscapes. For example, we may eventually find that a critical level of red foliage exists such that until that level is reached, bark beetle-caused tree mortality may have little effect on crown fire initiation or spread. Additionally, we may also find that the spatial arrangement of the mortality within a stand (either highly clustered or randomly distributed) may have little overall impact on fire behavior. These questions can only truly be answered in the field, particularly as they relate to wildland firefighter safety and operations, which is where the need for such research ultimately arises. However, this does not preclude the use of physics-based models as a valuable research tool in these forests (Hoffman and others 20120) but even those models must be evaluated against field data in order to feel confident in their use, especially when it comes to firefighter safety.

Wildfire Resistance to Control in Lodgepole Pine Forests

Concerns about the impacts of mountain pine beetle-caused tree mortality on wildfire potential in lodgepole pine forests have to date largely focused on the potential for extreme fire behavior, including the development and spread of crown fires. Given that the fire environment in which wildland fire managers and firefighters work is composed of many interacting physical and human factors, viewing crown fire behavior as the only or even the most important outcome of the tree mortality associated with a mountain pine beetle outbreak is questionable. Proper assessment of wildfire potential entails a broader approach, which requires expanding the concept of wildfire resistance to control to include an analysis of all relevant factors and their interactions. In this regard, Page and others (2013b) advocated a holistic approach to analyzing the impacts of mountain pine beetle-caused tree mortality on wildfire potential in lodgepole pine forests on the basis of fire behavior characteristics, fire suppression operations, and firefighter safety considerations within the framework of the three recognizable stages of the approximate time since the initiation of an outbreak: "red" (~1 to 5 years), "gray" (~5 to 15 years), and post-epidemic (~15+ years).

Conclusions

Bark beetles are a natural disturbance agent in the conifer forests of western North America having caused periods of significant tree mortality for thousands of years (e.g., Brunelle and others 2008). Thus, the relatively recent tree mortality caused by eruptive outbreaks of these beetles and the direct and indirect effects on forest structure and fire behavior should also be considered a natural part of the life history of these forests (Wright and Heinselman 1973; Brown 1975; Lotan and others 1985).

Although the changes to forest structure, fuel loads, and subsequent fire behavior caused by the tree mortality are considered natural, there are significant consequences of these changes related to human factors such as wildland firefighter safety and fire suppression operations (Page and others 2013b). Fire managers and wildland firefighters alike should be cognizant of the impacts of recent tree mortality on potential fire behavior regardless of whether the changes are considered natural or not. Therefore, it is important that the research be undertaken, as outlined by Page and others (2013a, 2013b, 2014b), to quantify and understand the various factors affected by bark beetle-caused tree mortality that

impact potential fire behavior and the consequences of those changes for wildland firefighters (Moriarty 2014).

Given that there are still substantial uncertainties associated with crown fire potential in recently attacked forests, wildland firefighters should continue to be cautious when working in these forests and prepare for fire behavior that is not easily predicted using conventional operational fire behavior models and guidelines. It is only very recently that a rough guide to crown fire initiation and a model for predicting crown fire rate of spread for the red stage of bark beetle-attacked lodgepole pine forests has been developed in the context of the Canadian Forest Fire Danger Rating System (Perrakis and others 2014).

Acknowledgment

This work was supported by the Joint Fire Science Program projects JFSP 11-1-4-16 (MJJ) and JFSP 09-S-03-1 (MEA). The reviews by B.C. Hawkes and D.T. Hicks are hereby duly noted.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Forecasting Distribution of Numbers of Large Fires

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Abstract—*Systems to estimate forest fire potential commonly utilize one or more indexes that relate to expected fire behavior; however they indicate neither the chance that a large fire will occur, nor the expected number of large fires. That is, they do not quantify the probabilistic nature of fire danger. In this work we use large fire occurrence information from the Monitoring Trends in Burn Severity project, and satellite and surface observations of fuel conditions in the form of the Fire Potential Index, to estimate two aspects of fire danger: 1) the probability that a 1 acre ignition will result in a 100+ acre fire, and 2) the probabilities of having at least 1, 2, 3, or 4 large fires within a Predictive Services Area in the forthcoming week. These statistical processes are the main thrust of the paper and are used to produce two daily national forecasts that are available from the U.S. Geological Survey, Earth Resources Observation and Science Center and via the Wildland Fire Assessment System. A validation study of our forecasts for the 2013 fire season demonstrated good agreement between observed and forecasted values.*

Introduction

Forest fire danger rating systems typically rely on indices and components such as the Burning Index (BI) and the Energy Release Component (ERC) of the U.S. National Fire Danger Rating System (NFDRS) (Deeming and others 1977) to provide relative measures of potential fire severity. The BI is used to describe the potential amount of effort needed to contain a single fire in a particular fuel type within a rating area. The ERC is a cumulative or "build-up" type of index. As live fuels cure and dead fuels dry, the ERC values get higher, thus providing a good reflection of drought conditions. Theoretically it is assumed that doubling of fire danger indices, such as the BI or the ERC, would reflect a doubling of fire potential. Given some experience, fire managers can mentally associate fire danger indices with fire activity in their area, but questions remain, i.e., how can these heuristic validations be quantified in order to perform a statistical assessment? How can the qualitative 'fire potential' be translated into expected numbers of large fires, and where are fires most likely to occur across the national landscape? Guidance on these issues could substantially improve the management of national firefighting assets.

Because the location and timing of large fires is probabilistic in nature, it seems reasonable that the next step in fire danger forecast procedures should be to provide information that depicts large fire occurrence in probabilistic terms. Two products that do just that are discussed here: 1) a daily "Large Fire Probability" indicating the percent of the time that a small (1 acre) fire will grow to exceed 100 acres, and 2) a forecast of the "Expected number of large fires within a Predictive Service Area (PSA)". *PSA's* are sub-geographic areas of similar climate, fuels and topography defined by geographic area coordination center (GACC). For the second product, "large fires" are defined according to Monitoring Trends in Burn Severity (MTBS) protocol as 500+ acres in the eastern U.S. and 1000+ acres in the west (Eidenshink and others 2007).

The "large fire probability" indicates the risk of an ignition exceeding 100 acres, based on local fuel conditions, but this forecast does not take into account the probability of an ignition on the given day and location. The "expected number of large fires within a PSA" accounts for the risk of occurrence of a fire that burns an area larger than 500 (eastern U.S.) or 1000 (western U.S.) acres in size.

The fire danger index utilized for this work is the Fire Potential Index (FPI), developed by Robert Burgan and implemented by the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center and fully described in an earlier publication (Burgan and others 1998). The FPI was used because it was readily available and provides relatively high resolution (1 km) data for national scale mapping purposes. This paper briefly reviews the FPI model and the inputs it requires, and then describes the statistical models used to produce the two maps previously mentioned. Additionally, we measured the accuracy of the forecasted values by presenting reliability diagrams for the two maps. The statistical procedures presented in this work could be used to assess the forecast skill and accuracy of other fire danger metrics.

Fire Potential Index

The FPI is linearly scaled from 0 to 100, with 0 occurring when the vegetation is near or fully green and the 10

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

hour dead fuels are too moist to burn. The 10 hour dead fuel timelag represents fuels (stems, litter) 0.25 – 1.0 inch in diameter. The FPI is 100 when the vegetation is fully cured and the 10 hour dead fuel moisture is 2 percent.

Relative Greenness

Vegetation greenness is one of the primary inputs to the FPI calculations. It is assessed weekly via a Relative Greenness (RG) (Burgan and Hartford 1993) computed from the Normalized Difference Vegetation Index, which is derived from 1-km spatial resolution Advanced Very High Resolution Radiometer observations (Eidenshink 2006). The RG indicates the current level of vegetation greenness compared to its historical absolute maximum greenness. RG data are used to adjust the maximum live ratios for current conditions. The 1-km maximum live ratio map depicts the estimated maximum proportion of the total surface fuel bed that is green under the current greenness conditions.

The 1-km resolution Extinction Moisture Map was derived from the NFDRS fuel model map (Burgan and others 1998) by assigning a dead fuel extinction moisture value to each square kilometer of the conterminous U.S. (CONUS). The dead fuel extinction moisture is the moisture content above which it is assumed a fire will not burn.

The 10 hour dead fuel moisture map is calculated from National Weather Service National Digital Forecast Data gridded daily weather observations for 6 forecast days (Glahn 2003). The 10 hour fuel information is provided by the U.S. Forest Service Missoula Fire Sciences Laboratory. The FPI is a ratio between the relative dryness of the 10 hour dead fuels as a proportion of the moisture of extinction (dryness fraction), and the current greenness of the living fuels as a proportion of their maximum greenness (greenness fraction). Figure 1 shows the inputs to the FPI.

The general form of the FPI calculation is:

$$FPI = (1.0 - deadfrac) \times dr \times 100.0$$

where deadfrac = (calculated 10 hour dead fuel moisture)/(moisture of extinction) and dr = the proportion of the vegetation that is dead. The daily FPI and 6 forecast days are calculated once daily for the CONUS at a spatial resolution of 1 km. The maps are available from the USGS Earth Resources Observation and Science Center (http://firedanger.cr.usgs.gov/viewer/viewer.htm) and via the Wildland Fire Assessment System (http://www.wfas.net/index.php/large-fire-potential-and-fire-potential-indexes-external-products-107.

Methods

In a previous study (Preisler and others 2009), we established the relationship between FPI values and the conditional probability that an ignition within a given 1-km cell in a given day will result in a large fire using a logistic regression model. In this study, we extended the capability by determining the probabilities of having at least 1, 2, 3, or 4 large fires within a PSA in the forthcoming week.

The availability of large fire occurrence data from the MTBS project enables the assessment of FPI as a predictor of large fire occurrence. MTBS has mapped 14,945 large fires that occurred between 1984 and 2010 (Finco and others 2012). The MTBS history of large fires for 1984-2010 was used to develop the "background" large fire occurrence. Over 11,600 records of large wildfire occurrence in the CONUS were extracted from the MTBS database (prescribed fires were excluded). The background condition established the geographic and seasonal distribution of large fires. These data were augmented by a random sample of locations and

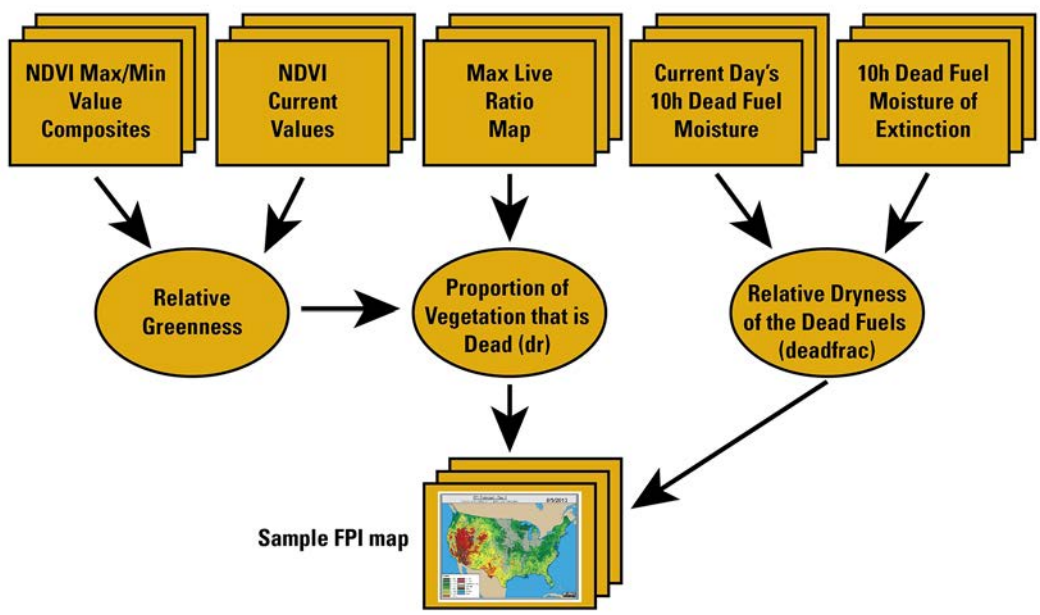

Figure 1—Inputs to the Fire Potential Index (FPI).

dates with no observed MTBS fires. Sampling of the areas with no MTBS fires was necessary to create a manageable data size. The total number of km×km×day, burned and unburned, samples in CONUS for the 26 years of the study period was over 350 million grid cells.

The next step was to establish the relationship between FPI and large fire occurrence in order to determine if FPI could be used as a predictor of large fire potential. We had produced FPI data using the 10 hour fuel moisture provided by the U.S. Forest Service Missoula Fire Sciences Laboratory since 2006. To determine this relationship, we sampled a 3x3-km grid (voxel) at the centroid of the perimeter of each large fire. The sampling was performed for 1663 large fires occurring in the years 2006, 2008-2010. FPI values were sampled for the day on which the fire was observed for the years 2006, 2008-2010 and the 6 days prior to the fire occurrence for the years 2008-2010. The 2006 forecast FPI data and the 2007 FPI data were not available. This sampling provided the FPI values for each of the 7 days in our 7-day forecast. In addition, we randomly sampled 19,661 3x3-km voxels outside the fire occurrence perimeters in order to discern how FPI represented burned and unburned areas.

Statistical Model

We developed a separate statistical model for each of the maps: 1) a map forecasting next-day conditional probability of an ignition (defined as a fire size of 1 acre) becoming 100+ acre fire, and 2) a map showing the expected distribution for the number of large fires within a PSA over the forthcoming week. Following are some details of the statistical models.

Conditional Probability of a 100+ acre fire

The conditional probability that an ignition within a given 1-km cell in a given day will result in a 100+ acre fire was estimated using the following logistic regression model:

$$\pi_{ij} = PR[Y_{ij} = 1 \mid m_{ij} = 1, x_{ij}] = \frac{\exp(\theta_{ij})}{1 + \exp(\theta_{ij})}$$

$$\text{with } \log\left[\frac{\pi_{ij}}{1 - \pi_{ij}}\right] = \theta_{ij} = A_i + \beta(x_{ij} - \bar{x})$$

where the random variable Y is a binary response variable with $Y_{ij} = 1$ if there was a 100+ acre fire at location j and date i, and zero otherwise; m_{ij} is the number of ignitions at ij (it is assumed that only one fire can occur in a 1-km^2 area in a given day); x_{ij} is the value of the FPI index at location j and day i; $\bar{x}$ is the mean FPI value over all locations and span of study. A_i and β are the intercepts and slope of the logit regression line to be estimated from the data. We estimated the spatially explicit intercepts by using a two-dimensional smoothing spline function (Hastie and others 2001). Further details of the estimation are presented in Preisler and others (2009).

The conditional probability forecast for April 21, 2014, is shown in figure 2. The accuracy of the forecast was assessed by producing a reliability diagram where the forecasted probabilities of 100+ acre fires are compared with the observed frequency of occurrence of 100+ acre fires. Specifically, we used cross validation by dropping one year's worth of data and fitting a logit line in equation 1 using the

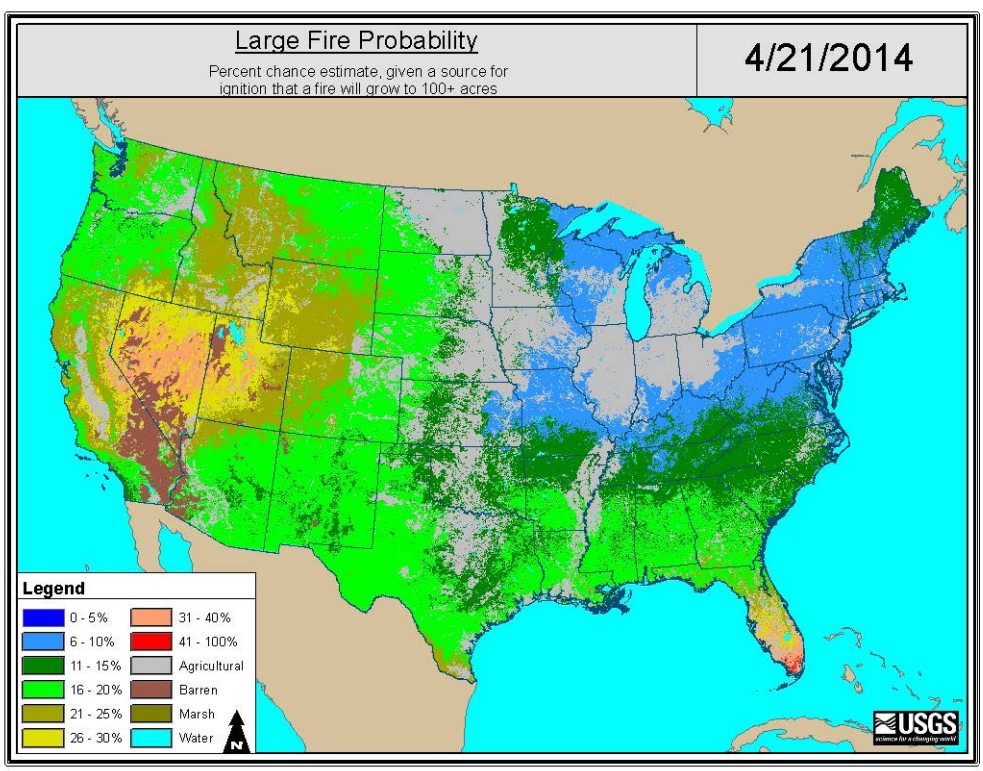

Figure 2—The conditional probability map for 100+ acre fires given ignition for April 21, 2014.

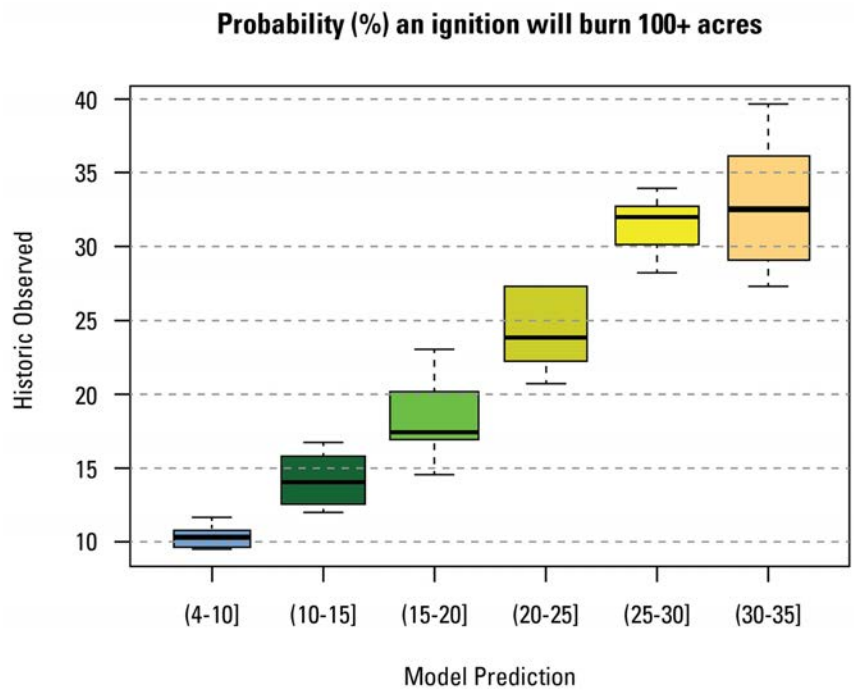

Figure 3—Reliability diagram for the daily forecast of conditional probability that an ignition will burn more than 100 acres. The box colors correspond to colors in forecast of conditional probability.

remaining years. Next we used the fitted model to evaluate the probabilities for the dropped year. The fitted values were then grouped into 40 probability levels and the fraction of observed large fires in each probability level was calculated. The reliability diagram we produced was a parallel boxplot (figure 3) showing the distribution of observed values in each category of the legend in the daily conditional probability maps. By matching the colors of the boxes in figure 3 with the colors in the forecast (figure 2) one can assess the accuracy of the map at each color level. For example, the light green box (corresponding to light green regions of the map) with model prediction category of (15-20 percent) states that in the 3 years of our study, we observed values from 15 to 23 percent with a median of 17 percent. For the green/yellow regions of the map with predicted probabilities of (20-25 percent), we observed values from 21 to 27 percent with a median at 23.5 percent and so on.

Forecasted distribution of number of large fires per PSA in upcoming week

In this section, we develop the distribution of expected number of large fires in the upcoming week as a function of the forecasted FPI values. Using the 26 years of MTBS data on locations and dates of large fires in CONUS and a random sample of voxels (1km x 1km x day units) with no MTBS fires, we estimated a logistic model for the probability of a large fire occurring in a given 1-km^2 grid cell on a given day. Estimation was done in two steps. First we estimated p_A, the average probability of a large fire on km^2 x day voxel regardless of year, using the model:

$$\log it(p_{Ai}) = \alpha + \log(1/\pi_1) + s(east_i, north_i, day_i)\ i \epsilon R \quad [2]$$

where R is the set of all 1km^2 x day voxels; p_{Ai} = Pr[Y_{Ai} = 1]; Y_{Ai} is a binary variable equal to one when there is a large fire in voxel i and zero otherwise; α is the intercept of the logit line; π is the known sampling proportion for voxels with no MTBS fires. We used a variable sampling proportion with larger number of random voxels chosen during the fire season. The term log(1/π), was necessary to account for the disproportionate sampling levels of locations with and without MTBS fires. The term s(east, north, day) is a three-dimensional smooth surfaceof location and day-in-year estimated from the data by penalized regression methods (Wood 2011). Penalized regression uses iteratively re-weighted least squares to estimate model coefficients and cross validation to estimate the smoothing parameters. Estimation was done using the generalized additive model (GAM) within the free statistical computing platform (R Core Team 2013) The estimated probability, p_A, represents the spatial and seasonal patterns of large fires due to factors (such as vegetation types, topography or ignition sources) that are assumed to be invariant over the years. The background spatial patterns for 4 days in the year, as given by $\widehat{P_A}$, are shown in figure 4. These maps (and hence the model) capture the average patterns of large fire occurrences over the CONUS fire season. The pattern, as indicated by the hot spots (locations with highest probabilities) start in the southwest in the beginning of the season where fuels are expected to be dry early. As the fire season progresses, the hot spots move to the northwest due to the many lightning caused fires. At the end of the season, we note some hot spots persisting in southern California through October due to dry conditions and human caused ignitions.

Once the background spatial and seasonal patterns are estimated we used the 7-day forecasted FPI values to estimate departures from 'norm' due to daily variability in fuel moisture. We developed seven logistic regressions, one for each day in the upcoming week, as follows:

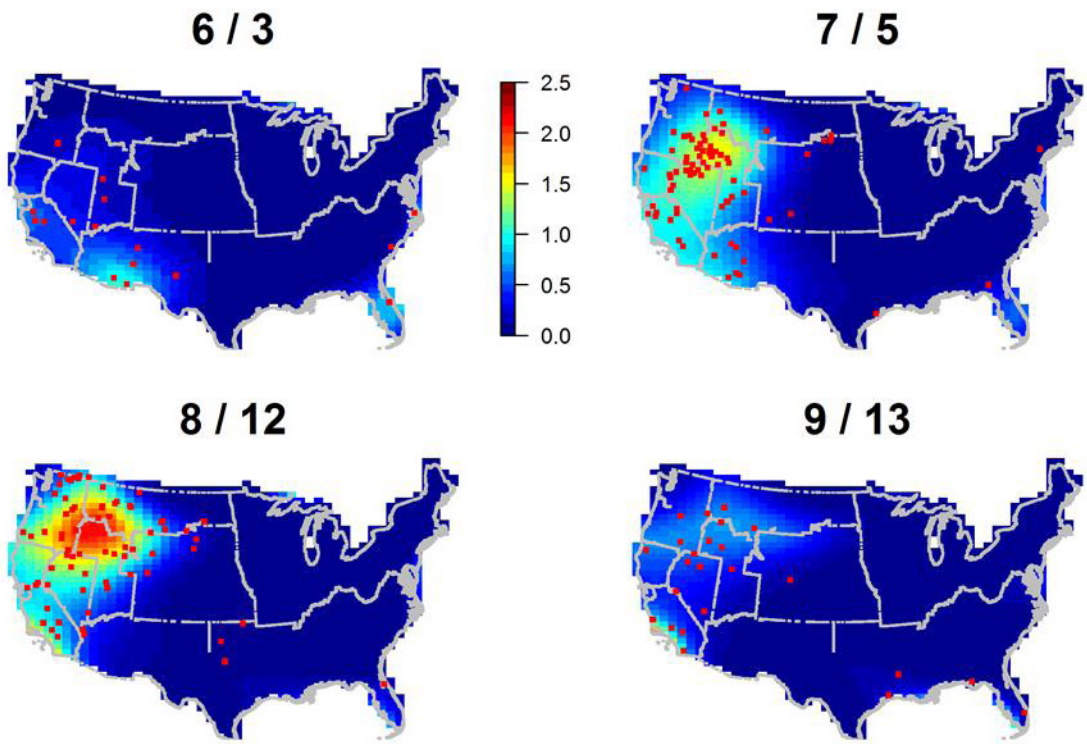

Figure 4—Estimated background probabilities of a large fire for four periods (days) during an annual fire season. The units in the color legend (vertical bar) are number of large fires ($1/10^6$ scale) per km^2 per day. The red dots are locations of large fires (MTBS fires) on that day during the 26-year study period. As the fire season progresses, the hot spots move to the northwest due to the many lightning caused fires. At the end of the season, we note some hot spots persisting in southern California through October due to dry conditions and human caused ignitions. The red dots are locations of large fires (MTBS fires) on that day during the 26-year study period.

$$logit(P_{ki}) = logit(\widehat{P_A}) + s(FPI_{ki}) \text{ with } k = 1,...,7 \text{ and } i \in R \quad [3]$$

and where FPI_{ki} is the forecasted FPI value for k^{th} day in upcoming week; $s(FPI_{ki})$ is a non-parametric spline function estimated from the data (Wood 2011); $p_{k\,i} = \Pr[\,Y_{ki} = 1]$; Y_{ki} is a binary variable equal to one when there is a large fire in voxel i and zero otherwise. We used seven different estimated logit lines because it is anticipated that the relationships between 1,2,…7 days-ahead forecasted FPI values and probability of fire will be different with FPI_1 having more forecast skill than FPI_2, etc. It is to be noted that the fire potential index did have skill in predicting large fires in that the odds of a large fire increased significantly with increasing FPI values. For example, we estimated a 2.6(1.8 – 3.8) times increase in the odds of a large fire on days with a forecasted FPI value of 90 relative to an average day with FPI equal to 40.

Given estimates for p_{ki}, the probability that a large fire will occur in voxel i in the upcoming week is equal to $p_i = p_{1i} + \sum_{k=2}^{7} \prod_{j=1}^{k-1} (1 - p_{ji}) p_{ki}$. The probability that more than one fire will occur in a given 1-km^2 grid cell in a given week is negligible and therefore is assumed to be zero. Consequently, we can assume that the random variable, Y_i, defined as one if there is a large fire in a given 1-km^2 grid cell in the upcoming week and zero otherwise, is a binary variable with probability of success given by p_i. Additionally, it is assumed that, given the explanatory variables used in our models (i.e., FPI and spatial location), the binary variables Y_i are independent.

In order to obtain the number of large fires in a given PSA in a particular week we need to sum the independent Bernoulli variables, Y_i, over all 1-km^2 grid cells in the PSA. The total number of fires per PSA per week, N_u (u = 1, … 245 PSA's in CONUS), is given by $N_u = \sum_{i=1}^{I_u} Y_i$ with I_u = number of 1-km^2 grid cells in the uth PSA. The distribution of N_u was approximated by the Poisson distribution with $E[N_u] = \lambda = \sum_{i-1}^{I_u} p_i$ (Le Cam 1960).

The second forecast produced in this study is the expected values of the Poisson distribution described above with a legend that gives the probabilities of exceeding x number of large fires (x = 0, 1, 2, 3, or 4+) evaluated from the Poisson distribution as follows:

$\Pr[\,N_u > x\,] = 1 - F_x(\lambda)$ where $F_x(\lambda)$ is the Poisson distribution function and λ is the estimated expected value of N_u as given above. For each value of λ (and hence for each color on the map) the legend gives the probabilities that there will be more than 1, 2, 3, or 4 large fires in the PSA in the upcoming week x (figure 5).

The accuracy of the forecast was assessed by producing a reliability diagram where the forecasted probabilities are compared with the observed frequencies of large fires. The reliability diagram requires the calculation of the 7-day forecasted FPI values for each 1-km^2 grid cell. These FPI values were not available for the historic data because FPI were

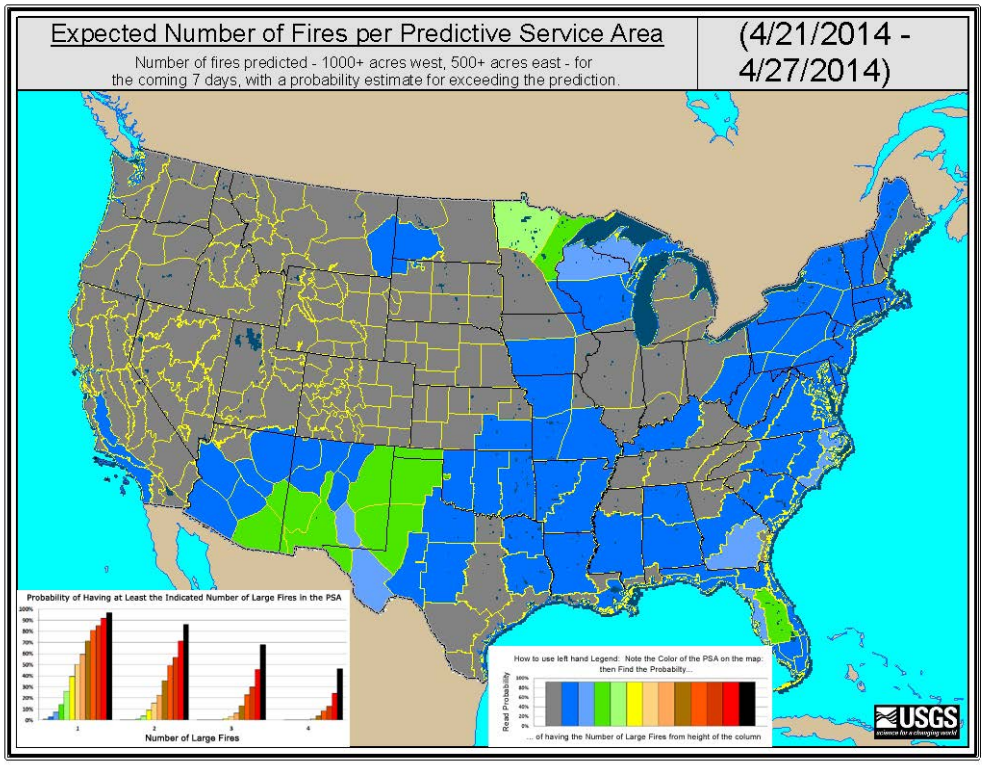

Figure 5—Forecasted distribution of total number of large fires in the upcoming week. The legend gives the probability of exceeding (x - 1) large fires (x = 1, 2, 3, or 4+) for each color in the map. Predictive Service Areas delineated with yellow outline.

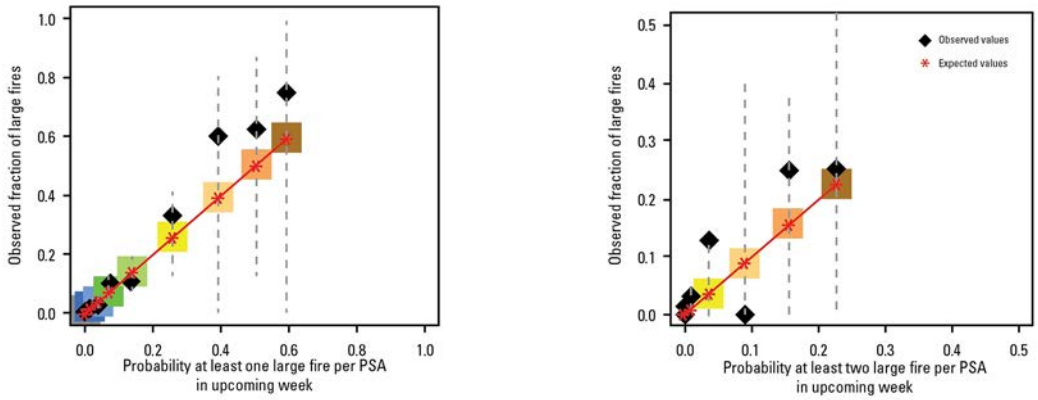

Figure 6—Reliability diagram for forecast of distributions of total number of large fires per Predictive Service Area (PSA) per upcoming week. The colors correspond to those used in the forecast (figure 5). The black diamonds are the observed fraction of PSA/week with at least one (left panel) or two (right panel) large fires in each of the color categories. The dashed vertical lines are the 95-percent confidence bounds. Specifically, confidence bounds indicate the range of possible values to expect when the forecasted value is at the indicated level.

calculated for all voxels with fires but only a small sample of voxels with no fires. Consequently, we were able to compare the observed and forecasted values for only 3 months starting July 15, 2013, when the maps started being produced in real time and FPI values calculated for each 1-km^2 grid cell in CONUS. The short period over which we were able to assess the accuracy of the model meant that we had very few observations, in particular for the grid cells with the highest probability values. This lead to having large confidence bounds for the highest probabilities (figure 6). Nevertheless, there seems to be reasonable correlation between the observed and predicted values. We plan to update the reliability diagram after the next fire season.

Conclusions

This study has shown that statistical procedures can predict the probability and expected number of large fires on a national scale, as well as provide a measure of the reliability of these predictions. Given that one of the major uses of any fire danger rating system is the prepositioning of personnel and equipment, it seems worthwhile to implement a limited field test to compare prepositioning decisions made with current methodology, to those augmented with the tools presented here. This would familiarize a few fire managers with a statistical approach to making preparedness

decisions while another year of data is collected for analysis to reduce the size of the confidence bounds. It would also generate discussion on whether these fire probability maps can augment the current decision-making processes and if so, how they might best be used. If the results of this effort, which would necessarily rely on the FPI for a measure of fire danger, are positive, further work could be done to determine whether adding standard NFDRS indexes would result in models with better forecast skill and, consequently, better decisions.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Assessing Predictive Services' 7-Day Fire Potential Outlook

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Abstract—*The Predictive Services program was created under the National Wildfire Coordinating Group in 2001 to address the need for long- and short-term decision support information for fire managers and operations personnel. The primary mission of Predictive Services is to integrate fire weather, fire danger, and resource availability to enable strategic fire suppression resource allocation and prioritization. Each Geographic Coordination Area (GCA) is comprised of individual forecast zones called Predictive Service Areas (PSAs). In 2006, Predictive Services began production of the 7-Day Significant Fire Potential Outlook for each PSA on weekdays during the core fire season to support efforts at informed regional and national fire suppression resource allocation and prepositioning. The Fire Potential Forecasts are made on a categorical scale of 1 to 9 for the current day and each of the subsequent 6 days, by combining the following factors: forecasted fuel dryness level, ignition triggers (from lightning and recreation), critical burn environment conditions (windy, unstable, hot and dry), and resource availability. We utilized historical fire occurrence data and archived forecasts to assess the performance of the 7-Day Outlook product in predicting fire activity, fire escape, and large fire potential, ultimately to characterize the effectiveness of this tool for prepositioning national firefighting resources. The historical fire occurrence data track ignitions on all land ownerships (Short and others 2013); from this dataset, we established number and location of ignitions and final fire size for the years 2009-2011 for the Northwest and Southwest GCAs. We then matched historical ignitions to the corresponding PSA and appropriate forecast for the current day and each of the six days prior to the ignition date. Final fire size was used as our metric to establish whether an ignition escaped initial attack, with fires greater than 300 acres considered escaped. We obtained Active Fire Detects from the MODIS satellite from the U.S. Forest Service to provide a relative measure of daily large fire activity. Active Fire Detects were subset to within 2 km of wildfire perimeters from the Monitoring Trends in Burn Severity database, which excluded most, if not all, detects from agricultural and prescribed burns while retaining detects associated with large fires. Our results show that 7-Day Outlook values demonstrate some skill in prediction of fire ignition, fire escape, and large fire activity in the Northwest and Southwest GCAs, with better-than-random prediction in the Northwest GCA as a whole, although there is some variation in this relationship across PSAs.*

Introduction

The Predictive Services program was established within the National Interagency Coordination Center (NICC) in 2000, with funding from the National Fire Plan. The NICC represents a collaborative effort among the United States land management agencies, with the focus of supporting resource mobilization (e.g., fire crews, incident management teams, and airtankers) for wildfires and other emergency incidents. The Predictive Services program was developed specifically to enhance decision-making capabilities related to allocation of fire suppression resources through proactive anticipation of significant fire activity (http://www.predictiveservices.nifc.gov/predictive.htm, accessed 5/8/2014).

Predictive Services issues the 7-Day Significant Fire Potential Outlook (a.k.a. 7-Day Outlook) on weekdays during the core fire season for individual Predictive Services Areas (PSAs) within each Geographic Coordination Area (GCA) across the nation (figure 1). PSA boundaries may represent geographic areas of similar climate based on statistical correlation of observed weather and fuel moisture data, or may be based on political or land ownership boundaries, depending on the GCA. PSA boundaries have changed over time in response to input from GCAs (figure 2). The 7-Day Outlook uses forecasted fuel dryness and specific high-risk weather events to predict the location and timing of demand for regionally and nationally shared suppression resources. Thus, it is essentially designed to anticipate significant fire activity. More specifically, Predictive Services defines "Significant Fire Potential" as "the likelihood that a wildland fire event will require mobilization of additional resources from outside the area in which the fire situation occurs" (www.nwccweb.us/content/products/fwx/fdrop/FDROP.pdf, accessed May 9, 2014). "Significant fires" are generally defined to be those larger than a threshold size, which vary geographically, based on historical fire sizes.

Each GCA issues 7-Day Outlook forecasts for their own PSAs, and they have reliably done so since 2007. The methods were pioneered by Terry Marsha from the Northwest GCA (Terry Marsha, personal communication, May 5, 2014). Other GCAs have adopted similar approaches, but the

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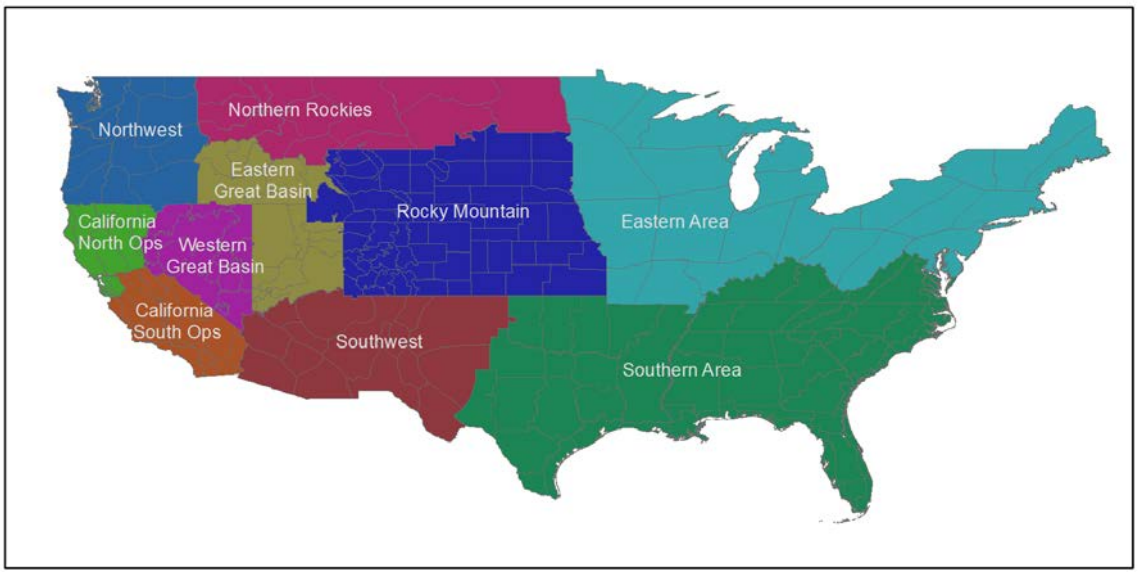

Figure 1—Geographic Coordination Areas (GCAs) of the conterminous US. The boundaries of the Predictive Service Areas (PSAs) for the year 2012 are shown in gray.

meteorologist in each GCA has the latitude to develop and implement variations on the methods, in order to incorporate regional differences in weather and fire regime. In some GCAs, the forecast methods have changed over time, as the meteorologist has endeavored to improve the performance of the forecasts. Because of regional variations inherent in the 7-Day Outlook calculations, it is not a homogenous product for the continental US.

The 7-Day Outlook is an important factor in decisions concerning allocation and positioning of firefighting resources at both the regional and national levels. At the GCA level, Predictive Services forecasts may prompt resource allocation personnel to move firefighting resources within the GCA, although movement of resources is at the discretion of resource managers and is not automatically triggered at specific forecasts. Prepositioning resources ahead of anticipated fire activity can be costly, so this tends to occur only when the forecast calls for high likelihood of a significant fire event (Terry Marsha, personal communication, May 5, 2014). The National Multi-Agency Coordinating Group (NMAC) holds national-level authority for direction and control of suppression resource allocation among GCAs (National Multi-agency Coordinating Group 2013). The NMAC uses the 7-Day Outlook to help inform resource allocation decisions across GCA boundaries during times of elevated national preparedness due to high fire activity and associated resource scarcity. However, the current approach is fairly subjective, balancing existing fire activity and risks, socio-political considerations, and forecasted weather.

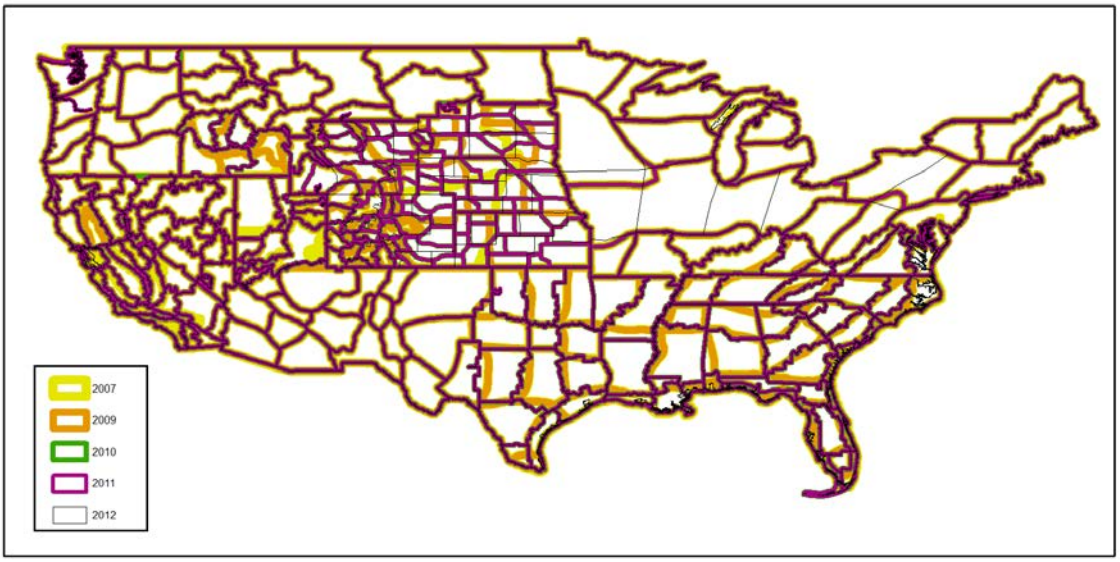

Figure 2—Boundaries of Predictive Service Areas (PSAs) in the conterminous US. Boundaries have changed significantly in some GACCs since their inception in 2006.

While the 7-Day Outlook has been reviewed and revised by some GCAs, a systematic effort to assess the product at the level of the conterminous US over the period of record has not been undertaken. Given the goals of Predictive Services in providing direction to managers regarding positioning of fire suppression resources, in this manuscript, we report results of initial analysis of the skill of the 7-Day Outlook in predicting wildland fire activity through statistical comparison of the daily forecast values with number of ignitions based on historical fire occurrence data. Additionally, we investigate forecast skill in terms of predicting lightning and recreation ignitions, escaped fires, and large fire activity. Skill of forecasts was assessed by checking if the observed distributions show a positive pattern in numbers of ignitions, escapes, or fire activity with heightened forecast level. Initial results for the Northwest and Southwest GCA are reported here.

Methods

Datasets

To assess the skill of the 7-Day Outlook, we first obtained archived daily 7-Day Outlook forecast values by PSA for the Northwest (NWA) and Southwest (SWA) geographic areas. These preliminary analyses were spatially constrained to these two GCAs, and temporally constrained to 2009 to 2011, in order to refine our methods prior to initiating a nationwide analysis. The 7-Day Outlook forecast may take on any one of nine categorical values (table 1). While the overall goal of the 7-Day Outlook is to predict significant fire activity, forecast level 4 is associated with lightning ignitions in particular, while forecast level 8 is associated with ignitions from recreation activities. Of the nine forecast levels, levels 1, 2, and 3 are based on fuel dryness alone, and are usually estimated by a combination of indices including Energy Release Component, 10- or 100-hour timelag fuel moisture, or Burning Index, depending on the GCA and PSA. The rest of the forecast values (4-9) are related to conditions with increased likelihood of fire ignitions (lightning or high recreation) or a more favorable burn environment (windy, unstable, hot and dry, or dry). These forecasts represent a "high risk" alert, and are issued only when the meteorologist assesses the outright probability of a new large fire as greater than or equal to 20 percent. These values appear much more rarely, and are triggered by the weather forecast information and thresholds that are unique to each GCA. For example, the NWA currently uses empirical regression equations between the predicted amount of lightning, fuel dryness, and predicted number of fire starts to decide when to issue a forecast of 4 (lightning ignition trigger). They rarely use the other forecast values because the required "20 percent probability of a large fire" threshold is virtually never attained for any event other than a lightning event. Other GCAs issue burn environment and ignition trigger forecast values based on the expert opinion of the meteorologist, and in some cases, the meteorologist will factor in the scarcity of available firefighting resources. Aside from the fuel dryness measures (values 1-3), the forecast values are not ordinal; for example, a 9 does not indicate higher significant fire potential than an 8.

While the forecast is issued daily for the current day and next six days, our initial analysis concentrates on the forecast values issued the same day as the fire activity took place (referred to as the Day 1 forecast). We report limited preliminary analysis of the forecast value from six days prior as well (referred to as the Day 7 forecast).

To compare historical predicted fire occurrence (via the 7-Day Outlook) with actual historical fire occurrence, we utilized the national all-lands wildfire occurrence database (FOD; Short 2013). Fire ignition locations from the fire occurrence database were intersected with annual PSA boundaries in ArcGIS 10.1. We utilized the cause field from the FOD to flag lightning-caused fires, and fires ignited by campfires, children, and fireworks were flagged as recreation-caused events. We also used final fire size from the FOD to assess whether a fire escaped initial attack containment efforts; for our initial analysis, escape was defined as any incident with a final fire size greater than or equal to 300 acres. In future research, we will also use the Significant Fire Size set by each PSA as an indicator of escaped fires, but this information was not available at the time of our analysis.

Table 1—7-Day Outlook forecast values. The daily forecast can take on any of these 9 values.

	Forecast Value	Forecast Description	Fire Environment
Increasing fuel dryness ↓	1	Moist Fuel Conditions	Little or No Risk of Large Fire
	2	Dry Fuel Conditions	Low Risk of Large Fire
	3	Very Dry Fuel Conditions	Low-Moderate Risk of Large Fire
High risk	4	Lightning	Ignition Trigger
	5	Windy	Critical Burn Environment Factor
	6	Unstable	Critical Burn Environment Factor
	7	Hot & Dry	Critical Burn Environment Factor
	8	High Recreation	Ignition Trigger
	9	Dry	Critical Burn Environment Factor

While the FOD gives information regarding the ignition date, cause, and final fire size, it cannot be used to establish the level of daily fire activity that may lead to significant resource utilization. Theoretically, the ignition date and containment date provide a means to establish the number of concurrent fires, but the FOD cannot be used to determine how much area was burned by a fire on any given day between ignition and containment. Further, the criteria for declaring fire containment are inconsistent between agencies, and declaring containment of a fire is inherently subjective. In order to establish an objective measure of significant daily fire activity by PSA, we utilized the Active Fire Detects product from the MODIS satellite (downloaded from http://activefiremaps.fs.fed.us/gisdata.php on 1/17/2014). The MODIS satellite passes overhead twice daily, and anomalies in the middle infrared and thermal infrared bands are used to identify 1-km pixels with active fires (Giglio and others 2003). Due to the 1-km resolution, this product preferentially detects larger fires, so in general, a MODIS Active Detect will be related to a significant fire event. However, the dataset also contains detects from prescribed fires and agricultural fires, which we did not want to include in our analysis since they usually do not require mobilization of additional suppression forces. In order to isolate Active Detects associated with wildfires, we selected all Active Detects within 2 km of fire perimeters in the Monitoring Trends in Burn Severity dataset (MTBS; downloaded from www.mtbs.gov on 4/25/14, data version released 4/16/2014). The MTBS dataset contains a field identifying whether the fire was prescribed, wildfire, wildland fire use, or of unknown origin; we omitted prescribed fire records for this analysis since they would not be intended to require mobilization of suppression resources.

Statistical Analysis

We confined our initial analysis to the NWA and SWA, where PSA boundaries have changed little during the analysis period of 2009 to 2011. Boxplots were used to assess the total number of ignitions by forecast level, as well as the number of lightning ignitions, recreation ignitions, escaped fires, and daily fire activity. We calculated 95-percent thresholds for each of these factors, in order to establish confidence levels. Skill of the forecast was assessed in more detail within the NWA. Due to time constrains, we were not able to perform similar analysis for the SWA. In the NWA, we used the log likelihood ratio to test whether the distribution of fire activity given the forecast was different from what would be expected randomly. The R statistical package was used to perform a G-test of independence with William's correction, and p-values were reported as a test of significance. Our hypotheses for the log likelihood ratio were as follows:

- Null hypothesis: fire activity occurs randomly with respect to forecast (therefore, the differences observed in the parallel boxplots are not statistically significant)
- Alternative hypothesis: fire activity is significantly different than random with respect to the forecast (the differences observed in the parallel boxplots are statistically significant)

In this work we conclude that a forecast has skill if the null hypothesis is rejected (in other words, fire activity is significantly different than random with respect to the forecast) and the boxplots show a positive pattern in numbers of ignition or escapes with heightened forecast risk level (in other words, ignitions or escapes increase across the ordinal dryness categories 1-3 and are higher in the high-risk categories 4-9 than in categories 1-3).

Results

Patterns demonstrating the skill of the 7-Day Outlook in the NWA and SWA are evident in boxplots appearing in figures 3, 4, and 5. The number of ignitions per PSA is lower at dryness level 1 (moist) than at dryness levels 2 (dry) and 3 (very dry), which have roughly the same distribution of number of ignitions (figure 3). The lack of an increase from category 2 to category 3 is perhaps not surprising, since the dryness levels were calibrated to the probability of large fires, not total ignitions (Terry Marsha, personal communication). The dryness level forecasts (levels 1 to 3) were issued more frequently than the other forecast values, with the number of forecast days decreasing as the dryness level increases (table 2). This seems appropriate, since a dryness level of 3 is meant to convey an awareness of heightened fire potential. However, since the distribution of number of ignitions was similar during forecast levels 2 and 3, it seems the forecast does not exhibit skill in discerning the number of ignitions during dry versus very dry conditions. Forecasts are issued relatively rarely for ignition trigger and critical burn environment values (levels 4 through 8), with the high recreation ignition trigger (8) being issued only four times during the period of analysis.

On average, a higher number of historical ignitions occurred coincident with ignition trigger and critical burn environment forecast values (4 through 8) than for dryness level 1 (moist), indicating some skill in predicting ignitions in these forecast levels as well. In the Day 1 forecast, on average, the highest numbers of ignitions occurred under forecast level 8 (high recreation), followed by level 6 (unstable), and level 4 (lightning), with the ignition numbers being higher than those for dryness levels 2 and 3. The high recreation forecast is most often issued on the 4th of July, when the FOD shows elevated levels of ignitions from fireworks. Evidently, days that the meteorologists forecast lightning do indeed experience higher lightning levels, judging by higher ignitions on those days. The level 6 forecast indicates unstable atmospheric conditions, which are often associated with thunderstorm development and lightning. Days with forecast level 5 (windy day) and level 7 (hot and dry) did not have higher numbers of ignitions than dryness levels 2 and 3, despite indicating high risk. Surprisingly, the patterns are relatively similar for the Day 1 and Day 7 forecasts, indicating that the 7-Day Outlook might be useful in prepositioning resources up to 7 days ahead, at least in the case of forecast

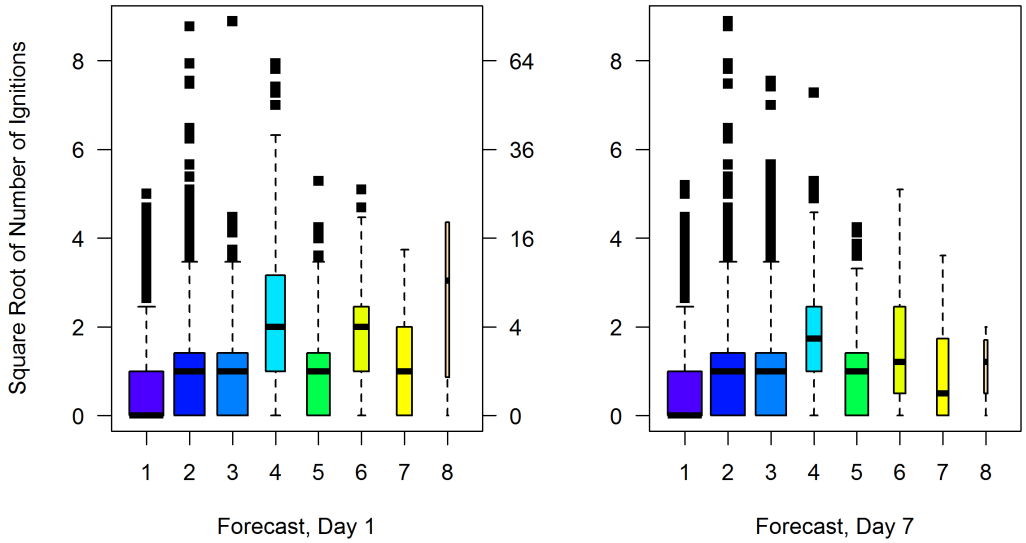

Figure 3—Distributions of number of ignitions (boxplots) in the Northwest and Southwest GCAs by forecast value, for forecast for current day (left panel), and forecast from 7 days before (right panel). Note that the y-axis represents the square root of the number of ignitions. The width of each boxplot is proportional to the square root of the number of times that value is forecasted (table 3). The square root scale was used on the y-axis to facilitate the visual comparison between distributions of counts that are heavily skewed to the lower value. In samples where the distribution of counts includes a few large outliers, patterns at the lower counts may be hard to see in plots with the original scale.

Table 2—Number of times each forecast level was issued for Day 1 forecasts, between 2009 and 2011, in the Southwest and Northwest Geographic Coordinating Areas (GCAs).

Forecast Level	1	2	3	4	5	6	7	8
Count	8805	4606	2237	139	590	61	75	4

levels 4, 6, and 8 (figure 3). To date, the bulk of our analysis has been focused on the Day 1 forecasts, therefore, comparison of Day 1 to Day 7 forecast results are preliminary. Ultimately, we will assess skill of the full range of available forecast data to determine forecast skill with respect to the timeframes needed for prepositioning a variety of suppression resources (e.g., airtankers vs. ground crews).

Boxplots give the 25th, 50th, and 75th percentiles of the distribution in addition to outliers. Ninety-fifth percentiles may also be a useful tool for managers. We calculated these for the number of ignitions, lightning ignitions, recreation ignitions, detects, and escaped fires, by forecast value and added them to the boxplots (figures 4 and 5). For example, historically, fewer than four ignitions per PSA were observed on 95 percent of days forecasted as moist (level 1) conditions (figure 4). The 95th percentile for ignitions is highest for days with lightning forecasts (level 4), at approximately 40 ignitions. Ignition numbers were not normalized to PSA size, a factor which will be included in future analyses.

Because forecast level 4 represents a special condition where the probability of a significant fire event started by lightning is assessed as greater than or equal to 20 percent by the GCA meteorologist, we analyzed lightning ignitions as a separate case (figure 4). The results are quite striking, with the number of lightning ignitions during forecast level 4 being markedly higher than for other forecast values, with a median value of approximately 3 versus 0, and 95th percentile of approximately 40 versus 1 to 16 for other forecast values.

Because forecast level 8 is issued only during days where the probability of a significant fire being ignited due to recreation activities is assessed as greater than or equal to 20 percent, we also analyzed recreation ignitions as a separate case. The results demonstrate higher levels of recreation ignitions on days with a forecast of 8, with a median of approximately 1 ignition on those days versus 0 ignitions during days with other forecast values, and 95th percentile of approximately 15 ignitions versus 0.5 to 4 for other forecast values (figure 4). Note that in the three years and two GCAs of the study, there were only four days with a Day 1 forecast of 8.

As noted previously, the forecast was designed to predict significant fire activity rather than ignitions, although of course ignitions are a prerequisite to significant fire activity. We assessed the performance of the forecast with regard to escaped fires (figure 5). Note that we used the Day 1 forecast from the day after the fire ignited to analyze escaped fires, since a fire ignited one day would not be expected to escape containment efforts until the next day. Because escaped fires are rare, the median (50th percentile) number of escaped fires

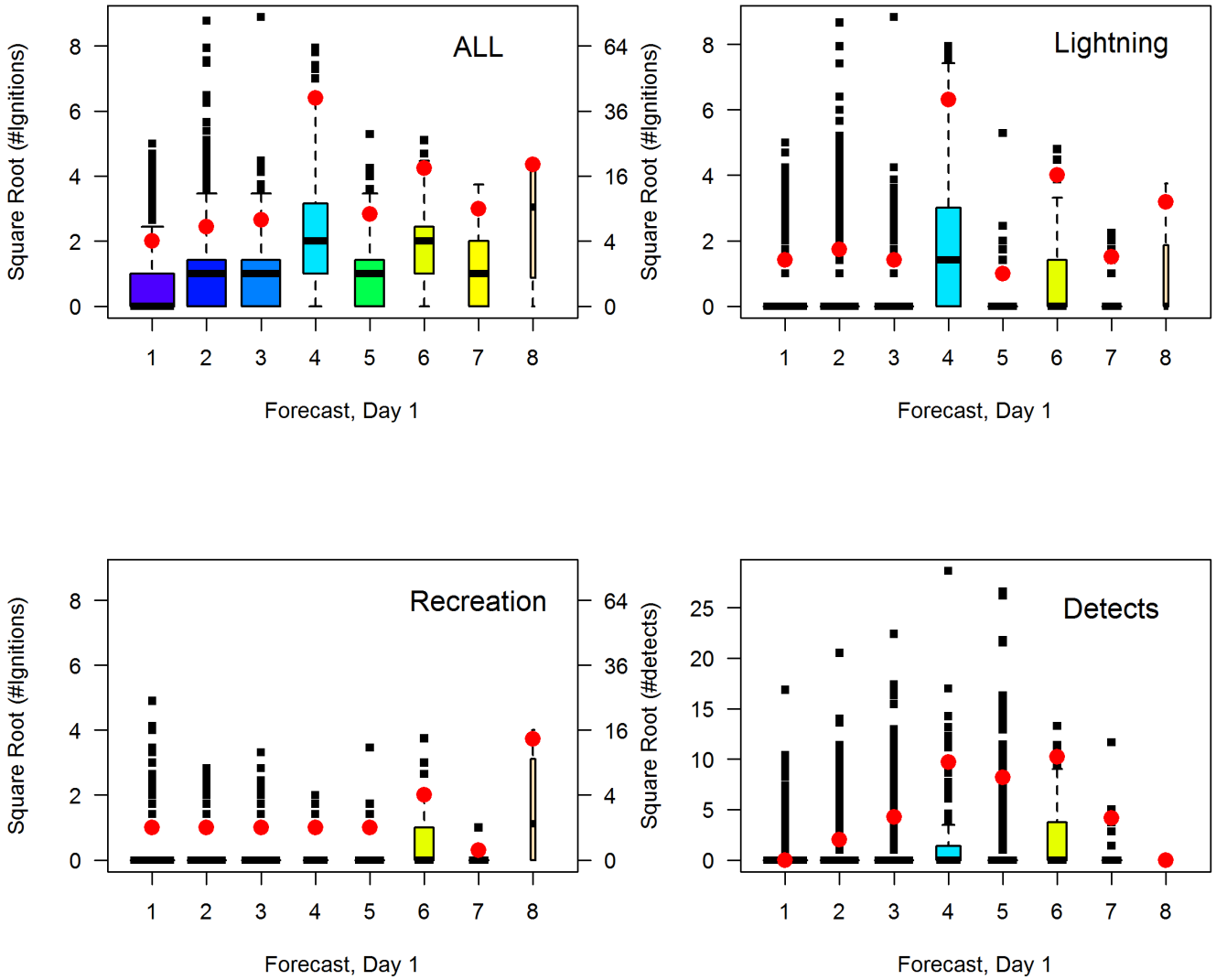

Figure 4—Distribution of number of ignitions, lightning ignitions, recreation ignitions, and MODIS active detects in the Northwest and Southwest GCAs by forecast value. The red dot signifies the 95th percentile.

on any given day per PSA is zero across all forecast values. However, the 95th percentile is 1 escaped fire during Day 1 forecasts of 3 (very dry), 4 (lightning), 5 (windy), and 7 (hot and dry), indicating that managers may expect no escapes on 95 percent of the days when the forecast is 1 (moist), 2 (dry), 6 (unstable), or 8 (recreation). In other words, there is less than a 5 percent chance of having at least one escape. But for forecast levels 3 (very dry), 4 (lightning), or 7 (hot and dry), the chance of at least one escape is more than 5 percent. The number of cases in forecast level 8 is too small to make any conclusions about the skill of the forecast for escapes for this level. It should be noted that we used a threshold of 300 acres across all PSAs to indicate an escaped fire, while each PSA has a different threshold for determining the size of a "Significant Fire", varying from 50 to 10,000 acres.

Daily fire activity was examined using MODIS active detects as a proxy. The median number of detects, and thus in general area burned by large fires, is zero across all forecast levels (figure 4). However, the 95th percentile value increases exponentially with dryness level, from zero for dryness level 1 (moist) to approximately 4 for dryness level 2 (dry), to approximately 16 for dryness level 3 (very dry) and level 7 (hot and dry). On a day with a forecast of 4, 5, or 6, there is 5 percent chance of having approximately 100 detects or greater, which indicates widespread burning. Level 8 (recreation) does not appear to be tied to active detects, similar to the pattern seen in escaped fires for Day 1 forecasts.

The statistical significance of the differences seen in the boxplots was tested using the log likelihood ratio. The log likelihood ratio tests, which were performed for the Day 1 forecasts in each PSA in the NWA, also indicate general skill of the 7-Day Outlook in predicting large fire activity (table 3). In the GCA as a whole (totals for all PSAs), fire activity with respect to the forecast occurred differently from random, indicating the forecast has skill at predicting ignitions, recreation ignitions, lightning ignitions, escaped fires, and MODIS Active Detects at the GCA level ($p <= 1.06e-14$). The distribution of recreation ignitions by forecast level was significantly different from random in all 12 PSAs. In 11 of 12 PSAs, the distribution of lightning ignitions and all ignitions by forecast level was significantly different from random. Assuming that the patterns seen in the NWA and

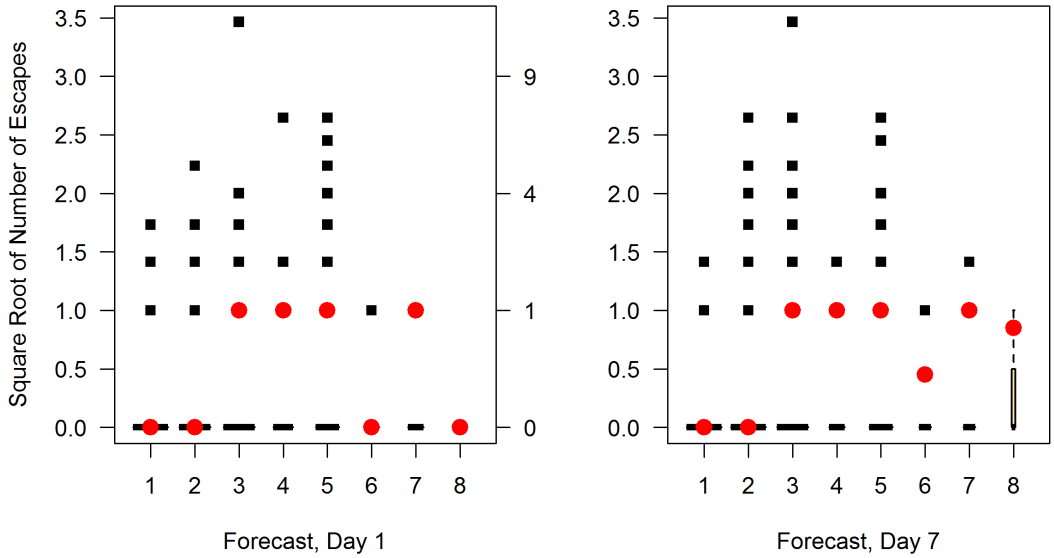

Figure 5—Distributions of number of escaped fires (final fire size > = 300 acres) using the same day forecast (left panel) and forecast value from seven days ahead (right panel) in the Northwest and Southwest GCA by forecast value. The red dot signifies the 95th percentile. Escaped fires were lagged one day, assuming that a fire ignited on one day will not usually escape initial attack and grow to 300 acres until the next day.

SWA PSAs are similar to those in the rest of the GCAs, then the result of the likelihood test indicates that the Day 1 forecasts had skill in predicting all ignitions, recreation ignitions, and lightning ignitions. However, the 7-Day Outlook did not perform as strongly in predicting MODIS Active Detects, when these were associated with the forecast on the same day (results were significant in 8 of 12 PSAs) or with a 1-day lag, assuming that a fire would not be large enough to be detected by MODIS until the day following the day of ignition (results were significant in the same 8 of 12 PSAs). This may indicate a shortcoming in the forecast, but it is plausible that in some cases MODIS was not able to detect the fires due to fast-moving grass fires that burned largely between the twice-daily satellite overpasses, an extensive smoke column, or thick clouds. In addition, because the MODIS Active Detects were subset to include only those within 2 km of an MTBS perimeter to exclude agricultural and prescribed burns, only fires with a final fire size greater than 1000 acres were included in this analysis, so some significant fires smaller than 1000 acres were likely excluded. The 7-Day Outlook had the most difficulty in predicting escaped fires, with results being significant in only 4 of 12 PSAs. The issue here may be that escaped fires are extremely rare, with 11 of 12 PSAs in NWA having fewer than 20 escaped fires during the period of analysis, making their prediction more difficult. In addition, because escaped fires are rare, the matrix of escaped fires versus forecast values was quite sparse in at least five of the PSAs, with numerous values of zero; the log likelihood ratio test does not always perform well when matrices are sparse.

Table 3—Log likelihood ratio test for fire activity for each PSA in the NW GCAs. Cases where the test was significant at alpha = 0.1 are highlighted in green. In some cases, p-values may have been inflated due to sparse matrices.

PSA/GA	Ignitions	Active detects	Active detects (1-day lag)	Lightning ignitions	Recreation ignitions	Escapes (>300 ac)
NW GA	< 2.2e-16	1.06E-14	5.55E-15	< 2.2e-16	< 2.2e-16	< 2.2e-16
NW01	0.85	0.08	0.05	2.17E-08	< 2.2e-16	0.60
NW02	< 2.2e-16	0.02	0.03	0.28	< 2.2e-16	1.00
NW03	< 2.2e-16	7.25E-06	6.38E-06	1.29E-07	< 2.2e-16	0.84
NW04	< 2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16	3.20E-12	0.05
NW05	< 2.2e-16	1.75E-05	5.89E-05	3.91E-07	< 2.2e-16	1
NW06	< 2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16	1.20E-08	0.000341
NW07	< 2.2e-16	3.99E-05	5.51E-06	< 2.2e-16	< 2.2e-16	0.76
NW08	< 2.2e-16	0.75	0.50	4.47E-09	9.61E-08	0.35
NW09	< 2.2e-16	1	1	< 2.2e-16	6.27E-06	1.00
NW10	< 2.2e-16	0.20	0.25	6.22E-05	8.88E-16	0.06
NW11	< 2.2e-16	< 2.2e-16	< 2.2e-16	< 2.2e-16	1.04E-07	0.84
NW12	< 2.2e-16	0.13	0.28	< 2.2e-16	0.03178	4.09E-05

Significant at alpha = 0.1

High p-value may be due to matrix being sparse

While the forecast demonstrates some skill in predicting significant fire activity, escaped fires occurred numerous times on days predicted to have low risk of significant fire. For example, although the chance of at least one escape was very small (approximately 2 percent) on days with forecast prediction level 1 (moist) or 2 (dry), indicating low risk of significant fires, the actual number of days that had at least one escape in these forecast levels and over the three years of the study was 318. Seven of those 318 days had more than 3 escapes. Escaped fires also occurred on approximately 70 days when the forecast was not issued, with as many as 10 escaped fires occurring in a single PSA, an instance which could be prevented by issuing the forecast year-round.

Discussion and Conclusions

Generally speaking, the 7-Day Fire Potential Outlook demonstrated better than random prediction of wildfire activity in the NWA. In the NWA and SWA, numbers of ignitions were lower at dryness level 1 (moist) than at dryness levels 2 (dry) and 3 (very dry) and on days with forecasts indicating lightning, unstable conditions, high recreation, windy conditions, or hot and dry conditions. A similar pattern existed for MODIS active detects, with the exception that forecast level 8 (recreation) did not appear to indicate increased fire activity. Escaped fires were more likely to ocurr under forecast levels 3 (very dry), 4 (lightning), 5 (windy), and 7 (hot and dry) than forecasts 1 (moist) and 2 (dry), with forecasts 6 (unstable) and 8 (high recreation) showing predictive skill seven days ahead but not during the same-day forecasts. Days with forecasts of 4 (lightning) and 8 (recreation) were successful in identifying days with higher numbers of lightning and recreation ignitions, respectively. The forecasts showed skill in identifying days with elevated numbers of ignitions and potential for escaped fires not only for the current day's forecast, but also for forecasts made a week before, indicating the forecast might be useful in national-scale prepositioning of fire suppression resources up to seven days in advance. In order to fully analyze this capability of the 7-Day Outlook, we will complete analysis of additional GCAs in the next phase of our research.

The 7-Day Outlook performed most consistently across PSAs in the NWA in predicting ignitions, which are a prerequisite for significant fire activity. However, the 7-Day Outlook was successful in only a fraction of the PSAs in predicting large fire activity, in terms of both MODIS Active Fire Detects and escaped fires. In addition, several hundred escaped fires occurred on days with forecasts of 1 or 2 or on days that were not considered to be part of core fire season and thus had no forecast. This result is interesting in light of the fact that the 7-Day Outlook is designed to predict large fire activity and not ignitions. Given a changing climate, expanding the season during which forecasts are issued could help to increase the number of days with heightened forecast values when escaped fires occur. Because escaped fires are quite rare, they are no doubt challenging to predict, and some of the statistical tests we employed may have failed due to the small sample size. The relationship between fuel dryness and fire ignitions is well established in the literature (Andrews and others 2003), and thus the increasing number of ignitions across dryness levels 1 to 3 makes sense, but the weather conditions leading to significant fire activity are less well understood, adding to challenges in predicting fire activity and escapes. Adding to the difficulty in forecasting rare events, gridded weather model output also contains uncertainties and imperfections, which are then passed to the fire models. In some instances, fire suppression resources may have been prepositioned based on the forecast and successfully contained fires that otherwise would have experienced significant activity. Such instances may have a confounding effect on our analysis.

In this initial work, we focused only on the years 2009, 2010, and 2011, and on two of the ten geographic areas in the conterminous U.S. We are currently in the process of expanding the analysis to include six years of reliable historical forecast data (2007 to 2012). Expanding the dataset will help to address the statistical issues with small sample sizes of escaped fires. We will also add analysis of additional GCAs, in order to begin to be able to address national-level resource allocation issues. In addition, we will examine geographical and fuels characteristics as well as longer-term fire history data to determine how non-weather-related variables predict outcomes.

Acknowledgments

The authors would like to acknowledge their appreciation for extensive engagement with Terry Marsha, Meteorologist with the Northwest Interagency Area Coordination Center, without which this work would not have been possible.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Emerging Concepts in Wildfire Risk Assessment and Management

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Abstract—*A quantitative measure of wildfire risk across a landscape—expected net change in value of resources and assets exposed to wildfire—was established nearly a decade ago. Assessments made using that measure have been completed at spatial extents ranging from an individual county to the continental United States. The science of wildfire risk assessment and management continues to build on the basic framework to develop new analysis techniques that address specific fire management problems. This paper reviews central concepts of the basic risk assessment framework and describes several emerging terms and concepts now under development. These new concepts include: 1) describing certain results of stochastic simulation systems as a wildfire event set, 2) defining a biophysical fireshed as the land area where fires can originate and eventually reach a designated point, line or area in a designated period of time, 3) defining a fireplain as the land area where fire originating from a designated point, line or polygon (or set thereof) can reach during a designated period of time, 4) an exceedance probability curve, which plots the magnitude of an event (or its effects) against the likelihood that magnitude will be exceeded during a designated period of time, and 5) an analysis of wildfire Risk Associated with an Ignition Location (RAIL analysis), which characterizes the wildfire risk where the risk originates rather than where it occurs.*

Keywords: *event set, exceedance probability, fireplain, fireshed, RAIL analysis*

Background

A quantitative measure of wildfire risk across a landscape—expected net change in value of highly valued resources and assets (HVRAs) exposed to wildfire—was established nearly a decade ago (Finney 2005). Continued development of that framework has produced a few general wildfire risk assessment concepts, primarily the conceptualization of wildfire risk as the wildfire risk triangle (Figure 1). Wildfire risk at a given location on the landscape is a function of the likelihood of wildfire burning the location, the fire intensity when it does burn, and the susceptibility of all exposed HVRAs that exist there.

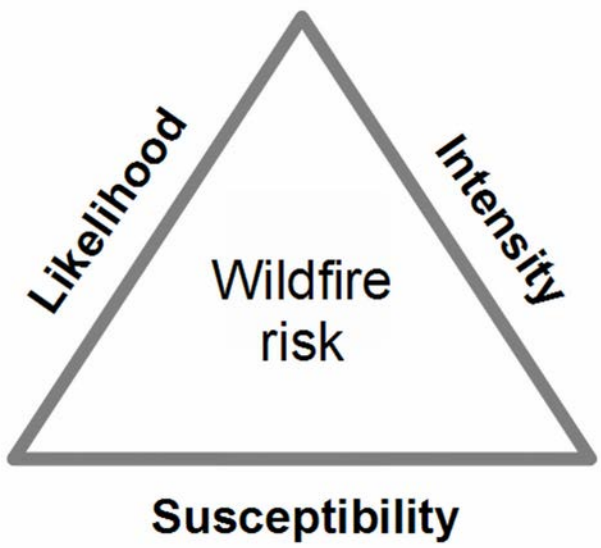

Figure 1—Wildfire risk triangle illustrates the major building blocks of quantitative wildfire risk assessment—the likelihood and intensity of wildfire and the susceptibility of resources and assets exposed to it (from Scott and others 2013).

Stochastic simulation of wildfire occurrence, growth, and behavior is the foundation of quantitative wildfire risk assessment. A stochastic simulation incorporates random variation in one or more simulation inputs. For stochastic wildfire simulations, the variable inputs fall into two categories: fire occurrence and weather. These inputs are accommodated in different ways in fire simulation software (Table 1). FlamMap5 (Finney 2006) has a stochastic fire simulation feature that allows simulation of many fires for one weather scenario, often the so-called "problem-fire" scenario. The problem-fire scenario is a weather scenario (wind speed and direction, fuel moistures, and fire spread duration) that leads to damaging short-duration wildfires (Bahro and others 2007; Moghaddas and others 2010). FSim (Finney and others 2011b) also simulates many fires (focusing on fires that escape initial attack and become large), but also simulates many weather scenarios. FSim is a valuable simulation system because its results represent a designated period of time—one complete fire season—and because it attempts to simulate the full range of escaped-fire sizes that can occur on the landscape rather than focus on a problem-fire scenario. FSPro (Andrews and others 2007; Finney and others 2011a; U.S. Forest Service 2009) is a stochastic simulation system used for incident management planning and decision-making (Calkin and others 2011). FSPro is used only after a wildfire

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Table 1—Matrix showing the primary fire modeling systems used for simulating one or many fires and one or many weather scenarios. FARSITE is a deterministic simulation system used for one fire and one weather scenario; the others are stochastic, incorporating variability in weather and/or fire occurrence.

	One weather scenario	Many weather scenarios
One fire	FARSITE[a]	FSPro[b]
Many fires	FlamMap5[c]	FSim[d]

[a] FARSITE is desktop software available at www.firelab.org; its functionality is replicated in the Wildland Fire Decision Support System (WFDSS) as "Near-term fire behavior" analysis.
[b] FSPro is currently available only within WFDSS.
[c] FlamMap5 is desktop software available at www.firelab.org. Some of its functionality is replicated in WFDSS; however, the stochastic simulation feature of FlamMap5 described in this paper is not available within WFDSS.
[d] FSim is custom software developed at the Missoula Fire Sciences Laboratory.

has already ignited, so it does not simulate fire occurrence, only growth for thousands of iterations starting with the same ignition point or perimeter under multiple weather scenarios. The user defines at run-time the duration of the simulation, usually 7 to 21 days. In contrast to these three stochastic simulation systems, the well-known FARSITE fire growth simulator (Finney 1998) is a deterministic simulation system that simulates one fire for one weather scenario, with no accounting for stochastic variability in its inputs.

Stochastic wildfire simulation systems produce raster outputs (a grid of cells or pixels) representing fire likelihood (burn probability) and conditional intensity given that a fire occurs (mean fireline intensity and, with additional calculations, conditional flame length), as well as polygons representing simulated final fire perimeters. Likewise, quantitative wildfire risk assessments can produce both pixel- and polygon-based results. An effects analysis (Scott and others 2013; Thompson and others 2011a, 2011b) is generally accomplished at the pixel-level. Polygon-based results are generally used in an exposure analysis (Scott and others 2012; Thompson and others 2013a).

Pixel-Based Risk

A pixel-based effects analysis quantifies wildfire risk where the effects occur on the landscape. Although effects can be measured and simulated in any unit of measure, it is typically measured as the net change in value of an HVRA due to burning (also called net value change, or *NVC*). *NVC* can be calculated for an individual HVRA, and also summed across multiple HVRAs of interest. Finney (2005) established the basic actuarial calculation of *NVC*; we modify that calculation here to produce two risk measures instead of one. Conditional net value change (*cNVC*) is the mean *NVC* that would be experienced given that a fire burns the location, incorporating only the intensity and susceptibility sides of the wildfire risk triangle (Figure 1). Expected net value change (*eNVC*) is the expected value of *NVC*, which incorporates all sides of the wildfire risk triangle, including the overall likelihood of burning. *cNVC* is calculated at a given location on the landscape (pixel) as

$$cNVC = \sum_j \sum_i NVC_{ij} * FLP_i$$

where NVC_{ij} refers to the net change in value for HVRA j if burned at fire intensity class i, and FLP_i refers to the conditional probability of fire burning in fire intensity (flame length) class i. Because FLP_i are conditional probabilities, the sum of FLP_i across all intensity classes is 1. Expected *NVC* can then be calculated from *cNVC* as

$$eNVC = cNVC * BP$$

where *BP* is the probability of burning at the location. The units of measure of *BP* depend on the system used—FSim produces annual *BP* values; FSPro produces *BP* for the next 7 to 21 days, as specified by the user at run-time; and FlamMap5 produces a conditional probability of burning given that a problem fire occurs. *eNVC* is an excellent measure of overall wildfire risk, but first calculating *cNVC* also permits extended analyses that integrate the pixel and polygon results.

Polygon-Based Exposure

All three stochastic simulation systems mentioned above can produce polygons representing the final perimeter of each simulated wildfire. These perimeters allow the characterization of the exposure of an HVRA to wildfire in a way not possible with the pixel-level results. For example, the annual likelihood that wildfire burns any part of a municipal watershed can be calculated by counting the iterations during which wildfire reaches the watershed and dividing by the number of iterations (Scott and others 2012; Thompson and others 2013a). Further, the distribution of conditional watershed area burned—how much of the watershed burns in one year, given that at least some part of it does—offers information about the potential cumulative effects on the watershed that is not possible with the pixel-level analysis alone (Figure 2).

Emerging Concepts

In the following sections we introduce a few emerging concepts in wildfire risk assessment and management. In some cases the concept simply brings a new name to an existing concept.

Event Set

Computer simulation of the economic losses to HVRAs (*NVC*) that can potentially be caused by hazardous natural phenomena is known as natural catastrophe modeling, or "nat cat" modeling (Clark 2002). An event is an instance of the natural phenomenon—a hurricane, an earthquake, or a wildfire, for example. In the context of wildfire, an event can be an individual wildfire or, when using FSim, a whole wildfire season. An event set is a simulated set of events, each with known probability of occurring, along with associated characteristics of each event. A wildfire event set is a set of fire perimeters and associated characteristics for

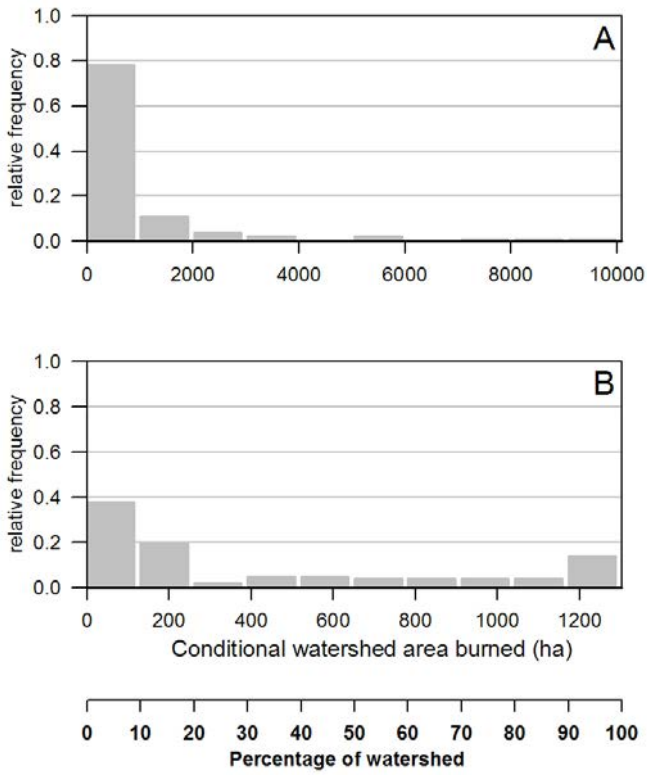

Figure 2—Polygon-based exposure to wildfire of two municipal watersheds on the Beaverhead-Deerlodge National Forest. Watershed A (top) is much larger (10,093 ha) than watershed B (1,330 ha) and therefore is likely to burn only a fraction of the entire watershed during a single fire event. Figure from Scott and others (2012).

each simulated wildfire in the set. The associated characteristics for each wildfire include the date and location of the ignition point, its duration, and its final size. Fire modeling software already exists to generate stochastic wildfire event sets on landscapes ranging from less than 1 million to more than 40 million ha.

The polygon results from a stochastic wildfire simulation system represent an event set (Figure 3). The annual probability of each simulated wildfire is $1/N$ where N is the number of iterations used in the simulation. The spatial nature of a wildfire event means it can be incorporated into analyses that are inherently spatial, such as the exposure analysis described above. The event set provides a basis for estimating the likelihood of a catastrophic event (an event producing effects above some threshold), and is useful for generating an exceedance probability curve (described below).

Fireshed Analysis

A watershed is the land area from which surface water drains to a specified point, line or area. Likewise, we define a fireshed biophysically as the land area within which a wildfire can start and eventually spread, during a designated period of time, to a specified point, line or area of concern (Thompson and others 2013a). Examples of points of concern include individual structures, communication and other administrative sites, historic cabins and small-extent wildlife habitat features like active nesting sites. Examples of linear features of concern include electric transmission lines, scenic highway corridors and wildlife travel corridors. Examples of areas of concern include human communities (towns), large-extents of wildlife habitat, high-value vegetation communities, and municipal watersheds. The "designated period of time" for determining the size and location of a biophysical fireshed depends in part on the stochastic simulation system used. FSim inherently represents a whole fire season; FlamMap5 represents one or a few burning periods (specified at run-time). The fireshed concept helps focus attention on the portions of the landscape where an ignition is most likely to reach a susceptible HVRA. For operational wildfire incident planning, the fireshed concept can inform evacuation planning and the development of management action points.

The term fireshed has previously been used to describe a fire management planning area based on relatively uniform characteristics: fire regime, condition class, fire history, and potential wildfire hazard and risk (Ager and others 2006; Bahro and Barber 2004; Collins and others 2010). That definition of a fireshed—relative uniformity of important characteristics—is more analogous to a forest stand than a watershed.

A biophysical fireshed can be generated deterministically or stochastically. Stochastically, a wildfire event set forms the basis for identifying a biophysical fireshed. In a GIS, all simulated perimeters that reach the designated point, line or area of concern are selected. The X- and Y-coordinate values from the attribute table are then used to plot the start locations of these wildfires. Finally, the fireshed can be delineated by tracing a line around the outermost ignition locations (for example, a concave or convex hull), with perhaps an additional buffer. For example, Thompson and others (2013) used this approach to delineate the whole-season fireshed for the habitat of a butterfly species listed federally as threatened, Pawnee Montane Skipper (*Hesperia leonardus montana*), on the Pike and San Isabel National Forests, Colorado, USA (Figure 4).

This approach works with FSim and FlamMap5 perimeters, both of which place ignitions randomly across the landscape. The fireshed concept does not work with FSPro because it uses a fixed ignition location. Under uniform weather conditions, the minimum-travel time algorithm used to simulate fire growth (Finney 2002) can be modified to deterministically simulate a fireshed. For example, the WildfireAnalyst software (www.technosylva.com) includes a feature called Evacuation Mode that deterministically generates the fireshed for a specified point or line for a given duration of spread under uniform weather conditions.

Fireplain Analysis

A floodplain is the land area inundated by water during a flood of a specified magnitude. We define a fireplain as the land area where wildfire can spread to from one or more points or lines of ignition during a designated period of time. As with the fireshed concept, the designated period of time is determined by the system being used and

Table

SSN_LF_RiskStarts

FIRE_NUMBE	ERC_STARTD	ERC_PERCEN	NUM_BURNDA	START_DAY	Xcoord	Ycoord	SizeHa	Thd_yr	Fire-level NVC
0	100	99	79	172	356419.073165	3931681.51135	82330	100001	-176502
1	100	99	79	172	158064.404416	4281627.97771	66791	100001	0
2	97	99	71	180	232776.588329	4157935.67847	51920	100001	-353795
3	97	99	71	180	243386.580591	4162046.21413	51300	100001	-337523
4	92	98	66	181	205262.808455	4172825.39691	52263	100001	-231691
5	85	93	40	204	331357.762945	3946304.08671	17542	100001	-3186
6	85	93	50	204	331319.631472	3983601.27514	20787	100001	-22757
7	85	93	50	204	300666.182291	4098183.8414	25789	100001	-61822
8	92	98	33	221	232444.06319	4175763.28906	17127	100001	-17843
9	94	99	28	226	165885.758963	4291153.01009	3965	100001	0
10	94	99	28	226	346553.195548	3900806.99899	4511	100001	0
11	81	88	16	157	195443.382527	4210690.96989	694	100002	-5976
12	81	88	82	157	332774.847411	3949952.32079	38073	100002	-34015
13	78	85	26	163	224869.44338	4130369.36488	889	100002	0
14	78	85	76	163	333158.036222	3959847.1354	33219	100002	-33722
15	78	85	76	163	235840.455374	4153553.86258	69276	100002	-509844
16	85	93	57	210	342478.988306	3986628.65023	46521	100002	-15918
17	85	93	57	210	163820.735036	4285169.48526	30008	100002	0
18	85	93	48	210	196543.568662	4256128.01666	30401	100002	-777904
19	84	92	37	230	345580.148457	3870172.91121	16942	100002	0
20	83	90	10	250	188099.450566	4184843.47214	55	100002	0
21	75	81	27	154	195471.508841	4219237.30643	4664	100003	-54918
22	75	81	53	154	339541.153085	3991812.06666	4880	100003	-6610
23	74	80	46	196	353261.605897	3912064.12364	2417	100003	0
24	86	93	24	220	193605.686865	4186215.8799	182	100003	0
25	81	88	53	201	233442.735082	4124527.82039	6166	100005	0
26	75	81	48	206	201951.346215	4199109.28587	9691	100005	-51477
27	75	81	48	206	342033.509168	3888895.52876	5766	100005	0
28	74	80	42	185	220722.344571	4210468.22335	2288	100007	-2986
29	86	93	24	227	339716.208571	3961571.75741	594	100007	-45
30	76	83	19	238	237222.197098	4116887.43884	95	100007	0
31	80	87	10	251	348217.892826	3921770.98964	68	100007	-33

0 (0 out of 529458 Selected)

SSN_LF_RiskStarts

Figure 3—Tabular representation of a wildfire event set produced by FSim. Pictured here is the attribute table associated with a set of polygons representing the final perimeters of 529,458 wildfires occurring during 20,000 iterations on a landscape encompassing 9.7 million ha.

by run-time settings. The term fireplain is a neologism that puts a name to the form of analysis that started with FSPro, which indicates the fireplain for the period of time designated by the analyst at run-time, usually one to several weeks, from the current wildfire perimeter. In FSPro, the fireplain is visualized as a *BP* "footprint", which becomes larger for longer durations (Figure 5). An incident fireplain as produced by FSPro is useful in its own right for strategic planning of the incident, and also forms the basis for an incident-level risk assessment (Calkin and others 2011).

In its default application, FSim simulates fire starts across the entire landscape. By manipulating the ignition density grid input, it can be also used to simulate fire occurrence and growth from any portion of the landscape (Thompson and others 2013b). When used in this way, FSim produces season-long fireplains for ignitions arising from a designated area of the landscape. For example, FSim was used in the southern Sierra Nevada range, California, USA, to simulate the occurrence and unsuppressed growth of lightning ignitions originating within the portions of the landscape where mechanical fuel treatment is not permitted—Wilderness areas, inventoried roadless areas, wild and scenic river corridors, and so on. The resulting burn probability map indicates the fireplain for such wildfires (Figure 6).

A third form of fireplain analysis is used in a new type of risk assessment called a RAIL analysis (described below), which characterizes the wildfire risk associated with a specific ignition location, rather than where the effects occur on the landscape. This last form is currently implemented in custom stochastic fire modeling software that systematically simulates fire growth, under variable weather, for all ignition locations of concern (Ramirez, personal communication). With this type of fireplain analysis, fire growth from all potential ignition points is simulated with the same set of weather scenarios so that variation in results is due to the fire growth potential related to fuel and topography (Figure 7). The period of fire growth for this form of fireplain analysis can vary from very short (hours) to an entire fire season, depending on the application. In concept, this type of fireplain analysis is like doing an FSPro simulation for all ignition locations of concern, even though a wildfire has not yet ignited.

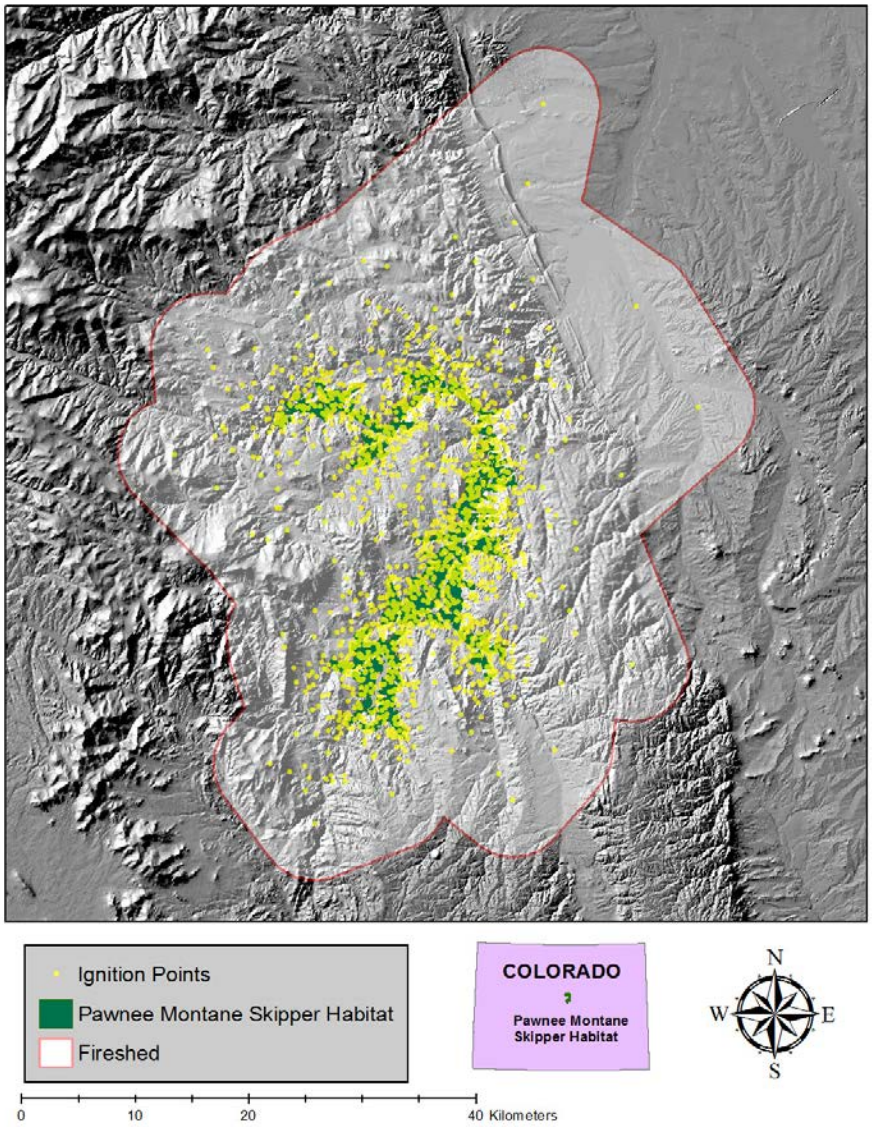

Figure 4—Delineated fireshed for the Pawnee montane skipper habitat on the Pike and San Isabel National Forests, Colorado, USA, including ignition locations for all simulated wildfires that reached habitat polygons. The delineated fireshed is a five km buffer around the concave hull of ignition locations of simulated wildfires that reached any part of the habitat. From Thompson and others (2013).

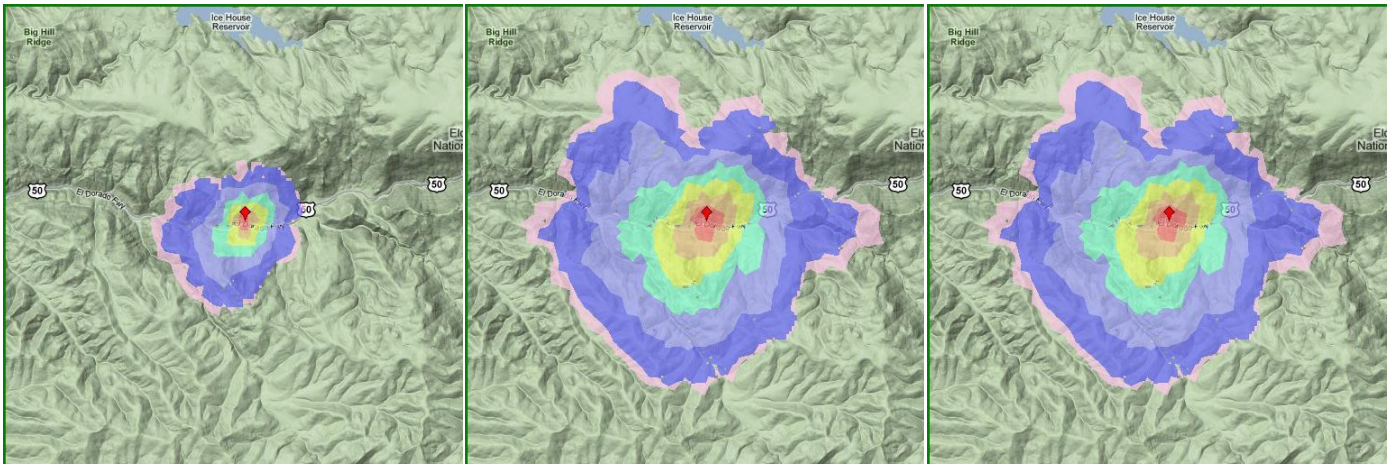

Figure 5—Hypothetical fireplains as simulated with FSPro for 7 days (left), 14 days (center) and 21 days (right). These fireplain simulations are useful for managing individual wildfire incidents and allocating resources among simultaneous incidents.

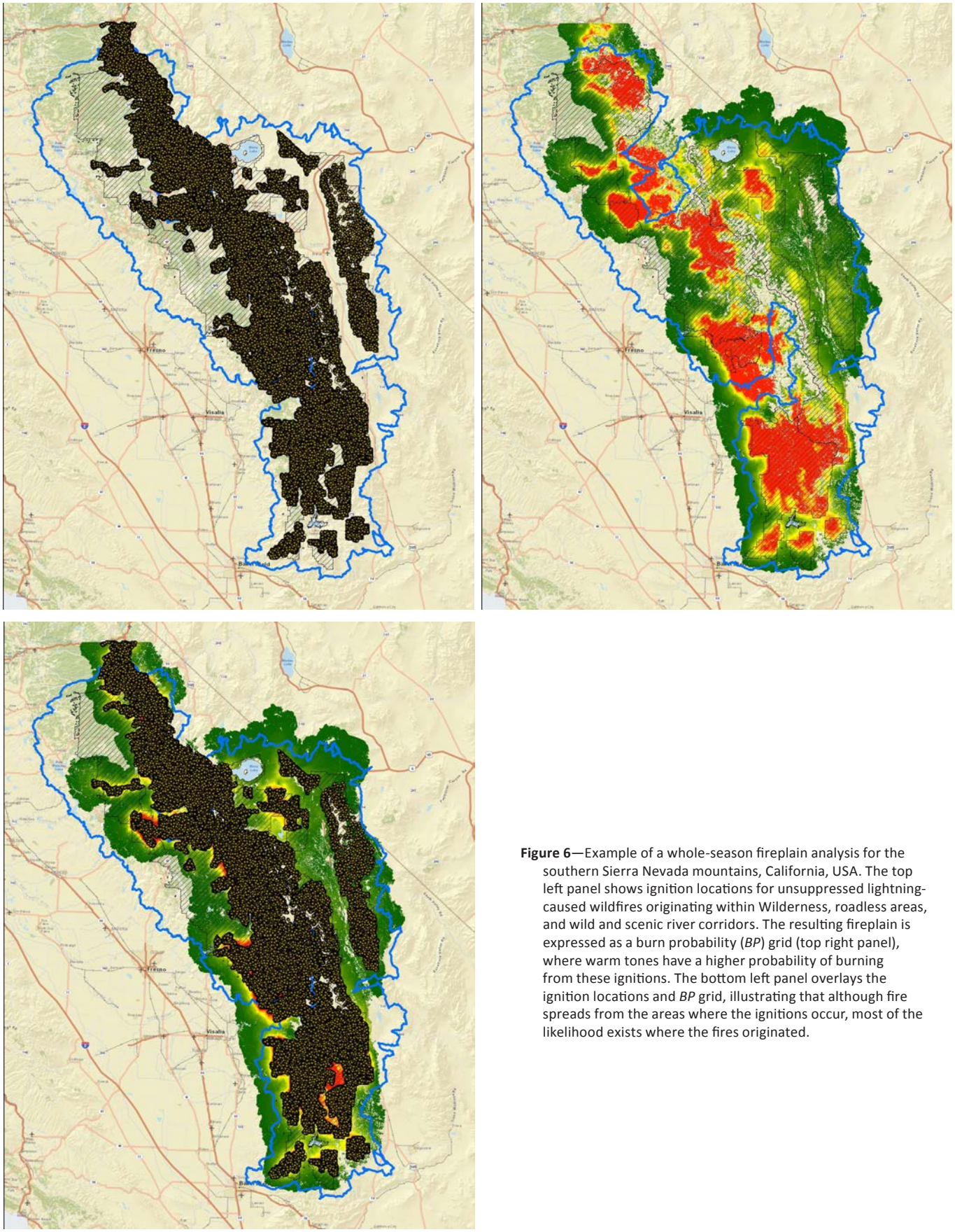

Figure 6—Example of a whole-season fireplain analysis for the southern Sierra Nevada mountains, California, USA. The top left panel shows ignition locations for unsuppressed lightning-caused wildfires originating within Wilderness, roadless areas, and wild and scenic river corridors. The resulting fireplain is expressed as a burn probability (*BP*) grid (top right panel), where warm tones have a higher probability of burning from these ignitions. The bottom left panel overlays the ignition locations and *BP* grid, illustrating that although fire spreads from the areas where the ignitions occur, most of the likelihood exists where the fires originated.

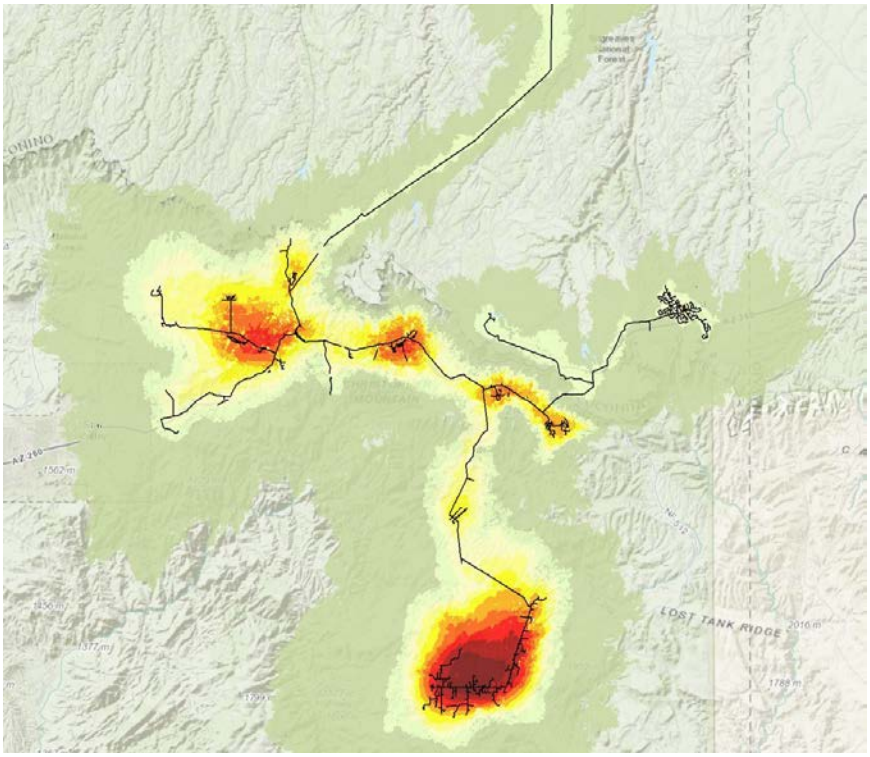

Figure 7—A short-duration fireplain for a single burning-period for an electric power distribution network where each segment of the network is treated as a potential ignition location with equal likelihood of igniting a wildfire.

Exceedance Probability

Spatially resolved risk assessment results (*cNVC*) and fire effects models (for example, fire-caused sedimentation or debris-flow probability and volume) can be used to augment the information available for each record in the event set. For example, a model of fire-caused sediment production, like WEPP (Elliot 2004), can be used to assign total estimated sediment production to each simulated wildfire. This augmented event set can then be used to produce an exceedance probability (EP) curve that relates the magnitude of a fire effect (sediment production, fire size, suppression cost, etc.) to the likelihood of exceeding that magnitude. As with other concepts presented in this paper, the time period for that likelihood varies from a few hours to a whole fire season depending on the simulation system used as well as user-defined settings.

The *EP* for event *k* in the set is calculated as

$$EP_k = \frac{rank(M_k)}{N+1}$$

where EP_k is the exceedance probability for event *k* and rank(M_k) is the rank (largest first) of the magnitude of event *k* (M_k) among all *N* events or simulations. For example, let's say that a 7-day, FSPro simulation produced 1,008 simulated wildfires with a minimum final size of 2,015 ha and a maximum of 20,477 ha (we're using fire size as a measure of magnitude in this example). The rank of the minimum-size fire is 1,008, so the probability of exceeding that size is 1,008/1,009, or 99.9 percent. The rank of the largest fire is 1, so its *EP* is 1/1,009, or 0.099 percent. An *EP* curve is a plot of M_k on the X-axis against EP_k on the Y-axis for all events in the set (Figure 8). For the dataset described above, there is a 1 percent chance (*EP* = 0.01) of exceeding 17,848 ha after 7 days of growth. Note that 1-*EP* is the percentile rank, so 17,848 ha is equivalent to the 99th percentile size.

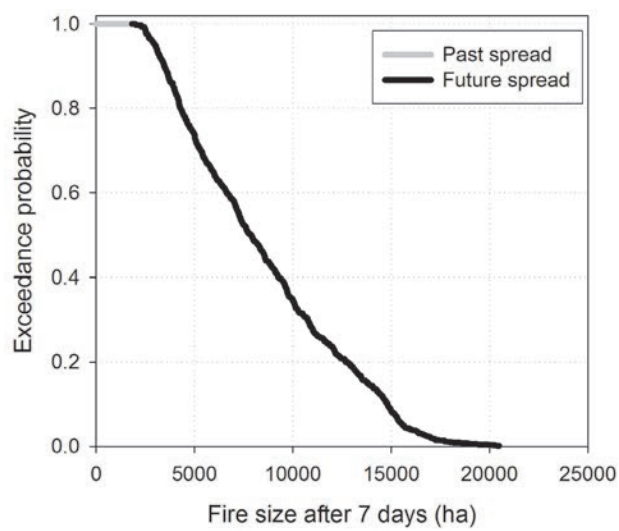

Figure 8—Exceedance probability curve for fire size after 7 days of fire growth based on FSPro simulation of 1,008 7-day periods of unsuppressed fire growth. Fire size at the beginning of the simulation was 4,500 ha.

By integrating the pixel-level fire effects and polygon representation of fire perimeters to augment an event set attribute table, an *EP* chart that displays the likelihood of exceeding a range of effects thresholds can be plotted. For example, in an unpublished analysis associated with the Mokelumne Watershed Avoided Cost Analysis study (Buckley and others 2014), the total fire-caused sediment load associated with each simulated wildfire event, generated with FSim, was added to each wildfire that

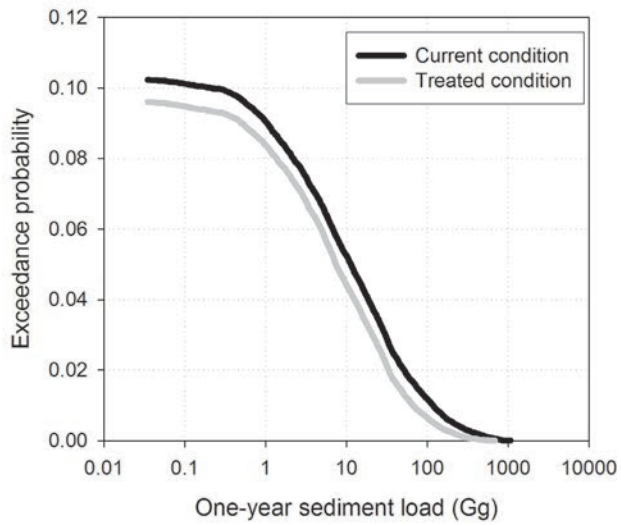

Figure 9—Exceedance probability curves (semi-log scale) for fire-caused sediment load into a small reservoir in the upper Mokelumne River basin in the Sierra Nevada mountain range, California, USA. Curves are shown for the current landscape condition (black line) and a hypothetically treated landscape (gray line). Two effects of the hypothetical fuel treatment can be visualized from this chart—the change in sediment production for a given likelihood is represented by the horizontal distance between the curves at any probability; the change in likelihood for a given sediment load is the vertical distance at any sediment load

Figure 10—RAIL analysis triangle. The wildfire risk associated with an ignition location is a function of the likelihood of ignition at the location and the fire growth potential and the vulnerability of resources and assets in the area surrounding the location.

reached the watershed of a small reservoir in the upper Mokelumne River basin in the Sierra Nevada mountain range, California, USA. The analysis was conducted on a representation of the current fuelscape and a hypothetical representation of a fuelscape after being managed with a variety of mechanical and prescribed-fire treatments. In this example of a polygon-based exposure analysis using FSim, there was only a 10.2 percent chance in any year that a wildfire would burn any part of the watershed; the hypothetical fuel treatment reduced this to 9.6 percent (Figure 9). For the current landscape condition there is a 1 percent chance ($EP = 0.01$) of causing 117 Gg sediment in any year; that was reduced to 67 Gg for the hypothetically treated landscape (Figure 9).

RAIL Analysis

Through a variety of techniques, it is possible to estimate the wildfire risk (measured as expected net value change) associated with a particular ignition location. This analysis takes into account the ignition potential at the location, fire growth potential surrounding the ignition location and HVRA vulnerability in that area (Figure 10). An analysis of the risk associated with an ignition location (RAIL analysis) identifies locations where ignitions tend to have high consequences due to spread potential and HVRA vulnerability. Such an analysis is useful for suggesting where prevention and pre-suppression activities may have the greatest benefit, and assisting in pre-wildfire strategic response planning. Two potential RAIL analysis techniques include: 1) a dedicated ignition-focused simulation, and 2) geospatial analysis of an augmented wildfire event set.

A dedicated ignition-focused stochastic simulation is one for which weather varies stochastically but ignition locations are deterministic (limited to the ignition locations of concern). Fire duration can vary from a few hours to a whole season, depending on the simulation system used. For example, the wildfire risk associated with overhead electricity distribution equipment, which are possible wildfire ignition sources, can be assessed by stochastically simulating fire growth and effects from each potential source (Ramirez, personal communication). In the absence of information about the likelihood of ignition for each point, the result is a map of conditional net value change resulting from an ignition at each point (Figure 11).

A wildfire event set that has been augmented to include spatially cumulative *NVC* for each event can be used in a landscape-wide RAIL analysis. This is typically a coarse-resolution analysis due to the dispersed nature of the ignition points available for most simulations. For example, *cNVC* was estimated for each 90-m pixel across the southern Sierra Nevada mountains. The total *cNVC* for each wildfire was estimated by summing the *cNVC* values for all pixels within each simulated fire perimeter. That sum was then associated with each fire's ignition location. The ignition locations (points) were converted to a 2 km raster using ESRI's Point to Raster tool; each 2 km cell was assigned the mean *cNVC* of all ignition points falling within the cell. This raster was then smoothed with two low-pass filters to mitigate graininess. The resulting grid (Figure 12) indicates the mean effect of wildfires—whether positive or negative—originating from different parts of the landscape. This information may prove useful in planning the response to wildfires before one occurs.

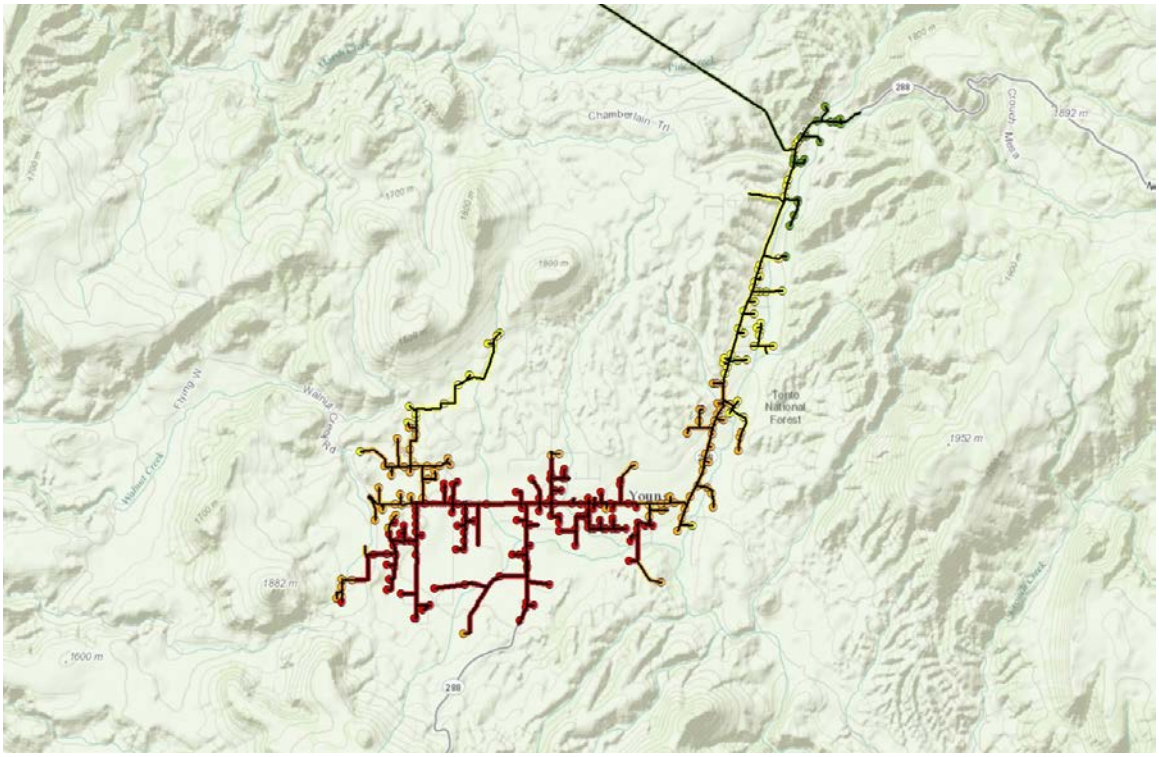

Figure 11—RAIL analysis for an electricity distribution network. The relative conditional risk (given that a fire start occurs somewhere on the network) associated with each potential ignition location on the network.

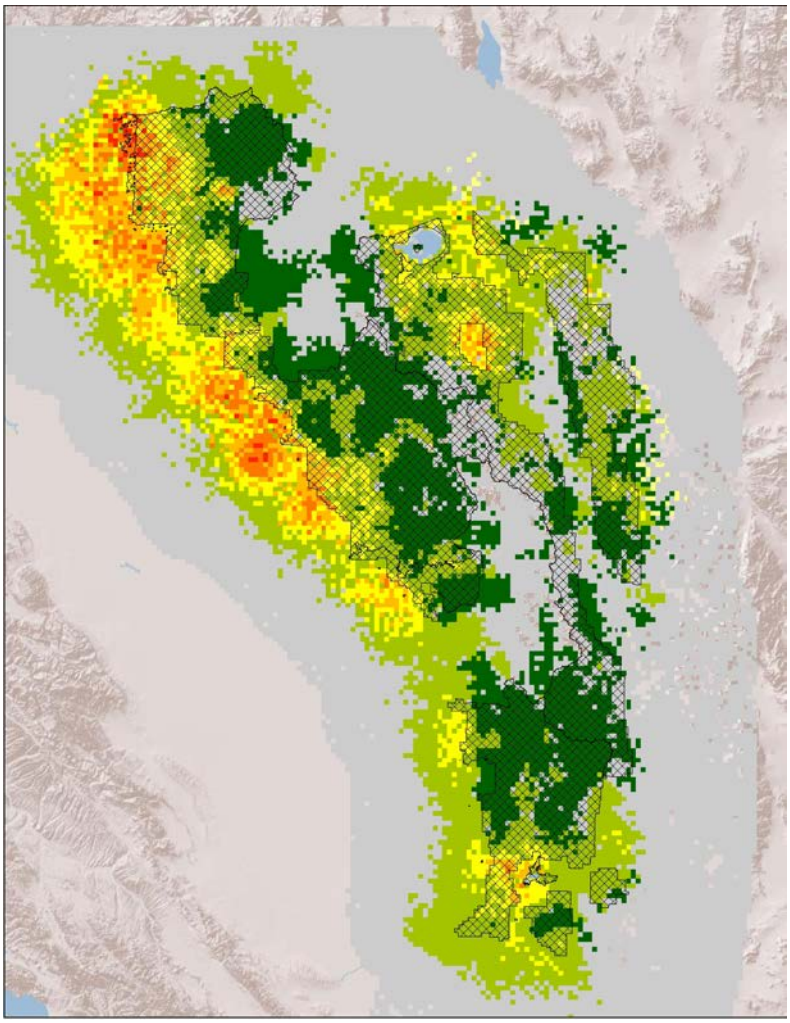

Figure 12—Landscape-wide RAIL analysis for the southern Sierra Nevada. The total *cNVC* for each wildfire was estimated by summing the *cNVC* values for all pixels within each simulated fire perimeter. That sum was then associated with each fire's ignition location. The ignition locations (points) were converted to a 2 km raster using ESRI's Point to Raster tool; each 2 km cell was assigned the mean *cNVC* of all ignition point falling within the cell. This raster was then smoothed with two low-pass filters to mitigate graininess. The resulting map indicates the regions of the landscape where fire ignitions tend to cause adverse effects (warm tones) and where they tend to result in net beneficial effects (greens).

Conclusion

The quantitative wildfire risk framework first promulgated by Finney (2005) has proven itself useful for addressing a variety of fire management problems at a variety of spatial scales (Miller and Ager 2012). The concepts presented here build on that basic framework by bringing into the field of wildfire risk assessment and management some terms and concepts used in other fields, either directly or with some adaptation to fit within the special characteristics of wildfire occurrence and behavior. The concepts presented here will require further refinement before being brought into standard use, but nonetheless represent another step forward.

Acknowledgments

The examples used in this paper were drawn from a variety of published and unpublished projects conducted with our colleagues; we are grateful for their contributions: Phil Bowden, Region 5 of U.S. Forest Service; David Buckley, Timmons Group; Julie Gilbertson-Day, Rocky Mountain Research Station; Don Helmbrecht, TEAMS Enterprise; Erin Noonan-Wright, Wildland Fire Management RD&A Program; Joaquin Ramirez, Technosylva, Inc.; and the entire team on the Mokelumne Watershed Avoided Cost Analysis project. We also thank Erin Noonan-Wright and Greg Dillon, Missoula Fire Sciences Lab, for their reviews of this manuscript.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Reconsidering Wildland Fire Use: Perspectives from the Northern Rockies

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Abstract—*The idea that more wildfires should be allowed to burn for resource benefit is widespread in federal fire management in the United States and the research community is heavily invested in strategies, tools, data, and information to provide decision-making support for these fires. In the context of the very large wildfires that are now occurring with frequency, it is generally believed that previous fires will confer benefit when large fires threaten. This paper examines whether federal fire management policies and practices in the United States are evolving to support more extensive use of fire. It argues that 2009 fire policy guidance, intended to increase decision flexibility by addressing all management options for every fire, may be inadvertently discouraging managers from preparing adequately for resource benefit fires. A consequence is the stagnation in strategic use of wildfire to improve forest health, treat fuels, and reduce costs, accompanied by deterioration in experience, energy, and enthusiasm for use of fire for resource benefit. Decades of Wildland Fire Use show that without extensive planning, managing wildfire for resource benefit will rarely be selected as the first option. Even when resource benefit fire is promoted in Fire Management Plans, it is seldom considered seriously beyond the few areas where it has significant historical legacy. Further, existing decision support systems are rarely invoked to support the first and most important decision on new starts. Instead, initial decisions are made quickly, often under duress, by the few individuals present when a fire is detected, which often favors aggressive initial attack. The energy and sense of purpose of the Wildland Fire Use community of a decade ago provided powerful motivation for change as well as vectors for distribution of new ideas and approaches. That community has largely dissolved, the influence of the Wildland Fire Implementation Plan (WFIP) has been removed, and it is uncertain whether new policies and practices are advancing resource benefit fire as intended. It is worth considering whether fire management removed the distinction between Fire Use and Suppression too soon and made it too easy to select the status quo.*

Introduction

This paper considers the status of fire for resource benefit, formerly known as Wildland Fire Use (WFU), in the context of changes in policy and practice that have occurred in the past decade. It contends that the blurring of lines between fire for resource benefit and suppression that occurred following the 2009 policy revision (USDA and USDI, 2009) is resulting in unanticipated consequences for the long-term use of fire for resource benefit. I intend to provoke reflection on the health and welfare of wildland fire use and to initiate thought on how to invigorate it. The terms 'fire use' and 'fire for resource benefit' are used interchangeably, recognizing that 'fire use' is antiquated by recent policy. The current ambiguity in how to describe fire use is a symptom and issue central to the future of resource benefit fire that will be addressed later in this document. The paper is organized in four sections: (1) a review of fire for resource benefit in policy and practice; (2) a discussion of the implications of recent changes in policy for the use of fire for resource benefit; (3) a look back at WFU from a decade ago highlighting the factors that made it successful, exciting and important; and (4) some suggestions to invigorate use of fire for resource benefit. The paper is predicated on the assumption that current levels of fire use are inadequate to meet ecosystem needs and significant growth in WFU is desirable. The advantages of natural fire have been expounded upon extensively in the scientific literature from perspectives of ecology (e.g., McKenzie and others 2011), economics (e.g., Houtman and others 2013), and risk (e.g., Finney and others 2007; Parks and others 2014). The barriers to implementation of fire use have also been documented (e.g., Doane and others 2006).

Fire for Resource Benefit in Policy and Practice

Federal policy has promoted fire as an essential natural process since 1968 when the National Park Service changed its policy to allow some wildfires to burn in order to meet ecological objectives. The Forest Service followed suit in 1974 after two years of experimentation with natural fires in the White Cap Fire Management Area of Idaho (van Wagtendonk, 2007). Although the premise of fire for resource benefit has been revisited many times following high profile events such as the Yellowstone Fires, WY (1988),

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the South Canyon Fire, CO (1994) and the Cerro Grande Fire, NM (2000), it has been reaffirmed each time (USDA and USDI, 1989; 1995; USDA and others 2000). The Federal Wildland Fire Management Policy and Program Review (1995) which occurred as a direct result of fourteen firefighter fatalities on the South Canyon Fire near Glenwood Springs, CO directed that "fire, as a critical natural process, will be integrated into land and resource management plans and activities on a landscape scale, and across agency boundaries." This document energized use of fire for resource benefit on federal lands and its ecosystem-centric approach to fire has been consistently and repeatedly reaffirmed through many subsequent national policy reviews, plans, and strategies (USDA and USDI, 2000; 2001; 2003, 2009; 2014; USDA and others 2005; 2009). In sum, federal fire policy and direction has clearly promoted fire as an essential natural process for nearly five decades, and it continues to do so in new guidance documents such as the National Cohesive Wildland Fire Management Strategy (2014).

Implementing policy to support ecological fire has largely occurred through application of Wildland Fire Use (formerly Prescribed Natural Fire -PNF) and prescribed fire. PNF programs emerged in the National Park Service (NPS) and United States Forest Service (USFS) in the late 1960s and early 1970s to allow a few lightning-caused fires to burn in remote areas (Parsons and others 1986). These programs grew slowly but steadily, eventually giving way to Wildland Fire Use (WFU) in 1998 (although the term wasn't sanctioned officially until 2003). Prominent programs developed in the expansive wilderness of the Selway and Gila and in Sequoia-Kings Canyon and Yosemite National Parks, among others (Parson and Landres, 1998). Fire Use acres continued to grow, punctuated by episodic declines following controversial fires and political events. By 2006, there were nine Wildland Fire Use Teams and at least 30 Fire Use Modules dedicated to WFU. The Wildland Fire Use Implementation Procedures Reference Guide (2005) directed managers to justify suppression actions in writing when WFU was not selected in areas where it had been approved. Although small in impact compared with total acres burned, the practice of allowing fire to burn for resource benefit seemed to be entering the mainstream consciousness of all levels of federal fire management.

Largely as a result of WFU, many federal fire managers and scientists now recognize the role of fire as a critical ecological process and are invested in strategies, tools, data, and information to encourage decision-making to support these fires. However, considering that fire use has accounted for only 2-4 percent of total annual acres burned in the period 2000-2013 (USDA Forest Service, 2014), its status as a viable management alternative is fragile, particularly in the face of changing land use patterns, societal expectations, economics, and climate change and variability. Although the belief systems of many federal fire managers and scientists favor fire for resource benefit, barriers to implementation remain significant and are often related to "the circumstances under which a fire occurs, and the likely consequences on firefighter and public safety and welfare, natural and cultural resources, and values to be protected" (USDA and USDI, 1995). The resource protection focus of many state-level land management agencies is largely incompatible with fire use, and the public and politicians remain largely unconvinced of its benefits. Even within the federal fire management community itself, there is considerable disagreement about the feasibility of the practice despite policy encouraging more WFU. Responses of fire managers to the 2012 letter from USFS Deputy Chief James Hubbard (USDA Forest Service, 2012) requesting aggressive initial attack to reduce suppression costs showed how easily managers revert to suppression-oriented behaviors even in the vast areas of large wildernesses. In that year, fire use accomplishments in terms of acres burned dipped sharply to their lowest point since 2005 (USDA Forest Service, 2014).

Implications of Changes in Policy Guidance

In February 2009, federal agencies received new policy guidance (USDA and USDI, 2009) regarding wildfire following two years of trial-and-error under Appropriate Management Response doctrine (USDA Forest Service, 2007). The new guidance provided for two types of fire – unplanned wildfire and planned prescribed fire. Federal agencies could now manage wildfires for many objectives concurrently and change those objectives as fire moved across the landscape. This differed from previous guidance which distinguished sharply between wildland fire use and everything else and required fire managers to classify each fire as fire use ('good' fire) or suppression ('bad' fire) and to use different decision processes for each.

The new guidance was welcomed by fire managers wanting to use fire for resource benefit because if resource benefit was identified as an objective in the land resource management plan (LRMP), managers gained unprecedented flexibility in decision-making to support fire use. Whereas previously only acres burned in fire use counted toward resource benefit, fire use acres now could accrue to any naturally ignited wildfire when they were moved toward desired future conditions specified in LRMPs regardless of goals and objectives of individual fires. Further, the decision document, support system, and risk assessment tools became the same for every fire regardless of objectives.

An expectation of the new guidance was that there would be more resource benefit accomplishments because fire managers could modify suppression tactics on any fire when risks were low to encourage ecological outcomes. Data from the USFS show that fire use acres on Forest Service jurisdictions have indeed trended upward since 2009, averaging 296,000 per year compared with 166,000 per year from 2001-2008 (USDA Forest Service, 2014). Although fire use acres remain a small fraction of total acres burned, the percentage of USFS fire use acres to total

burned acres roughly doubled from 2.3 percent in 2001-2008 to 4.6 percent in 2009-2013.

Interpreting this trend is difficult, however, because it is not possible to know whether the observed increase is a result of fire use or due to changes in accounting practices in which more acres that would have burned anyway are now available for classification as fire use. If the uptick in fire use acres is primarily a product of failed suppression efforts, then WFU is becoming an incidental outcome rather than a management strategy. This would not be an entirely negative outcome if fire managers were encouraging fire use by not actively suppressing all parts of existing fires where previously they might have, but it is a poor substitute for allowing fires to burn by intention. In the long term, the practice of using fire for resource benefit by accident would exacerbate a problem identified recently by fire scientist Mark Finney who noted in The New York Times that "by suppressing fires in all the conditions we can, we're saving the landscape for the worst conditions. We won't say that's our policy, but by our actions, we are selecting for only the most extreme fires. We need to choose good fire over bad fire." (Tullis, 2013).

Prior to 2009, WFU was clearly concerned with selecting naturally occurring fires that would *not be* initial-attacked and allowing those fires to burn within certain environmental and geographic constraints to achieve resource benefits (e.g., modified suppression). Today, fire use also includes acres that meet ecological objectives specified in LRMPs on any naturally occurring unplanned ignition regardless of manager's intent. While the former practice still occurs in large wildernesses and national parks where viable fire use programs emerged in the 1970s and 1980s, it is not easy to distinguish from the practice of attempting to suppress fires while counting their acres as resource benefit or providing initial attack on only parts of fires. Without distinction between intentional WFU and serendipitous benefit acres, it cannot be known if fire management is fulfilling its policy goal of allowing wildland fire "to be used to protect, maintain, and enhance resources and, as nearly as possible, be allowed to function in its natural ecological role" (USDA and USDI, 1995), nor can trends in fire use practices be interpreted correctly.

The implications of dissolving the WFU program into fire management at large extend beyond shortcomings in monitoring accomplishments and trends. Without identity, the successes of WFU are increasingly overlooked within fire management and have become virtually invisible to the public as the context in which WFU is implemented and communicated has changed. The energy and enthusiasm that sustained WFU and caused it to grow through the early 2000s is being lost. The extensive planning necessary to implement and expand WFU effectively is at risk of being replaced by seat-of-pants decision-making that favors aggressive initial attack. For better or worse, fire use as it has been known for the past 25 years has changed. While it is too early to know if the practice of fire use is contracting in the new policy environment, it is not too early to consider whether it is at risk given its historical sensitivity to whims in policy and politics.

The Role of Planning, Communication, and Public Education

Fire use today is constrained primarily by two factors: a lack of time and energy devoted to planning for it and by association, a lack of commitment in communicating it clearly and consistently to the fire workforce and the public. New policy guidance has inadvertently caused many fire managers to disregard planning for fire use because any fire can now be managed for any objective in the LRMP. A consequence of not planning is that resource benefit is rarely selected as the initial response and often becomes an objective only after suppression efforts fail or resources are in short supply. It is difficult to communicate the purpose of resource benefit or take credit for managing it under these circumstances. Further, because both the public and large sectors of fire management are still generally unsupportive of fire use, not communicating it clearly and repeatedly virtually assures that they will remain unsupportive.

Ultimately, the selection of 'good' fires should occur primarily in the initial decision-making process, informed by current and expected environmental conditions—what WFDSS (Wildfire Decision Support System) calls the preplanned response. This means selecting fire use as the desired alternative before a fire occurs. Today, suppression is the de-facto pre-planned response, and although this has mostly been the case for the past 80 years, it was only ten years ago that fire-use was the pre-planned response in those areas where fire use was an option. The Wildland Fire Use Implementation Plan (WFIP) required managers to opt-out of fire use overtly for an admittedly small fraction of landscapes, but an important fraction nonetheless. Today, justification for a suppression response is not required in any phase of the selection process and the choice of suppression where fire use was warranted is rarely questioned.

In understanding the pre-planned response, it is necessary to recognize that most decision-making in fire management is local and completed in real-time. When a new fire is identified, the important decision of whether to suppress or not is typically made quickly by a few people in a local office, often under duress, and with limited information in front of them. It is only after the most important decision is made and initial attack fails that the WFDSS is invoked to support decision-making, and then as a process usually separate from on-the-ground management. In the absence of the necessary planning, communication, and analysis for successful WFU, conventional suppression is the low-risk choice even if managers intend more complex objectives if the incident escapes. As Uncle Stu noted in his 2007 Underground, Practical Approach to Planning for and Implementing WFU for Beginners, "if wildfire use was easy, they would call it suppression."

Historically, the energy for promoting fire use came from a few individuals committed to it. They pushed to amend fire and land management plans to allow for resource benefit objectives within specified management units and conducted the extensive planning and communication necessary for the events to come. They made pre-season contacts with permittees and landowners describing the intent and purpose of WFU; established formal agreements with neighbors; reviewed closure types annually; conducted pre-season risk analyses; provided constant, clear communication and education with locals and employees about current and future WFU; trained Line Officers down to FFT2s in WFU goals and procedures; developed specific recommendations for the Line Officer; gave daily briefings to firefighters on where and how WFU would be implemented (or not); organized and managed data, modeled fire behavior and risk; and conducted constant risk assessment (Anonymous (Uncle Stu), 2007). The planning was for events that would happen years from now or even after the career of the fire manager was over. Without it, fire use was rarely a viable option.

Today, fire use still requires a dedicated and consistent commitment of time and energy by managers and their line officers. Yet, the day-to-day grind of managing a fire program often supersedes preparation for fire use. As each seemingly longer fire season winds down, managers must implement prescribed fire with a shrinking and often tired workforce followed by use-it or lose-it annual leave and the holidays. The New Year brings hiring in a dysfunctional government hiring environment along with still more training in an increasingly burdensome training regime. Spring brings preparation for the coming fire season, prescribed fire, and fuels treatments. Then another fire season starts the grind all over again. In this environment, without explicit focus and resources dedicated to its application, fire use may not succeed without access to outside help, perhaps coming from specialists whose primary purpose and job description is WFU implementation and planning.

Looking Back

The pinnacle of WFU was reached in 2006, when nine Wildland Fire Use Teams and at least 30 Fire Use Modules were used to implement this fire management alternative. Fire Use was in the news constantly, often controversial, but being talked about nonetheless by firefighters and the public. Land managers from all federal agencies were writing fire use into plans at an unprecedented rate. WFU team rosters were often full and many young firefighters were lining up to get involved. They sensed opportunities to change fire management, develop exciting careers, work with new technology, and explore new techniques, often with fewer bureaucratic constraints and sometimes fewer training requirements. Fire use modules were purposeful, innovative, and attractive to firefighters, particularly motivated, tech-savvy, ecologically-minded young people. WFU had champions at many administrative levels to convey its purpose and serve as role models for a new cohort of fire managers. Agencies such as NPS and USFS were integrated around common goals and purposes and they communicated WFU consistently. WFU also connected fire management directly with Fire Science by serving as a training ground for skilled ecologists and fire modelers who were normally either disinclined to participate in fire or not invited. WFU seemed on the cusp of changing business as usual in fire management. Within the WFU community, there was a growing sense that fire use was different from the rest of fire—perhaps perceived as smarter, more-grounded, more innovative, more tech savvy, more efficient, and more frugal than the suppression ranks. WFU represented opportunity and change to young firefighters and provided an environment conducive to development of future leaders.

Leading up to changes in policy guidance in 2009, fire use appeared strong enough to stand on equal footing with fire management at large. But at the same time, there were also concerns that WFU was becoming too distinct from suppression, with divergent training and qualifications threatening to create two fire organizations. In the context of these factors, the policy changes made sense. Yet, six years have passed since the new policy guidance and it is not evident that fire for resource benefit is gaining ground. There is currently one Wildland Fire Management Team nationally that operates more as a type II suppression team than a fire use team. The Wildland Fire Modules are reorganizing, typing, and exploring new technology, but lack high-level leadership and purpose. The roles of the Strategic Operational Planner are not widely understood. Fire Use is no longer in the public eye and its practice is rapidly losing it champions, role models, and leaders. It isn't the policy guidance itself that has caused these changes. It is the associated breakdown of the structures, terminology, and clarity of purpose that has. In retrospect, perhaps fire use still needs a name, its teams, modules, and Fire Use Managers. At a minimum, it needs renewed energy, focus, and commitment.

Looking Forward

The 2009 Policy Guidance is the most progressive and flexible guidance to fire managers in the history of the US fire policy. New policy isn't necessary to invigorate fire use. Instead, fire management should consider resurrecting elements of the old WFU program, rebuilding a resource base dedicated to its implementation, and communicating its purpose and accomplishments widely. To achieve these outcomes, fire management might consider the following eleven recommendations:

1. Recognize WFU as a practice distinct from other types of fire management and provide a clear name and policy for it. Having more than one type of fire allows flexibility in crafting procedures for individual types of fires, enables clear communication of goals and objectives, and prevents blanket changes from inadvertently affecting one type negatively. Particularly as fire management trends toward emergency management under the umbrella of organizations

such as FEMA, the natural resources will benefit from fire use as distinct from emergency response.

2. Re-establish procedures of the WFIP to encourage formal justification of a suppression response where fire use is approved.
3. Create specialized resources, including leadership positions, whose priority is fire use so that resources are available when the time for fire use is right. More importantly, rebuild a community of fire use practitioners and consider sabbatical-like programs to create opportunities for fire managers to focus on fire use, share their wisdom, and learn from others. Growth, innovation, and leadership in fire use will come from a workforce dedicated to its implementation.
4. Build strong tracking mechanisms and rules to differentiate between types of resource benefit from fire. For example, allowing fires to burn for resource benefit is fundamentally different from accomplishing resource benefit as collateral to suppression, and not suppressing part of a fire has a different meaning if it is accomplished intentionally with resource benefit goals in mind.
5. Champion fire use constantly, intentionally, and publicly. WFU still needs a clear, consistent, long-term communication strategy to gain traction as a common land management tool. Accomplishing resource benefits primarily by accident or under the guise of other management practices will ensure that WFU remains controversial and misunderstood.
6. Identify priority areas where fire for resource benefit is desirable and share them publicly in the form of maps. If fire management officers can't justify specifically where and why the landscape needs fire, it is difficult to imagine them selecting WFU when a fire does occur there.
7. Work to creatively integrate wildfire, WFU, prescribed fire, and mechanical fuel treatments.
8. Link decision support tools such as WFDSS more directly to the pre-planned response. Although it is not practical to use WFDSS substantially after every new start, most of the risk needs to be known before a fire occurs. This argues for a more nimble support system in which fire use is pre-identified and anticipated based on current and future environmental conditions.
9. Integrate fire planning and land management planning to ensure compatibility of land management goals with the realities of managing fire. The hand of fire management continues to be forced by planning decisions that are not informed by fire.
10. Incentivize fire use by creating career opportunities for young firefighters emphasizing education, innovation, and technology.
11. Redouble efforts to produce a holistic, defensible definition of resource benefit, probably relying on better understanding complex ecological concepts such as variability, heterogeneity, resiliency, and recovery. Fire for resource benefit still suffers from an inability to clearly articulate what its benefits are.

Conclusions

Fire management's refrain of 'doing the right thing in the right place at the right time' was fully enabled by the changes in policy guidance of 2009. Ironically, those same changes may be discouraging managers from exercising a full range of options. The option of fire use has lost energy and focus and it is not evident that the practice is growing under current policy despite increases in acres claimed. Invariably, at least some resource benefit accrues to every wildfire regardless of management actions. Replacing fire use with these accomplishments would be a negative outcome of fire policy. Invigorating the practice of fire use calls for a look back at the practices and behaviors that led to its successes and perhaps reviving some of them. The importance of the fire use program as a means of developing talented fire use managers should not be overlooked. The Wildland Fire Modules are attempting to resurrect themselves and refocus attention on fire use, and fire managers are still learning how to use new decision support systems effectively. With strong leadership, a vibrant community of practitioners, and active communication with firefighters and the public, there is reason to be optimistic that fire use can flourish and grow.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Comparison of Six Fire Severity Classification Methods Using Montana and Washington Wildland Fires

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Abstract—*Fire severity classifications are used in the post-fire environment to describe fire effects, such as soil alteration or fuel consumption, on the forest floor. Most of the developed classifications are limited because they address very specific fire effects or post-burn characteristics in the burned environment. However, because fire effects vary so much among soil, hydrology, vegetation, chemistry, particulate, and spatial distribution, it is important to realize that the impressions of burn severity are governed by the method used to classify the fire effects. The objective of this study was to determine (1) how severity classes derived from each tested method compared with the Composite Burn Index, which is a standard field assessment for fire severity that is commonly used in the United States; and (2) how well the fire severity classes obtained from six different classification methods agreed with each other.*

Comparisons of fire severity classes were made on 289 field plots from 15 fires across Montana and Washington. Severity classes were made for two types of field classifications, including (1) a fire severity matrix (Ryan and Noste 1985), and (2) soil post-fire indices (Jain and others 2012); three remote sensing methods, including (1) the Monitoring Trends in Burn Severity (MTBS) classification (Eidenshink and others 2007), (2) a modification of the relativized differenced normalized burn ratio (RdNBR) classification for plots in the northwestern United States, and (3) the Burned Area Emergency Rehabilitation (BAER/BARC) classification; and a modeling approach created by Keane and others (2010) called FIREHARM. The severity classes derived from these six methods were compared to on-site field assessments of fire severity using the Composite Burn Index (CBI). The two field classifications corresponded best with CBI (Kendal tau b > 0.61, ASE = 0.4). Remote sensing classification classes corresponded to CBI classes only half of the time (Kendal tau b = 0.53, ASE = 0.04). The modeling approach had low to negative correlations with all other methods and the average correspondence among all the classification types was 38%.

Keywords: *Composite Burn Index, dNBR, FIREHARM, fire severity matrix, RdNBR, soil post-fire indices*

Introduction

Fire and burn severity classifications are used by land managers to describe, summarize, and communicate the physical and chemical effects of burning after prescribed burning or wildland fire. These summary classifications are often very specific to certain attributes of the ecosystem and, in general, describe only a restricted portion of the fire effects that occur due to burning. Severity designations derived from these classifications are used by managers to specify ecological damage after wildfire or plan management activities for ecological and economic recovery of the burned area. Management activities may include restoration of vegetation in general (Lentile and others 2007) or rare and endangered species in particular (Dudley and others 2012), plans for mitigating food and habitat loss for specific wildlife species (Hanson and Odion 2014), recovery of the soil or hydrologic features (Cerda and Robichaud 2009; Erickson and White 2008; Kinoshita and Hogue 2011), post-fire vegetation response (Epting and Verbyla 2005), logging activities to remove dead tree boles (Fraver and others 2011), or assessment of future fire danger after initial fuels have burned (Holden and others 2010). They may also inform perceptions on timelines for economic recovery or the future of a burned area for tourism and recreation. In this paper, the term fire severity is used to denote the magnitude of fire-caused damage to vegetation and fuels and general descriptions of fire impacts, such as fire effects on soil (Simard 1991). Burn severity is reserved for classifications created in remote sensing applications because the term has a long history of use in the remote sensing field (Dillon and others 2011; Lentile and others 2006; Lentile and others 2007). Using either fire or burn severity classifications, the response to, or and planning for, burns classed as "high severity" may be very different than for burns classed as "low severity" so it is important to choose a classification that accurately assesses and summarizes the physical or chemical effects of a fire.

Today, individual fire severity classifications exist for field observations, simulation modeling, and remotely sensed fire effects but each classification system has its limitations. Most are generally stand-alone entities. Most are not designed specifically to match field observations of severity at the plot or site scales; nor are they necessarily designed to evaluate the

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

same types of fire effects. Many are tailored to meet the needs of a specific application, such as classifying changes in soil characteristics, vegetation, or fuel consumption. They are not designed to provide a detailed description of the range of multiple fire effects that occur with fire. Specific fire effects on soils have been characterized in descriptions and classifications by DeBano (1991), Jain and others (2009), and (Parsons and others 2010). Fuel characterizations of fire severity include descriptions and classifications by Cushon and others (2003), Lutes and others (2009), Ottmar and others (2007), and Sikkink and Keane (2012). Classes of vegetation damage from first- and second-order fire effects have been described by Lutes and others (2006), Thompson and Spies (2009), Perez and Moreno (1998), and Brown and others (2000). Fire severity classifications have been created for post-fire vegetation response (Agee 1981; Hessburg and others 2007; Keane and others 2004; Russell-Smith and Edwards 2006) and for prediction of post-fire response (Brown and Smith 2000; Keane and others 1990; Lutes and others 2009; Sikkink and Keane 2012). Alternately, classes of burn severity are also created using the difference between pre- and post-fire satellite images (Key 2006; Key and Benson 2006; Miller and Thode 2007). Red and infrared signals capture differences between pre- and post-fire scenes to calculate the normalized difference burn ratio (NDVI). NDVI integrates changes in greenness (i.e., loss of vegetation or increase in soil exposure) and a post-burn charcoal signal (i.e., increased post-fire infrared signal) to describe the degree of post-fire change on large spatial scales. The data used to create each of these fire and burn severity classifications reduce complex interactions of fire, fuels, biota, and the biophysical environment into three general categories of low, medium, and high.

The objectives of this study were to (1) determine how well the classes from each classification method agreed with the burn characteristics assessed at each field site where a common, standard measure of fire severity in the United States was used; and (2) explore how well the classes derived from the various classifications agreed with each other. By exploring how a diverse set of classifications with different origins and scales compared in their assessments of fire severity, the problems encountered when using each method can be highlighted and improvements can be made to the entire fire severity classification process.

Methods

This study compared burn severity classes obtained using the Composite Burn Index (CBI) and six current classification methods of very different types (Table 1). CBI integrates two methodologies to describe changes due to burning, which include calibration and validation of 30-meter Landsat data (e.g., the Normalized Burn Ratio) with on-site change and relative change in the vegetation and soil characteristics from the pre-burn conditions that are detected in the field sampling (Key and Benson 2006). CBI is semi-quantitative and summarizes fire effects that have occurred in five different strata on each site, as well as changes in soil characteristics, into a single fire severity number. Changes in vegetation are assessed from the ground substrate to upper tree canopy making the site assessment with CBI more complete than many other classification systems. Each site is also analyzed individually for changes from the pre-burn condition for each CBI assessment, so the resulting burn severity values can normally be compared across different landscapes (Key and Benson 2006). The six classification methods included (1) a fire severity matrix designed by Ryan and Noste (1985), (2) the soil post-fire indices designed by Jain and others (2012); (3) a simulation model that used weather and tree canopy information specific to each fire location to predict fire effects at each site (Keane and others 2010); and remote sensing classification systems from the (4) Monitoring Trends in Burn Severity (MTBS) web site (Eidenshink and others 2007), (5) RdNBR classes developed by the University of Washington (Cansler 2011; Kopper 2012; Prichard and others 2010), and (6) classes from the Burned Area Emergency Rehabilitation (BAER/BARC) program (www.fs.fed.us/eng/rsac/baer/barc.html). Classification methods 1 and 2 are normally assessed in the field and utilize changes in substrate and tree canopy as primary characteristics for the severity assessment. Classification 3 is a predictive, pre-fire technology tuned to local vegetation, fuels, moistures, or historical fire regime. Classification methods 4, 5, and 6 are remote sensing techniques that classify amount of change between a pre- and post-fire environment.

Reference Data

The reference or "ground truth" used in the classification comparisons was field data from Composite Burn Index (CBI) assessments (Key and Benson 1999; Key and Benson 2006). CBI field data was collected at 289 plot locations from within 15 fires across Montana and Washington, USA (Fig. 1). The CBI plots were established within fire perimeters that differed in burn year, burn season, acres burned, ignition cause, and dominant vegetation (Table 2). All CBI assessments were done one year post-burn at each site using the form designated by Key and Benson (2006). Locations of all plots were logged with personal GPS units (accuracy +/- 15 m). CBI work was conducted with a crew of two to four employees; Montana sites were measured by Forest Service personnel and Washington sites were measured by professors and students from the University of Washington.

Although CBI may not be a perfect candidate for ground truth, the completeness of CBI fire data, its known relationship to remote sensing classifications (Miller and others 2009; Miller and Thode 2007), and its wide-spread use in the United States made it the most comprehensive, on-site evaluation of burn severity available to use as "ground truth" for this study. Many studies have found correlations between CBI and burn severity measurements derived from satellite imagery (French and others 2008). Other research has revealed relationships between image-based metrics and specific measurable fire effects (Hudak and others 2007; Karau and Keane 2010; Keeley and others 2008; Miller and others 2009). In many of these studies, CBI was the metric used to evaluate comparisons of burn severity classes with fire effects on the ground. GeoCBI,

Table 1—Summary of characteristics and source information for the six severity classification methods.

Classification Name	Classification Type	Reference Abbreviation	Number of Classes	Classification Purpose	Main Variables Used to Create Classification	Citation
1 Fire Severity Matrix	Field	FSM	5 broad (20 sub)	Describe fire effects using a fire severity matrix with semi-quantitative variables	Depth of Char, Flame Length	Ryan and Noste, 1985
2 Soil Post-Fire Indices	Field	SPFI	5 broad (12 sub)	Create a consistent index that describes post-fire environment and ecosystem recovery	Organic matter consumed, mineral soil color	Jain et al, 2012
3 FIREHARM Model	Simulation	FIREHARM	4	Create maps of fire hazard and risk across multiple spatial scales (burn severity is one output of FIREHARM)	Weather inputs, fuel moisture, fuel characteristics, tree layers, soil depth and texture, leaf area index	Keane and others, 2010
4 Monitoring Trends in Burn Severity (MTBS) differenced Normalized Burn Ratio	Remote Sensing	dNBR	4	Consistently map burn severity and fire perimeters for the United States	Pre-burn and post-burn satellite imagery (reflectance bands)	www.mtbs.gov
5 Relativized differenced normalized burn ratio (RdNBR) Cansler adjustment	Remote Sensing	RdNBR	4	Utilizes regression analysis adjustment to customize MTBS RdNBR for northwest U.S. forests	Pre-burn and post-burn satellite imagery (reflectance bands)	Cansler, 2011; Cansler and McKenzie, 2012; Miller and Thode, 2007
6 Burned Area Emergency Rehabilitation (BAER)	Remote Sensing	BAER/BARC	4	Evaluate burned area within 7 days of burn for threats to life, property, or natural resources due to post-fire flooding and erosion	Vegetation consumed, soil characteristics, geologic characteristics, tree layers, hydrology	http://www.fs.fed.us/eng/rsac/baer/barc.html

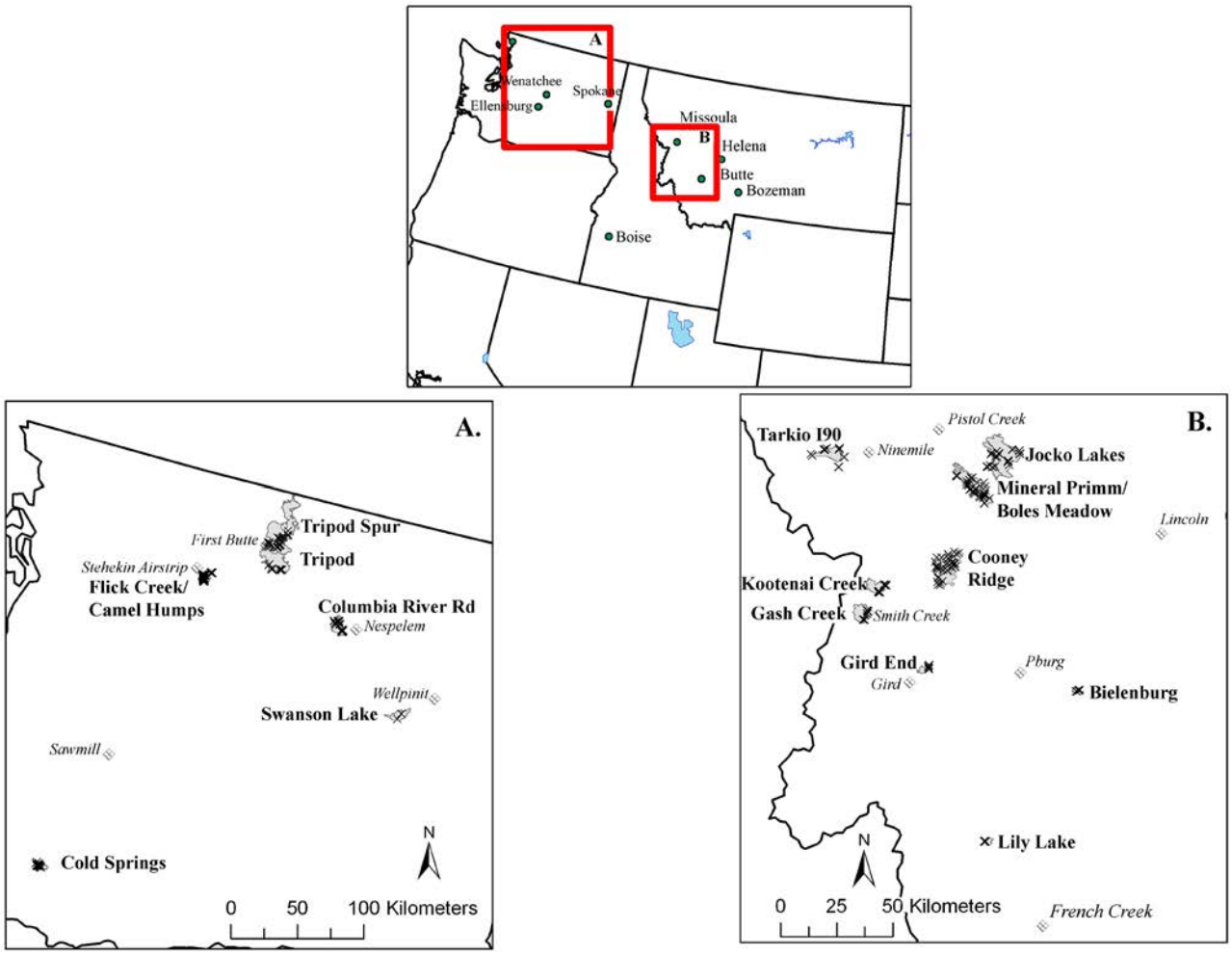

Figure 1—Fire locations in Montana and Washington, USA, used in the comparisons for this study. Weather stations are shown as diamonds near the sites.

which was developed by De Santis and Chuvieco (2009) to improve the correlations between CBI and satellite imagery, was not utilized in this study because neither the fraction of cover nor the leaf area index for each vegetation strata were collected with the field data. Therefore, GeoCBI values could not be computed.

Within the CBI field forms, fire effects were evaluated for five vegetation strata that ranged from substrate at the ground to the upper canopy of big trees. The characteristics used to gauge fire severity in the CBI stratum are defined in Table 3. Within each stratum, a fire severity index was assigned a value from zero to three based on (1) percentage of change due directly to burning or (2) on actual measurements of fire effects (e.g., char height). The values ranged from unburned (CBI = 0) to high fire severity (CBI = 3). Key and Benson (2006) assigned the breakpoints between the low, medium, and high severity values based on their field experience, desire to balance the factors and criteria to not over or under estimate fire effects, and correlation work with remote sensing values. CBI totals were summed and averaged by strata and by site to provide a single number representing an ordinal classification of fire effects at each site. The sites for this study ranged from very lightly burned (CBI<1.0) to severely burned (CBI = 3.0) (Fig. 2).

Fire Severity Classifications

Classifications created from post-fire field assessments of fire effects included Ryan and Noste's (1985) fire severity matrix (FSM) and Jain and others's (2012) soil post-fire indices (SPFI). The FSM classification used flame-length height and depth of char (i.e., unburned to deep) as critical factors in differentiating classes (Ryan and Noste 1985). Because the FSM used forest floor conditions, especially duff consumption and soil alteration, to determine the depth of char, two characteristics from the CBI form, Substrate A: Duff consumed and Substrate A: Soil Rock Cover Color, were used in tandem to determine a CBI value for depth of char (Table 3). Char height from the big trees (Substrate E) was used to determine flame-length (Table 3). If no big trees were present on the plot, char height was assessed using Substrate D: Intermediate trees. The Ryan and Noste (1985) classes could be grouped into four general classes from the CBI assessments, which corresponded to "unburned," "low," "moderate," and "high" fire severity as shown on Table 4.

The soil post-fire index (SPFI) used the abundance of surface organic matter and mineral soil color to differentiate five fire severity classes from zero to four (Jain and others 2012). Each of the five broad classes was divided into subclasses

Table 2—Characteristics of the tested wildfires fires from Montana and Washington.

Fire Name	State	Total CBI field plots	Acres burned	Fire Year	Start Date[A]	Cause[B]	Date 100% Contained	Dominant Vegetation
Bielenburg	MT	6	1,480	2009	7/12/2009	L	10/23/2009	Interior Douglas Fir
Cooney Ridge	MT	26	25,740	2003	8/8/2003	L	12/31/2003	Interior Douglas Fir
Gash Creek	MT	5	9,880	2006	7/24/2006	U	12/8/2006	Englemann Spruce-Subalpine Fir
Gird End	MT	9	3,270	2009	9/9/2009	L	10/26/2009	Lodgepole Pine-Englemann Spruce
Jocko Lakes	MT	13	35,560	2007	8/31/2007	L	12/4/2007	Interior Douglas Fir
Kootenai Creek	MT	14	8,410	2009	7/12/2009	L	11/31/09	Interior Douglas Fir
Lily Lake	MT	9	2,020	2009	8/13/2009	L	10/16/2009	Lodgepole Pine-Interior Douglas Fir
Mineral Primm	MT	25	20,890	2003	8/6/2003	L	12/31//03	Interior Douglas Fir
MP Boles Meadow	MT	3	4,290	2003	8/8/2003	L	8/23/2003	Interior Douglas Fir
Tarkio I90	MT	9	10,950	2005	8/4/2005	U	8/17/2005	Interior Douglas Fir/Interior Ponderosa Pine
Camel Humps	WA	28	130	2008	7/23/2008	L	8/1/2006	Englemann Spruce-Subalpine Fir - Whitebark Pine
Cold Springs	WA	28	7,729	2008	7/12/2008	L	8/1/2008	Interior Douglas Fir/Grand Fir
Flick Creek	WA	100	7,050	2006	7/26/2006	H	10/19/2006	Interior Douglas Fir
Tripod	WA	14	59,710	2006	7/24/2006	U	11/9/2006	Interior Douglas Fir
Tripod Spur	WA	29	115,120	2006	7/3/2006	L	11/9/2006	Interior Douglas Fir/Ponderosa Pine/Engleman Spruce- Subalpine Fir

[A] Based on National Incident Management Coordination Center (NIMCC) incident management situation reports
[B] Cause: L = Lightening; U = Undetermined; H = Human

Table 3—Composite Burn Index (CBI) characteristics used in this study and their corresponding fire severity values (from Key and Benson 2006).

Strata Rating Factors	Fire Severity Scale						
	No Effect	Low		Moderate		High	
	0.0	0.5	1.0	1.5	2.0	2.5	3.0
A. Substrates							
Litter/Light fuel consumed	Unchanged	—	50% litter	—	100 % litter	80% light fuel	98%
Duff	Unchanged	—	Light Char	—	50% loss deep char	—	Consumed
Medium Fuel, 3-8 in.	Unchanged	—	20% Consumed	—	40% Consumed	—	>60% loss, deep char
Heavy Fuel, > 8 in.	Unchanged	—	10% Loss	—	25% loss, deep char	—	>40% loss, deep char
Soil and Rock Cover/Color	Unchanged	—	10% Change	—	40% Change	—	>80% change
B. Herbs, low shrubs and trees less than 3 feet (1 meter)							
% Foliage altered (black-brown)	Unchanged	—	30%	—	80%	95%	100% + branch loss
Frequency % living	100%	—	90%	—	50%	<20%	None
C. Tall Shrubs and trees 3 to 16 ft (1 to 5 meters)							
Frequency % living	100%	—	90%	—	30%	<15%	<1%
D. Intermediate Trees (Subcanopy, pole-sized trees)							
% Canopy mortality	None	—	15%	—	60%	80%	100%
Char height (meters)	None	—	1.5 m (5 ft)	—	2.8 m (9.24 ft)	—	>5m (16 ft)
E. Big trees (Upper canopy, dominant, codominant trees)							
% Canopy mortality	None	—	10%	—	50%	70%	100%
Char height (meters)	None	—	1.8 m (6 ft)	—	4 m (13 ft)	—	>7m (23 ft)
Pre-fire Conditions:							
% pre-fire cover: Litter = Duff = Soil/Rock =							
Pre-fire depth (inches): Litter = Duff = Fuel Bed =							

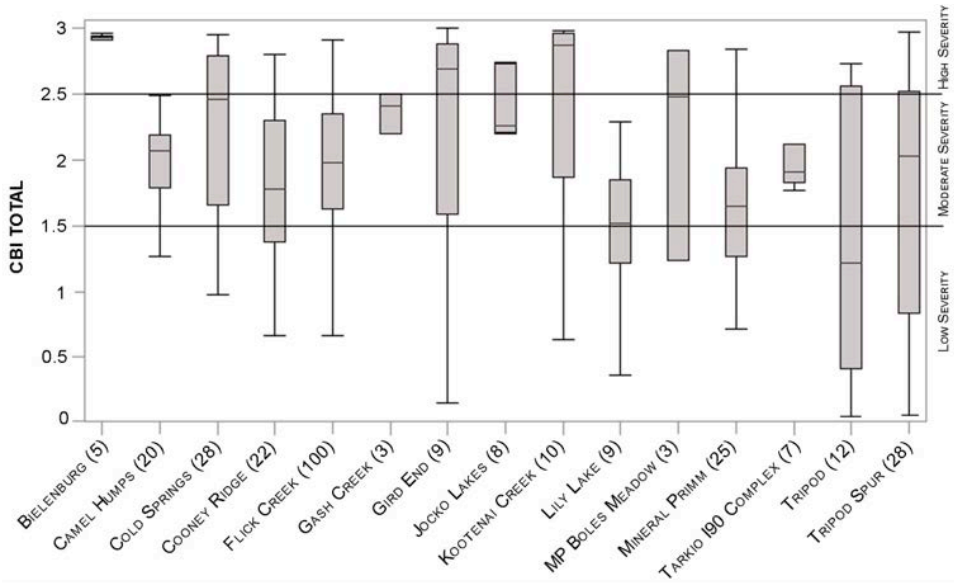

Figure 2—Distribution of Composite Burn Index (CBI) values used in the six-method comparison. CBI breakpoints for low, moderate, and high severity from Lutes and others 2006 are shown on right. Total number of field CBI plots is shown for each fire in parentheses beside the fire name. Boxes show the 25th, 50th, and 75th percentiles; whiskers show the maximum and minimum values. All CBI plots were collected one year post-burn from areas within mixed-conifer forests.

Table 4. Ryan and Noste (1985) classification linked to the CBI characteristics and values that would correspond to each class. The CBI equivalents are taken from the CBI data form (Lutes and others 2006). Ryan and Noste (1985) flame length classes are linked to big tree char height (far right). Ryan and Noste (1985) depth of char classes are linked to CBI substrate A and soil effects as in the lower table. Cell shading designates classes used in this study: white = unburned, light gray = low severity; medium gray = moderate severity; dark gray = high severity.

Flame Length Class	Char Height (m) Equivalent to Flame Length classes					CBI Equivalent (Big Trees Char Height)
5	>35.6 m	5-U	5-L	5-M	5-D	NA
4	19.50-35.59 m	4-U	4-L	4-M	4-D	NA
3	7.0-19.49 m	3-U	3-L	3-M	3-D	3
2	2.0-6.99 m	2-U	2-L	2-M	2-D	2
1	0-1.99 m	1-U	1-L	1-M	1-D	1
		Unburned	**Light**	**Moderate**	**Deep**	
			Depth of Char Class			

CBI Equivalents to Depth of Char Class (above)

	Unburned	Light	Moderate	Deep
Substrate A	0-0.49	0.5-1.49	0.5-1.49	1.5-3.0
Soil and Rock Color/Cover		0-1	>1	

based on the percentage organic matter consumed. The SPFI criteria were converted to CBI equivalents by matching two characteristics from the CBI form. These included (1) Substrate A: Soil Rock Cover Color and (2) Substrate A: Frequency of living material after fire (Table 3). The two CBI characteristics were matched to the soil indices as shown as in Table 5. Where the author's requirements did not exactly match percentages within the CBI data, the percentages with the least difference between the author's and the CBI form were chosen. The five categories for this comparison were designated as shown in Table 5.

The fire severity classifications derived from simulation modeling were based on output from the Fire Hazard and Risk Model (FIREHARM) (Keane and others 2010) and the First Order Fire Effects Model (FOFEM) (Keane and others 1995). The FIREHARM model required inputs of biomass values, weather conditions, and fuel moistures from each fire location for the time of the burn. Weather conditions for the period of the fire were obtained from the Western Regional Climate Center. Information on the fires was obtained from situation reports produced by the National Fire and Aviation Management (National Interagency Fire Center 2012). Fuel moistures were obtained by inputting weather conditions from the nearest weather stations for the period of the fire into Fire Family Plus (FFP) (https://www.frames.gov/rcs/7000/7026.org and http://www.firemodels.org/index.

Table 5. Jain and others (2012) soil indices used to classify post-fire severity based on soil color and organic matter present. Equivalent CBI values based on soil alteration (shown at right of table) and frequency of living material (shown below table) were assigned to the nearest percentage or soil characteristic that would fit the CBI data form. Cell shading designates classes used in this study: na = not applicable; white = unburned, light gray = low severity; medium gray = moderate severity; dark gray = high severity.

Soil Alteration						**CBI Equivalent (Substrate A: Soil Alteration)**	**CBI Burn Severity Class Substrate**
Orange charred soil	NA	NA	2.4	3.4	4.4	3.00	High
Grey-white charred soil	NA	NA	2.3	3.3	4.3	2.01 to ≤ 3.0	High
Black charred soil	NA	NA	2.2	3.2	4.2	1.01 to ≤ 2.0	Moderate
Unburned mineral soil	0.0	1.0	2.1	3.1	4.1	≤ 1.0	Unburned-Low
	100	≥85	>85 to ≤40	<40	0%		
	Surface Organic Matter Present (%)						
CBI Equivalent (Frequency of living material)	0 to ≤ 0.5	0.51 to ≤ 1.25	1.26 to ≤ 2.25	2.26 to < 3.0	3.0		

php/firefamilyplus-software/firefamilplus-downloads). The fuels, fuel moistures, and soil moistures (if available) were incorporated into a FIREHARM model run. The results assigned a predicted fire severity value to each pixel within the fire perimeters for each run. FIREHARM results for severity were one (low), two (medium), and three (high), which were considered to correspond to low, medium, and high CBI fire severities, respectively.

The remote sensing data for classifying burn severity using the differenced normalized burn ratio (dNBR) was obtained from the Monitoring Trends in Burn Severity (MTBS) web site (http://mtbs.gov). This data was based on assessments of vegetation change, charcoal signal, soil characteristics, and other biological changes after fire. It consists of four classes: unburned, low, medium, and high. Normally, MTBS recommends using continuous dNBR rasters instead of the class thresholds in fine-scale studies like the small burned areas examined in this study so that better results may be obtained in the classification process. For this study, a geospatial information system (GIS) layer containing both continuous raster values and the class values for dNBR was downloaded for each of the 15 fires to compare the values at each site. The class values were ultimately used for comparisons because they seemed more comparable to the distinct classes of the other burn severity methods, but it could be argued that the fine-scale comparison to CBI should not be expected to perform well using these class values. Fire severity class and continuous values were extracted for dNBR at each CBI plot location using Geospatial Data Extraction Library (GDAL) software (Open Source Geospatial Foundation 2011). The pixel values were derived from cells within a 5 x 5 grid cell area (each cell was 30m x 30m) at each CBI field location to provide average classed values for fire severity using dNBR. The 5x5 grid provided variation for the burn severity that could not be obtained from a single grid cell. The unburned, low, medium, and high severity classes resulting from dNBR pixel extractions were considered to correspond to CBI unburned (<0.49), low (0.5-1.49), moderate (1.5-2.49), and high (≥2.5), respectively.

Classified RdNBR data were also obtained from MTBS. Some research has shown that RdNBR is better for classifying vegetation change across large landscapes than dNBR because it removes bias from the amount of pre-fire vegetation and provides a relative rather than absolute measure of the changes in vegetation between pre- and post-fire imagery (Miller and Thode 2007). It has also been shown to be more regionally consistent in its relationship to field-measured burn severity (Zhu and others 2006; Miller and Thode, 2007). However, others have found that RdNBR is either not superior to dNBR (Cansler and McKenzie 2012; Soverel 2010) or other indices work better than RdNBR for severity classifications (Parks and others 2014; Sparks and others 2014). Because of its relative nature, RdNBR could conceivably produce different classification values for each CBI sample site within the 15 fires. For this study, we further adjusted the relative RdNBR values using breakpoints suggested by Cansler (2011), which were shown to improve RdNBR measures for forested areas in the Northwest and more closely match field CBI values taken from northwestern forests. The Cansler (2011) modification uses cutoffs of 106, 218, and 456 for remotely sensed class thresholds for dNBR; and cutoffs of 189, 372, and 703 for low, low-moderate, and moderate-high remotely sensed class thresholds for RdNBR (Cansler and McKenzie 2012). As with the dNBR, GIS layers for RdNBR were downloaded from MTBS, pixel values extracted from 5x5 grid cell units for each CBI site, and the RdNBR, CBI, and other classification techniques were compared. The RdNBR classes corresponded to CBI values as stated above for dNBR.

The Burned Area Emergency Recovery (BAER) Program produces recovery plans using burned area recovery classifications (BARC) that show changes in burned area reflectance due to loss of vegetation and charring of soil. GIS layers for BAER were produced by the USDA Forest Service Remote Sensing Application Center and downloaded for this study from the MTBS website (www.mtbs.gov). BARC layers are produced only for fires requested by BAER teams, not for all fires that are processed via MTBS. When BARC classifications

are produced, however, they have the same range of correlation values as the RdNBR and dNBR when the layers are available, so they are no better or worse than the dNBR or RdNBR data from which they are created. However, they have a different purpose and focus than other remote sensing products, which can be reflected in their classification process. They were included in this study because BARC data are used for very specific purposes in recovery plans and they can classify burn severity differently because of their particular focus on erosion and soil heating. The extraction procedures, classifications, and relationships to CBI were the same as with the dNBR and RdNBR data.

Data Analyses

A contingency table was created from the table analysis procedure using table analysis with the SAS statistical program (SAS Institute Inc. 2008). The table shows the total number of CBI plots that matched on four severity classes – unburned, low, moderate, and high – and how differences varied between each of the method pairs. Because each method had varying amounts of missing data due to lack of some characteristics in the field data, percentages of agreement were calculated based on the number of plots available for each comparison not on the total number of CBI plots available to the study. A non-parametric ordered class statistic, the Kendal Tau statistic (K) (Canover 1999), was used to show the strength of the relationship between pairs of ordered classes and the direction of correlation. Kendal Tau b = +1 represented paired classes that increased in value together (i.e., a perfect positive correlation); Kendal Tau b = -1 represented an increase of one class with a corresponding decrease with its paired class (i.e., a perfect negative correlation). The Jonckheere-Terpstra (J) test (Canover 1999) was the non-parametric test used to investigate whether there were significant differences in the correlation in the medians of ordered classes. Differences were considered statistically significant if $p<0.05$.

Results

Comparisons of the CBI field assessments with results from each of the classification methods showed that the SPFI had the highest significant positive correlation with CBI classes (K = 0.75) but this index also had the smallest number of plots that could be assigned soil index values (Table 6). The other field classification that was developed by Ryan and Noste (1985), the FSM, also correlated reasonably well, and positively, with CBI at K = 0.66. The dNBR and RdNBR remote sensing classifications had lower correlations with CBI at approximately 50%, and BARC classes did not correlate with CBI well at all (K = 0.18). All of the classifications compared to CBI were significant in direction and strength using the J test.

The comparison of classification results with each other resulted in a wide range of correlation strengths and directions. The strongest correlations were between the two remote sensing classifications. The dNBR correlated with RdNBR strongly and positively at K = 0.76. The two field classifications, the FSM and the SPFI, also correlated well with each other (K = 0.70). SPFI also correlated moderately well with classes from remote sensing methods, including the dNBR (K = 0.43) and RdNBR (K = 0.57); but no correlations could be computed between SPFI and FIREHARM or BARC because so few plots could be assigned the soil index values. The simulation modeling method (FIREHARM) correlated weakly with all other methods (Table 6) and ranged from 0.01 with dNBR to 0.29 with FSI. The correlations of FIREHARM with RdNBR and BARC were both slightly negative, but only significant for BARC (J = 0.001). The least correlation overall occurred with BARC, which had weak correlations with all classification types except the RdNBR Cansler classification (K = 0.44). In combination, all classification methods varied considerably in their correlation strength and direction and the average percentage of agreement between any two methods was 38% for all pairs (Table 6).

For the FSM, dNBR, and RdNBR classifications, the total percent of classes that did not agree with the CBI assessment was spread relatively evenly among all the other classes so no consistent under- or over-assignments in classification were detected. For the CBI:SPFI pair, most of the classification differences came in the Soil Index Class 4 (44%). For the CBI:FIREHARM pair, the most classification differences were in its moderate and high severity classes. However, because FIREHARM had no unburned (Class 1) assessments for these fires, the value of this trend is limited.

Discussion

Classifications describing fire severity on the landscape have traditionally filled important roles in fire research because they integrate complex interactions and fire effects into more limited systems that are easy to understand. They have enabled managers and researchers to communicate impressions of severity with a common language. They have also acted as springboards for deeper inquiry and research on many different types of fire effects. The drawback of having many different classifications for describing fire severity is that it can be confusing to choose which classification will best describe fire effects on any given burned area or landscape; it also complicates communication. For some locations and purposes, fire effects may be adequately communicated by the simplistic, low-medium-high terminology; for others, a more robust classification may be required to adequately describe a full range of fire effects. Currently, communicating a range of fire effects is cumbersome because it requires determining a burn severity class from a specialized classification that does not necessarily match classifications obtained from other methods. It can also be confusing because the terms fire severity and burn severity have been used interchangeably in the past (Keeley 2009).

Assigning classes to unburned, low, medium, and high categories within this study was difficult for a number of reasons. Each classification method required unique interpretations and/or judgment calls to condense its classification into four standard classes that ranged from unburned to high. For the

Table 6. Contingency table showing statistical comparisons for each fire and burn severity classification method using 5 x 5 analysis grids to evaluate burn severity. Comparisons were based on the number of plots that matched in paired fire or burn severity classifications using unburned and low, medium, and high severity categories. Percentages are based on the number of plots analyzed for the respective methods divided by 289 total plots. CBI = Composite Burn Index used as ground truth; FSM = Ryan and Noste's (1985) Fire Severity Matrix; SPFI = Jain and others (2012) soil post-fire index; FIREHARM = Fire Hazard and Risk Model (Keane and others 2010); dNBR = differenced normalized burn ratio from Monitoring and Trends in Burn Severity; RdNBR (Cansler) = relativized differenced normalized burn ratio using Cansler's (2011) adjustment specifically for vegetation in the Northwest, USA; and BARC/BAER = Burned Area Reflectance Classification. Kendall's tau values are color coded as follows: <0.2 white, 0.2 to 0.4 light gray, and >0.4 dark gray. Group medians tested in the Jonckheere-Terpstra (J) non-parametric test were considered significantly different at <0.05.

Compared method	Field methods		Modelling methods	Remote-sensing methods		
	FSM	SPFI	FIREHARM	dNBR	RdNBR (Cansler)	BARC/BAER
CBI	**217 (75%)**	**25 (9%)**	**288 (99%)**	**288 (99%)**	**288 (99%)**	**183 (63%)**
missing values	72	264	1	1	1	106
Kendall's tau[a]	0.607	0.752	0.120	0.539	0.527	0.181
J test[b]	<0.0001	<0.0001	0.015	<0.0001	<0.0001	0.003
FSM		**25 (9%)**	**218 (75%)**	**218 (75%)**	**218 (75%)**	**153 (53%)**
missing values		264	71	71	71	136
Kendall's tau[a]		0.704	0.294	0.394	0.342	0.058
J test[b]		<0.0001	<0.0001	<0.0001	<0.0001	0.410
SPFI			**25 (9%)**	**25 (9%)**	**25 (9%)**	**0 (0%)**
missing values			264	264	264	289
Kendall's tau[a]			**	0.433	0.576	**
J test[b]			**	0.017	0.0005	**
FIREHARM				**289 (100%)**	**289 (100%)**	**184 (64%)**
missing values				0	0	105
Kendall's tau[a]				0.012	-0.074	-0.219
J test[b]				0.411	0.087	0.0014
dNBR					**289 (100%)**	**184 (64%)**
missing values					0	105
Kendall's tau[a]					0.761	0.325
J test[b]					<0.0001	<0.0001
RdNBR (Cansler)						**184 (64%)**
missing values						105
Kendall's tau[a]						0.441
J test[b]						<0.0001
Total plots	**218**	**25**	**289**	**289**	**289**	**184**

[a] Kendall's tau test (K) for differences between classes of ordered, categorical data; values $-1 \leq K \leq 1$; -1 = perfect negative correlation, +1 = perfect positive correlation, 0 = no correlation.
[b] Jonckheere-Terpstra non-parametric test for differences in medians between ordered classes. Values are probabilities <1.0.
** Unable to calculate statistics because rows or columns are all zeros.

FSM method, assigning a class required determining a flame height for a classification whose upper limits reached 35+ meters from CBI char height, but height was not evaluated higher than 5 m in the field. For the SPFI, the process of assigning fire severity to the CBI plots required using soils literature to determine how a color change from black to red in the substrate should be interpreted from the CBI substrate values. In some cases, assigning classes to appropriate categories was problematic because the CBI form was not filled out completely in the field. Missing values for pre-fire conditions, including litter and duff, made converting the SPFI and the FSM to appropriate fire severity classes especially difficult. For these particular burn severity classification methods, alteration of the substrate due to fire was critical to class assignments and would have been easier to do if the percent pre-fire cover of substrate fuels had been completely filled out on the CBI long form in the field. It can be argued that if a single decision had been made differently when assigning values to fire effects in any of these methods it may have changed the outcome of some of the paired comparisons. No doubt, this is true, but the process of determining which specific factors need to be measured after a burn or which fire effect needs to be highlighted for management action will, in any event, require similar decisions to be made by managers.

One notable result from this study is that remote sensing classification methods do not agree on class designations among themselves more than 75% of the time for the same grid space on the ground or correlate with CBI values more than 53% of the time. One probable reason is that the RdNBR used for this study was altered from traditional RdNBR thresholds to improve its accuracy in forests of the northwestern U.S. Even though both RdNR and dNBR are mapped at 900 m^2 using extensive quality standards, the different methods of processing the satellite data (continuous vs. class thresholds) do give different results for site and point locations especially when "tuned" to a specific landscape. While CBI correlations with remote sensing classes are only marginal in this study, the lack of agreement between remote sensing classifications and the CBI should not be a surprise. A significant amount of literature has demonstrated either poor correlations between CBI and remotely sensed data or correlations that are comparable in scale to those found in this study. Cocke and others (2005) found 75% agreement between dNBR and CBI and Robertson (2006) found 79% agreement compared to the 53% correlations of this study; but poor correlations were found by Clark and Bobbe (2006), Epting and others (2005), and Kasischke and others (2008), among others.

Modeling approaches to classifying burn severity are problematic because models are, by definition, only general representations of what happens in nature. The FIREHARM model correlated best with the FSM but the correlation was not strong (K = 0.29). Both of these classification methods use substrate and tree canopy in some manner to assign fire severity; but FIREHARM had very little variation within the 289 plots tested for this study (i.e., 83% of the CBI plots fell in the Moderate-Severity class), so the odds of agreeing with other methods that classified most burns as moderate were greatly increased (42% of the CBI values in FIREHARM and FSM were moderate severity). In contrast, the classes developed by Sikkink and Keane (2012) also resulted from a modeling approach but their classes could be related to CBI classes more closely because they encompassed soil heating with fire charcteristics and had a larger number of severity categories (Table 7).

Although the classification methods explored in this study utilize very specific fire effects to determine a picture of severity, their usefulness to managers and research is limited by the specificity and lack of flexibility of each classification. Many fire effects are important to the public in addition to vegetation loss and soil charring. For some managers, smoke production and hydrophobicity are just as important for public health and soil recovery. Many fire effects like these are not included in common fire severity classifications and currently have no possibility of being included in them in the future. Improving the classification process to meet the diverse needs of users may require a new approach that integrates field and remote sensing of burn characteristics more completely than in the past. It may involve developing modules within a classification that objectively describe classes of fire effects in soils (changes in color, texture, hydrophobicity, nutrients, etc.), the canopy (char height, canopy color, loss of greenness), hydrology (erosion, leaching, changes in rock color, etc.), fuels (percent biomass reduction, percent substrate change, etc.), the atmosphere (smoke, chemicals, etc.), and the landscape (percent changes in greenness, canopy loss, exposure of soil) (see Morgan and others (in press)). Integrating modules that describe different type of fire severity into a multifaceted classification system could provide a more comprehensive description of fire effects and create a more encompassing tool for classifying local and landscape effects and heterogeneity of fire severity on the landscape. It could also make classification and characterization of fire severity more objective, versatile, standardized, and inclusive in order to better meet research and management needs.

Acknowledgments

This paper was funded under Joint Fire Science Program project #09-1-07-4. CBI data was supplied for burn plots in Montana and Washington by Greg Dillon and Eva Karau, RMRS Fire Sciences Laboratory in Missoula, MT; Alina Cansler, Susan Prichard, and Karen Kopper, University of Washington; Tony Guay, USDA Forest Service, Remote Sensing Application Center; and Stacy Drury, Sonoma Technology Inc., CA. Kevin Ryan, Missoula Fire Sciences Lab, and Teresa Jain, RMRS in Boise, ID, provided guidance on converting their fire severity classifications to classes of low, medium, and high. Greg Dillon provided guidance on making the GIS raster extracts. Jason Herynk, Systems for Environmental Management, ran the FIREHARM simulations. Robert Keane, Missoula Fire Sciences Lab, and Penny Morgan, University of Idaho, shared stimulating discussions on why this comparison study was needed. Comments and suggestions from three anonymous reviewers greatly improved the quality of this paper.

Table 7—Relationship between the fire effects and fire characteristics used to create nine-classes of burn severity in Sikkink and Keane (2012) and the assignment of Composite Burn Index (CBI) values (Key and Benson 2006). PREDICT classes 4, 5, and 6 correspond to CBI low burn severity (i.e., CBI <1.5); classes 5, 6, 8, and 9 to CBI moderate severity , and classes 1, 7, and 8 to CBI high severity (CBI ≥ 2.5).

Fire Effect/ Fire characteristic	Unit	Matching CBI effect	PREDICT's Severity Classes								
			1	2	3	4	5	6	7	8	9
Soil heating (upper 1 cm)	°C	Substrate A: soil and Rock Cover/color	201	28	41	20	22	20	209	101	20
Soil heating (depth heated to 60°C) [a]	cm	Substrate A: Soil and Rock Cover/color	5	0	0.5	0	0	0	6	3	0
Total consumption kg m^{-2}	kg m^{-2}	Substrate A: Fuels Consumed	38	17	33	55	81	34	66	26	75
% duff and litter [b]	%		88	82	87	93	37	68	30	73	96
% cwd [c]	%		12	18	13	7	63	32	60	27	4
Fire Intensity	KW m^{-2}		115	88	4,374	12,839	125	58	116	72	153
Flame duration	sec		1,140	300	60	60	3,810	1,185	3,180	1,095	1,245
Smoke duration	sec		9,975	7,365	3,795	4,088	29,430	13,890	24,225	10,110	17,040
Total burn time	sec		3,225	1,485	75	60	7,995	4,875	7,995	3,825	3,885
		CBI assignment:	**2.5**	**1.0**	**1.0**	**0.5**	**1.5**	**1.5**	**2.5**	**2.5**	**1.5**

[a] Soil heating depth = 0 is surface heating only
[b] Percent computed on the total median value of biomass for duff and fine fuel component for each class
[c] Percent computed on the median value of total coarse woody debris biomass for each class

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Fire Patterns of South Eastern Queensland in a Global Context: A Review

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Abstract—*Fire is an important driver in ecosystem evolution, composition, structure and distribution, and is vital for maintaining ecosystems of the Great Sandy Region (GSR). Charcoal records for the area dating back over 40, 000 years provide evidence of the great changes in vegetation composition, distribution and abundance in the region over time as a result of fire. Fires have shaped landscapes and ecosystems, creating fire-dependencies and fire disturbance-adapted flora and fauna with traits to survive fire, such as resprouting post-fire and serotiny of cones and fruit. However such traits are not necessarily only developed as a result of fire as a process of natural selection, other factors may play a role in such trait development within plants. Paleo-records and modern observations show a definitive link between fire and climate (temperature and precipitation), with an increase in fire with increasing temperatures. This has serious implications in a warmer world there will be an increase of wildfire risk. Of importance is the understanding of the interactions between multiple drivers of fire regimes from the past and present. This is critical for developing fire regime management protocols for the Great Sandy Region and other similar fire-prone regions into the future.*

Keywords: *Fire regime, vegetation dynamics, evolution, fire dependency, wildfires, paleofire*

Introduction

The Great Sandy Region (GSR) of South East Queensland is an iconic landscape, including the largest sand island in the world (Fraser Island), as well as the significant mainland Cooloola sand mass. The importance of this region has been highlighted by a number of Queensland, Australian, and international environmental protection agreements, including World Heritage and the Convention on Wetlands of International Importance (Ramsar) listings for Fraser Island, protection for the Great Sandy Strait between Fraser Island and the northern parts of the Cooloola region and National Park status for most of the GSR (Figure 1).

This paper provides a review of the global, Australian, and local context for changing fire regimes for the GSR. This will provide important contextual information into undergoing research on the fire regimes for the past, present and future that will be vital for sustainable fire management plans for this significant region. Paleofire history of the earth in general and changes to fire regimes over time and space as well as linking these to changes and fluctuations in the climate to the present are discussed with a view to focus on Australia and the GSR locality. The focus of this paper is on shifts in fire regime over space and time and impacts that changes in climate have had on fire regime history. Linking past with present fire regimes being an integral part of the discussion, with an overarching view to look at possible drivers and changes to future fire regimes with a shifting tropical belt that is an important driver for future climate change, particularly fire management protocols

Climate and Wildfire

There is strong evidence that the atmosphere is warming and that there is an increase in warm El Niño Southern Oscillation (ENSO) years with a weakening of the Walker circulation over the past decades (Knopf and Petoukhov, 2007; Meng and others. 2012). Present data show that there has been an increase in width of the tropical belt of between 2° to 4.8^{o} latitude north/south over the past 30 years (Seidel and Randel, 2007; Grassi and others. 2012; Davis and Rosenlof, 2012; Allen and others, 2012a b). This expansion has seen the shift in the subtropical subsidence, leading to an enhanced mid-latitude tropospheric warming and poleward shift of the subtropical dry zone, jet streams, and storm tracks, which is expected to contribute to an increased frequency of mid-latitude droughts in both hemispheres (Seidel and others, 2008; Grassi and others, 2012; Wilcox and others, 2012; Allen and others 2012a; Cai and others. 2012).

Evidence of fire has been recorded in charcoal deposits dating back to 440 million years ago (mya) when the first stomata-bearing plants evolved (Pausas and Keeley, 2009). These fires were thought to have been low intensity fires, probably due to the limited biomass available to burn and reduced atmospheric oxygen. However according to Pausas and Keeley (2009), charcoal deposits increased substantially around 345 mya during the Carboniferous Period, which correlates with the increase in atmospheric oxygen levels of the oxygen maxima through to around 2.5 mya when

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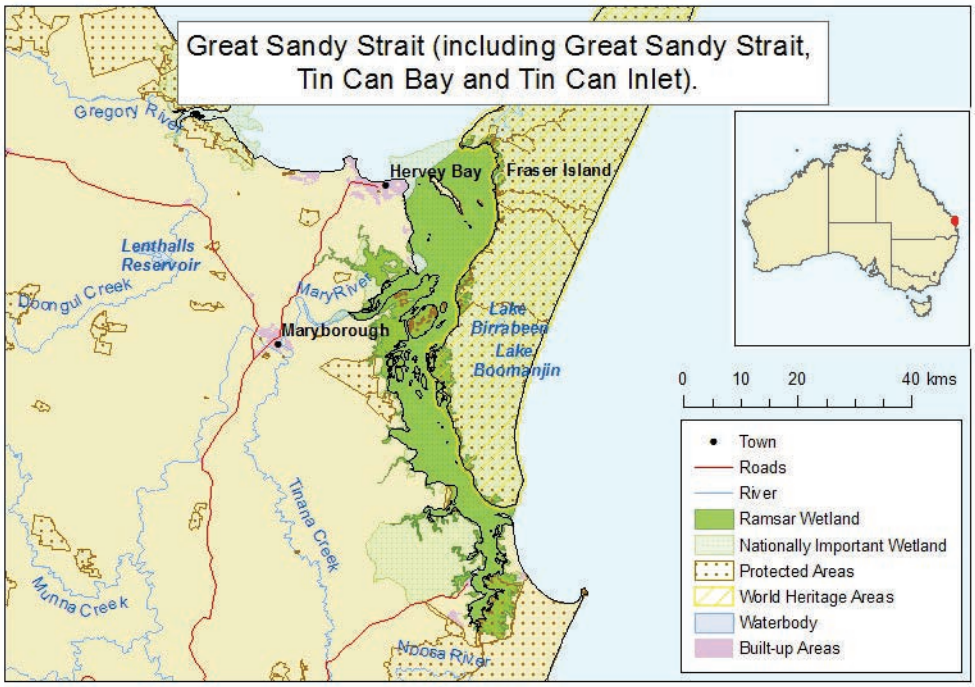

Figure 1—Map of the Great Sandy Strait Region, showing the major protected areas (i.e., Fraser Island National Park and Cooloola Recreation Area), Ramsar listed wetlands and World Heritage listed areas (Fraser Island). Source: http://www.environment.gov.au/cgi-bin/wetlands/ramsardetails.pl?refcode=51.

early hominids started evolving and using fire. In northeast Queensland, records of Aboriginal fire have been recorded between 45 and 43 thousand years ago up until the arrival of Europeans approximately 200 years ago when charcoal deposits possibly increased due to land clearing and modification of the landscape (Turney and others 2001; Rule and others 2012).

The south eastern Queensland region of eastern Australia (incorporating the GSR) has had limited research into past fire regimes and the links to human occupation. Direct archaeological evidence traces human occupation to around 20,000 years ago at the Wallen Wallen Creek site on North Stradbroke Island (Neal and Stock 1986) and longer charcoal records (extending back to 45,000 years) from North Stradbroke Island suggests a complex fire history (Moss and others 2013). The Native Companion Lagoon site, located on the west coast of the island and within 5 km of the Wallen-Wallen site, suggests higher fire frequencies from 45,000 to 40,000 years ago, which may be analogous to the North Queensland findings. However, a similar aged record from the high dunes of the island at Tortoise Lagoon, finds no evidence of increased burning during this time, with charcoal peaks apparently related to dry climatic phases in the record. This suggests that site characteristics and local to sub-regional factors may play a key role in charcoal records and multiple sites may be required to fully understand past fire regimes for a region (Moss and others, 2013). More recent charcoal records from North Stradbroke Island at Myora Springs may reflect the influence of climate change and people on past fire regimes (Moss and others, 2013). With a shift to a warm ENSO period from between 800 to 500 years ago caused dryer conditions to prevail on the island, resulting in drought and higher anthropogenic fire frequency during this period. This was followed by cooler, wetter conditions developing around 500 years ago which correlates with a decline in charcoal deposits (Moss and other 2011). With the arrival of Europeans fire regimes once again changed around 200 years ago, resulting in more frequent fires and burn-offs for agricultural, residential and industrial purposes. These changes led to changes in the landscape to fire-tolerant vegetation, *Eucalyptus* forest and *Melaleuca* swamp paperbark at the expense of less fire-tolerant species like Casuarinaceae (Moss and others 2011). According to Haberle and others (2010), "No single driver can explain past fire patterns and many events may be the result of multiple drivers interacting on differing temporal and spatial scales" (p. 80). Of critical importance is an understanding of these interactions between multiple drivers of fire regimes from the past and present which is critical for developing fire regime management protocols for Australia in the future (Haberle and others 2010).

According to Seidel and others (2007) an unequivocal sign of climate change has been the warming of the atmosphere and oceans, with the thawing of land and melting of ice at the poles, and the expansion of the tropical belt. Several studies (Hu and Fu 2007; Seidel and others 2008; Lu and others 2009) have looked at the expansion of the tropical belt and poleward migration of the divergent air of the Hadley cell, which has important implications for subtropical populations due to possible changes in the global climate. This suggests that a shift in precipitation in the temperate regions of the planet will have profound impacts on fire regimes, ecosystems, plant communities, crop production and agriculture (Spratt and Sutton, 2008; Nitschke and Innes. 2013). Further, Lucas and others (2014) state that recent decadal observations suggest changes in the hydro-climate with an increase in the frequency of droughts and reduced precipitation as has been observed in southern portions of Australia. This is supported by research undertaken by Moss and others (2012a) suggesting that natural climate factors can significantly alter fire frequency

and intensity, such as increased climate variability associated with the ENSO phenomenon that dramatically impacts fire regimes.

Wildfires have increased in size and intensity over recent decades that may be linked to extreme weather events such as extended droughts (Liu and others. 2013; Westerling and others. 2006) and where frequent low intensity surface fires in forest ecosystems have transitioned to severe fire behaviour due to climate change (Bigio, 2013). These recent increases in large fires globally have caused concern about the influence climate change and humans may have on future fire regimes, with predictions of shifts to climatically driven fire for the 21st century (Pechony and Shindell, 2010). Pastro and others (2011) states that more intense and frequent wildfires are predicted in the future due to climate change. A better understanding of climate and wildfire interactions will be required to mitigate impacts of future fire regimes.

Collins (2014) shows a trend for a strong increase in the occurrence of high to extreme fire weather since the mid 1990's across the northern Sierra Nevada, USA. In addition to this De Groote and others (2013) reviewed recent studies using several General Circulation Models that show a general increase in future fire weather severity with increased fire season in many regions around the globe. Added to this is the suggestion by McKenzie and others (2014) that smoke from wildfires in the future may be more intense and widespread, further increasing the effects of greenhouse gases in the atmosphere by exerting positive radiative forcing within the short term (Simmonds and others, 2005; McKenzie and others, 2014).

Present forecasts of climate change indicate an increase in temperatures, with warmer springs and earlier runoff and longer fire seasons (Westerling and others, 2006; Flannigan and others, 2013). Any increase in wildfire extent and intensity would affect human safety, livelihoods, landscape biodiversity and vegetation communities (Litschert and others 2012; Rogstad and others 2012). Measuring the rates of change (changes in frequency, intensity, season and sequence) in wildland fire and understanding the mechanisms responsible for such changes are important research goals (Hessl 2011). A number of modeling studies project increases in wildfire activity in future decades; however few empirical studies have documented change in modern fire regimes. Identifying generalised pathways through which climate change may alter fire regimes is a critical next step for understanding wildland fire under a changing climate (Hessl, 2011).

In a study by Nitschke and Innes (2013) a statistically significant increase in mean fire (increase in the average size of wildfire) size was predicted to occur along with an increase in maximum fire size and decrease in the mean fire interval. Changes in fire regimes will have direct implications for ecosystem management as the combination of large, flammable fuel types and fire-prone climatic conditions increase the risk of larger more frequent fires (Nitschke and Innes 2013; Loepfe, 2012), with greater impacts on biodiversity and plant communities with increasing wildfire intensities (Beck and others 2011; Bigio 2013).

Fire History and Evolutionary Response

Originally climate and soil were thought to control the distribution of ecosystems with fire only playing a limited role (Pausas and Keeley 2009). However fire is and has been an important driver in ecosystem evolution, composition and distribution through its impact on biota (Bond and others 2005; Pausas and Keeley 2009; Coneder and others 2009; Bowman and others 2011; Batllori and others 2013). Fire has played a key role in the evolution of plant community composition, distribution and abundance within ecosystems from around 440 million years ago (mya) when the first stomata plants evolved on the planet (Glasspool and others 2004; Bond and Keeley 2005; Pausas and Keeley 2009) to present. Further charcoal records show that there has been continuous fire activity from the late Silurian to present, a period of approximately 400 million years according to Bowman and others (2011).

Fire-modified ecosystems has resulted over time and space in biomes becoming fire dependent (Bond and others 2005; Conedera and others 2009) where fire is a major evolutionary force creating fire disturbance-adapted ecosystems. Bowman and others (2011) state that fire has been an important factor in plant evolution, shaping some biomes such as the flammable savanna communities of the late Cenozoic Era. Ecosystem response and adaptation to fire has been shown to evolve over short evolutionary timescales as suggested by Litsios and others (2014) with fire response traits impacting plant evolution (Wells 1969) resulting in diversity increase. However Litsios and others (2014) state that this is still controversial, providing examples where rates of diversification are not associated with fire response traits for five plant genre found in fire prone habitats.

According to Conedera, and others (2009) wildfire is a key factor in changing the climate as it affects the chemistry of the atmosphere and carbon cycle. Pausas and Keeley (2009) suggest that due to the importance of fire as an ecosystem modifier, plants developed traits to survive fire, such as resprouting post-fire and serotiny of cones and fruit. However such traits are not necessarily only developed through fire as a process of natural selection, other factors may play a role in such trait development within plants (Bowman and others 2009).

According to Power and others (2008) fire has varied globally on a continuous basis since the last glacial maximum (LGM) between 22-19 thousand years BP (Adams-Hosking and others 2011) in response to changes in climate, vegetation and human land use (Bowman and others 2011). Fuel availability and weather conditions are important drivers of wildfire and can be both directly and indirectly linked to climate (Duguy and others, 2013) vegetation type and human activity. Further, with the domestication of fire, humans substantially changed the natural fire regimes (Conedera and others 2009), which in turn has changed ecosystem constituent species. Originally anthropogenic burning was thought to have created the flammable biomes, and to a certain extent this is true, however natural fires occurred millions of years before humans existed on the planet (Bond

and Keeley 2005). At the biome level the variation in fire regime and biomass burnt changes with a changing climate, fuels and ignition sources (Pyne and others 1996; Power and others 2008).

Daniau and others (2012) state that paleo-records and modern observations show a definitive link between fire and climate (temperature and precipitation) with an increase in fire with increasing temperatures. This has serious implications as in a warmer world there will be an increase in wildfire risk (Daniau and others 2012). Daniau and others (2012) further suggest that increases in wildfire due to increased temperature can be off-set by precipitation; however, this will depend on whether or not there is an increase or decrease in precipitation at a regional level.

Fuel-limited regions of today could see increased wildfire with increased precipitation, especially with the expansion of the tropical belt and monsoons associated with future warming (Meehl and others 2007; Daniau and others 2012). Associated with the expansion of the tropical belt are increases in drought in the shifting subtropical dry regions (Seidel and Randel 2007) and enhanced risk of wildfire. However according to Daniau and others (2012) any increase in fire due to increases in temperature for example maybe offset by changes in fuel dynamics due to changes in precipitation. The global incidence of wildfire decreased during the twentieth century despite increasing temperatures, which could be linked to landscape fragmentation and fire exclusion (Marlon and others 2008; Daniau and others 2012; Marlon and others 2013; McWethy and others 2013; Buma and others 2013). However it has been suggested that the level of landscape fragmentation is no longer an effective means of wildfire suppression due to the evidence of an increase in wildfire due to natural and anthropogenic change (Mickler and others 2013) and in particular the increases in wildfire being linked to global warming (Daniau and others 2012).

It is well documented that wildfire regimes have been affected by climate change in the past and that future fire regimes will be driven by changes in future climates, with longer wildfire seasons, more frequent, severe and larger wildfires (Duguy and others 2013; Brotons and others 2013). According to Power and others (2008) regional climate change has directly affected ignition and fire spread while indirectly affecting vegetation composition and structure and available fuel loads. Pechony and others, (2010) state that there has been an increase in concern about the influence of climate change and human activity on future wildfire and that comparatively little is actually known about the importance of these factors on wildfire. Such changes would have significant impacts on species abundance, distribution, ecosystem dynamics, and on both atmospheric and biogeochemical cycles, impacting the climate (Zinck and others 2011).

Fire regime and an understanding of organism response to wildfire is essential for ecological management of any natural system and the conservation of biodiversity as changes to the natural cycle of wildfires can negatively impact constituent species structure, abundance, distribution and density (Driscoll and others 2010; Farnsworth and others 2014). This brings into question whether pyrodiversity begets biodiversity, as Farnsworth and others (2014) argue the importance of scale when burning for biodiversity.

Fire regimes comprise of fire interval, intensity, season, frequency, sequence of fires and the temporal, spatial fire history and patch mosaic dynamics (Parr and Andersen 2006). Fire regimes are used to manage ecosystems to achieve conservation goals by focusing on the landscape scale to maintain spatially heterogeneous patches of different fire history (Kelly and others 2012). According to Barrett and others (2013) an understanding of the patterns of the spatially heterogeneity is important for predicting future fire regime shifts at regional scales. Within this context any inappropriate fire regimes would negatively impact organisms within the fire prone ecosystem on the landscape scale (Avitabile and others 2013) and act as a key threatening process to some of the ecosystems organisms (Avitabile and others 2013).

Wildfire regimes have changed over time for any given climate or vegetation group due to human influence (Martin and Sapsis 1991) and are expected to change (Thonicke and others 2013) unexpectedly and rapidly in response to future climate change. This change will impact all fire prone ecosystems on the planet changing the complex spatiotemporal patterns of vegetation biomass, composition, and structure (McKenzie and others 2011).

Australian Fire Regimes

Fire is an essential process in the Australian landscape and its ecosystems, playing a vital role in plant evolution, distribution, and adaptation (Watson and others 2004). Cary and others (2012) state that fire has been evident in Australia from charcoal records since the Paleogene Period (65 mya) and throughout the Neogene period to present. According to Lynch and others (2007) fires have been a consistent feature within the Australian landscape, increasing in importance with the evolution of the sclerophyll vegetation and in determining the distribution of fire sensitive vegetation such as rain forest communities (Bowman 1998; Enright and Thomas 2008). Natural fire regimes created self-sustaining eucalypt ecosystems, an important evolutionary driver of the Australian landscape, creating a dynamic equilibrium (Jurskis 2005b) maintaining eucalypts and other sclerophyll taxa as the dominate species. It is also suggested that fires may increase within periods of climate warming, which is supported by the close relationship between fire and ENSO (Lynch and others 2007; Cary and others 2012). Mooney and others (2011) suggests that the important evolutionary role of fire in Australia led to the development of plant responses to fire with morphological and reproductive adaptations to fire such as resprouting and obligate seeders. The palaeoenvironmental records show a consistent response to climate change by fire and that this response is rapid, where there are fewer fires under colder climates compared with warmer climate with a greater number of fires (Mooney and others 2012).

Enright and Thomas (2008) suggest that almost all fire ignitions prior to the arrival of people on the Australian continent would have been the result of lightning strikes and that the frequency of ground flash lightning shows a strong north to south gradient. This is in agreement with Murphy and others (2013) in that Australian fire regimes are related to the latitudinal gradient in the summer monsoon, where frequent low intensity fires occur in the tropical rainfall regions of the north with infrequent high intensity fires in the temperate southern regions (Murphy and others 2013). The latitudinal gradient is postulated as the main driver of fire regime on the continental scale by Murphy and others (2013) and not biomass accumulation. Further Murphy and others (2013) states that Australian fire regimes are relatively frequent surface fires of grasses and herbage in the different vegetation types of the continent. The spatial arrangement of fire regimes and the influence on the viability of species is poorly understood in an Australian context (Driscoll and others 2010).

Collins and others, (2013) found that precipitation regimes play an important role within wildfire regimes including spatial fire severity. Future fire management strategies will need to be adaptable to spatial variation in mean annual precipitation with changes in future climates. In support of Driscoll and others (2010), Haberle and others (2010) state that "current severe drought and plant mortalities are increasing fire hazard and raising concerns about the trajectory of post-fire vegetation change and future fire regimes" (p. 80) in Australia, indicating further research is required to answer what possible changes to vegetation may arise and what are possible future fire regimes.

Bowman and others (2012) say that there is mounting concern that wildfire frequency and intensity could increase with climate change. Fire regimes are affected by fire weather and fuel characteristics, and there is evidence of an increase in fire weather in southern Australia. Dunlop and Brown (2008) question as to how we should respond to the changing fire regimes. They suggest that we manage the consequences of a changing fire regime, ensuring habitat survival for sensitive species and human infrastructure.

Fire regime on the landscape scale level involves a range of spatiotemporal disturbance variables which has led to the belief that diversity in fire regime would promote biodiversity (Faivre and others 2011). According to Pastro and others, (2011) there is evidence that ecosystem heterogeneity created by burning patches of vegetation can increase biodiversity; an example is the spinifex grasslands of central Australia where fire heterogeneity increases mammal and reptile diversity. However it must be pointed out that fauna and flora in Australia are resilient to fire and therefore there is little if any differentiation between assemblages found in unburnt and burnt habitats (Pastro and others 2011). The ecological balance in many Australian eucalypt ecosystems has been upset through changes in fire regimes with the exclusion of fire by Europeans, which has resulted in a decline in both the abundance and health of these systems (Attiwill 1994; Jurkis 2005a; Jurkis 2005b).

The Great Sandy Region

In Queensland fire has been recorded from charcoal taken from sediment core samples as early as 130 000 years ago as a result of dry conditions at the end of the penultimate glacial period in combination with the phase of high ENSO activity (Moss and Kershaw 2007). Evidence of anthropogenic fires first date to around 45 000 years ago with the advent of Aboriginal occupation and fire stick practises (Fensham 1997; Turney and others 2001; Moss and Kershaw 2007; Moss 2008). Aboriginal burning continued until the settlement of Europeans in the 1800s, when there was a shift in fire regimes with an increase in anthropogenic fires (Haberle and others 2010) supported by an increase in charcoal deposits during that period.

The GSR is dominated by eucalyptus woodlands, mangrove forests, peat swamps and coastal heath plant communities (Figure 2) that are fire promoting and highly flammable (Moss and others 2012) and rainforest. Fraser Island has important mycorrhizal fungi occurring naturally in the sand providing nutrients for the diverse plant community occurring on the island (Kurtböke and others 2007). In the GSR fire history records have been collected and are well documented using radio-carbon dating and charcoal records. Moss and others (2013) state that there are "three records of vegetation and burning from North Stradbroke Island provide the first continuous records extending past the Last Glacial Maxima" (p. 270) to around 47000 years BP. According to Moss and others (2011) research undertaken at Myora Springs on North Stradbroke Island indicates a link between a warm ENSO and drought between 800 to 500 years ago that promoted an increase in burning and flammable vegetation such as open eucalyptus forests and Melaleuca paperbark swamp.

Research undertaken by Longmore (1997) shows that the GSR, and in particular Fraser Island, has undergone substantial changes in vegetation community structure over time from climax through to advanced retrogressive stages. The vegetation has changed from a predominantly rain forest with *Araucaria* sp. to a dryer rainforest with *Podocarpus* sp. between 600ka to 350ka to more sclerophyllous forest until before the Last Glacial Maximum (LGM). This change in the plant community was primarily driven by climate change and accelerated by increased burning. According to Longmore and Heijnis (1999) evidence of fire is low at the start of the record, but increases from around 350ka to the LGM, thereafter increasing with frequent fire records during the Holocene. Changes to the island's vegetation are thought to have been through succession, fire and climatic change (Longmore and Heijnis (1999). Around 500 years ago a cool ENSO persisted and the vegetation shifted once again to a fire sensitive Casuarinaceae dominated landscape (Moss and others 2011). According to Moss and others (2012b), there was a regional shift in fire regimes of the Sand Masses associated with European settlement, with a decline in burning and an expansion in eucalyptus and corresponding decline in Casuarinaceae, which needs

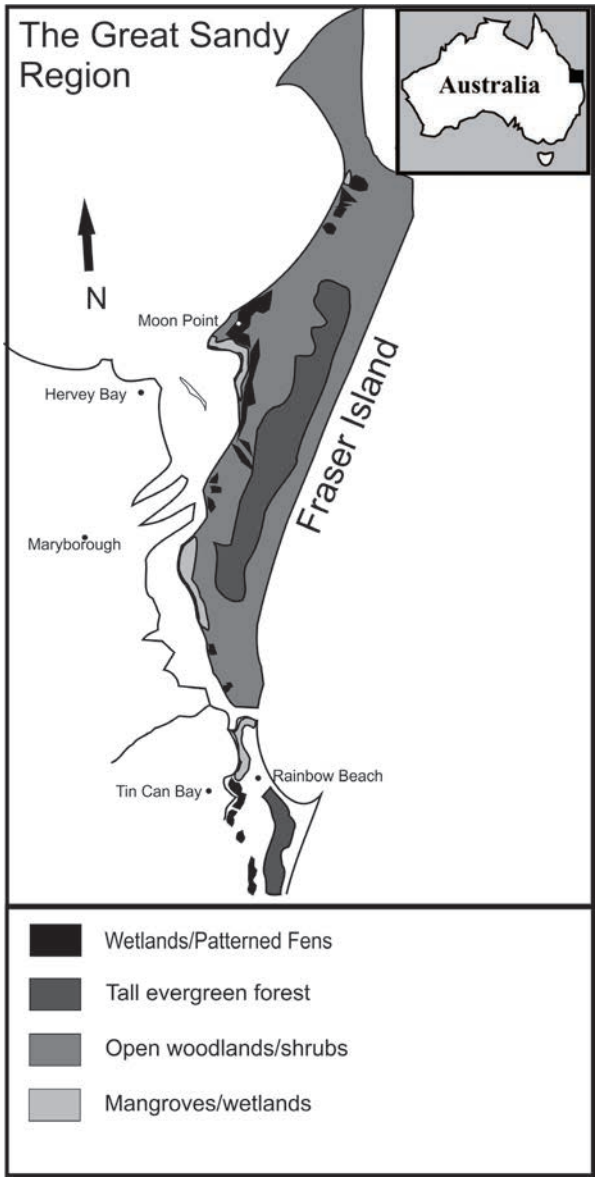

Figure 2—Map showing the location of the Great Sandy Region in relation to the Australia east coast and the four dominant vegetation communities of the region showing the location of rain forest or tall evergreen forest, mangrove swamp and wetlands, open eucalyptus woodlands and the peat swamp or patterned fens.

further investigation as to why there was a decline in fire sensitive plants (Moss personnel communication).

Late Quaternary fire regimes of the Sand Masses of south east Queensland are extremely complex according to Moss, and others (2012b); site location could be a factor in determining the dominance of either anthropogenic or climate factors as the control (Moss and others 2012b). Questions resulting from this research asked by Moss and others (2012b) include what are the long-term ecological impacts of altered fire regimes on biodiversity, what are the vegetation shifts across the region and what factors are behind the higher fire regimes of the pre-European arrival to the region?

According to Jurskis (2005b) fires were ignited by lightning and Aborigines over time and space; however, the extent of these fires were governed by climatic and edaphic conditions. Research by Fensham (1997) shows that Aboriginal burning during the initial contact with Europeans was prevalent along the coast of Queensland with high frequency of fires occurring compared with infrequent burning undertaken inland and with limited fires being lit in the summer and spring months.

Present fire regimes of the region are managed by the Queensland Government's Department of National Parks, Recreation, Sport and Racing through prescribed burning and wildfire management. Fire is managed according to fire protection policy, biodiversity conservation and through fuel reduction activities. According to Hocking (1998) monitoring the impacts of fire on Fraser Island vegetation consists of two elements, fixed point photography of before and after (fire events) and fixed plots using the standard Braun-Blanquet method. Prescribed burning is undertaken for ecological burning, hazard reduction burning, wildfire suppression activities, or burning for weed control and site rehabilitation for the purpose of the protection of life and property, and to ensure the maintenance of biodiversity through continued natural processes (Queensland Government 1994).

Conclusion

Fire has been recorded since the advent of the first vascular plants, and fire regimes have shifted with changing climatic and atmospheric oxygen levels (Pausas and Keeley. 2009) driving evolutionary processes of ecosystems such as distribution and composition of species. These shifts in fire regime continued and were modified by humans through migration, settlements, and land clearing practices over the millennia further impacting ecosystem dynamics and composition. Aboriginal and European settlers in Australia have had a substantial impact on natural fire regimes altering natural ecosystems to and from fire tolerant species depending on the fire regimes at that time.

According to Driscoll and others (2010) quantification of fire regimes is still unknown and in its infancy and how species are influenced by the spatial arrangement and temporal sequences of fires. Parr and Andersen (2005) suggest that the "ecological significance of different burning patterns is still unknown and has led to fire-management plans being based on pyrodiversity rhetoric that lacks substance in terms of operational guidelines and capacity for meaningful evaluation" (p. 1610).

Further unknown factors are how herbivory, predation, fragmentation, invasive species and weather interact with fire to alter species responses to fire directly, or via changes to the fire regime (Driscoll and others 2010). Lastly what are the long-term ecological impacts of an altered fire regime for the conservation of south-east Queensland's biodiversity (Moss and others 2012b). The answers to these questions are paramount to successful management of future fire regimes of the region.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Sensitivity to Spatial and Temporal Scale and Fire Regime Inputs in Deriving Fire Regime Condition Class

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Abstract—*The Fire Regime Condition Class (FRCC) is a composite departure measure that compares current vegetation structure and fire regime to historical reference conditions. FRCC is computed as the average of: 1) Vegetation departure (VDEP) and 2) Regime (frequency and severity) departure (RDEP). In addition to the FRCC rating, the Vegetation Condition Class (VCC) and Regime Condition Class (RCC) are produced to indicate the status of each. FRCC assessments are applied as ecological condition measures across the U.S. for land and fire management plans, National Environmental Policy Act documents, project plans, burn plans, and agency reporting. Input data to FRCC computation include proportions of different successional stages within biophysical settings, estimates of current fire frequency and severity, historical reference conditions for successional stages, frequency, and severity, and the analysis area extent. Hydrologic unit maps, frequently referred to as Hydrologic Unit Codes (HUCs), for regional and local assessments and LANDFIRE Map Zones for national assessments commonly represent the analysis extent area. Mapping methods and quality have substantially improved with the development of the FRCC Mapping Tool with the associated User Guide and Tutorial. Our tests of mapping FRCC indicate that resulting FRCC metrics are highly sensitive to analysis scales of landscape extents, assumptions of current and historical fire regimes, and resolution of input maps. Examples of these effects and management implications are presented along with recommendations. We conclude that, when appropriately mapped, the Strata FRCC is a very useful measure of ecological condition, while the Stand FRCC is a very useful measure for prioritizing local vegetation and fuel treatments. The Regime Conditions of frequency and severity are highly useful for prioritizing wildland and prescribed fire options, as well as for designing vegetation and fuel treatments.*

Introduction

The Fire Regime Condition Class (FRCC) is a composite departure measure that compares current vegetation structure and fire regime to historical reference conditions. Measures of departure as indicators of ecological condition and resilience to disturbance originated during the 1990s (Morgan and others 1994; Keane and others 1996; Hann and others 1998). The original FRCC concepts and definitions were presented at the conference 'Integrating spatial technologies and ecological principles for a new age in fire management' in Boise, Idaho, USA, June 1999 (Hardy and others 2001; Hann and Bunnell 2001; Schmidt and others 2002).

The various methods of generating FRCC assessments, described in the Interagency Fire Regime Condition Class Guidebook (Barrett and others 2010), were developed in 2003 by an interagency working group and The Nature Conservancy (TNC). Following development of the first guidebook, the National Interagency Fuels Technology Team (NIFTT) was formed to support technology transfer for FRCC, along with LANDFIRE and other fire and fuel management technical projects and products. NIFTT is now managed by the Wildland Fire Management Research & Development group under the title Wildland Fire Management Research & Development Fuels and Fire Ecology group (WFMRDA-FFE).

The intent in developing the FRCC process was to provide managers with a relatively simple, fast, and effective way to evaluate landscapes across the wide array of biophysical settings throughout the U.S. The result of the process is a measure that characterizes landscape health in terms of vegetation and fire regimes in relation to those that existed during the historical pre-EuroAmerican settlement reference era. In completing the FRCC assessment, managers fulfill reporting requirements and gain useful information about naturally functioning ecosystems for planning tasks ranging from broad to fine scales.

The generation of Regime Condition Class (RCC), Vegetation Condition Class (VCC), and Fire Regime Condition Class (FRCC) assessments at various scales and for a wide variety of landscapes is dependent upon landscape-scale input data. Fire *frequency* in an FRCC context is the average number of years between fires across all pixels of the biophysical setting and its landscape perimeter. Fire *severity* refers to the proportion of all pixels in the upper canopy layer of green vegetation that is consumed in the fire. High fire severity refers to a consumption of upper layer vegetation of over 75%, while moderate severity is 25-75% consumption, and low severity refers to areas where less than 25% of the green canopy is consumed. The VCC measure compares the distribution of successional classes across all pixels of each Biophysical Setting to pre-EuroAmerican reference composition. FRCC is

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

a classification of the average of the fire regime and vegetation departures (RDEP and VDEP, respectively).

The VCC layer is a quantification of the amount of departure of current vegetation compared to simulated historical vegetation reference composition. Three condition classes represent levels of low departure (VCC 1, 0-33%), moderate departure (VCC 2, 33-66%), and high departure (VCC 3, 66-100%) (Barrett and others 2010). Low departure means that the distribution of area between successional classes within biophysical settings is similar to the pre-EuroAmerican settlement conditions, while a high departure means that some successional classes are over or under represented, or that uncharacteristic vegetation dominates the area. Uncharacteristic vegetation is generally composed of native vegetation with a composition and structure that did not occur historically or exotic plant species. High values for VDEP/VCC do not necessarily mean higher risk for wildfire occurrence, rather it is a measure of ecological departure of the vegetation.

FRCC, as with other models, is dependent upon input data. Although input data is available from various sources; in some instances, or locations, input data may not be available. For example, in developing the input spatial layers of fire frequency and severity for creation of coarse-scale data for fire and fuel management, data was collected from historical fire databases; however, there were many instances where data were not available or appeared to be in error and hence not included (Hardy and others 2001). This was particularly the case on large areas of private land where the federal fire occurrence database did not contain data. In the current Landscape Fire and Resource Management Planning Tools Prototype Project (LANDFIRE) system, the Succession Class (SCLASS) input layer is available for determination of VDEP and VCC, but fire frequency and severity are not provided for determination of the RDEP or RCC (www.landfire.gov). The raw data for determination of fire frequency and severity are available from LANDFIRE, Monitoring Trends in Burn Severity (MTBS), and local data sources (Hamilton and Hann, this Proceedings). In many cases, expert opinion and local knowledge may assist in accumulating the most accurate input data.

In this study, we compare four approaches for deriving FRCC, and its components VCC and RCC, in a case study in a western juniper, sagebrush steppe ecosystem. The first approach is an unaltered VCC product available at the LANDFIRE data distribution website; the other approaches utilize the FRCC Mapping Tool (Hutter and others 2010). During this assessment, we evaluate the fire regime (RCC) and vegetation (VCC) variables at various scales, ranging from entire landscapes to individual stands. Assessments for the fire regime variables *frequency* and *severity* are included.

Methods

Study Area

The study area encompasses 275,000 hectares of Juniper Mountain located in Owyhee County of southwestern Idaho (116°W, 43°N, Figure 1). The area is dominated by mountain big sagebrush steppe (*Artemisia tridentata* ssp. *vaseyana*), low sagebrush (*Artemisia arbuscula*), mountain riparian, and western juniper (*Juniperus occidentalis* ssp. *occidentalis*) LANDFIRE Biophysical Settings (BpS). Across the area, western juniper has been expanding into areas previously dominated by sagebrush steppe. The area is rich in wildlife and summer grazing by livestock occurs across the area on private and public lands.

The elevation in the area ranges from 1480 m to 2074 m. Precipitation ranges from 300 to 600 mm, increasing with elevation. Soil types include mountain loams and clay loams. The majority of the winter precipitation is snow while the majority of the spring precipitation is rain, with a dry summer and fall. The annual average temperature varies from a low of -6.6 °C in December to 26.7 °C in July.

Input Data

In each of the four scenarios, there are five common input layers needed to assess VCC and RCC: Biophysical Settings (BpS; Figure 2), Succession Classes (SCLASS; Figure 3), and the three Hydrologic Unit Code layers, (HUC 8, 10 and 12; Figure 4 and Table 1). Two of these layers, BpS and SCLASS, are models developed by the LANDFIRE Prototype Project (Long and others 2006; Holsinger and others 2006; Rollins 2009) and are available at the LANDFIRE data distribution site (http://landfire.cr.usgs.gov/viewer/).

The BpS layer is a vegetation data product that is intended to provide land managers with a description of potential natural vegetation expected to occupy a site based on biophysical factors such as soil, slope, precipitation, and growing season length and associated historical disturbance dynamics (Barrett and others 2010; Rollins 2009). This model of the

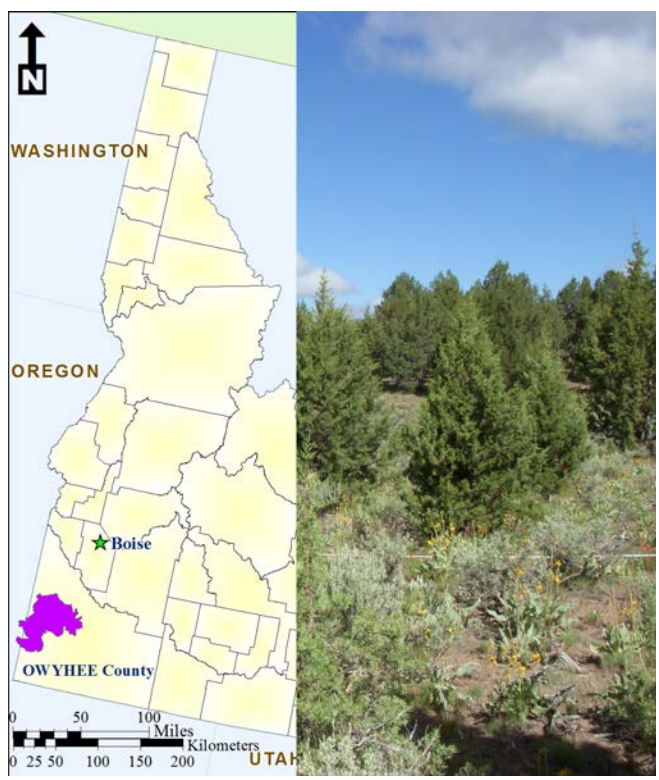

Figure 1—Study area in southwestern Idaho.

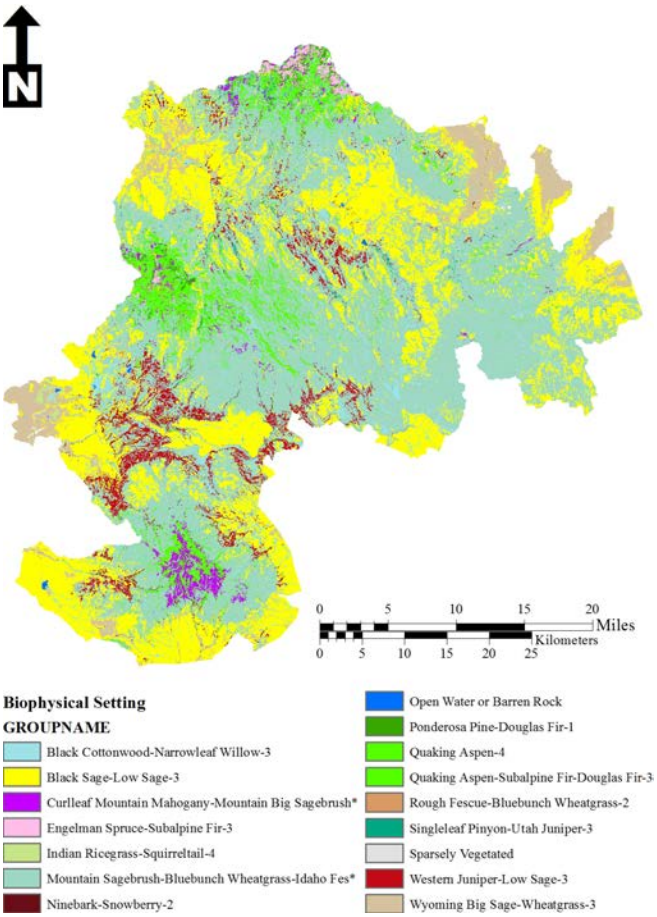

Figure 2—Biophysical settings within the study area.

vegetation depicts an approximation of the plant communities that existed prior to Euro-American Settlement. Dominant mapped BpS types within the study area include Mountain Big Sagebrush Steppe and Low Sagebrush (Figure 2).

The SCLASS layer represents the current successional state of vegetation within a Biophysical Setting including vegetation species composition, cover, and height ranges of successional states (Barrett and others 2010; Holsinger and others 2006; Long and others 2006; Rollins 2009). These stages include five succession classes (A, B, C, D, and E) as well as sparsely vegetated, uncharacteristic native vegetation (UN) and uncharacteristic exotic vegetation (UE). The succession classes represent seral stages of plant communities. A large portion of the area is mapped as UN vegetation in the SCLASS layer because western juniper has been expanding into areas historically dominated by sagebrush steppe vegetation (Figure 3).

The purpose of the HUC layers is to serve as landscape calculation units for the FRCC algorithm assessment. The size of each HUC delineation determines the total pixel count for which the composition of a given metric class is calculated. FRCC is a scale-dependent metric (Barrett and others 2010). In the U.S., subbasins (HUCS) are commonly selected for local FRCC assessment to represent boundaries applicable to fire regime variation within the study area (Figure 4). The hydrologic unit code layers at the 8th, 10th, and 12th level are available from the USGS Water Resources website (http://water.usgs.gov/GIS/huc.html).

Scenarios

We compare four approaches to calculating FRCC ecological departure metrics. Each of these approaches requires common input layers of BpS, SCLASS, and HUCs but vary in use of software and the frequency and severity inputs (Table 1). Scenarios #2, #3, and #4 utilized the FRCC mapping tool ($FRCC_{MT}$; Barrett and others 2010; Hamilton and others 2014a). $FRCC_{MT}$ is a GIS application that uses the amounts of SCLASS, frequency, and severity within a BpS and the appropriate HUC scale to calculate the outputs. Output layers include FRCC, RCC, VCC, and their associated departures at the Landscape (HUC), Strata (BpS), and Stand (SCLASS) scale. Spatial scale for all inputs and outputs was 30-meter pixel. The spatial extents of the landscape and strata HUC layers was somewhat different for Scenario #1 versus 2, 3, and 4. The scale of time for calculation of the departure and class outputs for FRCC, RCC, and VCC was the 2008 year of LANDFIRE mapping compared to the historical reference conditions.

Scenario #1 is the most commonly used data used in ecological assessments for local, regional, and national fire, fuel, and vegetation management planning and monitoring applications; it is the LANDFIRE Refresh 2008 VDEP and VCC layers. This method is simply a download from the LANDFIRE data distribution site and does not require running the FRCC mapping tool software (Figure 5). FRCC,

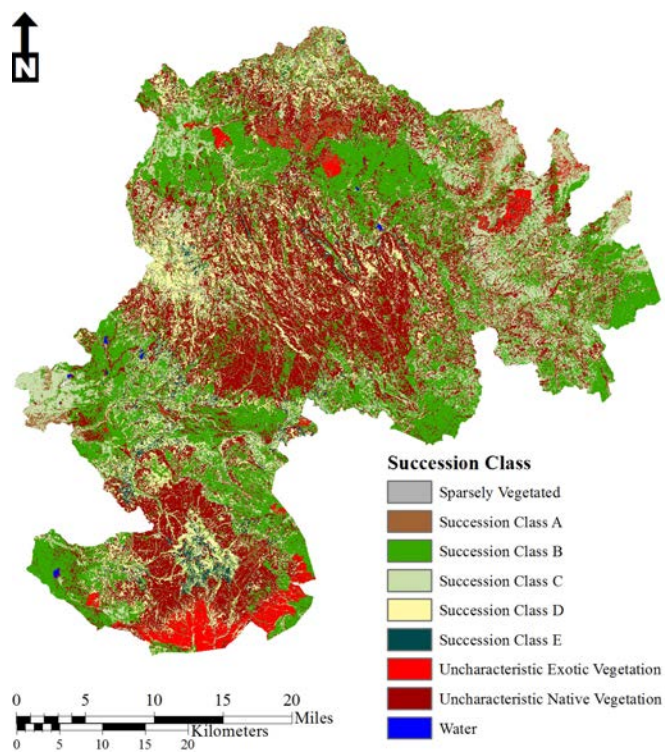

Figure 3—Succession classes within the study area. A – early successional; B – mid successional, closed canopy; C – mid successional, open canopy; D – late successional, open canopy; E – late successional, closed canopy.

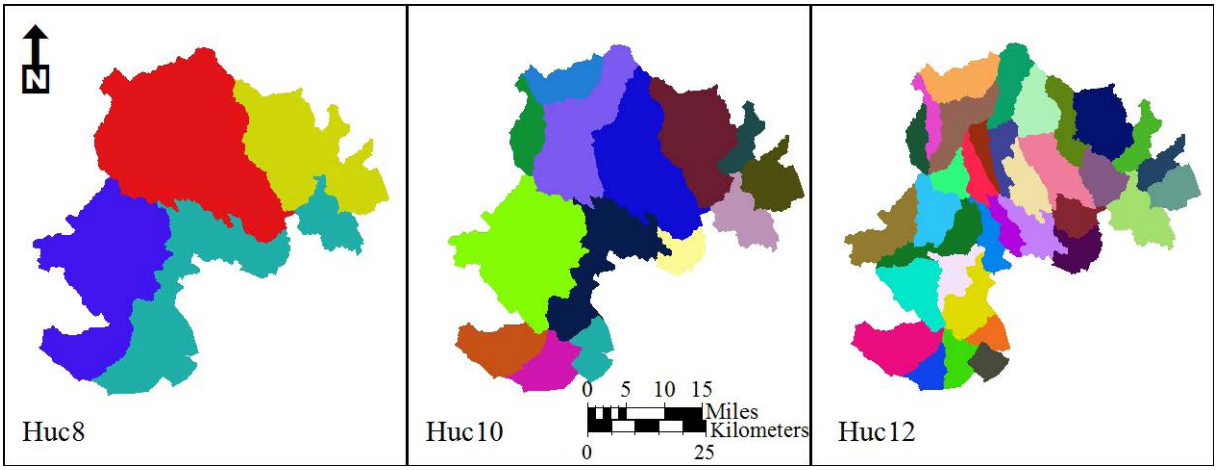

Figure 4—Hydrologic Unit Code Layers within the study area as defined by the U.S. Geological Survey available at https://water.usgs.gov/GIS/huc.html.

Table 1—Scenario Inputs and Outputs.

		INPUTS				OUTPUTS			
Scenario	**Source**	**BPS**	**S-Class**	**HUC**	**Source of Current FRQ and SEV**	**Vegetation**	**Regime**	**Strata FRCC**	**Stand FRCC**
1	Download from LANDFIRE	BPS Group	S-Class	LANDFIRE 8, 10,12	NA	VCC/VDEP	NA	NA	NA
2	Run $FRCC_{MT}$	BPS Group	S-Class	Other source 8, 10, 12	NA	VCC/VDEP	NA	NA	Stand FRCC
3	Run $FRCC_{MT}$	BPS Group	S-Class	Other source 8, 10, 12	Expert opinion	VCC/VDEP	RCC/RDEP	Strata FRCC	Stand FRCC
4	Run $FRCC_{MT}$	BPS Group	S-Class	Other source 8, 10, 12	LANDFIRE Disturbance Layer Wildland Fire Assessment Tool (WFAT)	VCC/VDEP	RCC/RDEP	Strata FRCC	Stand FRCC

RDEP, and RCC are not currently available to download from LANDFIRE, and RCC or FRCC were therefore not possible to derive for Scenario #1.

Scenario #2, 3, and 4 apply methods that use the $FRCC_{MT}$ and the common input layers described above. In Scenario #2, 3, and 4 we derived VDEP and VCC using HUCs obtained from the USGS Water Resources website, which were not identical to the HUCs used by LANDFIRE to derive the downloadable VCC layer used in scenario #1. The study area boundary for scenarios 2, 3, and 4 were generated by selecting most of the HUC 12s within the HUC 8s, but not all as was done by LANDFIRE fore scenario #1. Therefore the spatial scale of the landscape analysis area was a slightly different delineation of HUCs for scenarios 2, 3, and 4 as compared to Scenario #1. The $FRCC_{MT}$ calculation of the VDEP and VCC departure of SCLASS from historical SCLASS reference composition was based on the 2008 year of mapping.

Scenario #3 uses the $FRCC_{MT}$, the common input layers, and additional data in the form of an expert opinion for current fire frequency and severity. The expert opinion (Table 2) contributes data about the fire frequency and fire severity for each major BpS group in the study area. This expert opinion comes from study of the local fire history literature and local field studies. The spatial scale of variation in the BpS and SCLASS assignments was at a 30-m pixel, while a single expert opinion estimate of fire frequency and severity was applied uniformly across the BpS for each HUC. The scale of time for $FRCC_{MT}$ calculation of the VDEP and VCC departure of SCLASS from historical SCLASS reference composition was the 2008 year of mapping; a single time year, same as for Scenarios #1 and #2. The scale of time for estimating the average fire frequency and severity expert opinion across the BpS and HUC area was general, approximately early 1900s to current. This average was then compared to the reference conditions which were the average for the pre-settlement period.

Scenario #4 also uses the $FRCC_{MT}$, the common input layers, and additional data about the fire frequency and fire severity. The fire frequency layer was developed through analysis of LANDFIRE disturbance layers spanning a 10 year time period from 1999 through 2008 (Hamilton and

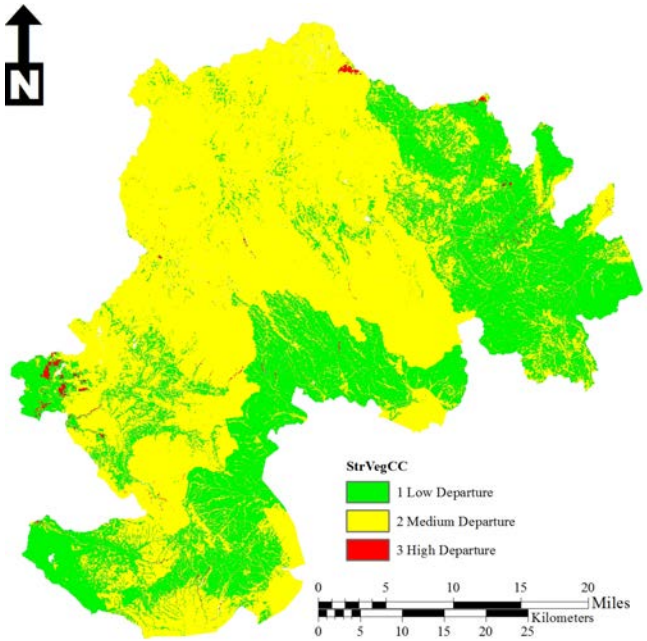

Figure 5—Scenario #1. Strata Vegetation Condition Class downloaded from LANDFIRE and clipped to the study area boundary.

Hann, this Proceedings). The fire severity layer was developed through use of LANDFIRE fuels layers and the Wildland Fire Assessment Tool (WFAT; Hamilton 2014b). The WFAT generates the FRCC severity metric at a pixel scale through use of a series of algorithms that analyze inputs of fuels and fire effects layers combined with a weather scenario. In this scenario, the scale of the BpS and SCLASS input layers to $FRCC_{MT}$ was at a 30-m pixel, same as for Scenarios #1, #2, and #3. However, differing substantially from Scenario #3, this Scenario the variation of fire frequency and severity occurs at the 30-m pixel scale common to BpS and SCLASS, rather than as a single estimate across the whole BpS extent. In addition, the scale of time for the fire frequency summary of fire disturbances downloaded from LANDFIRE and MTBS for BpS with more frequent historical fire regimes was the 1999 to 2008 period, essentially only a single decade, as contrasted to approximately 100 years for Scenario #3. As indicated previously, in substantial contrast to Scenario #3, the fire severity was modeled using WFAT at a 30-m pixel based on the LANDFIRE fuels data from 2008.

Results

We noted different results in VCC, RCC, and FRCC outputs depending on the input layers and parameters. Inputs and selected outputs for each scenario are listed in Table 1. The four columns on the right of the table list the output layers generated for each scenario. The output layer common to each scenario is the Vegetation Condition Class (VCC) layer.

Scenario # 1 outputs consist of only two data layer results, the Strata VCC and VDEP layers. These data layers are available at the LANDFIRE data distribution website. The basis of these calculations is the departure of SCLASS composition of each BpS from reference conditions. The historical vegetation reference condition composition of SCLASS types are a simulation generated with the disturbance dynamics model Vegetation Dynamics Model (VDDT; Barrett and others 2010; Beukema and others 2003; LANDFIRE-Vegetation Condition Class 2014). The Strata VCC shows moderate and low departure across the study area, meaning that the distribution of successional classes within BpS types is only departed from historic conditions at low or moderate levels. From a user perspective, this would be the easiest of the scenarios, as the VDEP and VCC data layers can be downloaded directly from LANDFIRE. However, we found this scenario to be the most prone to possible misinterpretation for several reasons: 1) The VDEP and VCC layers may be used by an uninformed user to infer more than just vegetation departure from historical reference, such as inference about the FRCC, the fire regime, or resilience; 2) The process of downloading just the VDEP or VCC does not provide the user the opportunity to review the SCLASS to BpS layer assignments and modify or recognize potential errors; and 3) The scale of landscape summary used by LANDFIRE may not fit the scale appropriate for the application.

Table 2—Current fire frequency (FRQ) and severity (SEV) estimated with expert opinion according to this table for Scenario #3. FRQ refers to the average number of years between subsequent fires. SEV stands for severity, which in a LANDFIRE and FRCC context is defined as the % removal of biomass caused by the fire.

Expert Opinion for Input Data of Scenario #3					
BpS GROUPNAME	**Area (ha)**	**Reference FRQ years**	**Reference SEV %**	**Current FRQ years**	**Current SEV %**
Mountain Sagebrush-Bluebunch Wheatgrass-Idaho Fescue	128090	550	1100	1120	80
Black Sage-Low Sage	79670	885	337	2250	50
Black Cottonwood-Narrowleaf Willow	17760	661	222	1120	22
Quaking Aspen	17360	1100	1100	1150	80
Wyoming Big Sage-Wheatgrass	15810	559	662	225	90
Western Juniper-Low Sage	10740	998	226	2250	50
Curlleaf Mountain Mahogany-Mountain Big Sagebrush	3750	664	226	1150	50
Quaking Aspen-Subalpine Fir-Douglas-Fir	2280	554	446	1120	65

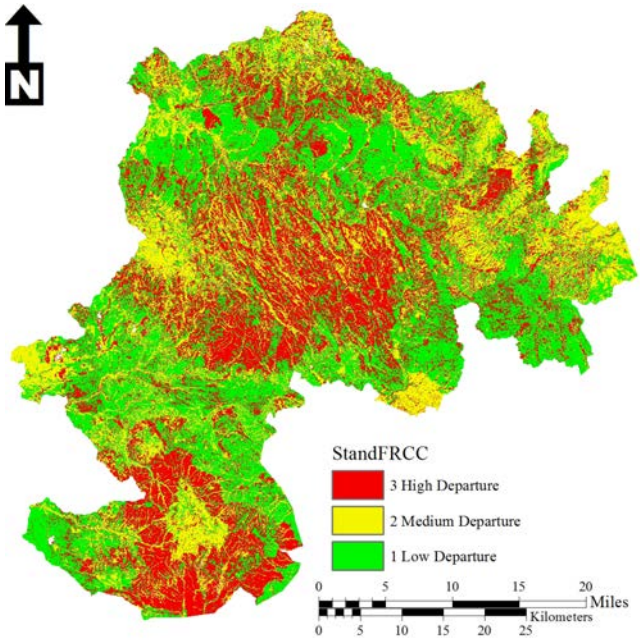

Figure 6—Scenario #2-4. Strata Vegetation Condition Class derived using the FRCC mapping tool.

Scenario # 2 is a method that includes the use of the $FRCC_{MT}$. We generated three data outputs, the Strata VCC and VDEP and the Stand FRCC layers (Figures 6 and 7). These layers are calculated using the FRCC algorithms described in the FRCC Guidebook. Strata VCC for Scenario #1 (downloaded from LANDFIRE; Figure 5) and Scenario #2-4 (derived using $FRCC_{MT}$; Figure 6) are relatively similar. We observed some differences between VCC derived according to Scenario #1 and #2 procedures due to the differences in the HUC layers used in the two analyses. A different HUC delineation results in a different total pixel count and differences in SCLASS counts that then affects the composition calculations. Stand FRCC (Figure 7) clearly shows high ecological departure in areas where western juniper has replaced sagebrush steppe while remaining areas show low or moderate departure from historic reference conditions. These results bring forth an important concept relative to interpretation of these data. The SCLASS layer in itself has no value without the context of its BpS and the reference composition. In contrast, the Stand FRCC has considerable stand-alone value as it identifies the SCLASS pixels that are in excess or in deficit compared to their BpS historical reference composition. From a user perspective, this would be the second easiest of the scenarios, as the process requires the use of the $FRCC_{MT}$ to output the VDEP and VCC, but the input SCLASS and BpS data layers can be downloaded from LANDFIRE, modified if appropriate, and the user can choose the scale of landscape summary. We found this scenario to be somewhat prone to possible misinterpretation for a similar reason as the first scenario. The VDEP and VCC outputs from the $FRCC_{MT}$ may be used by an uninformed user to infer more than just vegetation departure from historical reference, such as inference about the FRCC, the fire regime, or resilience. However, because the user has evaluated the BpS, SCLASS, and scale of landscape summary this misinterpretation is less likely.

In Scenario #3 and #4, we derive RCC (Figure 8 and 10) and FRCC (Figure 9 and 11) in addition to VCC. The RCC derived using expert opinion for current fire frequency and severity departures via inputs in the Frequency and Severity Editor in $FRCC_{MT}$ (Scenario #3) shows moderate ecological departure across most of the area (Figure 8). This departure can be explained by the fact that most of the study area has missed 1-3 fire cycles resulting in a shift from shrub and

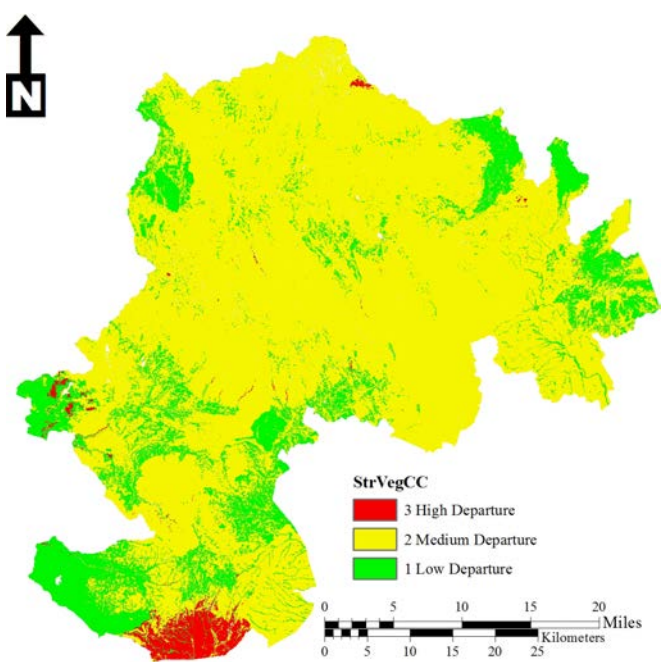

Figure 7—Scenario #2. Stand FRCC shows high ecological departure in areas where western juniper has expanded into areas classified as mountain big sagebrush steppe biophysical setting.

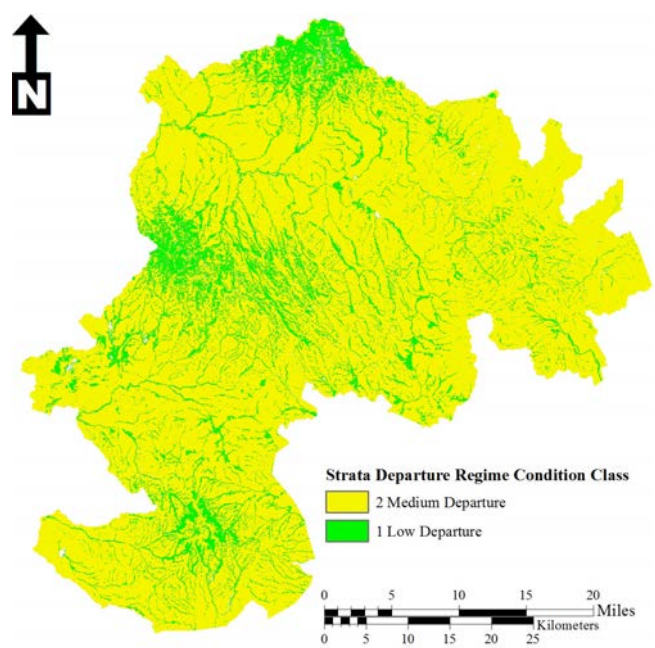

Figure 8—Scenario #3. Strata Regime Condition Class derived using expert opinion for current fire frequency and severity.

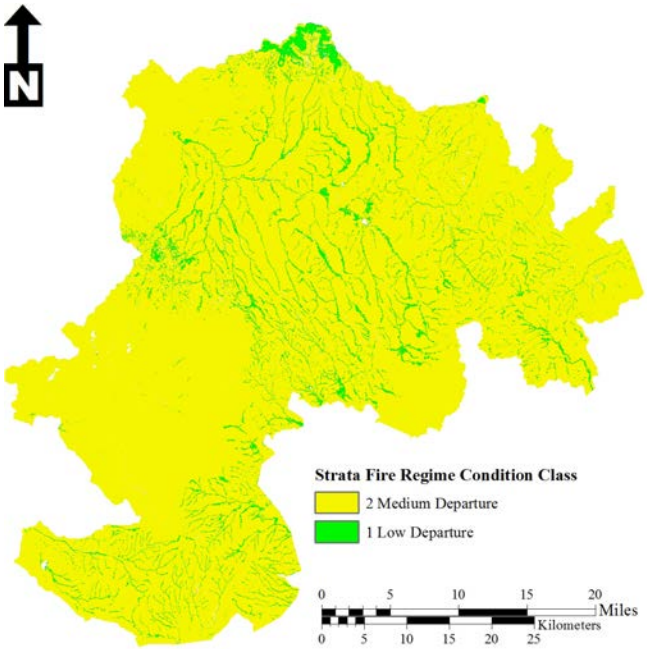

Figure 9—Scenario #3. Strata FRCC derived using expert opinion for current fire frequency and severity.

grass fuels to woody tree fuels. This is most likely due to reduction of potential fire starts and spread because of loss of grass fuels via excessive livestock grazing within the area during the early 1900s and fire suppression since the 1930s. In addition, the scale of time for the Scenario #3 estimate using expert opinion was an average for the period of early 1900s to current for fire frequency and the last two decades for fire severity. RCC derived using the LANDFIRE disturbance layers (Scenario #4) shows a high ecological departure for the entire area (Figure 10). The fire frequency input layer generated from LANDFIRE disturbance layers only incorporates fire disturbances for a relatively short time period, approximately two decades prior to 2008 (1989-2008). In Scenario #3 and #4, we also derived the Fire Regime Departure as the average of VDEP and RDEP and subsequently classified it to FRCC (Figure 9 and 11). From a user perspective, Scenario #3 would be more difficult than Scenario #1 or 2, but less difficult than Scenario #4. The process requires the use of the $FRCC_{MT}$ to output the VDEP and VCC, RDEP and RCC, and FRCC. We found these two scenarios to be much less prone to possible misinterpretation as it requires the user to closely evaluate the $FRCC_{MT}$ input and output data and methods.

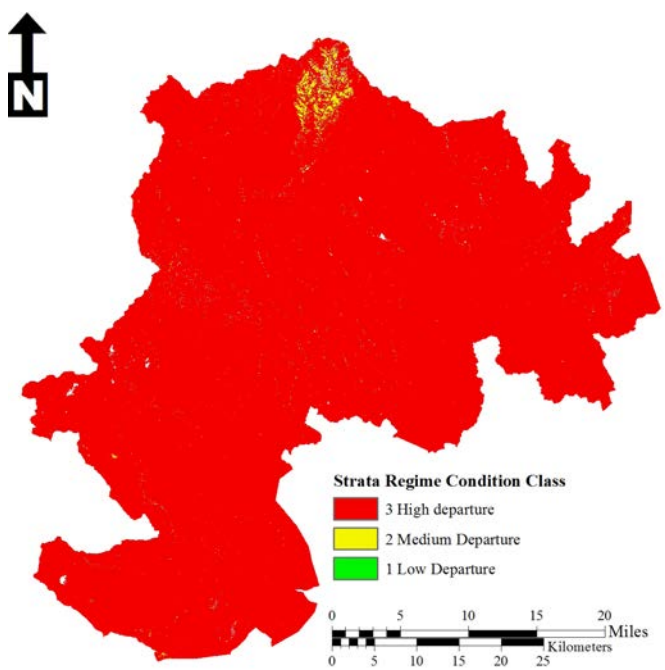

Figure 10—Scenario #4. Strata Regime Condition Class derived using fire perimeters from 1984-2008 (from MTBS) and the Wildland Fire Assessment Tool to derive current fire frequency and severity.

Discussion

The result that is common to each scenario is the VDEP and VCC layers. With these four scenarios, the results for Scenario #1 differ from the results of Scenarios #2, #3 and #4. Our analysis indicates that this is a consequence of the slight differences in the delineation of the HUC input layer. For all scenarios, the BpS and SCLASS download versions from LANDFIRE were not modified, essentially held as a constant. The LANDFIRE methodology for developing this layer includes all of the HUC 12 units encompassed in the HUC 8 units, whereas in our processing, some of the HUC 12s on the edge were clipped from the HUC 8 layer. Thus the VDEP and VCC algorithms receive different values on the edges of the study area, hence producing different results.

The Regime Condition Class (RCC) or the Regime Departure is computed by comparing the current fire frequency and severity to the historic reference condition. RCC is therefore highly dependent on methodologies used to estimate current and historic frequency and severity. In Scenario #3, we used expert opinion and long-term knowledge of the local area to estimate the current fire frequency and severity as an average over a relatively long time period of early 1900s to 2008. In Scenario #4, for fire frequency we calculated the current fire interval from the LANDFIRE disturbance layers and MTBS data attributed with a fire disturbance. This accounted for a relatively short two-decade time-period of 1989-2008 for fire frequency. Fire severity was modeled for the conditions of 2008, a single year time period. In addition, the Scenario #3 applied a single estimate of frequency and severity across all pixels of a BpS within a HUC 8, while in Scenario #4 the frequency and severity were modeled at the pixel scale and summarized for each BpS within a HUC 12. The two methods of estimating fire frequency and severity result in different outputs where in this case Scenario #3 resulted in mostly RCC 2 (Figure 8) while Scenario #4 resulted in mostly RCC 3 (Figure 10).

We attribute this difference to both the temporal and spatial resolution differences in current fire frequency and severity methods. For frequency, the expert opinion (Scenario #3, Figure 8) applied long-term knowledge of the area and estimated in the range of 100 years while our use of

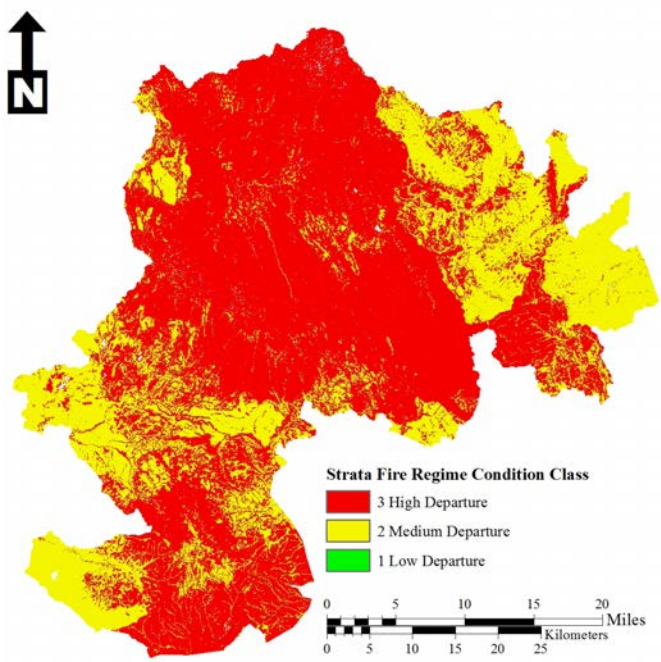

Figure 11—Scenario #4. Strata FRCC derived using fire perimeters from 1984-2008 and the Wildland Fire Assessment Tool to derive current fire frequency and severity

the LANDFIRE disturbance and MTBS datasets only incorporated information since 1989, approximately two decades. Areas with a fire frequency longer than 15 years could easily be misrepresented by this dataset with a shorter time span. On the other hand, expert opinion can be subjective and incorrect. Ideally, a fire perimeter dataset spanning a time-period longer than any fire return interval within the study area should be used in the RCC assessment. These long-term fire-atlas datasets are not currently available. However, the interim expert opinion can be combined with available data to create a combination of the two approaches that improve on both methods (Hamilton and Hann, this Proceedings). In addition, the differences in temporal scale were substantial, as the expert opinion assignment was at the BpS by HUC 8 scale, while the frequency datasets were analyzed at the BpS by HUC 12 scale. Similar differences in temporal and spatial scales of methods for determining severity resulted in a similar pattern of results as occurred with frequency.

The Strata FRCC is determined by averaging the VDEP (0-100) and the RDEP (0-100) producing values ranging from 0 to 100 and then classifying into low (0-33), moderate (33-66), and high (66-100) (Barrett and others 2010). This method of calculating FRCC weights these two variables equally and is considered to be a more comprehensive measure of ecological status (FRCC Guidebook , Chapter 2, page 32). Scenario #3 results in a stratum FRCC dominated by class 2 (Figure 9) while Scenario #4 results in mostly class 3 (Figure 11). Even though the VDEP and VCC are identical for Scenario #3 and #4, RDEP and RCC are mostly class 2 for Scenario #3 and class 3 for Scenario #4, resulting in the FRCC layers in Figure 9 and 11. When evaluating an FRCC output, it is important to recognize that FRCC departure consists of the average of VDEP and RDEP where one of the components may express a high ecological departure while the other may not. From a management implication perspective it is important to look at the VDEP and RDEP values and their distribution more intently than the broad three class results of VCC and RCC. Upon closer inspection, we find that the shift to the class 3 can be caused by minor increases in departure values that cross class thresholds. From a restoration prioritization perspective, the actual departure of the FRCC, VCC or RCC class of 2 may be borderline to Class 1 or to Class 3. While Class 1 may require maintenance activities Class 3 may require restoration activities. Although the FRCC, VCC, or RCC class may be useful from a visual mapping perspective we find it very important to focus on the departure values and closely evaluate areas that close to class thresholds.

The Stand FRCC represents pixels with SCLASS types that are over- or under-represented compared to the SCLASS reference composition for the BpS. Stand FRCC in Figure 7 shows that the sagebrush steppe BpS is highly departed in areas over-represented by uncharacteristic native vegetation, western juniper in this case. The Stand FRCC map is useful to management because it spatially identifies areas that are strong candidates for management activities, either conservation of under-represented SCLASS types or restoration of over-represented SCLASS types. In-depth evaluations of the outputs from the $FRCC_{MT}$ in conjunction with field visits, can help prioritize treatment areas or design conservation strategies. The fire severity departure modeled with WFAT, demonstrated in Scenario #4, also has high potential for application at the stand scale.

The strength of the FRCC at three different scales (stand, strata BpS/HUC, and Landscape), combined with VDEP and VCC and RDEP and RCC outputs provides a very strong set of variables for evaluation of the condition of the fire regime, land health, and resilience to disturbance. In essence, the stand scale provides information at the pixel scale concerning SCLASS conditions that may be in excess or deficit from historical to support local conservation or restoration strategies. The RCC at the strata scale provides a ranking between BpSs for condition of the fire regime and used to prioritize efforts to change frequency or severity of fire at local or regional scales. Further investigation of the frequency and severity layers can support evaluation of BpS resilience to fire. The FRCC measure at strata scales, with its combination of vegetation and regime, provides data for evaluating land health locally and regionally. The landscape scale with its condition class measure across a large HUC area provides data useful for regional or national summary or prioritization.

Conclusions

- The VCC output is highly sensitive to the analysis extent. We recommend a standardized hydrologic unit layer available for download in conjunction with the LANDFIRE inputs of BpS and SCLASS. We further recommend that the HUC 8 layer is not clipped to specific analysis area

boundaries, rather that the study area consists of selected HUC 8 units. It is recommended that the analysis area is large enough to reflect the historic range of variability within the BpS types.

- The VCC output is highly sensitive to the SCLASS layer used in the analysis. The user should pay attention to the development year of the SCLASS layer and determine if recent succession or disturbances have occurred that may have changed the SCLASS layer.
- The SCLASS, fire frequency, and fire severity layers are highly sensitive to the BpS layer as it is the summary unit within a HUC. The extent of the BpS can substantially affect the summary calculations of SCLASS, fire frequency, and fire severity. Users should evaluate the BpS layer to assure that it represents the vegetation types provided in the LANDFIRE BpS model descriptions. Fire frequency and its effect on RCC are highly sensitive to temporal resolution of the fire perimeter data. The difference in spatial scale between expert opinion assigned to BpS and HUC versus 30-m fire disturbance frequency calculation can be substantial. We recommend careful considerations when selecting the current inputs for frequency and severity. Expert opinion is recommended if the available fire atlas data has a shorter timespan than the fire return interval for the BpS in question. From a national perspective, we recommend a standardized approach to analysis of the various fire disturbance data (Hamilton and Hann, this Proceedings).
- The FRCC methodology needs to have additional metrics or specifications that indicate how much *frequency* and *severity* are above or below reference conditions. Current reporting of FRCC frequency and severity departures do not provide information of whether fires burn more or less frequently or severely compared to the reference condition. The $FRCC_{MT}$ and Guidebook provide metrics for evaluating VDEP and VCC as to SCLASS types that are under- or over-represented. This same type of information should be available for frequency and severity as it is important for land management treatment planning and implementation.
- The latest version of LANDFIRE does not include any of the FRCC metrics except VDEP and VCC. Although other metrics were available in the past, they are not currently available as downloads from the LANDFIRE website. The $FRCC_{MT}$ derives these additional metrics, such as Strata FRCC, Stand FRCC, Relative Amount, Frequency Departure, and Severity Departure. $FRCC_{MT}$ may be the only standardized ecological departure and resilience tool for planning documents. We recommend continued emphasis on technology development and transfer of these important concepts, data, tools, and management implications. The complete suite of FRCC metrics are highly valuable as ecological measures of status and resilience (Hamilton and Hann, this proceedings) for application in management activity prioritization, planning, and gaining understanding from the public. These metrics are complex to compute and can be subject to error in calculation and interpretation. We recommend incorporation of these data and processes in the web-based decision support systems for fire, fuels, and vegetation management.
- Depending on the objective, some FRCC measures are more suitable than others. For example, the FRD or FRCC or RDEP or RCC measures may be useful to infer land health, ecological status, or trends in resilience in discussions with management teams or the public, but may not be useful for prioritization or planning of specific projects. In contrast, Stand FRCC and VDEP or VCC, whose development is an output from SCLASS current composition as compared to reference composition for the BpS at a single point in time, may be useful for the prioritization and planning of vegetation management projects. Comparison of VDEP and VCC changes over multiple time periods can be used to infer trend. Of major value to fire and fuel management is the perspective of the fire frequency departure and condition, and ability to determine how much needs to be burned or not burned, to achieve the historical range of fire frequency. The fire severity departure and condition can be used for a different application with emphasis on severity of fire effects on the upper layer of vegetation, which may result in changes in SCLASS.

In summary, we recommend continued use of FRCC, VCC, RCC, and associated measures as ecological metrics for landscape, strata, and stand scale ecological status and resilience to disturbance. However, the input spatial and tabular data impacts the output and must be evaluated to manage for quality results and interpretations.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Extended Abstracts

Practical Tools for Assessing Potential Crown Fire Behavior and Canopy Fuel Characteristics

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Abstract—*This presentation recapitulates the main points made at a technology and information transfer workshop held in advance of the conference that provided overviews of two software applications, developed by the authors, for use in assessing crown fire behavior and canopy fuel characteristics. These are the Crown Fire Initiation and Spread (CFIS) software system and the Canopy Fuel Stratum Characteristics Calculator. Both of these application tools are based on model formulations and performance evaluations that have appeared in the scientific peer-reviewed literature. The software and publications associated with each are available for downloading at: http://frames.nbii.gov/cfis.*

CFIS incorporates several models designed to simulate certain characteristics of crown fire behavior in live, boreal and near-boreal like, conifer-dominated forests (Alexander and others 2006). The two main outputs are: (1) the likelihood of crown fire initiation or occurrence and (2) the type of crown fire (active vs. passive; Van Wagner 1977) and its rate of spread. A secondary output, the minimum spotting distance required to increase a fire's overall forward rate of spread, is also provided. The onset of crowning can be predicted through one of two distinct approaches. One approach relies on the knowledge of canopy base height and certain components of the Canadian Forest Fire Weather Index System and/or the 10-m open wind speed (Cruz and others 2003b). The other approach requires the 10-m open wind speed, the estimated fine fuel moisture (Rothermel 1983), fuel strata gap or canopy base height, and an estimate of surface fuel consumption as inputs (Cruz and others 2004). Required inputs to predict crown fire rate of spread are 10-m open wind speed, estimated fine fuel moisture, and canopy bulk density (Cruz and others 2005). The minimum spotting distance to affect overall crown fire rate of spread, which assumes a point ignition and subsequent fire acceleration to an equilibrium rate of spread, requires the predicted crown fire spread rate and an ignition delay as inputs (Alexander and Cruz 2006). This latter model should be considered as theoretical in nature at this time and lacks evaluation.

The primary models incorporated into CFIS have been evaluated against independent datasets involving both experimental fires (Cruz and others 2003b, 2005) and wildfire observations (Alexander and Cruz 2006) with good results. CFIS has applicability as a decision support aid in a wide variety of fire management activities ranging from near-real time prediction of fire behavior to analyzing the impacts of fuel treatments on potential crown fire behavior (Alexander 2007). All or parts of the system have to date been applied to situations in Australia, North America, and Europe (e.g., Cruz and others 2008, 2014; Smith 2011; Osiowy 2012; Fernández-Alonso and others 2013; Watt 2014; Bried and others 2015).

Presently, the main limitations of CFIS are as follows:

- *Ideally, CFIS is most appropriate for use in fuel types that mimic the original datasets (i.e., healthy, single-age and single stratum conifer forests). Thus, one should not expect accurate predictions in conifer forests with highly variable vertical complexity (e.g., old growth wet forests in Pacific Northwest), highly drought-stressed forests, and stands with a prominent medium or tall understory shrub layer.*
- *Not appropriate for use in "dead" conifer forest stands resulting from insects and disease (e.g., mountain pine beetle attacked lodgepole pine).*
- *Valid for free-burning fires that have reached a pseudo steady-state (i.e., a "line fire" as opposed to a point source fire); they are not considered applicable to prescribed fires or wildfires involving ignition patterns that deviate from this simplistic situation (e.g., spot grid, strip-head fires, backfiring, ring fire).*
- *They do not at present consider the mechanical effects of slope steepness on crown fire behavior.*

The other software application, the Canopy Fuel Stratum Characteristics Calculator, is based on the regression equations developed by Cruz and others (2003a) for estimating the canopy base height, canopy bulk density and canopy fuel load for four broad coniferous forest fuel types found in western North America

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

based on three stand characteristics (i.e., average height, basal area and stand density). The regression equations have been programmed into an excel spreadsheet (Alexander and Cruz 2010). Tabular versions of the equations have also been prepared (Alexander and Cruz 2014). Three of the types involve relatively pure stands of Douglas-fir (Pseudotsuga menziesii), ponderosa pine (Pinus ponderosa) and lodgepole pine (P. contorta). A mixed-conifer type was also identified, which consisted of seven different forest cover types: Engelmann spruce (Picea engelmannii), Engelmann spruce–subalpine fir (Abies lasiocarpa), white fir (A. concolor) or grand fir (A. grandis), western red cedar (Thuja plicata), western hemlock (Tsuga heterophylla), mountain hemlock (T. mertensiana)–subalpine fir, and western larch (Larix occidentalis)–Douglas-fir.

Two evaluations have been undertaken of the Cruz and others (2003a) canopy fuel regression equations (Cruz and Alexander 2012). The first evaluation involved a random selection of 10 stands each from the four datasets used in the original study. These were in turn subjected to two simulated thinning regimes (i.e., 25 and 50% basal area removal). The second evaluation involved a completely independent dataset for ponderosa pine consisting of 16 stands sampled by Keyser and Smith (2010). The results of both evaluations clearly show that the stand-level models of Cruz and others (2003a) are, considering their simplicity, quite robust in nature.

The Cruz and others (2003a) regression equations have been used by investigators for over a decade now (e.g., Stevens-Rumann and others 2012).

Keywords: *canopy base height, canopy bulk density, canopy fuel load, onset of crowning, rate of fire spread, spot fire distance*

Acknowledgments

The work reported on here was originally supported in part by Joint Fire Science Program Project 09-S-03-1. The reviews by D.B.B. Perraskis and S.W. Taylor are hereby duly noted.

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Contemporary patterns of burn severity heterogeneity from fires in the Northwestern U.S.

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Introduction

Historically, frequent, low-severity fires maintained open-grown structure of dry ponderosa pine forests (Hessburg and Agee 2003). Thus, an open forest structure may be a reasonable template for ecological restoration in those particular forest types (Allen and others 2002). In contrast, setting goals for ecosystem management and restoration targets in the vast majority of forests that are typified by mixed-severity fire, where forest structure historically varied across time and space, has proven more difficult (Halofsky and others 2011; Perry and others 2011).

Mixed-severity fire regimes historically maintained landscape heterogeneity in fuels and ecological conditions, which both limited fire spread and supported diverse species assemblages (Figure 1; Hessburg and others 2005). Fire historically produced significant heterogeneity (Hessburg and others 1999), which likely maintained high beta diversity (i.e., different species compositions among local sites) while creating landscape feedbacks limiting the spread or severity of subsequent fires (Parks and others 2013). Interactions between fires whereby fire reduces the spread or severity of subsequent fires have been referred to as fire's self-limitation (Collins and others 2008), can give rise to patterns consistent with theories of self-organized criticality (Pueyo and others 2010), and have been termed "landscape memory" by some ecologists (Peterson 2002). In mixed-severity fire regimes, one hypothesis is that landscape memory has been lost through fire exclusion that created a contagious landscape prone to biologically homogenizing patterns of burn severity (Figure 1).

Whether forests historically characterized by mixed-severity fire have been altered through fire exclusion and timber harvesting to the point where active intervention is needed to sustain biological diversity and ecosystem function remains uncertain and controversial (Schoennagel and Nelson 2011; Williams and Baker 2011; Fulé and others 2013; Larson and others 2013a). If forested landscapes have become more contagious and prone to homogenization by fire, then the heterogeneity of burn severity within fires may have decreased over time, theoretically shifting fires toward proportionally higher severity burns.

While it is difficult to compare historical burn severity composition and heterogeneity to contemporary patterns, remotely-sensed estimates of burn severity can be used to investigate patterns of recent fires, which should provide insights into patterns of fire across the landscape. I used Monitoring Trends in Burn Severity (MTBS, Eidenshink and others 2007) data to evaluate patterns fire severity from 1984 to 2008 in the Northwestern United States. I investigated the composition of burn severity among and within different vegetation cover types, and also explored how the relative and total composition of burn severity scaled with fire size.

Methods

I obtained tabular MTBS data for years 1984-2008 that included classified burned severity area within fire perimeters for the northwestern U.S. (including Washington, Oregon, parts of Northern California and Nevada, Idaho, and western Montana). I calculated the composition of burn severity for each fire as the relative proportion of area within each severity class (high, moderate, low, low or unburned, increased greenness). The analysis was conducted for all LANDFIRE land cover types recorded within each fire perimeter, as well as three separate vegetation cover types including evergreen and mixed forests, shrub and herbaceous vegetation, and deciduous forests. To display and easily quantify how burn severity composition varied across a gradient of relative high severity, I rank ordered fires by proportion high-severity fire, and then ranked those fires with zero high-severity fire by proportion of moderate-severity fire, and then ranked those with zero high- or moderate-severity fire by proportion of low-severity fire (Figure 2). To investigate how patterns of burn severity varied across fire size, I plotted and regressed the relative and total area of high- and low-severity fire against total fire perimeter size for all fires.

Results

The composition of burn severity is highly heterogeneous irrespective of dominant vegetation cover types considered (Figure 2). Few fires were dominated by high-severity burn regardless of vegetation type. For instance, less than 2 percent of fires were characterized by ≥50 percent high severity and only about 14% of fires experienced ≥25% high severity across all vegetation types (Figure 2, Table 1). The proportion of each fire characterized by high-severity burn varied slightly by cover type (Table 1), and forests experienced relatively more high-severity fire compared to other cover types.

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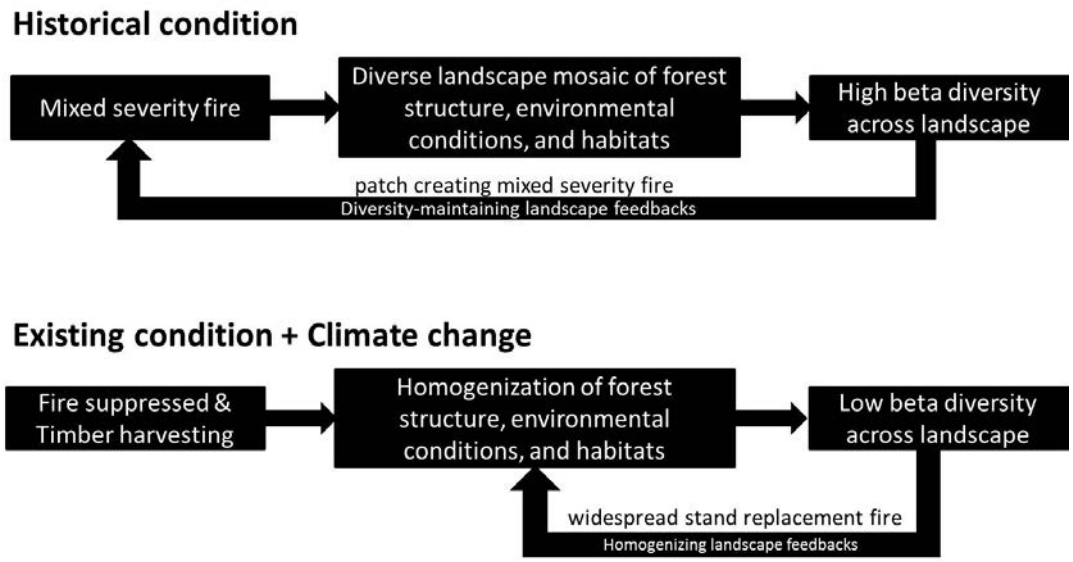

Figure 1—Conceptual figure describing the hypothesized historical role of mixed-severity fire (top box and arrow diagram) compared to the existing condition including the role climate change may play in driving contemporary fires (bottom diagram). Historically, mixed-severity fire created diverse landscape conditions that influenced high levels of beta diversity (i.e., variability in species composition among sites) across landscapes. These heterogeneous conditions gave rise to landscape-level feedbacks (i.e., ecological memory) whereby patches of past fires created barriers to subsequent fires, which maintained diverse conditions among sites. Through fire suppression and timber harvesting, forest conditions have been homogenized by removing patch-creating fires, reducing beta diversity and removing diversity-maintaining landscape feedbacks. Existing landscape-scale forest conditions may be contagious to spatial processes, such as fire and insect spread. These contagious conditions across landscapes lacking old, large fire-resistant trees may be at risk of being homogenized by large drought-influenced fires.

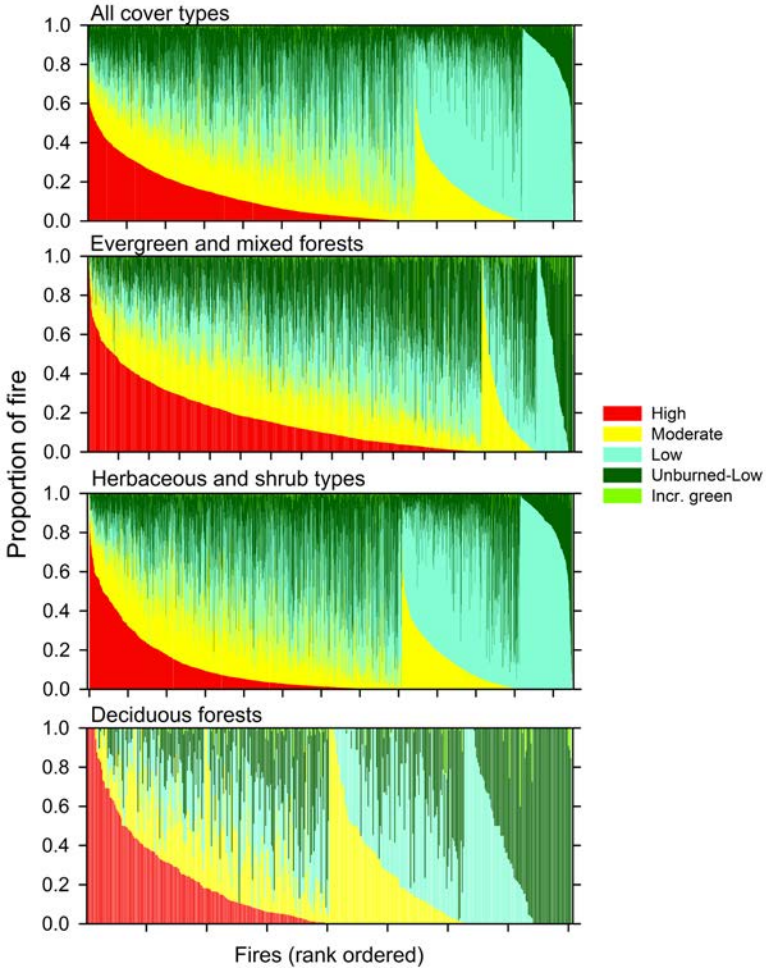

Figure 2—Relative composition of burn severities across all cover types and three vegetation cover types in fires that burned between 1984 and 2008 in northwestern states of the U.S. rank ordered on amount of fire burned under high severity (top panel). Fires are shown as stacked bar graphs next to each other to highlight the variability in burn severity across fires. Number of fires for each panel including some statistics on proportion high severity are shown in Table 1.

Table 1. Number and percentage of total fires characterized by at least 50% or 25% area of high burn severity for all cover types and broken down by dominate vegetation. Data are shown in Figure 2.

	Number of fires with ≥ 50% high severity burn area	Number of fires with ≥ 25% high severity burn area	Total number of fires with each cover type	Percent of fires with ≥ 50% high severity burn area	Percent of fires with ≥ 25% high severity burn area
All cover types	44	342	2501	1.8	13.7
Evergreen and mixed forests	87	372	1587	5.5	23.4
Herbaceous and shrub types	70	278	2497	2.8	11.1
Deciduous forests	32	81	403	7.9	20.1

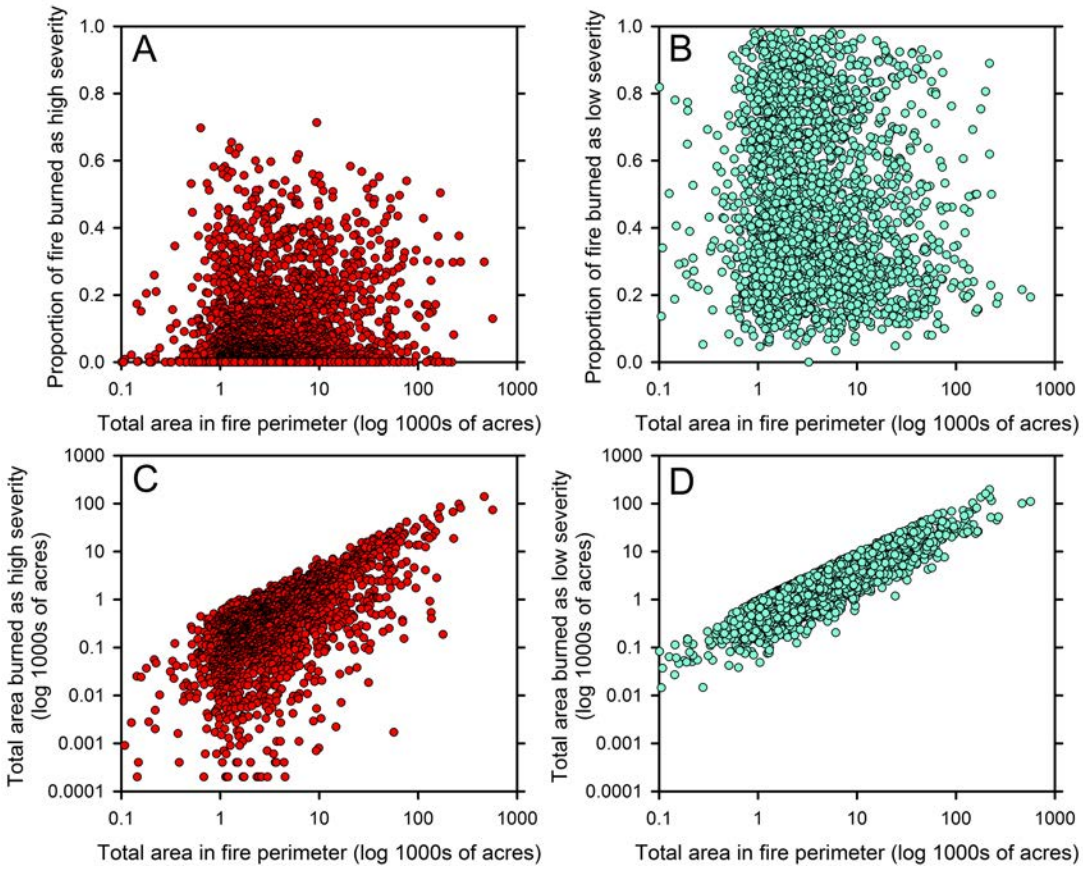

Figure 3—Relationships between log total area within fire perimeters and the proportion of fires and log total area burned under high (A and C, respectively) or low (B and D, respectively) severity.

The proportion of either high (Figure 3A) or low severity (Figure 3B) burn with a fire event was unrelated to fire size, suggesting that larger fires are not compositionally different than small fires in terms of the relative area of different burn severities. However, the total area burned under high (Figure 3C) and low (Figure 3D) severity did scale with increasing fire size. In other words, larger fires produced greater total (but not relative) area of high- and low-severity fire. Total high-severity burn area was less tightly correlated with total area burned with a less steep slope compared to how total low-severity burn increased with total fire area (compare Figure 3C-D). This pattern suggests that larger fires predictably produce more area of low severity burns compared to areas of high severity burn.

Discussion and Conclusions

Most contemporary fires in the northwestern U.S. produced a mixture of burn severities covering the full gradient from high severity to unburned areas (cf., Kolden and others 2012). This heterogeneity makes traditional categorical classification of fire regimes unrealistic. Agee (1993) represented this well by depicting the continuously variable proportions of all fire severities across fire regime classes. Classification

of fire regimes may be relatively simple for forests at the extremes in terms of the proportion of high- and low-severity fire (e.g., low-severity ponderosa pine forests, Allen and others 2002, vs. high-severity lodgepole pine forests, Turner and others 2003). However, most forest types actually fall within some kind of mixed-severity fire regime (cf., Schoennagel and Nelson 2011). Rather than thinking of a mixed-severity classification as a "holding place" for ecosystems that do not clearly fall into one of the two extreme classes of fire regimes, research and management should focus on mechanisms that give rise to variability in burn severity and landscape feedbacks (e.g., self-limitation of fire through landscape memory).

Quantifying patterns of burn severity in contemporary fires is an important step in understanding mechanisms that create mixed-severity fire, such as climate and biophysical drivers of fire severity and pattern (Cansler and McKenzie 2014). Understanding mechanisms governing fire severity, and how burn severity may be conditioned upon interactions among various factors (e.g., wind speeds, topography, species composition, climate, previous fire mosaic) should inform questions about whether, where, and how to actively restore forested landscapes historically characterized by mixed-severity fire.

Large fires create ecological, economic, social, and political challenges, which may be exacerbated by climate change (Westerling and others 2006). While the relative composition of fires does not appear to change with fire size, the amount of area burned under different severities does increase with fire size. Large fires produce large areas of high burn severity, but they also produce significant heterogeneity with more area of low-severity burn that may result in desired forest structure and fuel loadings resilient to subsequent fires (Cansler and McKenzie 2014). Even patches of high-severity fire can be desirable for the maintenance of many plant and animal species populations (Swanson and others 2011).

While contemporary fires have clearly produced significant heterogeneity in burn severity, whether the heterogeneity is within the historical range of variability is more difficult to determine. Have fires of the past 3 decades produced more severe and homogeneous conditions following decades of fire exclusion, timber harvesting, and climate change compared to historical fires? If so, questions remain about whether prescribed fuels reduction can actually reduce the risks of homogenizing high-severity burn areas. Despite the high levels of compositional heterogeneity shown here, contemporary fires may produce larger and more severe and homogeneous patches of high-severity fire now compared to historical conditions (Figure 1).

Heterogeneity is often stated as a goal of restoration in some mixed conifer forests, but goals of forest restoration should be explicit about the kinds of desirable and ecologically-informed heterogeneity across scales. Goals of forest management should be described in terms of patch size distribution and arrangement of patches, in addition to compositional landscape heterogeneity. Determining desired conditions for these types of landscape metrics may be complex and challenging, but methods do exist for some areas historically dominated by mixed-severity fire regimes (e.g., Churchill and others 2013; Hessburg and others 2013). More research should also investigate how various measures of heterogeneity produced by fires influences native biological diversity.

In the southwestern Crown of the Continent of western Montana, a collaborative supported with the Collaborative Forest Landscape Restoration Program (CFLRP), has worked to embrace the uncertainty about what kind of heterogeneity is desirable, whether existing conditions have been altered and are at risk of homogenizing landscape feedback (Figure 1), and which treatments might help set the landscape up to burn in a way that restores ecological patterns and processes, while also increasing the decision space for managers to allow some fires to burn. Given the uncertainty associated with restoration in forests characterized by mixed severity fire regimes, the collaborative is working toward applying a rigorous experimental design to projects that will set up an active adaptive management program to shed light on some of these questions (Larson and others 2013b). Ultimately, restoration forestry must focus on social, economic, and ecological considerations about how to restore fire's role as a sculptor of landscape heterogeneity.

Acknowledgements

Thanks to Greg Aplet, Alina Cansler, Michele Crist, Laura Burkle, Jonathan Myers, Andrew Larson, Cory Davis, Cara Nelson, Jon Haufler, Tim Love, Matt Dietz, Paul Hessburg, and others for rich conversations or helpful comments that informed this analysis or improved text. Andrew Larson, Dick Hutto, and Bob Keane provided comments and editorial suggestions that significantly improved the content. NSF Award#1256819 partially supported the research.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Vegetation Clearance Distances to Prevent Wildland Fire Caused Damage to Telecommunication and Power Transmission Infrastructure

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Abstract—*Towers and poles supporting power transmission and telecommunication lines have collapsed due to heating from wildland fires. Such occurrences have led to interruptions in power or communication in large municipal areas with associated social and political implications as well as increased immediate danger to humans. Vegetation clearance standards for overhead conductors in the US have been specified to prevent ignition due to arcing from the power line to ground or to minimize potential fire ignition by hot sparks from a line fault that fall into vegetation on the ground. The California Public Resources Code (PRC) section 4292 suggests "clearance of flammable fuels for a 10-foot horizontal radius from the outer circumference of power line poles and towers." Unfortunately, no studies were found addressing the question of what is the appropriate clearance needed to prevent damage to the conductors and support towers by wildland fires. Recognizing the lack of quantitative information, The Fire Sciences Laboratory (USFS) analyzed this question. The results suggest that steel towers provide the greatest resistance to fire damage; however when failure occurs it is catastrophic, wood poles and towers do not fail catastrophically and thus may provide longer term resistance to failure. Minimum clearance for steel towers in surface and crown fires is 1 to 5 m. The minimum clearances for wood poles exposed to surface fires of low to moderate intensity are on the order of 1 to 5 m. For crown fires in tall brush and tree canopies, wood poles and towers require clearances of 20 to 30 m. The study indicates that aluminum towers are most similar to steel in terms of clearance distances for fires in all vegetation types. The susceptibility of wood poles to ignition and sustained burning is dependent on the age and condition of the wood surface: aged poles that present fissures for ember accumulation have the greatest risk. There is evidence from the USFS study simulations that the possibility exists for overhead conductors to fail although this occurrence has not be observed. Transformer and junction enclosures were not susceptible to damage primarily due to the steel exterior material. Clearance around telecommunication towers is dependent on the exposure of cables, guy wires, and other materials near the ground. Analysis and conclusions from this study should be characterized as preliminary.*

Introduction

Flames and smoke from wildland fire can increase the possibility of phase-to-phase, phase-to-tower, or phase-to-ground faults that could lead to subsequent power outages and electrocution risk to humans (Martinez-Canales and others 1997; Andrade 2006; Vosloo and others 2008; Wu and others 2011; Kirkham 2012). Measures taken to reduce fire intensity and thereby minimize risk of faults include expansion of vegetation clearance around towers, reduction of vegetation maintenance intervals in high risk locations, identification of zones warranting more intensive vegetation management based on vegetation type, slope, or other fire risk factors to reduce the risk of crown fire (i.e., reduction of vegetation load to less than 10 tons/acre), removal of ladder fuels, thinning to a canopy density less than 40% closure, alteration of species composition from high flammability to lower flammability vegetation types, and modification of line patrol frequency (Blackwell and others 2011).

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The California Public Resource Code (PRC) section 4292 suggests a "clearance of flammable fuels for a 10-foot horizontal radius from the outer circumference of power line poles and towers." Section 4293 requires "clearance of all vegetation for a specific radial distance from conductors, based on the voltage carried by the conductors: four feet for 2.4-72 kV, six ft for 72-110 kV, and 10 ft for 110 kV." In addition it requires the removal or trimming of trees, or portions of trees, that are dead, decadent, rotten, decayed or diseased and which may fall into or onto the line and trees leaning toward the line (Anon 2008, 2011). One utility company in southern California (SDG&E) specifies a "minimum clearance from ground to any transmission conductor of 500 kV be at least 40 ft when the conductor is at maximum designed sag." The California Public Utilities Commission (Commission) recommends a minimum clearance of 18 inches must be maintained between line conductors and vegetation under normal conditions. One study concluded that in "any mountainous land, or in forest-covered land, brush-covered land, or grass-covered land," electric utilities maintain an 18 inch clearance around the power lines carrying less than 2.4 kV but they must still keep a 10 ft clearance around poles or towers "which support a switch, fuse,

transformer, lightning arrester, line junction, or dead end or corner poles" (Kim). Southern California Edison recommends that any wildland firefighter activity be minimized within 1.5 times the tallest portion of any power transmission or distribution line (personal communication with T. Whitman, Edison Fire Management April 23, 2014). All of these documents specify the clearance distance required to prevent fire ignition or risk to human safety due to arcing from conductors to ground or other conductors. None address the question of how to minimize the risk of fire-induced thermal damage to the transmission or telecom support structure caused by fire burning nearby. This question is the focus of the work described here.

There have been documented observations of steel towers failing in wildland fires. In a recent presentation Southern California Edison representatives stated that they have not observed failure of conductors or steel towers in their transmission and distribution systems in southern California caused by wildland fire; but they do regularly observe failure of wood poles

Past Work

Wood poles ignite but don't mechanically fail until a substantial portion of the diameter has been burned (Smith 2011). Galvanized steel poles can fail catastrophically at temperatures above 515 °C (Sakumoto and others; Smith 2011); however, fire resistant steels or coatings can be used to extend time to failure. Generally, aluminum's tensile strength rapidly drops and elongation accelerates as temperatures exceed 200 °C (Rincon and others 2009). Aluminum stranded conductors steel reinforced (ACSR) power lines are primarily used for power transmission and distribution. Of these lines, it was found that "when ACSR conductors are exposed or heated, their mechanical strength is reduced below the rated values of new conductors while their extension rate is increased. Moreover, the zinc layer on the steel strand may be removed and subsequent galvanic corrosion accelerated. This tends to corrode the aluminum strand in the interior layer as well as the bare steel strands. Thus any forest fire could be an important factor in reducing the life of ACSR conductors in service" (Kim and Morcos 2003). Porcelain insulators start to fail at 300 °C and are affected more by heating duration than heating cycle (Lee and others 2008b). Polymer insulators exhibit little-to-no fire-induced effect (Lee and others 2008a). However, deposition of smoke particles or fire retardant on either type of insulator can increase the potential for phase-to-tower faults. These and other related questions are being addressed in Canada and southern California (Anon 2008; Blackwell and others 2011).

Recognizing the need for information about vegetation clearances that would minimize the potential for fire caused failure of power and telecommunications infrastructure, the Joint Fire Science Program funded a study by the Fire Sciences Laboratory (USFS) in 2010 to explore this question. This report summarizes the findings.

Method

Vegetation clearing distances are dependent on two variables, the energy released from the fire and the thermal properties of the item of interest. Both are discussed here.

The Fire Dynamics Simulator (FDS) developed at the National Institute of Standards and Technology (McGrattan and others 2010) was used to simulate the energy release from fire and the thermal response of materials exposed to the heat. This model was designed to simulate structural fires and has complex chemistry and physics intended to accurately approximate the combustion processes and energy release from the flames. For this study FDS was formulated to simulate fires in various vegetation types and compute the thermal impact on power transmission lines, telecommunication lines, and support poles/towers composed of wood, steel, aluminum, and fiberglass. This study also explored thermal impacts on telecommunication towers and ground located transformer and junction boxes. Using fire intensity data collected from actual wildland and prescribed fires (Frankman and others 2012) simulations were formulated to replicate fires in three types of natural fuels (grass, brush, conifers) for a range of topographical and weather conditions.

FDS fire intensity was controlled by specifying a burning area, surface heat flux, residence time, and rate of spread. Increasing the surface flux and decreasing the surface area resulted in taller and narrower flames. Conversely, decreasing the surface flux and increasing the surface area resulted in shorter and thicker flames. All simulations indicated decreasing temperature with height. Flame height was defined as the height at which the gases above the burning surface decreased below the draper point (temperature above which materials emit visible radiation–525 °C or 977 °F). Simulated flames were longer than the observed flames for grass and brush (grass simulation flame length 3 m, brush flame length 6 m, crown flame length 30 m). This is considered a "built in" safety factor.

Model outputs included air temperature, radiative, and convective heating rates and a cable failure index. All poles were simulated as vertical rectangular prisms. Virtual surface temperature sensors at different heights along the pole were used to determine when thermal failure occurred. For towers, conductors, and transformer enclosures, failure was specified when the exterior temperature exceeded a specified material failure temperature limit. In the case of insulated cables the thermally induced electrical failure (THIEF) cable model (included in FDS) was used to determine cable failure (determined from a specified temperature limit). In all cases the temperature limits were determined from published literature. The temperature limit for steel was 538 °C (1000 °F), aluminum 162 °C (325 °F), wood 300 °C (572 °F) and fiberglass 350 °C (662 °F). The temperature limits for steel and aluminum were based on the approximate temperature at which elongation was greater than 10-30% for loaded members. In the case of fiberglass, the temperature limit is based on approximations to published values for mechanical elongation and ignition temperature. Published values for

piloted wood ignition temperatures vary from 210 to 497 °C (410–927 °F). A median temperature was selected as the threshold 300 °C (572 °F). Any of these assumptions could be varied based on the application, surface condition of the material and heating conditions.

Results

Findings were grouped into the dominant vegetation type sustaining the fire (i.e., grass, shrub, and crown) (Burgan and Rothermel 1984).

Conductors

Power transmission lines are usually bare aluminum conductor (All Aluminum Conductor, AAC) that may be steel reinforced (Aluminum Conductor Steel Reinforced, ACSR). For telecommunication lines, polymer jackets are placed around the wires to provide protection from U.V. rays, weathering, and human interference. These materials consist of high density polyethylene (PE), poly(vinyl) chloride (PVC), and cross-linked polyethylene (XLPE), the preferred material.

It has been observed that the spiral wound wires forming ACSR cable expand resulting in lower cable height, but constrict upon cooling. As stated above there is some evidence in the literature that exposure to heating from fires may compromise the zinc coating on the steel core wire of ACSR lines and may result in lessened conductor service life.

The study used the FDS cable model to simulate heating and failure of cables. Table 1 presents the clearance distances required to prevent thermal failure based on material thermal properties. The results were developed from the USFS study and are based on a simulation without consideration of wind or slope.

Table 1—Recommended clearance distances for overhead lines.

	Minimum distance from vegetation to overhead transmission lines (m/ft)	
	Bare wire	**Insulated**
Grass/litter	N/A[5]	N/A[5]
Low Brush	N/A[5]	4.5/1[5]
Tall Brush2	-2	-2
30 m tall Crown Fire	5/16 horizontal 20/65 vertical	25/80 vertical

[2] Tall brush was not simulated in USFS study.
[5] clearance distance much less than nominal height of conductor.

Utility Towers/Poles

Wood, steel, aluminum poles and towers were evaluated in both studies. The study also evaluated pultruded fiberglass poles. Table 2 presents vegetation clearance distances.

Wood poles are a special case as the failure criteria is ignition rather than degradation of mechanical strength. Data reported elsewhere (pp. 965 Babrauskas 2003) indicate that when there is an impinging flame on wood, ignition occurs in 100 to 800 seconds for a heating magnitude of 20 kW/m^2. As wood poles age they develop large cracks aligned with the long axis of the poles. These cracks provide points where embers can accumulate, ignite, and sustain long term combustion that can cause failure of the pole. Thus greater pole age reduces ignition limits which in turn lead to increased vegetation clearance distances.

One advantage of wood poles is that failure does not occur catastrophically during the fire, but rather occurs after main fire event has passed and smoldering combustion in wood joints or cracks has reduced the strength of the structure through combustion of the load bearing member. Thus fire risk is highly dependent on the age of the wood and to a lesser extent on the preservative treatment type.

Slope and Wind

Subsequent USFS analysis explored the impact of slope and wind on clearance distances for towers located in forests burning with fires of different flame heights. The results suggest steel and aluminum towers provide the greatest resistance to fire induced damage. Non-aged wood towers and poles are more dependent on distance (Table 3).

Surprisingly the results indicate little impact of wind or slope on clearance distances for steel and aluminum poles and towers. There is however a direct correlation between clearance distances and wind and slope for wood. The data also suggest a correlation between flame height and clearance distance for wood, steel and aluminum. The few data developed so far suggest that high wind, high slope or tall flames can mandate increases in vegetation clearance of up to 50%; however additional analysis is needed to further define this effect.

Telecommunication Towers

The study considered telecommunication towers (i.e., cellular network towers [guyed or free standing]). Towers and guy wires are typically constructed of galvanized or stainless steel, but towers may also be constructed of fiberglass

Table 2—Pole and Tower Vegetation Clearance Distances.

Material	Temperature (°C/°F)	Reaction	Grass Clearance (m/ft)	Brush Clearance (m/ft)	30 m Tall Crown Fire Clearance (m/ft)
Wood	300/572	Wood chars indefinitely	3/9	5/16	20/65
Steel	538/1000	Steel softens and breaks	02	0	5/15
Aluminum	162/325	Aluminum begins to lose strength	02	0	5/15
Fiberglass	350/662	Fiberglass begins to deform	02	--3	15/49

[1] depends on slope and wind exposure see Table 4 for additional information.
[2] simulations indicated little to no vegetation clearance needed.
[3] this material not simulated.

Table 3—Tower clearance as function of slope, wind, and flame height.

Slope %	Upslope Wind (mph)	Flame ht[1] (m/ft)	Clearance for wood poles (m/ft)	Clearance for steel poles (m/ft)	Clearance for aluminum poles (m/ft)
0	0	50/160	5/15	5/15	5/15
0	7	50/160	10/32	5/15	5/15
0	15	50/160	15/50	10/32	10/32
20	0	50/160	10/32	5/15	5/15
20	7	50/160	15/50	10/32	10/32
20	15	50/160	20/65	15/50	25/80

[1] There is some evidence that flame height can be scaled as two times vegetation height or vice versa; vegetation height is one half flame height.
[2] Not yet simulated.

Table 4—Junction/transformer Enclosures Vegetation Clearances.

Material	Temperature (°C/F)	Threshold used to determine failure	Grass Clearance (m/ft)	Brush Clearance (m/ft)	Crown Clearance (m/ft)
Steel	300/572	Steel properties start to change	<1/3	4/13	12/39
	538/1000	Steel softens and breaks	<1/3	<1/3	7/23

and wood. In the case of free standing towers, the clearance distances should be developed based on the limiting material. For guyed towers additional consideration should include clearance around guy wires. USFS simulations found that a 12 m (40 ft) vertical clearance and 4 m (13 ft) horizontal clearance was adequate for towers and guy wires. When galvanized guy wires are used, the zinc coating can melt at temperatures of (400°C). Once melted the corrosion protection can be compromised. Inspection of telecommunication tower sites suggests that signal cabling at the base of the tower is likely the most vulnerable point. Typically cabling in this area is encased in PVC or similar insulation, but has no specific protection from fire damage. Thus the focus from a fire management point-of-view should be to eliminate combustible materials below or near the signal cables and possibly install steel or aluminum cable enclosure around the cabling in this area.

Junction Boxes

The analysis considered thin wall steel junction and transformer boxes. PVC insulated cable at the center of the box was modeled. The failure criterion was the failure temperature for the insulated cable at the center of the box. In no cases did the cable temperature reach the critical threshold prior to the failure temperature of the steel. Therefore the limiting case was the steel box temperature (Table 4).

Discussion

The study indicates that steel towers provide the greatest resistance to fire-caused failure. However when they do fail it is immediate, while wood towers likely will survive some exposure and even outlast the fire event but can sustain longer term smoldering combustion that may ultimately result in failure after the fire event has passed. Minimum clearance for steel towers in surface and crown fires is 1 to 5 m. The minimum clearance for wood poles exposed to surface fires of low to moderate intensity are on the order of 1 to 5 m. For crown fires in tall brush to tree canopies, wood poles and towers require clearances of 20 to 30 m. The study indicates that aluminum towers are most similar to steel in terms of clearance distances for fires in all vegetation types. Regarding overhead power transmission or distribution lines, proximal fire can result in degradation of material strength and elongation of the line that may result in increased risk of fault (arcing) to nearby structures or ground and associated increased safety concerns. Heating may also impact expected service life. However, no observations of failure due to heating and separation of such lines have been reported. Regarding overhead telecommunication lines, the study indicates that 5 m clearance in brush and 25 m clearance for areas at risk of crown fire. All conditions simulated in the study indicated no risk of failure for ground located steel encased transformer enclosures.

In the absence of any other quantitative work this report represents the most relevant information available in the open literature to date. The findings from both studies are based on limited observations, computer simulations, and broad assumptions regarding material properties, ignition thresholds, and fire descriptors; therefore they should be considered preliminary at best.

Conclusions

This report summarizes the findings from a computational analysis initiated to address questions from land and utility managers about appropriate clearance distances

to minimize damage to power and telecommunication infrastructure from wildland fires. The approach follows a quantitative heat transfer and combustion physics method.

Anecdotal observations and the simulations presented in this report suggest that while rare, the potential for failure of power transmission line towers due to heating from wildland fire is real. The greatest risk of failure appears to be associated with towers located on or at the top of steep slopes covered with trees that can sustain crown fire where the magnitude and duration of heating can be high enough to cause material failure. Conductors fail even more rarely than towers and their failure seems to be linked to high intensity long term fire (i.e., greater than a few minutes resident time). The analysis suggests that telecommunication lines are susceptible to fire-caused damage, primarily due to the lower temperature limits of the insulation on the surface of the line. Telecommunication sites (i.e., cell phone system towers) present unique risks, primarily associated with signal and power supply lines at the base of the tower. In a fire event, reduction of vegetation in these areas and possibly the addition of protective coverings would be beneficial.

The clearance distances presented in this summary are based on idealized computer simulations of fire, energy release and support towers and overhead lines. The results have been compared against very few observations, primarily because they do not exist. Future focus should attempt to collect observations from field engineers. Due to the lack of data with which to verify the findings, they must at this point be considered preliminary.

Acknowledgments

Funding for this work was provided by the Joint Fire Science Program, the U.S. Forest Service and Brigham Young University.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

What Determines Area Burned in Large Landscapes? Insights From a Decade of Comparative Landscape-Fire Modelling

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Abstract—*Understanding what determines area burned in large landscapes is critical for informing wildland fire management in fire-prone environments and for representing fire activity in Dynamic Global Vegetation Models. For the past ten years, a group of landscape-fire modellers have been exploring the relative influence of key determinants of area burned in temperate and boreal forested landscapes using a suite of landscape-scale fire models from around the world. Three major simulation comparisons have been completed thus far, each incorporating five models and examining several different factors including fuel management, weather variability, climate change and landscape attributes. Comparison one found that variation in weather and climate was more important in determining simulated area burned than variation in fuel-load pattern and terrain in the majority of models. Comparison two demonstrated that year-to-year variation in weather and variation in efforts to reduce ignitions had a greater effect on area burned than fuel management across the range of modelled ecosystems. Finally, the third comparison explored the relative importance of vegetation dynamics, along with variation in climate and weather, in determining area burned. In this case, variation in climate was found to be a critical factor in most models - although vegetation succession was also important in some cases - emphasising the critical role that future climate change will have in controlling wildland fire. Similar to the concept of the "wisdom of crowds", the multiple-model perspective gained through these efforts provides considerable insights into examining commonalities across a range of ecosystems and simulation models.*

Introduction

Understanding what determines area burned in large landscapes is critical for informing wildland fire management in fire-prone environments (Bradstock and others 2012) and for representing fire activity in Dynamic Global Vegetation Models (DGVMs) (Lenihan and others 2003). Considerable knowledge exists on the effects of individual determinants of area burned across a range of landscapes from around the world. For example, the importance of weather in determining area burned is well understood (Flannigan and Wotton 2001), and insights into likely effects of climate change on fire dynamics are rapidly increasing (Cary and others 2012). Similarly, considerable evidence exists demonstrating the effectiveness of different fuel management treatments in achieving fire management objectives (for example, see Gibbons and others (2012) regarding house losses in wildland fire), yet fuel and fire management remains the focus of considerable debate. Further, while DGVMs represent weather, climate, and fire management effects by including a variety of relevant mechanisms, it remains difficult to identify which of them are most important for modelling spatial dynamics involving fire (Keane and others 2013). Thus, a critical question concerning the relative importance of factors in determining area burned in large landscapes has evolved from these earlier studies.

For the past ten years, a group of landscape-fire modellers have been exploring the relative influence of key determinants of area burned in temperate and boreal forested landscapes using a suite of landscape-scale spatial fire models from around the world. Simulation models are critical tools in this respect because they facilitate exploration across broad ranges of factors determining area burned, including rare extremes in fuel management intensiveness, and other circumstances like changed climates, that cannot be observed directly. Keane and others (2004) classified 44 Landscape-Fire-Succession simulation models using a series of statistical ordination, clustering, and keyword comparison techniques. The simulation efforts reported here drew from a common set of Landscape-Fire-Succession models that simulate wildland fire dynamics across large landscapes incorporating fine spatial resolution. They each implement either probabilistic or time-dependent deterministic fire spread, which is directly or indirectly influenced by fuel moisture, wind speed, fuel characteristics, and terrain. Each model represents fuel characteristics in various ways including fuel age and vegetation succession stage (Keane and others 2004).

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Table 1—Landscape-fire-succession models included in one or more model comparisons indicating general location, indicative vegetation types, inclusion in model comparisons and key reference.

Model	Location	Vegetation	Comparison	Key reference
EMBYR	Western USA	Lodgepole pine (LP)	1	Hargrove and others 2000
SEM-LAND	Western Canada	Boreal forest	1 2	Li 2000
FIRESCAPE	Southeast Australia	Eucalyptus forest	1 2 3	Cary and Banks 2000
LAMOS	Generic	Generic	1 2 3	Lavorel and others 2000
LANDSUM	Western USA	LP – Douglas fir (DF)	1 2 3	Keane and others 2006
CAFÉ	Southeast Australia	Eucalyptus woodland	2	Bradstock and others 1998
FIRE-BGC	Western USA	LP – DF	3	Keane and others 2011
FS-SWT	Southeast Australia	Grass/scrub/forest	3	King and others 2006

Here we summarise the three major simulation comparisons that have been completed thus far, each incorporating at least five models and examining the relative importance of several different factors, including fuel management, weather variability, climate change and landscape attributes. Our objective here is to highlight findings that emerged from considering all of the comparisons together. The model comparison work was initiated under the Global Change and Terrestrial Ecosystems project (GCTE Task 2.2.2), and has since been supported by a range of agencies (see acknowledgements) and simulation modellers from Australia, Canada, and the USA.

Synthesis of Modelling Studies

Each model comparison experiment involved a standardized design for simulating area burned in five landscape-fire-succession models. Due to logistical constraints, the subset of models varied somewhat from one comparison to the next; however, we maintained a common core of modellers throughout and three models were included in all three comparison experiments (table 1). In the comparisons, models incorporated vegetation dynamics and relevant climate (table 1) for the location in which they were originally verified and validated before the application of experimental treatments in this study.

Each comparison involved simulating annual area burned across all combinations of factors included in that comparison (table 2) (Cary and others 2006, 2009; Keane and others 2013). Simulation landscapes were comprised of 1,000 by 1,000 pixels that were each 50 by 50 m in size, for a total of 50 by 50 km. Variation in area burned explained by each factor, and all subsequent interactions between factors, were quantified by the Relative Sum of Squares (R^2) for factors and interactions in a Generalized Linear Model analysis of simulated area burned, after appropriate data transformations were applied. This analysis highlights the importance of factors contributing to area burned within each model, however variation in area burned between models was not formally investigated. Instead, our objective in each comparison was to evaluate consensus, or lack thereof, in importance of factors controlling area burned across the various models. We assumed that a factor could be regarded as important if it explained greater than five percent of total variation in area burned in a model (Cary and others 2006). Overall, around half of the combinations of the unique factor/model combinations were regarded as important when considering the three comparisons collectively.

Comparison one (Cary and others 2006) involved investigating variation in area burned that resulted from single year simulations across all combinations of: (i) mountainous, rolling or flat landscapes (Terrain); (ii) finely clumped or coarsely-clumped fuel pattern, with ten equally represented levels of fuel load or succession stage being linearly scaled from zero to a maximum value in initial simulation landscapes (Fuel pattern); (iii) observed climate, warmer-wetter climate, or warmer-drier climate (Climate); and (iv) ten different weather years selected from the historical weather record (Weather I) (see table 2 for details on factors). Results indicated that variation in weather and climate was more important in determining simulated area burned than was variation in fuel pattern and terrain in the majority of models (table 3). Year-to-year variability in weather (Weather I) resulted in considerable variation in area burned. Warmer climates, including in some cases those that were also wetter, resulted in large increases in area burned compared with historical climates (Cary and others 2006). These findings suggest that representing changes in climate variability (represented here by the weather factor) is as important as incorporating climate change in landscape-level and global models that include fire dynamics. Conversely, fuel pattern was not a major factor, suggesting that inclusion of fine-scale vegetation patterns in coarser models such as DGVMs may be unnecessary.

Building upon insights from the first experiment, Comparison two (Cary and others 2009) added factors more specific to fire management, including: (i) patterns of fuel treatment (Fuel management approach); (ii) amount of landscape involved in fuel treatments (Fuel management effort); (iii) proportion of simulated ignitions supressed (Ignition management effort); and (iv) different weather years selected from the historical weather record (Weather I) (table 2). In all models, variation in ignition management, from zero to 75 percent of ignitions prevented, and variation in weather (Weather I), were found to be more important in determining area burned than fuel management (less than five percent of variation in area burned explained) (table 4) (Cary and others 2009). This comparison reconfirmed the overriding importance of weather, and highlighted the critical role of ignition management, in determining area burned. Worth noting is that our definition of high ignition management effort

Table 2—Overview of factors included in one or more model comparisons indicating inclusion in model comparisons, number of levels, and brief indication of each level. See Cary and others (2006, 2009), and Keane and others (2013) for details.

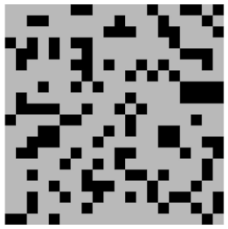
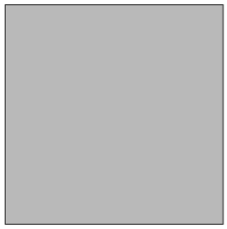
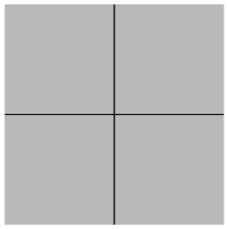
Factor	Comparison	Levels	Description of levels
Terrain	1	Three	Mountainous: 0 – 2,500 m elevation range; 30° maximum slope Rolling: 625 – 1,875 m elevation range; 15° maximum slope Flat: 1,250 m elevation; 0° maximum slope
Fuel pattern	1	Two	Fine: 25 ha square patches of fuel ages in initial landscape Coarse: 625 ha square patches of fuel ages in initial landscape
Weather I	1 2	Ten	10 distinct years of daily weather reflecting observed variability in mean annual temperature and precipitation in observed weather record for each location
Climate	1 3	Three	Observed: Historical climate for each location Warmer/Wetter: Historical; + 3.6° C; + 20 percent precipitation Warmer/Drier: Historical; + 3.6° C; - 20 percent precipitation
Fuel management approach	2	Three	Random fuel treatment  Narrow edge fuel treatment  Buffer fuel treatment  In each example, areas with fuel treatment (black colour) are located in or around a matrix of areas with untreated fuel (grey colour)
Fuel management effort	2	Four	Zero: 0 percent of landscape treated Low: 10 percent treated (Random); 100 m (Buffer); 50 m (Edge) Mod.: 20 percent treated (Random); 200 m (Buffer); 100 m (Edge) High: 30 percent treated (Random); 300 m (Buffer); 150 m (Edge)
Ignition management effort	2	Four	Zero: 0 percent of ignitions prevented Low: 25 percent of ignitions prevented Mod.: 50 percent of ignitions prevented High: 75 percent of ignitions prevented
Vegetation succession	3	Two	Static: Landscape does not age; fire does not effect vegetation Dynamic: All successional dynamics simulated
Weather II	3	Two	Entire: Long-term sequences of daily weather incorporating historical inter-annual variability Constant: Sequences of daily weather from five 'median' years

Table 3—Results of model comparison one indicating factors considered important (•) in explaining variation in simulated area burned (Relative Sum of Squares > 0.05 in a Generalised Linear Modelling analysis) for five landscape-fire-succession models. Importance is indicated for factors (Terrain, Fuel pattern, Climate, Weather I) only. Importance of interactions among factors, while evaluated, is not displayed. Modified from Cary and others (2006).

Source of variation	Model				
	EMBYR	FIRESCAPE	LAMOS	LANDSUM	SEM-LAND
Terrain		•			
Fuel pattern	•				
Climate		•	•	•	•
Weather I	•	•		•	•

Table 4—Results of model comparison two indicating factors considered important (•) in explaining variation in simulated area burned (Relative Sum of Squares > 0.05 in a Generalised Linear Modelling analysis) for five landscape-fire-succession models. Importance is indicated for factors (Fuel management approach, Fuel management effort, Ignition management effort, Weather I) only. Importance of interactions among factors, while evaluated, is not displayed. Modified from Cary and others (2009).

Source of variation	Model				
	CAFÉ	FIRESCAPE	LAMOS(HS)	LANDSUM	SEM-LAND
Fuel mgmt approach					
Fuel mgmt effort					
Ignition mgmt	•	•	•	•	•
Weather I	•	•	•	•	•

Table 5—Results of model comparison three indicating factors considered important (•) in explaining variation in simulated area burned (Relative Sum of Squares > 0.05 in a Generalised Linear Modelling analysis) for five landscape-fire-succession models. Importance is indicated for factors (Succession, Climate, Weather II) only. Importance of interactions among factors, while evaluated, is not displayed. Modified from Keane and others (2013).

Source of variation	Model				
	FIRE-BGC	FIRESCAPE	FS-SWT	LAMOS(HS)	LANDSUM
Succession			•	•	•
Climate	•	•	•	•	
Weather II			•		

equating to 75 percent of ignitions being prevented is arguably conservative, with frequency of fire containment on initial attack higher than this for some landscapes (Arienti and others 2006), and thus we may have underestimated the importance of ignition management overall.

The first two comparisons were conducted using single-year simulation runs that did not invoke vegetation succession or fuel development through time. Comparison three (Keane and others 2013) addressed temporal fuel changes through simulation runs corresponding to the length of each model's 'succession cycle', which varied from 10 – 450 years, depending on the nature of fuel and vegetation dynamics implemented in each case. Here we explored effects on average annual area burned of combinations of: (i) static or dynamic vegetation succession and fuel development (Succession); (ii) observed climate, warmer-wetter climate, or warmer-drier climate (Climate); and (iii) long-term sequences of daily weather data that fully incorporated historical inter-annual variability, or more restricted sequences of daily weather drawn only from five median weather years (Weather II) (table 2). In this comparison, variation in climate was an important factor in determining simulated area burned in four models while vegetation succession alone was an important factor in three out of five cases (table 5). Interestingly, the weather factor, which was implemented differently in this experiment, was no longer found to be important for long-term average area burned in the majority of models. In this case, variation in weather (Weather II) was introduced by looping through either the entire daily weather record for a model (typically 30 – 40 years), or looping through daily records from the five years with mean annual temperature and precipitation values closest to the overall climatic means. In both cases, the long-term mean annual temperature and precipitation were approximately the same. In comparison one and two, by way of contrast, the weather treatment (Weather I) was comprised of ten separate years of daily weather, thus incorporating large differences in mean annual temperature and precipitation for different sets of simulation runs, and effectively introducing an additional level of climatic change. Comparison three suggests that, for long simulation runs, intra-annual variability in weather is playing a greater role than inter-annual variability, in explaining simulated area burned.

Conclusions

A series of multi-model comparisons have demonstrated that variation in climate, commensurate with climatic shifts expected in a future, warmer world, is consistently important in determining area burned in large landscapes compared with other factors. Individual years, characterised by weather that is on average warmer and drier or cooler and wetter than mean values will also result in significant additional variation in area burned. However, for long simulations, the extent of inter-annual weather variation is apparently less important than intra-annual variability for variation in area burned over longer periods. Fuel pattern and fuel management was consistently found to be largely unimportant in determining variation in area burned in large landscapes. On the other hand, greater ignition management effort—representing all activities that minimize or prevent ignitions including education programs, fire bans and rapid initial attack of fires—had an important effect across all models, underscoring its roles in contemporary wildland fire management.

Simulation of wildland fire dynamics is a well-established research field. However, we propose that our ensemble approach, comprised of standardised comparisons across multiple drivers of fire and multiple models, has

provided robust new insights into what determines area burned in large landscapes. Similar to the concept of the "wisdom of crowds" (Galton 1907; Surowiecki 2005), the multiple-model perspective gained through these efforts provides considerable insights into examining commonalities across a range of ecosystems and simulation models.

Acknowledgments

We gratefully acknowledge Dr. Trent Penman and Dr. Marta Yebra who provided highly constructive feedback on our manuscript. We also gratefully acknowledge additional funding and other support from: The National Center for Ecological Analysis and Synthesis, USA; The Bushfire Cooperative Research Centre, Australia; NASA's Earth Science Applications Division, USA; The Program for Energy Research and Development (PERD) of Natural Resources Canada; The US National Fire Plan; The Joint Fire Science Program, USA; and The National Science Foundation funded Wildfire-PIRE project, USA.

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Fuels Treatments in the 21st Century—Do They Matter?

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Abstract—*Fuels treatments have long mattered, and are expected to into the future. Mangers are trying desperately to quantitatively answer the question "How much of the risk of wildfire to key values is being reduced through fuels management programs? Serious challenges to continued implementation of fuels treatments persist, such as lack of sufficient resources to accomplish meaningful risk reduction, where to apply those limited resources, how fuels programs contributed to the goals of the Cohesive Strategy, what level of wildfire intensity are treatments designed to mitigate, and can fuels programs be expected to address the "wildfire paradox." Do we have the societal will and resources to make a substantive reduction of wildfire risk in the wildlands of the US?*

In my mind, fuels treatments have long mattered, and I expect that they will long into the future. There is no doubt among natural resource and fire management professionals that wildfire behavior is modified through the manipulation of fuel beds in advance of wildfires. That general conclusion is obviously dependent upon the post-treatment fuel bed characteristics, the weather at the time the fuel bed burns during a wildfire event, the terrain in which the wildfire is burning, and the time elapsed since treatment; but it is nonetheless inescapable; less fuel available to burn in a wildfire results in a wildfire of less intensity than before treatment, which in turn results in a reduction in susceptibility to wildfire of the values that we are interested in protecting. This is the fundamental premise upon which the Department of the Interior (DOI) and the U.S. Forest Service fuels management programs exist.

That said, the fundamental question that we're trying to answer on the federal level, not only at the behest of such entities as the Government Accountability Office (GAO), the Office of Management and Budget (OMB), and the DOI Office of the Inspector General (OIG), but because it's good business to, is "How much of the risk of wildfire to key values is being reduced through the fuels management program?" That question has been posed in various forms by GAO, OMB, and OIG for 20 years or more. We're getting closer all the time to being able to answer it more authoritatively, but it's not a trivial endeavor.

So, then, what are the steps that we're taking in order to answer the question? That's the basis of the DOI Fuels Management Program Revision Project, and the Forest Service's effort to define a risk-based program. We're each using the "risk assessment framework"[1] from Scott, Thompson, and Calkin as our guide. DOI is attempting to adapt the framework for a national overview, while the Forest Service is creating unit- and regional-level analyses first. Both are busy identifying priority treatment areas, based on the estimated risk of wildfire to several Highly Valued Resources and Assets (HVRA). The Forest Service has identified 11.3 million acres nationally as being the highest priority to treat, while the DOI isn't far enough along in our analysis to determine such a figure yet. It is expected that fuels funding allocations to bureaus, regions, and units will be focused on these priority areas.

Answering the question of how much risk is actually being reduced remains the challenge. The oversight agencies would like us to develop a metric or set of metrics that incorporate risk reduction with treatment and program costs, too. That problem has eluded researchers and economists for years. We have, however, turned to our partners in the Joint Fire Science Program (JFSP) for help. JFSP already has three projects that were funded in FY 2013 that we expect will help us answer the question, and several more in FY 2014 are expected to be funded to help as well.

So much for a brief summary of the status our efforts to place the DOI and Forest Service fuels programs on a risk basis. Why do I think that fuels treatments will continue to matter into the future, and maybe more importantly, what are the challenges to fuels treatments that I see coming?

Simply put, I think that fuels treatments will continue into the future, as there will always be some key values on the landscape that we can and should mitigate the effects of wildfire to through the manipulation of fuel beds. That said, there will never be enough resources available to treat all of the areas that managers conclude deserve treatment. Therefore, a strategic, almost surgical precision will be required in order to provide treatments where they are most needed. Determining where those treatments should be, and allocating the resources to implement them, will always create angst among the agencies, the public, and some politicians. Our managers and decision makers will need to make hard allocation decisions for a long time to come.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

[1] Scott, Joe H.; Thompson, Matthew P.; Calkin, David E. 2013. **A wildfire Risk Assessment framework for land and resource management.** Gen. Tech. Rep. RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p.

The determination of where to place those treatments, is then, what I consider to be our biggest challenge, now and into the future. Ultimately, the decision makers will be faced with difficult choices, not the least of which will be the choice of maintaining an area already treated, where the wildfire risk is presumably at an acceptable level, versus treating an area of similar value, but where the wildfire risk exceeds some threshold. Since the advent of the National Fire Plan in 2001, the DOI and Forest Service have treated some 52.5 million acres to reduce or maintain fuel loadings. Depending on circumstances, many of those areas previously treated are due or overdue for re-treatment. Do we focus our efforts on maintaining these areas, depending upon the values they seek to protect, or do we seek to treat previously untreated areas?

Additionally, how can we incorporate the other goals of the Cohesive Strategy? What, exactly, is the program's contribution to restoring and maintaining the resilience of natural systems to wildfire; or in providing strategic opportunities to increase our capability to manage wildfire for resource benefits; or to increase public protection and firefighter safety? It will take time and effort to sort out those details, too.

I think that another challenge managers face is determining what level or intensity of wildfire we try to plan our treatments to mitigate. Are we talking about a wildfire that we would expect to burn under "average" seasonal weather conditions? 95th percentile conditions? 100th? Then, how do changing conditions resulting from a changing climate affect where and how we intend to treat fuels?

A fourth challenge is a persistent one, especially among the federal agencies, but not unknown to other jurisdictions and interested parties. It's the wildfire paradox, as identified by Calkin[2] and others, which maintains that using wildfire suppression to eliminate large and damaging wildfires ensures the inevitable occurrence of these fires. "Wildfire suppression, effective 95% to 98% of the time, inevitably leads to ecologically significant wildfires with higher intensities and rapid growth that are unable to be suppressed," they write. How, given the significant alterations to most fuel beds as a result of about 150 years of organized fire suppression (I date the beginning of organized fire suppression, especially by the federal government, to 1872, when the US Army was assigned to manage Yellowstone NP), can a fuels program with significantly fewer resources than are available for wildfire suppression be expected to reduce wildfire risk in any but the most limited of manners?

The last challenge that I'll mention is one that many fuels and fire managers see and lament regularly. I've personally seen it in places like the east slopes of the Cascades in Washington and Oregon, the Sierra foothills of California, and some locations in the southeast. I'm referring to the intolerance of the public and air quality regulators for short, two or three day smoke intrusions from prescribed fires. Many argue that they would rather take their chances that a wildfire will not directly impact them during fire season, and that they expect smoke for long periods anyway during the fire season. This attitude leads me to fear that our opportunities to use prescribed fire as a tool for fuels management are declining.

So, as Dr. Reinhardt asks, what, indeed, have we accomplished? What do we hope to accomplish? What may be unrealistic for us to hope to accomplish? Is it reasonable to expect that the fuels program will help reduce suppression expenditures, as many today have suggested? Can the fuels management programs of DOI and the Forest Service meaningfully contribute to the goals of the Cohesive Strategy? Does it make sense to invest so heavily in preparedness and suppression, at the expense of fuels treatments, as so many speakers today have previously asked? Given the program challenges that we face, will the only fuels treatments of the future be the footprints of previous wildfires?

In conclusion, we somehow need to discover how to, politically, organizationally, and professionally, move beyond simply placing treatments designed to mitigate risks to our highly valued resources and assets (HVRA), to placing treatments across landscapes so that the inevitable wildfires can be more safely managed, and to relieve the "wildfire paradox." In many places across the nation, especially in the more arid western United States, wildfires are becoming possibly the most important vegetation management "tool" at our disposal. In order to use that tool as effectively as possible, more wildfires will need to be allowed to burn of their own accord, which will be of concern to many. This is possible only if fuels treatments are integrated or aligned with previously burned areas, so as to create compartments to allow for more passive or *laissez faire* management of wildfires. Otherwise, the "wildfire paradox" will surely continue.

As my formal career in the field lasts only about another week, I won't be the one to answer these questions. That I leave in your capable hands. I remain, however, confident that indeed, fuels treatments matter a great deal now, and will into the foreseeable future.

[2] Calkin, David E.; Cohen, Jack D.; Finney, Mark A.; Thompson, Matthew P. **How risk management can prevent future wildfire disasters in the wildland-urban interface.** In Proceedings of the National Academy of Sciences, pnas. 1315088111

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Enhancing Scientist-Manager Relationships to Foster Ecosystem Resilience

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Abstract—*This extended abstract describes the preliminary results of a study that sought to determine the most effective ways to develop and apply sceintific information about resilience for on-the-ground management. Interviews were conducted with scientists, managers, and other stakeholders in the Southwest U.S. following a workshop on ecosystem resilience held in Tucson, Arizona in February 2014. The interviews asked respondents to consider how useful current scientific information is for decision-making, what research or products are most needed, how scientists and managers can most effectively work together, and what communication strategies are most effective. Results from this study are preliminary, but a number of recommendations for effectively developing and applying scentific information about resilience for on-the-ground management have already been identified.*

Introduction

Ecosystem resilience has recently become a buzzword in natural resource management as climate change has begun to alter many natural disturbance regimes. Natural resource managers are increasingly faced with the challenging question of how to manage for ecological resilience, especially after disturbances like large wildland fires that may result in novel fire effects or post-fire ecosystem trajectories. Addressing resilience is not simply a management concern, as there is also a great deal of scientific uncertainty around ecological, as well as social resilience before, during, and after disturbances. Interpreting what constitutes resilience, as well as identifying strategies for fostering resilience, is not yet well understood from management or scientific perspectives.

Natural resource managers are tasked to use the "best available science" to inform their decision-making (Sullivan and others 2006; USDA Forest Service 2009). However, this can be difficult with issues like resilience where there are still many unanswered scientific questions. Compounding this is what has been characterized as a disconnect between science, management, and policy (McNie 2007; Sarewitz and Pielke 2007). To better align these factions and corresponding processes, there have been increasing efforts to match the goals and needs of scientists, managers, and policymakers in order to facilitate the application of science to decision-making (Corburn 2009; Jacobs 2002; Rice and others 2009). However, developing and applying science with evolving decision-making circumstances remains a challenge.

In an effort to understand how to facilitate a better connection between science and management, a study was conducted with scientists, managers, and other stakeholders in the Southwest. The main question driving this study asked: what are the most effective ways to develop and apply scientific information about resilience for on-the-ground management? The primary goal was to develop actionable recommendations for more effectively connecting science and management in order to foster the relatively novel and pressing concept of ecosystem resilience, especially in light of climate change effects.

Methods

In February 2014, the Southwest Fire Science Consortium hosted a workshop in Tucson, Arizona, called "Fostering Resilience in Southwestern Ecosystems: A Problem-Solving Workshop." The purpose of the two-day workshop was to help managers and scientists in the Southwest better understand resilience and start to identify strategies for fostering resilient ecosystems. More than 180 participants with diverse backgrounds attended the workshop and provided input on the following topics: defining resiliency, fire preparedness, fire as a resiliency tool, post-fire management, fire-adapted communities, and strategy development.

Immediately following the workshop, post-workshop interviews were conducted with nine managers, eight scientists, and four individuals employed by non-profit or private organizations for a total of 21 interviews. The study attempted to capture a balanced number of scientists and managers. Respondents were differentiated as those who primarily conduct research (scientists), those who primarily work in land management at the local, state, or federal level (managers), and those who work for a non-profit or private organization involved in land management (other).

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The interviews were open-ended (Dunn 2008), guided by 24 primary questions, and covered four topics: demographics, data and information use and needs, workshop outcomes, and future projection. They were conducted in-person and over the phone in March 2014 and lasted an average of 40 minutes. Interviews were recorded and transcribed and are being coded and analyzed for salient themes, patterns, and interactions among themes (Bazeley 2009; Cope 2008). The interviews sought to identify barriers and opportunities to the effective development and application of science for management, as well as to evaluate the workshop itself.

Results

Analysis of the interviews is still ongoing. However, a preliminary question-by-question analysis approach was initially used to review responses to specific interview questions from the data and information use and needs section. Responses to four of these questions are provided below. Responses to the first question are differentiated among the different categories of respondents, while responses to the following three questions are grouped among respondents.

Utility of Current Scientific Information for Management

Respondents were asked, "How useful is current scientific information on ecosystem resilience for on-the-ground application?" The majority of managers noted that the current scientific information is useful in a number of ways. Managers stated they use scientific information to write more robust prescriptions for on-the-ground management actions, to inform the larger planning process on projects, and to improve decision-making credibility with the public and other audiences. Managers also stated that scientific information is used to supplement and inform an individual's personal knowledge and experience in the field. One manager also described using scientific information to refute or clarify research taken out of context by special interest groups on controversial issues such as diameter caps or threatened and endangered species.

The majority of managers also noted that there are a number of limitations to the use of scientific information. Specifically, they noted that it is difficult to utilize scientific information when there is a mismatch between the scale of a study and the scale of management concerns. Research is inherently bound in space and time, and this can limit its utility and application in decision-making. This is especially apparent with the topic of resilience, where there is still scientific uncertainty. Managers also cited other forms of knowledge as being important, such as experience in the field, gut instinct, or local knowledge, and it can be challenging when scientific information conflicts with or overshadows these other forms of knowledge. Lastly, managers noted that because scientific information is constantly evolving, there are instances where the most recent research conflicts with legal mandates in Forest Plans or National Environmental Policy Act (NEPA) documents, for example, which can make for decision-making challenges.

The majority of scientists noted that scientific information is most useful when it directly addresses management concerns. Scientists noted that some research is too fundamental or theoretical to be directly applicable in management, but this research is still important and needs to be conducted. At the same time, scientists had some concerns about the utility of common scientific concepts, for example historic range of variability, for management application. Scientists were also concerned that new and evolving research, such as research on ecosystem resilience, may be difficult to apply in decision-making. The scale and generalizability of scientific information for on-the-ground application was also a concern for many scientists.

The respondents that represented the other group were generally pleased with the utility of current scientific information. These respondents noted that many of the tools and technologies for understanding and communicating scientific concepts have improved in recent years, making results much more accessible and useful. However, this group was concerned that scientific information is too easily brushed aside for political or economic concerns. In general, all respondents pinpointed both advantages and limitations about the utility of current scientific information and noted that there is still a great deal of room for improvement.

Research Needs

Respondents were also asked, "What research or products are most needed to improve our understanding of resilience for decision-making?" A common response from many respondents was the need for more experiments designed to test management actions. Respondents also cited the need for experiments and studies that are designed to answer landscape-scale questions, as opposed to many current studies, which tend to be plot or stand-scale and may not provide enough generalized information across the landscape to managers. Although it is impossible to design studies or management treatments across all scales, many respondents expressed a desire to better align the scale of scientific studies and management needs.

Numerous respondents noted that there is a need for more social science to address questions about social resilience, garnering public support for landscape-scale management, communication and networking strategies, and wildland urban interface issues. Additionally, while there is preponderance of research in ponderosa pine and dry mixed conifer ecosystem types in the Southwest, respondents who work in other ecosystems, such as woodlands or grasslands, expressed a need for more research in these understudied ecosystems. Respondents also expressed an interest in developing different reference conditions that better reflect potential future conditions, as there was some concern that pre-settlement reference conditions may become irrelevant as climate change effects are considered. Many respondents also noted that there is a need for spatially explicit data and models that more accurately depict

local conditions and topographic variation, such as locally downscaled climate models and fuel models with higher spatial resolution. Lastly, respondents expressed an interest in developing centralized and aligned interagency datasets in order to streamline the collection and use of data and results.

Strategies for Working Together

Respondents were also asked, "How can scientists and managers work together to effectively develop and apply scientific information on-the-ground?" Overwhelmingly, respondents emphasized that scientists and managers need to spend time together in the field and away from the office. Learning and relationship building is seen as most effective when it occurs within specific locations where research is being conducted or management actions are being applied. Respondents noted that it is critical for scientists to "put themselves in the managers' shoes" and learn about management challenges in order to be most effective. Additionally, some respondents felt that the first step of research design should include time spent in the field with the appropriate local managers.

Respondents also noted that it is critical to create structured opportunities, in addition to time in the field, for interaction and discussion of research design and results. These interactions may take the form of workshops or meetings, but it is important to plan for and facilitate engagement throughout the research process. These structured interactions help to develop open and sustained lines of communication, cited as being critical by the majority of respondents, as they ensure a steady flow of information and resources. Lastly, respondents noted that it is especially important that everyone be clear and consistent about what they can or cannot contribute to a partnership. Scientists need to explain what kinds of questions they can answer, and managers need to explain what kinds of actions they can take within the context of the laws and regulations by which they must abide.

Effective Communication

Respondents were also asked, "What are the most effective ways to communicate or share scientific information about resilience?" Again, many respondents noted that ongoing and sustained communication throughout the research process is crucial. However, once research results are available, the most frequently cited strategy for sharing results is in-person, whether in the field or in an informal meeting. Secondly, workshops and formal meetings, especially with small groups, were also cited as being effective. Webinars and presentations at conferences or interagency meetings were also cited as being helpful, though less so than the more personalized approaches. With written results, concise summary formats such as white papers or fact sheets are seen as most effective. These types of approaches allow for communication of key research results and recommendations to busy audiences. Lastly, while many mangers do access and utilize scientific journals, this should not be the only forum for communicating research. In general, respondents noted that it is important to tailor communication to each audience and to present results in a range of formats that appeal to different audiences.

Discussion

The preliminary results from this study indicate that scientific information is most useful when it directly addresses management concerns. Scientific information can be difficult to use when there is a scale mismatch between science and management, when scientific information conflicts with or overshadows other forms of knowledge, when recent research conflicts with legal regulations, or when scientific concepts are difficult to apply in management. The key research needs and products identified were experiments to test management actions, social science, research in understudied ecosystems, different reference conditions to reflect potential future conditions, spatially explicit data and models, and centrally aligned interagency datasets. More effective development and application of scientific information can occur through structured interactions and interactions in the field. It is also important that scientific results be shared in a wide range of formats and tailored to appeal to different audiences. These results suggest that there are still many challenges in developing and applying scientific information about resilience for management, but that there are a number of potential approaches to mitigate these issues.

Recommendations

Although results from this study are preliminary, the following recommendations may serve as a guide from which to continue discussion of strategies for developing and applying scientific information about resilience for on-the-ground management. While there are cultural and institutional differences between science and management that are difficult to overcome, the following recommendations may help to alleviate some of those differences.

1. Facilitate engagement between researchers and managers before the research process begins.
2. Develop and create time for ongoing, in-person interactions before, during, and after research and on-the-ground application.
3. Develop common goals and design projects to meet those goals while allowing all contributors to focus on their strengths and skills.

Conversations between scientists and managers need to be encouraged before requests for proposals to determine (1) what managers' concerns and needs are, as well as their legal and regulatory limitations (2) what the scientific community can contribute in terms of resources and capacity, and (3) where those needs and resources overlap, where there are gaps, and where those gaps can be filled. It is critical to

foster collaborations between research institutions, whether academic or agency-based, land management organizations, and funding organizations to ensure that there is communication and collaboration that allows individuals within these organizations to effectively work together while focusing on their strengths. These suggestions would allow scientific, management, and funding organizations to operate within their institutional bounds while still collaborating.

Future Research

Final results from this study will be completed by early 2015. Future research to test and refine the recommendations from this study is suggested help to identify the most actionable strategies for effectively connecting science and management about ecosystem resilience.

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Influences of Previous Wildfires on Change, Resistance, and Resilience to Reburning in a Montane Southwestern Landscape

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Land use legacies and climate have altered fire regimes across montane forests of much of the southwestern US (Allen and others 2002), and several recent wildfires have been extremely large and severe (Dennison and others 2014). Large openings resulting from high-severity fire in former ponderosa pine (*Pinus ponderosa*) and mixed conifer forests may be persistent given the lack of sufficient tree seed sources, climatic constraints on reproduction and survival, and competition from herbaceous and shrubby vegetation (Bonnet and others 2005; Haire and McGarigal 2010). Additionally, subsequent burning is hypothesized to reinforce vegetation changes originating from the initial fire (Savage and Mast 2005). Consequently, there are growing concerns that recent wildfires have exceeded thresholds of ecological resilience for these forests (Savage and Mast 2005).

In 2011, the 63,000-ha Las Conchas fire reburned portions of several earlier high-severity burns in the eastern Jemez Mountains of northern New Mexico. Montane forests in this landscape historically were largely composed of ponderosa pine and mixed-conifer types, and characterized by frequent, low-severity fires (Touchan and others 1996). Fires essentially ceased with the onset of heavy livestock grazing in the 1890's, until the 1977 La Mesa fire, which was the first in a series of increasingly large (6000-20,000 ha), severe fires to burn the area (Foxx and others 2013). The purpose of our research was to examine how previous fires influenced the Las Conchas burn pattern and attendant vegetation changes. We hypothesized that prior exposure to fire, across a range of burn severities, would (1) foster ecological resistance to subsequent wildfire via reduced reburn severity, imparted by changes in fuel type, availability, and continuity, and (2) enhance resilience to reburning via the establishment and maintenance of vegetation types better adapted to rapid post-fire recovery—meaning also that changes wrought by previous wildfires would be reinforced by subsequent reburning in the Las Conchas fire.

Methods

We evaluated how fire severity of the Las Conchas fire varied by time since previous fire and severity of previous fire. Fire severity was measured using the delta normalized burn ratio (dNBR; Key and Benson 2006) and the relativized burn ratio (RBR; Parks and others 2014a), which are Landsat Thematic Mapper satellite-inferred measures fire-induced ecosystem change. For each pixel within the Las Conchas fire perimeter that reburned in a recent (since 1984) fire, we extracted the severity of the Las Conchas fire, time since previous fire, and severity of previous fire. Using both dNBR and RBR, we utilized linear models to test for the influences of previous burn severity and time since previous fire on the Las Conchas burn severity. To minimize the influence of spatial autocorrelation (Legendre and Fortin, 1989), we randomly subsampled our data at a frequency of 0.13%, and averaged p-values of 2500 models, following the methods described by Parks and others (2014b).

To examine relationships between previous wildfires, vegetation pattern, and vegetation change following the Las Conchas fire, we utilized field-sampled vegetation data from 335 plots sampled pre-Las Conchas (2003-2007; Muldavin and others 2011) and a subset of 80 of these plots that burned during the Las Conchas fire and were resampled in 2013. Pre-Las Conchas vegetation data were originally collected for a vegetation map of Bandelier National Monument; sampling methods are described fully in Muldavin and others (2011). Percent cover by all species and strata (tree, woody plants ≥ 5 m; shrub, woody plants < 5 m, includes tree seedlings and saplings; graminoid; and forb) were visually estimated in 20 x 20-m plots centered in vegetation polygons selected to maximize the range of variability captured by sampling while facilitating field sampling logistics (e.g., sampling plots in adjacent polygons with divergent vegetation types). Resampling was conducted utilized identical sampling methods.

[1] Severity of the 1977 La Mesa fire, which predated Landsat Thematic Mapper (TM) imagery, was quantified using dNDVI derived from Landsat Multispectral Scanner (MSS) imagery. We used the robust relationship between dNDVI and both dNBR and RBR from the Gila Wilderness ($r^2 > 0.7$; Parks and Holsinger, unpublished data) to calculate predicted values of RBR for the La Mesa fire.

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Relationships between pre-Las Conchas vegetation and burn severity were assessed through non-metric multidimensional scaling (NMS). Burn severity at each plot location was extracted from the dNBR and RBR grids described above[1] using bilinear interpolation. To assess patterns of vegetation response to reburning by the Las Conchas fire, we tested for differences in burn severity and vegetation change in the 80 plots resampled in 2013 for four groups differentiated by NMS scores: (1) unburned forest, not previously impacted by wildfire; (2) savanna and meadow, with low densities of trees and high cover by native grasses, burned previously at low to moderate severity; (3) oak scrub, resprouting shrubs and trees that burned previously at moderate to high severity; and (4) ruderal burn, high-severity burn interior patches with variable dominance by seeded grasses and/or New Mexico locust (*Robinia neomexicana*). We used ANOVA to test for differences in previous burn severity, Las Conchas burn severity, and pre- to post-Las Conchas change in vegetation composition (Sørensen distance) and cover.

Results

Previous wildfires strongly modulated the impacts of the Las Conchas fire through influences on burn severity and patterns of vegetation change. Consistent with expectations and the findings of studies elsewhere (for example, Parks and others 2014b), Las Conchas burn severity was strongly reduced in previous burns—mean Las Conchas RBR was 118 in reburned pixels, in comparison with 194 in pixels that had not previously burned. Though there is high variability, linear models show that this effect diminished with time since previous fire and increased with previous burn severity (Fig. 1; $r^2 = 0.12$, $P < 0.05$, RBR model; $r^2 = 0.10$, $P < 0.05$, dNBR model, not shown). Prior to the Las Conchas fire, previous burns showed pronounced structural and compositional differences compared to unburned areas, including reduced conifer canopy cover, expanded cover by resprouting shrubs, and increased native and introduced grasses (Fig. 2). These communities showed striking and significant differences in subsequent burn severity and post-fire recovery (Table 1; only RBR presented; dNBR results were similar but are not shown). Forested stands that had not recently been affected by fire tended to burn most severely and exhibited the largest changes in community composition (Sørensen distance) and losses in cover (Table 1), while communities previously exposed to wildfire exhibited decreased burn severity and/or reduced impacts of fire on vegetation composition and cover (Table 1).

Discussion and Conclusions

Our findings illustrate both the self-limiting and self-reinforcing tendencies of wildfire-vegetation interactions (for example, McKenzie and others 2011). Reductions in fuel consumed by previous wildfires created negative feedbacks limiting subsequent burn severity. However, previous burn severity was also positively linked to Las Conchas burn severity (Fig. 1), indicating positive feedbacks mediated through vegetation composition and fuel structure. Lastly, as hypothesized by Savage and Mast (2005), shifts away from conifer forest and towards alternative vegetation types were reinforced by reburning; decreased losses and/or more rapid recovery of vegetation composition and cover in the second burn.

While prior wildfires underlay major shifts away from the forest types that formerly dominated the study landscape, they also engendered considerable resistance (reduced burn severity) and resilience (recovery to pre-Las Conchas conditions) to subsequent fire. These findings have implications for fire and fuels management and post-fire rehabilitation strategies. In particular, our findings support the view of wildfire as a fuel treatment that reduces subsequent burn severity, though these effects diminished over 20-30 years. Our findings also indicate that, even over a wide range of severities, prior exposure to recent wildfire increases the capacity of vegetation to absorb and recover from subsequent fire. While this is to be expected—and is the basis of restoration treatments—for open, savanna-like ponderosa and mixed conifer forests preconditioned for low-severity fire (for example, Allen and others 2002), it also applies to alternative vegetation types generated and maintained by high-severity fire, such as communities dominated by resprouting shrubs. As such, a policy of

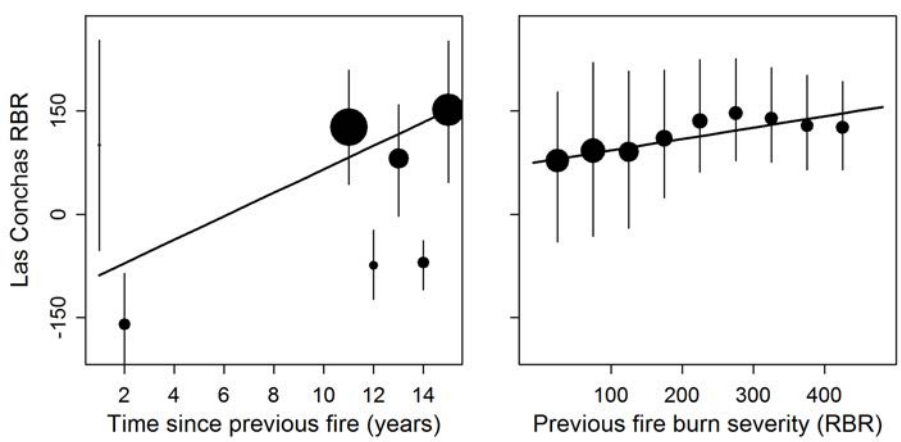

Figure 1—Relationships between the burn severity of previous wildfires, time since fire, and the severity of the Las Conchas fire. Shown are results from the model that utilized relative burn severity (RBR) as a metric burn severity; the dNBR model showed a similar relationship. Size of dots represents burn area for each year (time since previous fire) and bins representing 50 RBR units (previous fire burn severity); error bars represent 25th-75th percentile ranges.

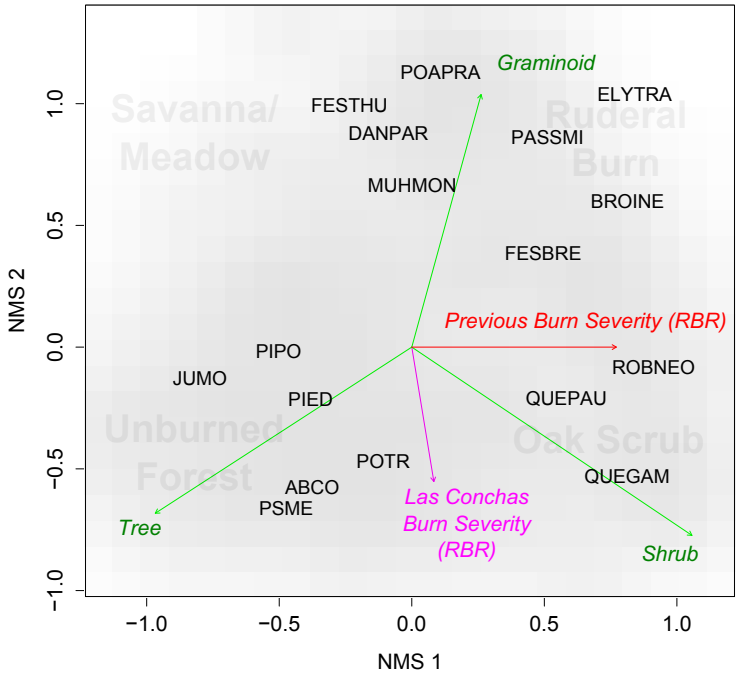

Figure 2—Non-metric multidimensional scaling (NMS) axes 1 and 2 of pre-Las Conchas vegetation. Axis 1 was closely related to previous burn severity. Axis 2 represents a transition from woody to grass-dominated communities, and is also negatively correlated with subsequent Las Conchas burn severity. Axis 3 (not shown) was strongly correlated with elevation. Vector direction and length indicates the correspondence and strength of relationships between vegetation, burn severity, and ordination axes. Locations of species codes indicates the centers of their distribution in ordination space. Species codes (4-letter codes for trees; 6 letter codes for shrubs and herbs) are as follows: ABCO, *Abies concolor*, JUMO, *Juniperus monosperma*; PIED, *Pinus edulis*; PIPO, *Pinus ponderosa*; POTR, *Populus tremuloides*; PSME, *Pseudotsuga menziesii*; BROINE, *Bromus inermis*, DANPAR, *Danthonia parryi*, ELYTRA, *Elymus trachycaulus*; FESBRE, *Festuca brevipila*; FESTHU, *Festuca thurberi*, MUHMON, *Muhlenbergia montana*; PASSMI; *Pascopyrum smithii*; POAPRA; *Poa pratensis*, QUEGAM, *Quercus gambelii*; QUEPAU; *Quercus pauciloba*; ROBNEO, *Robinia neomexicana*.

Table 1—Differences between pre-Las Conchas vegetation types in previous burn severity, Las Conchas burn severity, and changes in composition and cover two years after Las Conchas. Values given are means ± 1 standard deviation. Significant differences (Tukey's HSD <0.05) across vegetation types (rows) are indicated with different superscript letters.

	Group 1 Unburned Forest	Group 2 Savanna & Meadow	Group 3 Oak Scrub	Group 4 Ruderal Burn
Previous Fire Severity (RBR)	18.3 ± 63.4[a]	58.3 ± 84.14[ab]	190.3 ± 146.6[bc]	272.0 ± 202.3[c]
Las Conchas Burn Severity (RBR)	325.0 ± 174.8[a]	10.6 ± 176.2[b]	229.7 ± 121.2[a]	75.9 ± 157.5[b]
Compositional Distance	0.76 ± 0.17[a]	0.42 ± 0.22[b]	0.55 ± 0.19[b]	0.55 ± 0.17[b]
Cover Change	-52.8 ± 42.7[a]	-31.3 ± 28.9[ab]	-42.9 ± 37.4[ab]	-19.7 ± 39.3[b]

perpetual fire exclusion may both exacerbate severity and reduce resilience to inevitable future fire.

Acknowledgments

We thank the staff of Bandelier National Monument and the Santa Fe National Forest for access to field study sites. Esteban Muldavin and the New Mexico Natural Heritage Program provided invaluable pre-Las Conchas data and photos. We thank Sandra Haire, Carol Miller, and Bob Keane for helpful suggestions in reviews of this abstract. Funding for J. Coop and S. McClernan was provided by the Thornton Research Fund at WSCU. S. Parks and L. Holsinger acknowledge funding from the Joint Fire Science Program (project 12-1-03-19).

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Error Associated with Model Predictions of Wildland Fire Rate of Spread

Miguel G. Cruz, Bushfire Dynamics and Applications, CSIRO Land and Water Flagship, Canberra, ACT, Australia; and **Martin E. Alexander**, Department of Renewable Resources and Alberta School of Forest Science and Management, University of Alberta, Edmonton, AB, Canada

Abstract—*How well can we expect to predict the spread rate of wildfires and prescribed fires? The degree of accuracy in model predictions of wildland fire behaviour characteristics are dependent on the model's applicability to a given situation, the validity of the model's relationships, and the reliability of the model input data (Alexander and Cruz 2013b). We examined the error statistics associated with 13 operational wildland fire rate of spread models developed in Australia and North America (see Cruz and Alexander 2013, Table 1). We used 49 fire spread model evaluation datasets comprising 1278 observations (Cruz and Alexander 2013, 2014) involving seven fuel type groups (grassland, shrubland, conifer forest, eucalypt forest, mixedwood forest, logging slash, and hardwood forest). As it turned out, the compilation involved only empirically based models. The omission of physics-based model comparisons reflects the fact that there has been a minimal amount of evaluation against data collected in the field to date (Alexander and Cruz 2013a).*

Mean percent error varied between 20 to 310 percent and was homogeneous across fuel type groups. Underprediction bias was prevalent in model predictions for 75 percent of the 49 datasets analyzed. No significant differences in error statistics were observed between wildfires, prescribed fire and experimental fire observations. Empirically-based fire behavior models developed from a solid foundation of field observations and well-accepted functional forms adequately predicted rates of fire spread far outside of the bounds of the original dataset(s) used in their development. The study also confirmed that the rate of spread for surface fires is more difficult to predict than for crown fires. Only three percent of observations were considered as an "exact prediction" (i.e., when the error was less than ±2.5 percent of the observed rate of fire spread or in other words a 5.0 percent error band around an observed value). The analysis also suggested that a ±35 percent error interval constitutes a very reasonable standard for model adequacy when predicting a wildland fire's forward or heading rate of spread.

Keywords: *fire behavior, fire dynamics, fire environment, fire modelling, model applicability, model input accuracy.*

Acknowledgments

This work reported on here was originally supported by Joint Fire Science Program Project 09-S-03-1. Reviews by M.P. Plucinski and S. Matthews are hereby duly noted.

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Modeling the Spreading of Large-Scale Wildland Fires

Mohamed Drissi, Environmental Sciences Laboratory, University of Corsica, Corte, France

Abstract—*The objective of the present study is twofold. First, the last developments and validation results of a hybrid model designed to simulate fire patterns in heterogeneous landscapes are presented. The model combines the features of a stochastic small-world network model with those of a deterministic semi-physical model of the interaction between burning and non-burning cells that strongly depends on local conditions of wind, topography, and vegetation. Radiation and convection from the flaming zone, and ambient radiative heat loss are considered in the preheating process of unburned cells. The model is applied to an Australian grassland fire experiment. Predictions compare favorably to experiments in terms of rate of spread, area and shape of the burn. Second, the sensitivity of model outcomes (here the rate of spread) to six input parameters is studied using a two-level full factorial design.*

Keywords: *wildfire, network model, radiation, convection, sensitivity analysis, validation, prescribed burning*

Introduction

In the area of wildfires, there are generally two relevant scales: the macroscopic scale (the scale of the fire front) and the gigascopic scale (the aerial or satellite images). The models developed at the macro-scale are combustion models:Grishin 1997; Porterie and others 2000; Porterie and others 2007; Mell and others 2007 which are based, for the most part, on a two-phase description of the flow and have a great generality. Most of the basic phenomena that govern the emergence and spread of wildfire are generally considered at the macro-scale: gas transport, turbulence, thermal degradation of the material, turbulent combustion, radiation exchange between the gas and the solid medium. A detailed model **(**Larini and others 1998; Linn and others 1997**)** requires the numerical solution of the balance equations of mass, energy and momentum for each phase and the radiative transfer equation. These detailed models must be considered as models of knowledge for understanding the behavior of the fire, to test alternative hypotheses or enrich the models, but are not suitable for simulating the spread of fire at the large scale (gigascopic). At this scale, we deal with propagation models.

Unlike algorithms of expansion based on direct-contact or on only nearest neighbors such as Cellular automata or percolation (Albinet and others 1986; Beer and Enting 1990; Duarte 1997), the expansion algorithm used in this study expands the perimeter through considering long range effects between sites by taking advantage of the stochastic method of Monte Carlo to simulate radiative fluxes.

Recently, Adou and others (2010) used the Monte Carlo method but the quasi-physical macroscopic model doesn't incorporate convection effect and involves a circular neighborhood for each site which is a limiting procedure. The propagation model is based on elliptic expansion (Anderson and others 1982) but the correlations of ellipses parameters for propagation are not physically based.

The present model allows investigating 3D fire propagation on a landscape without making the assumptions of one-dimensional spread Catchpole and others 1989; Weber 1991 neither of quasi-steady propagation (Dupuy and Larini 1999). The vegetation and the flame are represented in three dimensions. The macroscopic model has emphasized the most possibly precise description of the phenomena that occur at the macroscopic scale, namely the preheating of the receptive fuel layer by the flame radiation and convection of hot gases, but also its radiative cooling to the surroundings. As we will see, this is based on the resolution of an unsteady energy balance equation including all eventual thermal processes. The rate of spread (ROS), the perimeter shape, the depth of the flaming front and the burnt area can be evaluated at each timestep.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

Nomenclature

V Control volume

D	Site diameter
H	Stratum height, Height
WFF	Wet fine fuel
DFF	Dry Fine fuel
T	Temperature
q	Power per unit of volume of heat transfer
n	Number of sites
t	Time
i	Index of a site on fire
j	Index of an intact receptor site
FMC	Fuel moisture content
FMC_0	Initial fuel moisture content
FPPC	Fuel pyrolysis products content
$FPPC_0$	Initial Fuel pyrolysis products content
c_p	Specific heat capacity
L	Specific enthalpy change
a	Absorptivity
p	Elementary power carried by a quantum
n"	Number of quanta emitted by each square meter of the flame
p"	Emissive power of the flame
SNB	Statistical narrow-banded
MCM	Monte Carlo Method
SFM	Solid flame model
B	Stefan Boltzmann constant
$\dot{Q}$	Rate of heat release within the flame
H_{f0}	Flame height without wind
H_f	Flame height with wind
S	Surface area
Δh_c	Heat combustion of volatile gases
t_c	The residence time of the flame
S_b	The superior surface area of the site
$\vec{U}$	Local wind
U	Wind speed
L	Length
D	Diameter
d	Distance
H	Height of the stratum
h	Mean convection coefficient
k	Thermal conductivity
$\vec{n}$	The Normal to the terrain (ground)
Re	Reynolds number
Pr	Prandtl number
g	Gravitational acceleration
X	Sensibility Factor
M	Matrix of levels
Ros	Rate of spread of fire
m	Mass

Greek symbols

δ	Penetration length of radiation (optical length)
δ_{eff}	Effective penetration length of radiation
α	Volume fraction or compactness
σ	Surface area/volume ratio
P	Fuel particle density
ε	Emissivity
α_f	Tilt angle of the flame
X_R	Radiant fraction of the heat release within the flame
ν	Cinematic viscosity
κ	Total absorption coefficient of the flame.
β	Average extinction coefficient

Subscripts

k	Solid phase
ign	Ignition
WFF	Wet fine fuel
FDF	Fine dry fuel
fb	Fuel bed
∞	Ambient
str	Stratum
char	Char
f	Flame
ij	Between (i) and (j)
c	Combustion

The Propagation Model

The Network

The vegetation can be homogeneous and uniform or, in the opposite case, it can be sparse and randomly distributed on the landscape. In the first case, the network can be constructed on a square or hexagonal based-structure. In the second case, it is necessary to build a poly-disperse (sites with different sizes) amorphous network with a density that fits the real rate cover (figure 1).

The Macroscopic Model Of Combustion

The propagation of the flame front is driven by the combustion of thin particles, typically smaller than 6 mm (such as leaves, needles and twigs) (Luke and Mc Arthur 1977) . The thick elements are involved in burning in the back of the fire front. The physical problem is displayed on the figure 2. We assume that the control volume involved in the processes of thermal degradation and combustion is a cylinder with volume $V = \pi D^2 \delta$, where D is the diameter of the fuel site and δ ($\delta \leq H$) the mean free path of radiation through the fuel bed. Beyond δ, we assume that the medium no longer interacts with radiation. δ is connected to the surface area/volume ratio σ_κ for fine fuel elements, and to the volume fraction of the solid phase α_κ, by $\delta = 4/\sigma_\kappa \alpha_\kappa$ (De Mestre and others 1989; Butler 1993).The combustion model is based on solving the balance equations of mass and energy for a receptor site. It assumes that the receptor site receives radiation from the flame front and a convective flux of hot gases carried by the wind. However, it is cooled by radiation to the surroundings. We follow then the evolution of the temperature of this receptor site until it ignites. Hence, it contributes in turn to the fire spreading.

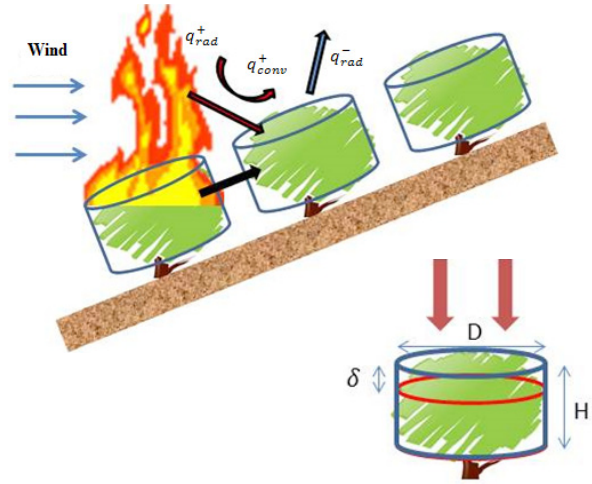

Figure 2—Heat transfers involved in the fire spreading and control volume of a site exposed to fire.

The combustion model assumes that the thermal degradation until ignition occurs according to four phases. The receptor site which is subject to the collective effect of sites constituting the fire front at time t is first heated to the temperature of vaporization of water, which is about 373K. It then dries at this constant temperature and inversely the fuel moisture content decreases until it becomes zero. Then, the dry fine fuel heats up to the temperature of pyrolysis. The last phase of pyrolysis is assumed to begin when the temperature of the dry fuel reaches the pyrolysis temperature. During this phase, if the quantity of pyrolysis products is sufficient, the site ignites. Thus, the energy conservation for a receptor site (j) exposed to N_{bc} burning sites at time t imposes:

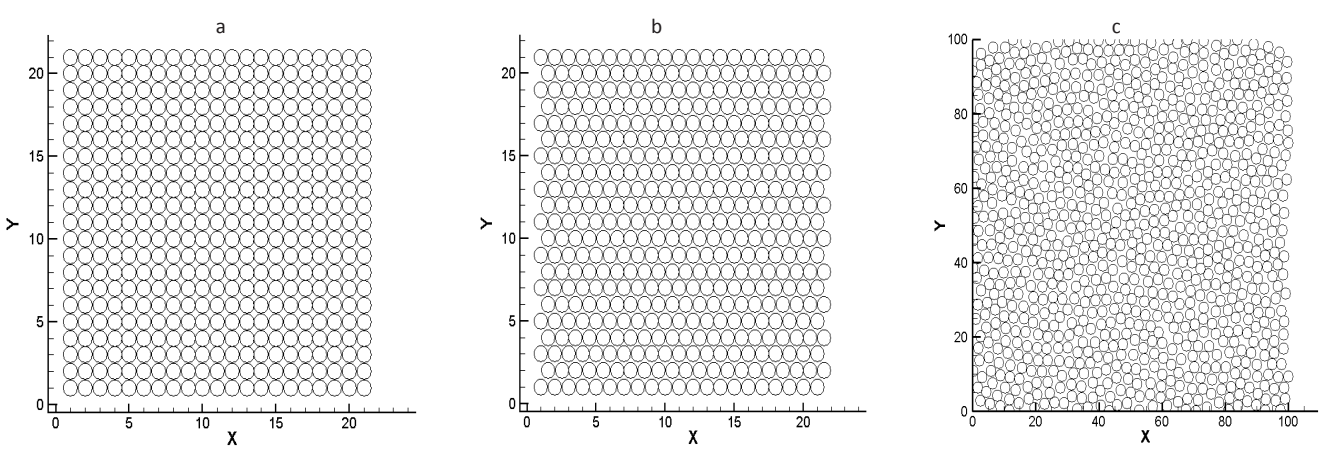

Figure 1—From left to right: examples of networks: a) Square based-structure network ,b) Hexagonal based-structure network and c) Amorphous network with a density of 70%.

$$\sum_{i=1}^{Nbc}\left[q_{rad}^{+}(i)+q_{conv}^{+}(i)\right]$$

$$=q_{rad}^{-}(j)+\left\{\begin{array}{c} P_{WFF}C_{pWFF}\alpha_k\dfrac{dT(j)}{dt}\,for\ T(j)<373K \\ -P_{DFF}L_{vap}\alpha_k\dfrac{dFMC(j)}{dt}\,for\ T(j)=373K \\ P_{DFF}C_{pDFF}\alpha_k\dfrac{dT(j)}{dt}\,for\ 373K<T(j)<T_{pyr} \\ -P_{DFF}\,L_{pyr}\alpha_k\dfrac{dFPPC(j)}{dt}\,for\ T(j)=T_{pyr} \end{array}\right\}$$

where $q_{rad}^{+}(i)$ and $q_{conv}^{+}(i)$ correspond to the heat transfers due to flame radiation and due convection of hot gases carried by the wind. The term $q_{rad}^{-}(j)$represents the radiative losses of site (j) to the surroundings. L_{vap} is the latent heat of vaporization of water, $FMC(j)$ the moisture content, defined as the mass of water divided by the mass of fine dry fuel, α_k is the volume fraction or compactness, $T(j)$ is the temperature of site (j), ρ and c_p are the density and the specific heat of the solid phase. DFF refers to dry fine fuel and WFF refers to wet fine fuel. L_{pyr} is the latent heat of pyrolysis and FPPC is the content of pyrolysis products of fine dry fuel. The initial FPPC is noted $FPPC_0$ and is defined by: $FPPC_0 = 1 - v_{char}$ where v_{char} is the initial content of char of dry fine fuel elements. Only the char remains if all the pyrolysis products are consumed. We assume moreover that the volume of fine fuel remains constant during the thermal degradation process. Each term of the energy balance equation is expressed below.

Radiation from the flame

The radiation received by the site (j) from the flame of site (i) is expressed as follows: $q_{rad}^{+}(j) = a_{fb}p_iN_{ij}/V_j$, where V_j is the control volume of site (j) and a_{fb} the absorptivity of the fuel bed.

In fact, a radiation model based on coupling the Monte Carlo method and the solid flame model is used. In the solid flame model, the flame is represented by a cylinder with only the surface that radiates. The Monte Carlo method is used to determine the number of quanta of energy launched from the site (i) on fire and which reached the receptor site (j). Each quantum carries an elementary power $p_i = P_i''/n''$ (in W), where n″ is the number of quanta emitted by each square meter of the flame and P_i'' is the emissive power of the flame attached to the site (i) on fire (see figure 3). The method is more detailed in Adou and others 2010. The radiation model is relatively simple but requires knowledge of the geometric properties of the flame and its emissive power. Moreover, the model takes into account not only the screening effect which manifests when another site on fire can exist between sites (i) and (j) , but also the attenuation of the radiation by the atmospheric air layer. The average transmittance of the air as a function of the thickness of the air layer crossed by radiation and of its relative humidity is determined using the Statistical Narrow banded Model of Malkmus (1967). The appendix A details how the attenuation is taken into account when using the Monte Carlo method.

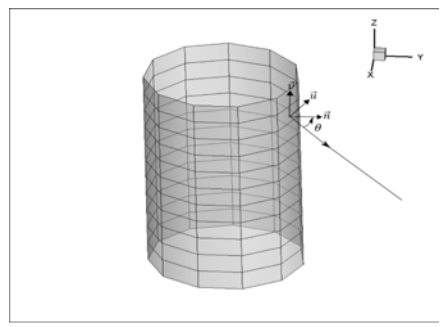

Figure 3—Energy beam leaving the flame mesh. The flame is assumed to have a cylindrical shape in the solid flame model.

Radiative losses

Radiative losses are a function of the emissivity of the fuel bed ε_{fm}, the Stefan-Boltzmann constant (B = 5.67 × 10^{-8} $W/m^2/K^4$) and the ambient temperature, $T\infty$, as follows: $q_{rad}^{-}(j) = \varepsilon_{fm}B(T_j^4 - T_\infty^4)/\delta$.

Convection of hot gases

The flame is not an impassable barrier and the wind, thanks to three-dimensional effects, can cross through it (Beer 1990). Thus, a site (j) located in the wake of a burning site (i) can be preheated by convection depending on the distance between the two sites, d_{ij}, according to a declining exponential law with a characteristic length approximately equal to three times the flame length (Koo and others 2005): $q_{conv}^{+}(i) = \frac{h}{\delta}(T_f - T_j)e^{-0.3\,d_{ij}/L_f}$, where L_f and T_f are the length and the temperature of the flame, h is an average convection coefficient for a turbulent flow on a flat plate (Pagni and Peterson 1973) defined as: $h = 0.037\ k\ Re^{0.8}\ Pr^{1/3}/d_{ij}$. The Reynolds number is defined by $Re = U\ d_{ij}/v$ based on

the tangential component of the local wind $\vec{U}$ to the terrain, $U = |\vec{n} \wedge (\vec{U} \wedge \vec{n})|$, where $\vec{n}$ is the normal to the terrain. The terms Pr, ν and k are respectively the Prandtl number, the cinematic viscosity, and the thermal conductivity of the air at the average temperature of $0.5(T_f + T_\infty)$.

The Input Parameters of the Propagation Model

The flame height in the presence of wind is evaluated by the correlation $H_f = H_{f0}(1 + 4\frac{U^2}{gH_{f0}})^{-0.5}$, where H_{f0} is the flame height without wind, deduced from the rate of heat released by combustion, $\dot{Q}$, and the source diameter, D, as ° : $H_{f0} = 0.0148\,\dot{Q}^{2/5} - 1.02\,D$. The rate of heat released corresponds to the flaming combustion of volatile gases, such as: $\dot{Q} = (1 - \alpha char)\frac{m''_{DFF}}{t_c}\Delta h_c S_b$ with $S_b = \pi D^2/4$.

As wind has little influence on flame length (Thomas and Pickard 1961; Thomas 1963; Nmira and others 2010), the flame length L_f, is assumed to be equal to the luminous flame height with no wind. The emissive power per unit area of the flame is expressed as a function of the flame's area, $S_f = \pi D L_f$ and the radiated fraction to the exterior, χ_R, as: $P''_f = \chi_R \dot{Q}/S_f$. We can then deduce the flame temperature assuming that the flame is a grey body with emissivity ε_f: $T_f = (P''_f/\varepsilon_f\, B)^{1/4}$ with $\varepsilon_f = 1 - e^{-0.6 L_f}$.

Model Validation

Prescribed Burning

In the aim to validate the propagation model, I compared results with the prescribed burning conducted in Australia by the team of Cheney (Cheney and others 1993; Cheney and others 1998) . The homogenous and continuous vegetation is mainly herbaceous *(Themeda Australis)* and covers a square plot of 200 m on each side. The wind direction is perpendicular to the left edge along which a line ignition of 175 m was performed.

The measured data are the following: U = 4.6m/s, $T\infty$ = 303K, RH = 42%, D = 3m, H = 0.51m, FMC_0 = 0.058, χ_R = 0.3, t_c = 6s, σk = 12240m^{-1}, m''_{DFF} = 0.391 kg/m², α_{char} = 0.2, c_{PDFF} = 1480 J/kg/K, P_{DFF} = 720 kg/m³, a_{fm} = 0.9, ε_{fm} = 0.9. On the figure 4, I have compared the fire contours predicted by the model (in red) and those measured after 56s (at left) and 86s (at right) of the ignition time (marked with square symbols). The comparison shows a very good agreement. After 86s, as mentioned by the authors, the comparison becomes impossible since the direction of wind has significantly changed.

In the example above, I should notice that the size of sites (strata) was conditioned by the flame height through the relation between the flame height and the size of a site as mentionned early, that can be considered as a means of calibration of the model.

I tested the radiative model (Adou and others 2010) and I realized that this model was insufficient and not able to correctly predict the fire behavior, at least in the case of this prescribed burn. It was necessary to introduce the convective contribution and the radiative losses which are non-negligible at the macroscopic scale of the fire front.

Real fire (Favone's Fire, Corsica 2009)

A second means of validation was conducted on a real fire that took place in Corsica in 2009. It is well documented in the work of Santoni and others 2011 . This anthropogenic fire took place on July 8, 2009 near the village of Favone in Corsica. The coordinates of the ignition's point have been identified to 41° 45' 57.08" in latitude, 09° 23' 44.84" in longitude and 33 meters of altitude. The fire was detected very early, around 3:00 pm. Its spread was sustained by a Southwest wind with a magnitude of 18 km/h. A total area of about 30 ha was burned. The Favone fire presents an interesting case to study the effects of slope on fire behavior, since first the fire propagated uphill between points A and B, then downhill, between points B and C (figure 5).

The shape of the topography and the intensity of fire didn't allow a direct attack at the heading fire front. Four tanker planes worked first on the left flank to protect urban areas

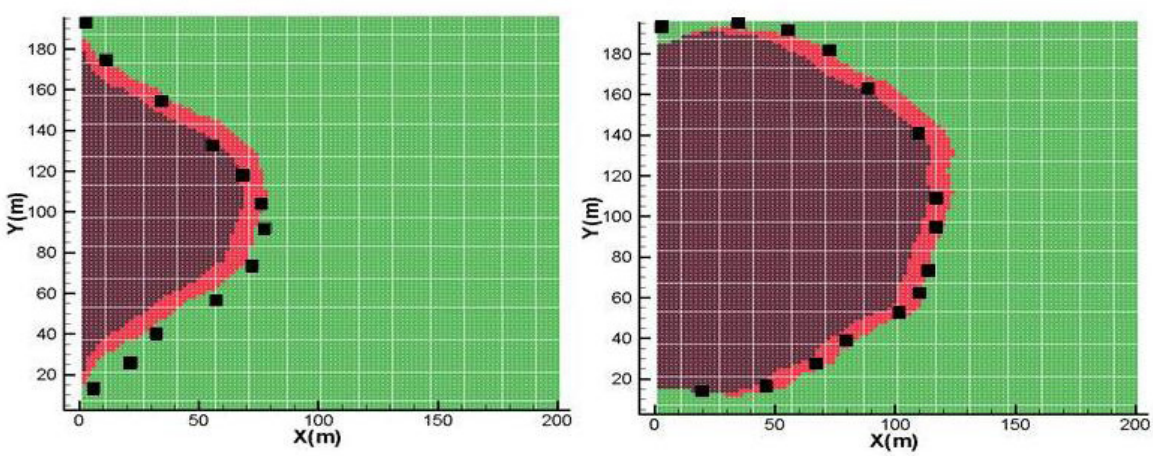

Figure 4—Fire contours predicted by the model (red line) and measured (■) after 56s (at left) and 86s (at right) of fire propagation.

Figure 5—Fire contours (in red) simulated every 5 minutes. The yellow line delimits the area actually burned.The measured times of the fire front passage are indicated (Santoni and others 2011).

and allow firefighters to respond safely. They then attacked the right flank in the hope of pushing the fire towards the sea. The fire crossed the road at 4:00 pm, reached the sea at 4:15 pm and was finally under control at 7:00 pm. Two wind regimes dominate in this area. The first, most common, is an east wind due to the effect of the sea breeze, present all day on the east side of Corsica. The second is a west wind due to large-scale atmospheric circulation. It blows mostly at night and after 4:00 pm when the effect of the sea breeze fades. The predominant wind directions in the region are typically west and southwest. In the case of Favone's fire, wind speed was between 5 and 7 m/s and the wind direction varied between 240° and 270°. The air temperature ranged between 25° C and 27° C during the fire, and the relative humidity of the air ranged between 41 and 46 percent.

I compared the rate of spread and the burnt areas predicted by the model and those measured. The figure 5 shows the fronts of the simulated fire every five minutes. The yellow line marks the real area ravaged by fire.

The rate of spread observed (figure 5) in the rising edge between A and B is 16.8 m/min, although the ROS predicted by the model is 14 m/min. There is still an underestimation between points B and C when the fire goes down. The burned area is overestimated and presents a lateral expansion. The differences are mainly due to a change in the wind direction during the spread of fire, the fact that the intervention of the fighting means was not taken into account and so have not been modeled, or a bad estimation of some input parameters. That is why a sensitivity analysis was carried out.

Sensitivity Analysis

The aim of this sensitivity analysis is to study the effect of some input parameters of the model that are a priori the most influential on the rate of fire spread. The vegetation is represented by a square-based structure network of sites distributed on a flat terrain of 100m × 100m (the study area). Each site is a cylinder having a diameter of 2 m, and a height of 2.5 m, We have used here as input parameters of the fuel, the thermo-physical and the geometric properties of Kermes Oak (Drissi 2013) Six input parameters were retained for two reasons: the first is that quite large interval of values for each parameter is found in the literature and the second is that they present a big uncertainty when they are experimentally measured. These parameters are: the dry load of fine fuel elements m''_{DFF}, the residence time of the flame t_c, the initial moisture content of the vegetal FMC_0, the ignition temperature T_{ign}, the fraction radiated χ_R and the wind speed U.

The response is the rate of spread of fire between points A and B in the study area located respectively on the lines Y = 20m and Y = 80m. Let's notice that a point's ignition was performed starting from the coordinates X = 49m and Y = 0m which corresponds to the middle of the bottom side of this domain. The sensitivity study is based on a two-level full factorial design. It consists in defining for each of the six retained parameter, a low level value and a high level value around a reference value. So $2^6 = 64$ simulations have been performed. The results are shown on a Pareto chart (figure 6): it describes how many of the selected factors and their interactions can affect the rate of fire spread. The factors with amplitude which exceeds the red line are the more significant parameters. According to this chart, the rate of spread is strongly influenced, in order, by: the wind speed, the load of dry fine fuel elements, the residence time of the flame, the fraction radiated, the initial moisture content and the ignition temperature. The second order effects are less significant like the interaction between the wind speed and the dry load. The third order terms have a negligible effect.

The negative or positive impact of the main parameters on the rate of spread can be evaluated through the chart of main effects. For example, as it can be seen on the chart,

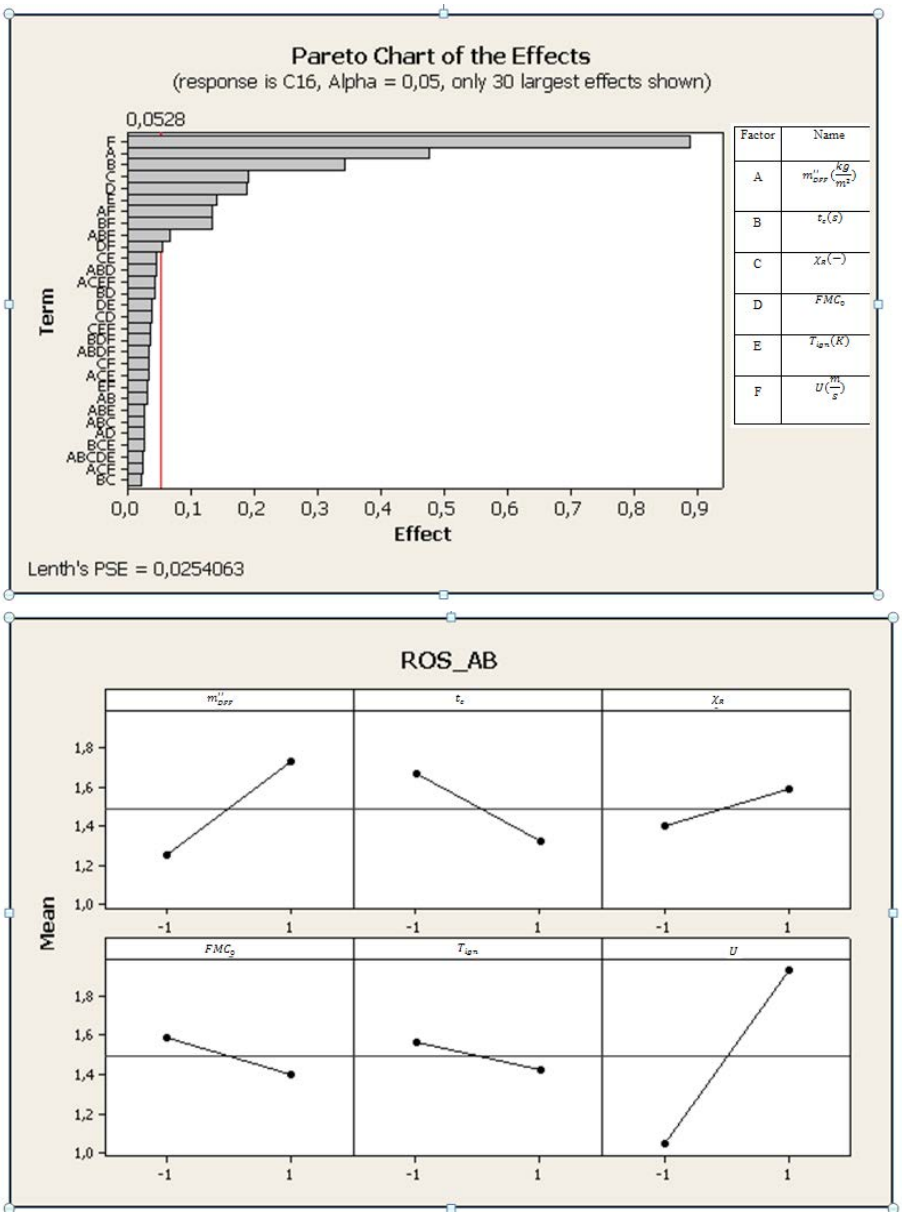

Figure 6—Pareto and main effects charts on the rate of fire spread.

when increasing the residence of flame time, the rate of spread decreases.

Conclusion

The hybrid model of propagation which combines the stochastic method of Monte Carlo and the semi-physical approach based on the resolution of the non-stationary energy equation was validated first on a prescribed burning that occurred in Australia and second on a real fire that took place in Corsica. There is an excellent fit in terms of rate of spread, fire contours and burned area. A full factorial plan of two levels allowed the classification and prioritization of the most influential parameters of the model as well as their interactions.

Acknowledgments

I would like to thank the Sciences Environmental team in Corsica and especially Professor P.A. Santoni for making available the data concerning the Favone Fire. I also thank Professor Noureddine Zekri for fruitful discussions about the topic. I thank the "Ministère de l'Education Nationale , de l'Enseignement Supérieur et de La Recherche , France" for the funding of this research.

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Characterization of the Large Fire Regime in SE France

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Introduction

Southeastern France is the most wildfire prone region of the country, covering 14.7 percent of its land areaentire country, is the region most affected by wildfires, with 55 percent of the total number of fires recorded in the whole country from 2006 to 2008. It is a typical Mediterranean climate with hot and dry summers, often with strong NW wind, and includes plant communities well adapted to these drastic climate conditions. These combined fuels and weather conditions significantly increase the fire risk in this regions. Regionally, large fires (≥ 100ha) may be up to 11 580 ha although they generally are not as big as in other Mediterranean countries. However, because of the high proportion of Wildland-Urban Interface in the region, these large fires are a major concern, especially in the most populated parts (départements Var and Bouches du Rhône) which also concentrate most fires.

Accordingly, it is important to characterize these large fires to improve regional fire prevention. This work intends to answer the following questions:

- What is the distribution of large fires in the study area?
- Is there a correlation between number of large fires and burned area?
- Is there a correlation between large fire metrics and the climate conditions?
- What are the fire return intervals of these large fires?
- Does the past fire regime impact the current fire size and the recent land cover?

Material and Methods

Study area

SE France is composed of 15 geographical districts called "départements". In this region there is spatial variation both in terms of burned area and fire occurrence and the départements Bouches du Rhône & Var are among the most impacted (Ganteaume and Jappiot 2013). This work will focus on these two areas of SE France.

Fire data

Using the geo-referenced wildfires database of the French Forest Office (1960-2010), the fire history focusing on large fires (size ≥ 100 ha) was studied for the 1960-2010 period in the study area. The total number of fires geo-referenced (size ≥ 1 ha) was 2710 and the large fires represented only 12 percent of the total number of fires but accounted for 90 percent of the total burned area.

We used spatial analysis (Arc GIS 10) to define the large fire regime in terms of the time interval since the last fire and of the fire recurrence (number of large fires that had occurred on a same spot and time interval between two large fires). Statistics on large fire occurrence, size and cause were used to highlight a possible spatial variation of these parameters in the study area.

Climate data

For this analysis, we selected total precipitation, summer precipitation and maximum temperature (monthly and yearly data). These parameters were recorded since 1960 in the 107 weather stations distributed in the study area.

Linear regressions were used to highlight correlations between large fire occurrence/size and climate conditions (yearly total precipitation and yearly maximum summer temperature).

Land Cover data

Six classes of the Corine Land Cover 2006 were taken into account in the analyses: coniferous stands, broadleaf stands, mixed stands, transitional woodland-shrubland, shrubland and grassland. The relationships between large fire regime and land use classes were investigated by spatial analysis and multivariate analyses.

Results and Discussion

Spatial variation of the large fires

In total, 338 georeferenced large fire ignitions were recorded in the study area between 1960 and 2010 (190 in Bouches du Rhône and 148 in Var) but the distribution of the number of large fires during the period studied did not significantly vary between the two départements contrary to the fire size (on average 583 ha/year burned in Bouches du Rhône and 2 217 ha/year burned in Var). This could be explained by the variation of landscape fragmentation between these two areas. Indeed, the département Bouches du Rhône presents a mosaïc of wildlands interspersed with agricultural areas, large fires being concentrated in natural spaces. In the department Var, large fires mainly occurred in the large wildland areas located on the coast. In the study area, the cause of large fires was known for

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

only 23 percent of them, being 50 percent of these due to negligence. However, the knowledge of large fire causes is far better in Var (68 percent of known causes) than in Bouches du Rhône (only 6 percent of known causes), according to the National Forest Office's fire database. There is no spatial variation on the causes of large fires and the main cause is negligence in both areas; however, arson may be strongly underestimated in the département Bouches du Rhône as many arson fires may be recorded as fires of unknown causes (Fig. 1).

Temporal variation of the large fires and of the climate conditions

The analysis of the large fire history in the study area (Fig. 2) between 1960 and 2010, showed that there was a positive correlation between the size of large fires and the number of large fires (linear regression $p<0.0001$; $R^2=0.30$). During this period, the fire history showed a slight decreasing trend in both parameters which was not significant, while the climate parameters showed a significant increasing trend in maximum temperature with time ($R^2=0.45$) and a non significant decreasing trend in total precipitation. This latter parameter did not vary spatially in the study area contrary to the maximum temperature which was significantly higher in the département Bouches du Rhône than in Var ($p<0.0001$).

Both, the size of large fires and their occurrence were negatively correlated with total precipitation (respectively $R^2=0.09$, $p=0.03$ and $R^2=0.11$, $p=0.017$) and only the number of fires was correlated with summer precipitation ($R^2=0.19$, $p=0.0015$). Maximum temperature was not a significant variable for the prediction of these variables.

Defining the fire regime

Between 1960 and 2010, the fire return interval (recurrence) in the two départements was up to five fires that had burned on a same spot but both were mainly affected by only one large fire event (46 percent of the total recurrence) or a recurrence of two fires (42.5 percent). In areas where the recurrence was high, large fires regularly occurred during the 50 year period, especially around cities and on the coast. In contrast, areas where the recurrence was low were mainly affected by old fires, especially inland (Fig. 3).

Large fire recurrence was mostly low (52 percent of the time intervals were longer than 16 years) with no spatial variation in the study area.

In the East of the study area (Var), the old fires were concentrated in the more fragmented plain area, which is located inland. In contrast, the most recent fires (time since the last fire shorter than six years) were located in the coastal wildland (Maures forest massif). No such trends were

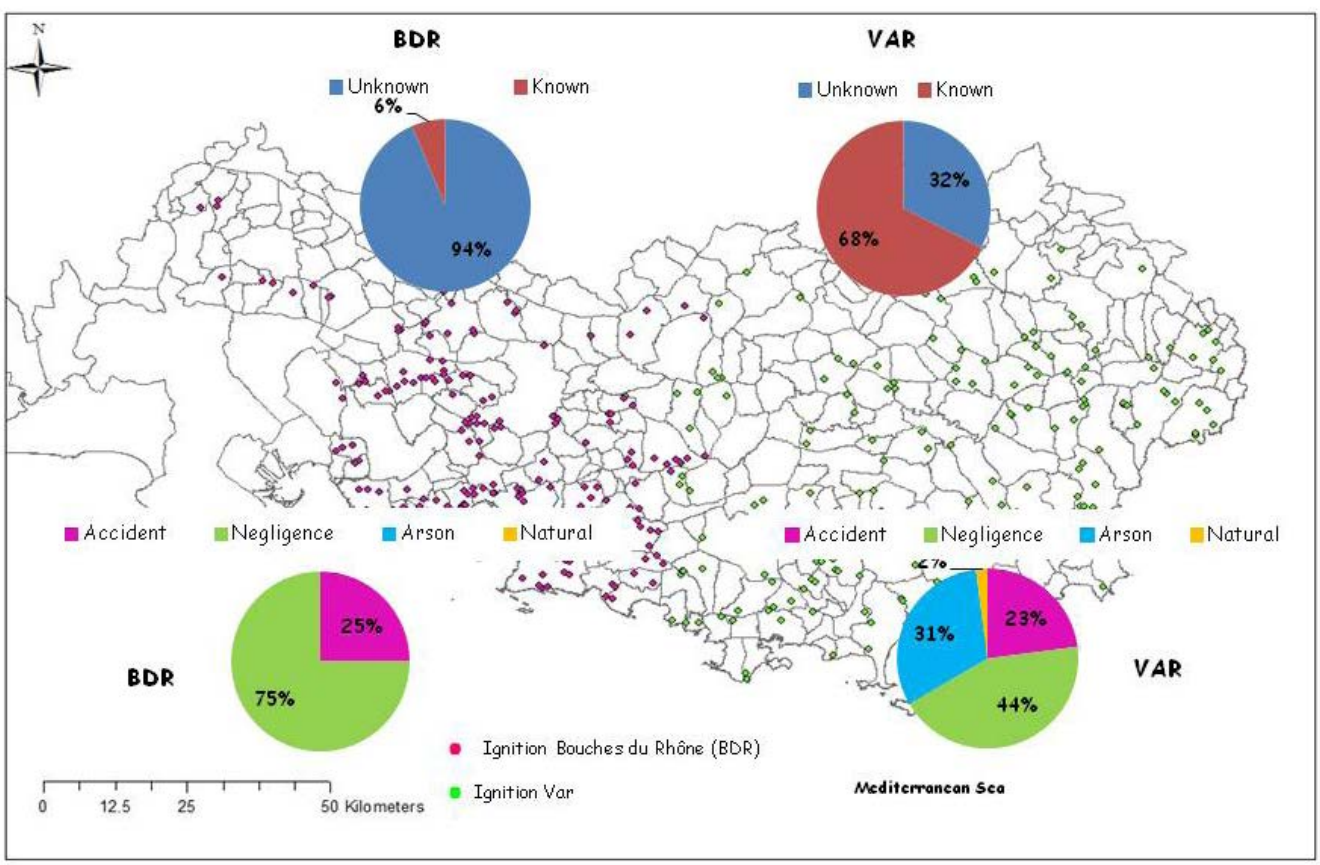

Figure 1—Large fire causes and their knowledge in the study area

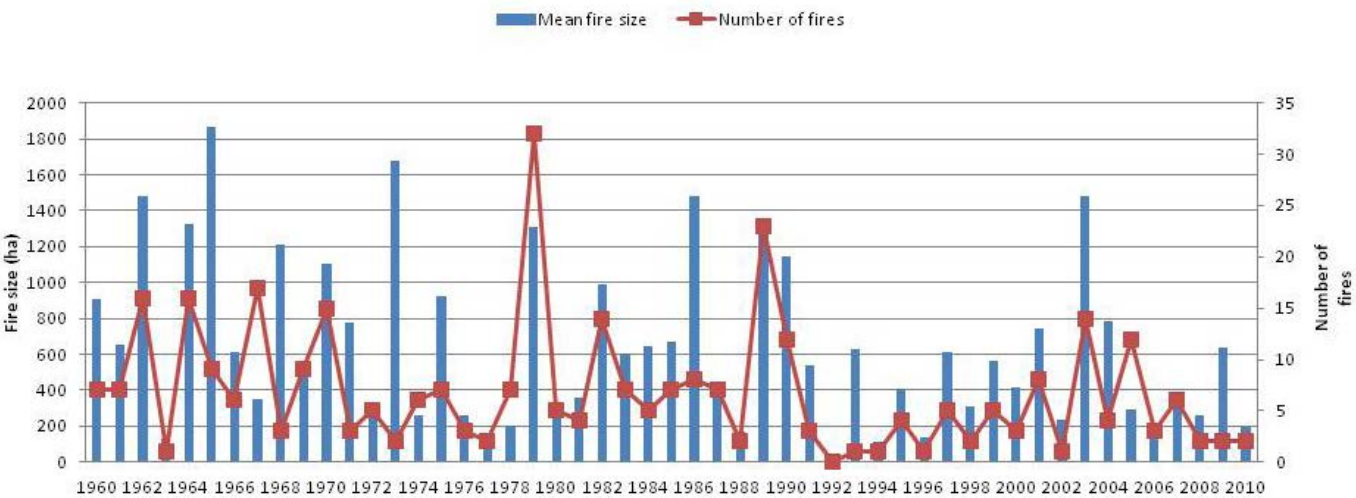

Figure 2—Large fire occurrence and size in the study area between 1960 and 2010

highlighted in the West of the study area where the distribution of old and recent fires was homogeneous.

Impact of the large fire regime on the size of the most recent fires and on the recent land cover

Statistical analyses showed that there was no effect of the time interval between two fires on the size of the most recent fire as well as there was no significant difference in size between two consecutive fires (for a fire return interval of at least 2 fires), even if the areas were reburned.

Multiple Component Analysis showed that there was an increase in the maturation of the vegetation (increase in forest land covers) with the decreasing number of fires and the increasing interval since the last fire. Moreover, the number of recurrent large fires had a significant effect on the recent land cover (Chi2=32.4; p=0.006) as well as the time interval since the last fire (Chi2=169.5; p<0.0001) but the time interval between two fires was not a significant variable.

Conclusions

A better knowledge of the large fire regime is necessary to strengthen fire prevention by providing valuable information on priority areas with high large fire hazard, especially in those areas where recurrent large fires are more likely to occur.

Large fires are spread homogeneously in the study area but their size is smaller when the landscape is more fragmented, especially in the West (Bouches du Rhône). Generally, these fires are due to negligence; however arson may be strongly underestimated in the western part of the study area where the knowledge of the large fire causes is very bad.

During the period studied (1960-2010), large fire occurrence and size presented a slight decreasing trend and large fire occurrence and size were positively correlated. Both large fire occurrence and fire size were negatively correlated with precipitation.

In the study area, the large fire regime is characterized by a fire return interval up to five fires on a same spot between 1960 and 2010, especially around the cities (in the West) and on the coast (in the East), mainly with a long time interval between two recurrent fires. The older fires are located mainly in the most fragmented areas, whereas the most recent ones mainly occur in the wildland areas where the recurrence is the highest. Only the number of recurrent large fires and the interval since the last fire have a significant effect on the recent land cover (maturation of the vegetation), although these parameters do not impact the fire size

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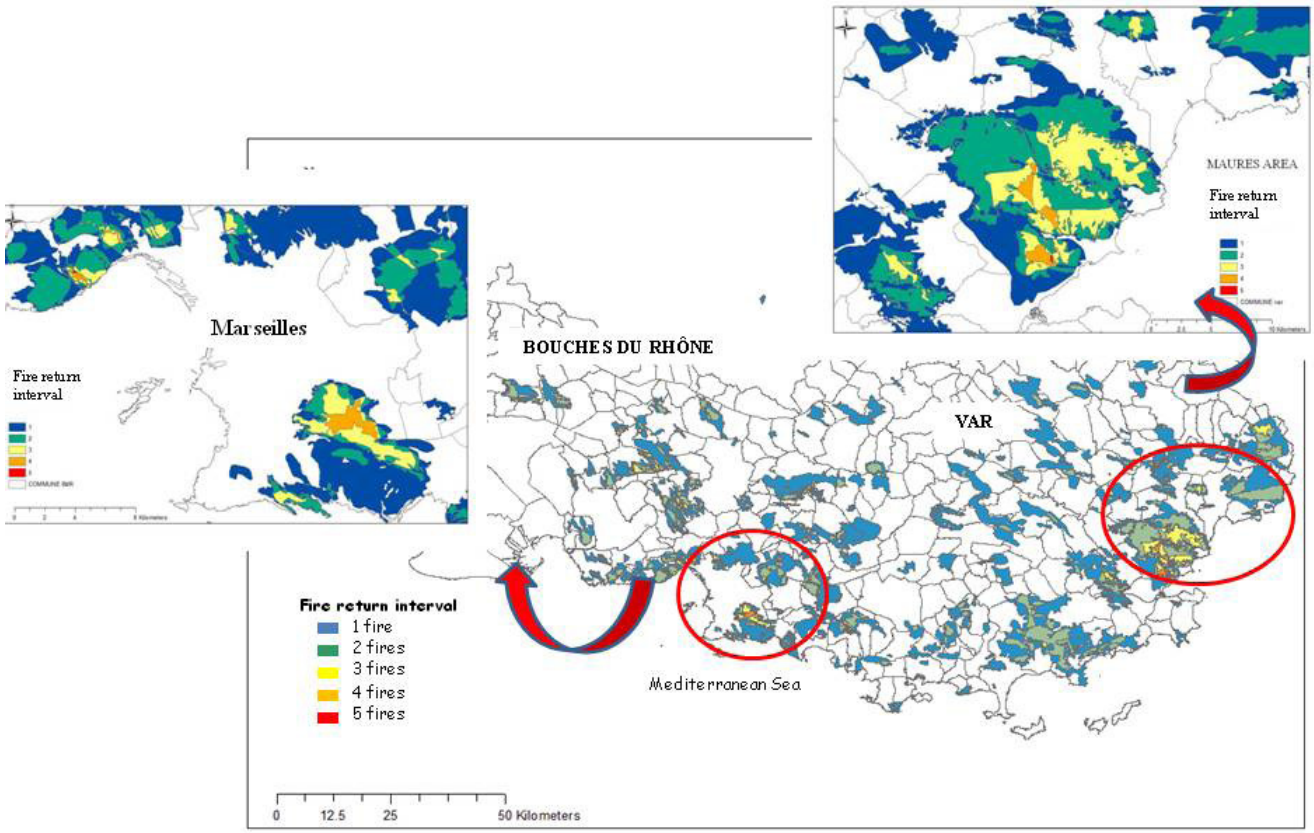

Figure 3—Map of the large fire scars according to fire return interval (number of fires) with focus on the most impacted areas

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A Tale of Two Fires: The Relative Effectiveness of Past Wildfires In Mitigating Wildfire Behavior and Effects

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Abstract—*The incidence of large, costly landscape-scale fires in western North America is increasing. To combat these fires, researchers and managers have expressed increased interest in investigating the effectiveness of past, stand-replacing wildfires as bottom-up controls on fire spread and severity. Specifically, how effective are past wildfires in mitigating the behavior and effect of future fires, and for how long?"*

Our research focused on two recent fires that encountered past wildfires but with significantly different outcomes. The 2006 Tripod Complex fires in Washington State flanked around, but did not reburn, the 1970 Forks Fire, while the 2012 Octopus Mountain Fire in Kootenay National Park in British Columbia reburned much of the 1991 Spar Mountain Fire area. In 2013 we sampled fuels and vegetation in unburned portions of the Tripod/Forks and the Octopus/Spar Mountain fire areas in order to quantify canopy and surface fuel characteristics and elucidate why fire behavior and effects were different between the two wildfire events.

Introduction

Following high-severity fire events, regenerating stands of lodgepole pine (*Pinus contorta* Carr.) and other high elevation forests may act as temporary fire breaks that are not apt to carry fire unless burned under extreme wildfire conditions. Over time, fuel succession recruits surface and canopy fuels that are susceptible to fire spread. Determining when a threshold to burning is reached, and under what fire weather conditions, is of concern to fire managers. In this pilot study, we investigated surface and crown fuel loadings in two post-fire areas (Figure 1) in order to determine which fuel elements of regenerating forests drive flammability and how quickly fuels develop in contrasting ecosystems.

Methods

Study areas

The first test case involves the 2006 Tripod Complex fires, which burned >80,000 ha of subalpine fir (*Abies lasiocarpa* (Hook.) Boivin.), Engelmann spruce (*Picea engelmannii* Goodman) and lodgepole pine forest in the east Cascades of central Washington State. During a series of significant fire growth days the fire flanked around but did not reburn the 1970 Forks Fire, a 1700-ha patch of 35-year old lodgepole pine regeneration (Prichard and Kennedy 2013, Figure 2). Fire weather varied over the fire progressions that bordered the Forks burn scar, but was generally represented by warm, dry weather conditions. Maximum temperatures ranged from 24 to 29 °C, minimum relative humidity ranged from 17 to 25 percent, and wind gusts were between 22 and 32 kph from the south and southwest. Topography in the study area is rugged with a pronounced ridgeline at the southern edge of the Forks burn perimeter.

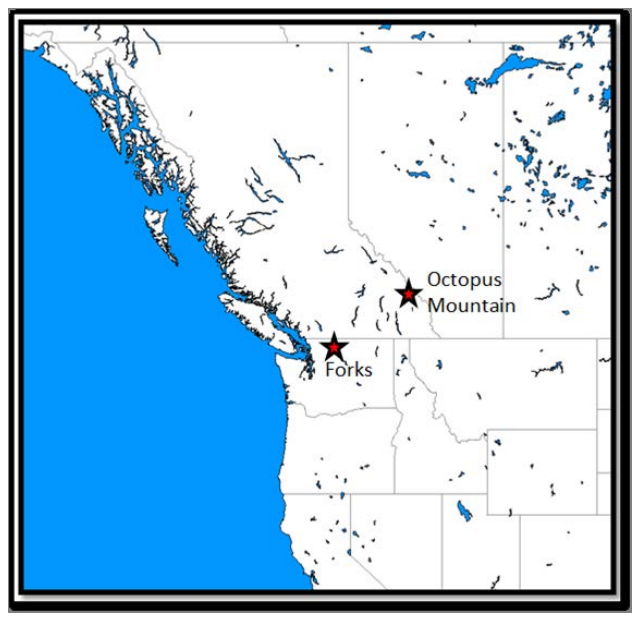

Figure 1—Location map of the Forks/Tripod study area in Okanogan Wenatchee National Forest, Washington State and 2012 Octopus Mtn/Spur Mtn study area in Kootenay National Park, BC.

The second test case involves the 2012 Octopus Mountain Fire in Kootenay National Park, British Columbia. The 1,200 ha fire originated in 300+ year old subalpine fir/white spruce (*Picea glauca* (Moench) Voss) forest but also burned

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Figure 2—Landscape photo of the 2006 Tripod Complex Fire with the 1970 Forks burn scar in the distance. Right panel—representative photo of surface fuels within the Forks burn.

through most of the 21 year old lodgepole pine forest that established following the 1991 Spar Mountain Fire (Figure 3). Fire weather on August 23rd when the fire reburned the Spar Mountain Fire area, was highly variable due to the influences of topography and a passing cold front. The fire was located on a steep, west-facing slope of Lachine Creek with a number of side-drainages both below and above it. These drainages contributed to complex, and highly variable wind patterns throughout the day and into the early evening. Maximum temperatures ranged from 21 to 23 °C while minimum relative humidity dropped to 30 to 40%. At 1300 hours winds were generally out of the south, southwest at 11.5 kph; however, between 1300 and 1700 hours the wind direction became highly variable with periods of sustained flow from the south then the north. At approximately 1750 hours, the winds stabilized out of the south and the fire made its run through the 1991 regeneration.

As part of a preliminary field study, sampling was conducted on five randomly located plots within the unburned interior of the Tripod/Forks study area, and four plots in unburned patches within the Octopus/Spar Fire study area. Fewer plots were sampled in Octopus/Spar because so little of the pre-fire fuels remained after the 2012 reburn. The standard plot used for the two studies consisted of four 30-m transects radiating 90° from a central point. At plot center we collected stand density by species and estimated canopy base height by species within a 1/100-ha fixed radius plot. Each of the four 30-m transects was inventoried for surface fuel load and vegetative cover.

Fuels were inventoried by time lag size class with 1-hr fuels recorded for the first 1.8 m, 10-hour fuels for the first 5 m, and 100- and 1000-hr fuels along the entire 30 m transect. Starting on the 5-m mark, litter and duff depths were measured every 5 m along each transect. Litter and duff depths were converted to loading using published bulk density values in Brown and others (1982). For cover transects the distance that an element bisected the line was recorded. Cover was recorded for vascular plants (grasses, forbs, shrubs, and trees), bryophytes, rock, litter, bare ground and coarse woody debris. Species and height were also recorded for all vascular plants.

Potential fire behavior was modeled using FMAPlus (http://www.fireps.com/fmanalyst3). Measured surface fuel characteristics were represented by fire behavior model 8 (timber litter) for Tripod/Forks and fire behavior fuel model 2 (short grass) for Octopus/Spar based on day-of-burn observations of fire behavior during the 2012 Octopus Mountain fire. Because the underlying Rothermel (1972) fire spread model only considers fine fuels as important for surface fire behavior (i.e., spread rate), coarse woody debris did not factor into modeling. Basic canopy characteristics including canopy base height and cover were used in FMAPlus to calculate canopy bulk density.

Results and Discussion

There was significant variability in fuel loading and vegetation cover between plots and between fires, and a higher sampling intensity was needed to adequately characterize surface and canopy fuels. Both study areas had low shrub and herbaceous cover (Table 1). Average shrub cover was 25% (± 15%) and herbaceous cover was < 2% (± 2%) in the Tripod/Forks area compared to an average shrub cover of 7% (± 5%) and average herbaceous cover of 21% (± 13%) in the Octopus/Spar Mountain area.

Fine wood was comparably low in both study areas (Table 2). Coarse wood and litter differed dramatically between the study areas with 83.0 (± 40) Mg ha^{-1} of ≥ 1000 hr fuels in the Octopus/Spar Mountain area versus 30.0 (±16) Mg ha^{-1} in the Forks/Tripod area and 16.5 (±17) Mg ha^{-1} of litter versus 8.3 (±4) Mg ha^{-1} (Figure 4).

Figure 3—Overflight photo of the 2012 Octopus Mountain fire which burned over a portion of the 1991 Spar burn area. Right panel—representative photos of surface fuels that burned and did not burn within the Octopus Mountain fire.

Table 1—Comparison of measured percent cover (%) between the two study areas.

	Octopus/Spar Mountain		Tripod/Forks	
	Mean	SD	Mean	SD
Graminoid	5.25	± 3.73	0.20	0.62
Forbs	15.88	± 8.91	1.00	1.84
Shrubs	7.13	± 5.02	24.90	14.77
Litter	37.75	± 8.74	52.45	14.64
Downed wood	17.38	± 4.70	10.45	4.57
Bare ground	16.88	± 13.21	8.95	6.96

Table 2—Comparison of estimated surface fuel loading (Mg ha-1) between the two study areas.

Surface fuel	Octopus/Spar Mountain		Tripod/Forks	
	Mean	SD	Mean	SD
1 hr	0.3	± 0.2	0.5	± 0.5
10 hr	1.8	± 1.5	2.0	± 1.6
100 hr	3.9	± 1.6	4.6	± 2.6
1000 hr	83.7	± 39.7	29.6	± 15.7
Litter	16.5	± 17.0	8.2	± 4.0
Duff	1.8	± 2.8	9.2	± 8.9
Total	108.1	± 55.6	54.2	± 18.8

Based on representative fuel models, predicted surface fire behavior was very different between the two study areas with much higher flame lengths and rates of spread predicted for the Octopus/Spar study area (Table 3). In contrast, based on the input canopy characteristics, the Tripod/Forks had greater potential for torching and crowning than the Octopus/Spar study area.

The two unburned islands in the Spar Mountain Fire contained high fuel loads of downed logs and substantial litter accumulations. The islands are also situated in the middle of a uniform and steep (>55%) slope on a westerly aspect (270°). These factors suggest that conditions of fuels and terrain were sufficient for both islands to burn; the reason they didn't could be due to patterns of fire spread. Fire spread over the course of the Octopus Mountain Fire was highly erratic with spread direction appearing to be influenced by slope, wind direction, and pockets of heavy fuel. It is possible that both islands did not burn due to shifting convection columns as the fire spread up the slope.

In contrast, the Tripod/Forks burn contained much lower large wood and litter loads than the Octopus/Spar study area. Although the Forks burn is surrounded by evidence of high-severity crown fire, the combination of low surface fuels, young lodgepole pine regeneration and a ridgeline that likely created a terrain break to fire spread, created an effective barrier to fire spread.

Conclusions

With such a small sample size it is difficult to explain with confidence why the Forks Fire did not reburn in 2006, 34 years since the last fire, but the Spar Mountain Fire reburned after only 21 years. However, the results from this pilot study suggest that after two decades following fire, sites with fuelbed characteristics similar to the Octopus/Spar study area will burn with very high intensity and severity. The dominant variables are likely surface loading of large woody fuels and consistent cover of a flammable substrate. Topography may have also played an important role in contrasting fire spread between the two study areas. A prominent ridge at the southern perimeter of the Forks fire, combined with the low

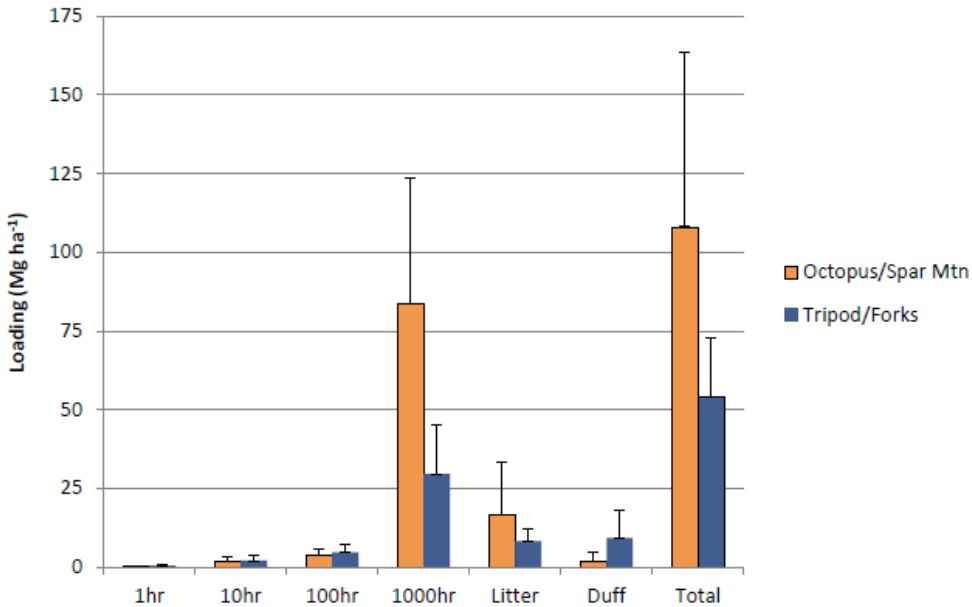

Figure 4—Comparison of fuel loading (Mg ha-1) between the two study areas.

Table 3—Predicted fire behavior from FMAPlus.

	Tripod / Forks	Octopus / Spar
Canopy base height (m)	0.3	0.3
Canopy bulk density (kg m^{-3})	0.4437	0.2515
Fuel model (13)	8	2
Torching index (km/hr^{-1})	31.9	0
Crowning index (km/hr^{-1})	5.6	3.4
Rate of spread (m/min^{-1})	0.46	16.8
Flame length (m)	0.26	2.5
Fire intensity (kW/m^{-1})	14	1698

surface fuels of the burn scar, may have acted as an effective barrier to fire spread. In contrast, the Octopus Mountain fire spread up a steep west-facing slope with no topographic barriers.

Acknowledgements

We would like to thank the following people for their assistance in the field: Jonathan Large, Jessica Hilton and Lindsay McPherson of Parks Canada, Mike Gall of BC Parks, and Richy Harrod of the Okanagan-Wenatchee National Forest. Parks Canada generously provided helicopter use for field sampling on the Octopus Mountain Fire.

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Manitoba Health's Emerging Work on Wildland Fire Smoke

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Abstract—*Smoke caused by wildland fire events is an important public health issue, involving major risks to the health of people and the environment. Smoke from wildland fires can travel hundreds of kilometers, affecting air quality far from the flames. Through a partnership with Health Canada, Manitoba Health's Office of Disaster Management (ODM) has undertaken a number of multi-year projects to improve our understanding of some of the aspects of these scientific and social issues related to wildland fire smoke. Through these projects, ODM will meet the following objectives: 1) develop specific smoke event health messaging for the general public, 2) develop First Nations messaging for smoke events, 3) examine the health outcomes and appropriate messaging for situations when the Air Quality Health Index (AQHI) rises above 10, 4) provide nationally-applicable guidance for decision-makers to protect people from wildland fire smoke, 5) examine the combined risks of smoke and heat and develop appropriate messaging for a combination smoke and heat event, and 6) determine the validity of using the AQHI as a wildland fire smoke response. As climate change models suggest an increasing probability for more wildland fires events in the future, it can be expected that wildland fire smoke events will increase as well. For Canadians to deal with these events effectively, an evidence-based approach to smoke response is needed which will allow health officials and emergency managers to appropriately message and communicate to them the extent of the risk of wildland fire smoke and to provide guidance for decision-makers during these events.*

Introduction

Wildland fires are an important part of the Canadian landscape. Canada has about 10% of the world's forests and each year over the last 25 years, about 8,300 wildland fires have occurred (Summers and others 2011). These fires occur in forests, shrub lands and grasslands. Some are uncontrolled wildland fires started by lightning or human carelessness. A small number are prescribed fires set by authorized forest managers to mimic natural fire processes that renew and maintain healthy ecosystems (Natural Resources Canada 2013). On one hand, wildland fires are a natural part of the forest ecosystem and important in many parts of Canada for maintaining the health and diversity of the forest, and on the other, wildland fires can threaten communities and destroy vast amounts of timber resources, resulting in costly losses.

While wildland fires are a hazard in and of themselves, within the burning boreal forests lay another hazard, one which has a much wider impact: dense smoke. Smoke from wildland fires can travel hundreds of kilometers, affecting air quality far from the flames (Lipsett and others 2012). Smoke rises from a fire in a plume consisting of liquids, gases, and particles of different sizes. Pollutants in smoke can include deadly gases like carbon monoxide and many solid and liquid elements known as particulates or particles. Many, like acrolein, formaldehyde and benzene, are toxic or carcinogenic for humans (Lipsett and others 2012). The health impacts from wildland fire smoke can include increased mortality, increased hospital admissions due to respiratory and cardiovascular diseases and increased emergency room and outpatient visits (Lipsett and others 2012).

The study of wildland fire smoke and its relationship to air quality and human health is a relatively novel and emerging field. Thus, with concern about climate change and climate variability mounting, new demands are being created for scientific, economic and social information to reduce the remaining uncertainties in these fields. Among the demands is the growing need for an evidence-based approach to consistent health messaging and guidance for decision-makers for wildland fire smoke events.

Manitoba Health & Health Canada Partnership In Wildland Fire Smoke

Smoke caused by wildland fire events is an important public health and safety issue, involving major risks to the health of people and the environment. Manitoba Health's Office of Disaster Management (ODM) decided to undertake the critical work of improving our understanding of some of the scientific and social issues surrounding wildland fire smoke.

In 2012, ODM signed a Memorandum of Agreement (MOA) with Health Canada to oversee a number of multi-year projects related to air quality and wildland fire smoke to gain a better understanding of the health impacts of wildland fire smoke to aid in the development of smoke-specific health messaging and guidance tools for decision-makers during a wildland fire smoke event. The scope of work from the MOA includes the following objectives:

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

- Develop specific smoke event health messaging for the general public;
- Develop First Nation messaging for smoke events;
- Examine the health outcomes and appropriate messaging for situations when the Air Quality Health Index (AQHI) rises above 10;
- Provide nationally-applicable guidance for decision makes to protect people from wildland fire smoke;
- Examine the combined risk of smoke and heat and develop appropriate messaging for a combination smoke and heat event; and
- Determine the validity of the AQHI as a wildland fire smoke response tool.

The work conducted through this MOA is based on the AQHI which is a public information tool that helps Canadians protect their health on a daily basis from the negative effects of air pollution by helping them understand what the air quality around them means to their health. This tool has been developed by Health Canada and Environment Canada, in collaboration with provinces and key health and environment stakeholders. The AQHI assesses the cumulative health impact of ground level ozone (O_3), particulate matter ($PM_{2.5}$), and nitrogen dioxide (NO_2) to calculate an index number from 1 to 10^+. The higher the number, the greater the health risk and the greater need to take additional precautions.

Objective A: Develop Specific Smoke Event Health Messaging

Health communication is important in public health as it is the principal way in which health officials can exchange health information with the general public. Given the challenges posed by wildland fire smoke events, health communication plays a strong role in providing those affected with accurate, useable and timely information. In the past year, ODM worked with a number of stakeholders to develop draft Special Air Quality Statements to be used when a smoke event forecast creates elevated AQHI forecasts. In the next phase of this project, ODM plans to validate the statements by testing the messages with sample communities, areas, or groups to determine their effectiveness and to identify any gaps in the messaging.

Objective B: Develop First Nation Messaging for Smoke Events

In the previous objective, Special Air Quality Statements were developed with all audiences in mind. It is noted from the existing literature that First Nations communities in Canada receive information through different means than non-First Nation communities (Driedger and others 2013). For this objective, ODM will work to develop a tailored approach for First Nations communities to ensure health communication messaging related to smoke is effective in reaching the First Nation audience.

ODM conducted research on health and risk communication on First Nations peoples and developed a preliminary plan to tailor the Special Air Quality Statements so they can be effectively used to communicate health information to First Nations communities. ODM plans to work with a number of stakeholders involved in wildland fire smoke response in First Nations communities including government agencies from all levels involved with responding to wildland fires, First Nation youth groups, and front-line staff in a number of interview rounds that will see messages being tailored at the end of each round and used in the beginning of the next.

Objective C: Examine the Health Outcomes and Appropriate Messaging for Situations When the Aqhi Rises Above 10

During wildland fire smoke events where $PM_{2.5}$ levels are elevated due to intense smoke, the publicly displayed AQHI reaches 10^+, the highest risk level. In the past year, ODM has studied a number of wildland fire smoke events and their health impacts and prepared a status report for Health Canada based on our findings. The status report identified a number of issues related to examining health outcomes using the AQHI.

Of the issues identified, two stand out as the most significant limitations of the AQHI when examining health outcomes using the tool. To date, no studies have attempted to quantify the health impacts of wildland fire smoke exposure using the AQHI which makes understanding the health effects of wildland fire smoke through the AQHI challenging. Existing literature on the health impacts of wildland fire smoke have focused on particulate matter emitted from the smoke as it is the primary pollutant from smoke and the most cause for concern. There are also various air quality indices utilized around the world which would make comparisons of health effects of wildland smoke from different countries difficult. Consistency in methods and variables are important to be able to replicate studies and determine whether an association exists or not. Research in this area has focused on particulate matter which suggests that this is considered best practice when researching the health effects of wildland fire smoke.

Another important issue that was identified during the development of the status report deals with the severity of serious air pollution events. When the amount of air pollution is very high, the AQHI reports the number as 10^+. For all serious air pollution events, the AQHI will describe the event as 10^+, regardless of the actual level of severity of the event. For wildland fire smoke events, all events are not the same with some being more serious than others. This may result in the AQHI communicating to users to reduce or avoid strenuous activities outdoors when in fact, $PM_{2.5}$ may

be elevated to levels that may require users to take additional precautions such as sheltering in place and voluntary and mandatory evacuations.

The findings suggest that the AQHI, as it is, may not be the best response/health communication tool for wildland fire smoke and that a new approach that can address these issues is needed. ODM will continue to monitor scholarly literature for new studies that may help address the gaps identified in the status report and prepare a final report for Health Canada in 2015.

Objective D: Provide Nationally-Applicable Guidance for Decision-Makers To Protect People From Wildland Fire Smoke

For this objective, ODM will develop operational guidance for provincial entities, using smoke forecasts and associated health impacts, which would be subsequently shared by Health Canada across the country. Guidelines currently being utilized for wildland fire smoke events in Manitoba have been based on visibility guidelines which can be subjective and open to interpretation. In the past year, ODM worked with stakeholders to develop a first draft of a package for decision-makers to provide them guidance during a wildland fire smoke event. In the next phases of the project, ODM will develop a second draft of the decision-makers' package, which will include a smoke enhanced revision to the wildland fire annex of the provincial emergency plan, critical care guidelines, and triage guidelines.

Objective E: Examine the Combined Risks of Smoke and Heat and Develop Appropriate Messaging for a Combination Smoke and Heat Event

Temperature is an important variable in assessing the probability of a wildland fire event. These events tend to occur when the ambient temperature is high, increasing the likelihood of drier conditions and lightning strikes which may increase the frequency of wildland fire events (Naeher and others 2007). As these events tend to occur when ambient temperature is high, there is a potential for interaction between wildland fire smoke and extreme heat to cause a synergistic health effect. This was demonstrated in the heat wave and wildland fire conditions in the summer of 2010 in Russia where there was a large health impact on the population with reported increases in adverse effects on respiratory health and mortality rates doubling from previous years.

In the past year, ODM examined the combined risks of wildland fire smoke and heat and prepared a report based on our findings. For the report, ODM conducted a systematic review of the existing literature related to the synergistic health effects of heat and wildland fire smoke. The primary objective was to determine whether any synergistic health effects occurred during a simultaneous heat and smoke event. Due to the limited literature on the combined effects of wildland fire smoke and heat, assumptions were made in the research phase, and subsequently, in the report, to include the combined effects of heat and air pollution and combined effects of heat and particulate matter.

While the World Health Organization (WHO) has stated that the combined effect of high temperatures, particulate matter and air pollution is becoming increasingly evident, the synergistic health outcomes for simultaneous wildland fire smoke and extreme heat events remain uncertain. While some of the available literature made reference to the combined health effects of heat and wildland fire smoke, the references were made in passing and did not attempt to make any scientific link. The wildland fire smoke and heat event in Russia in 2010 provides a great case study for possible synergistic health outcomes; however, there has been no study to date that has evaluated the possible combined effects of the two events. Current practice is therefore reliant upon extrapolation of their singular impacts and the impact of combined hazards with inherent similarities (air pollution and heat; particulate matter and heat).

In the next phase of this project, ODM will conduct a cross-jurisdictional scan for existing messaging for simultaneous wildland fire smoke and heat events and work with provincial and federal stakeholders to develop draft messaging for simultaneous heat and wildland fire smoke events.

Objective F: Determine the Validity of Using the Aqhi As a Wildland Fire Smoke Response Tool

The research conducted by ODM in the past year on health outcomes of wildland fire smoke and the AQHI showed that while the AQHI provides a useful mechanism to communicate local air quality conditions to Canadians, there is concern the tool may not provide sufficient information during wildland fire smoke events as the precautions being communicated to Canadians through the AQHI may not reflect the real risk of the situation or the precautions that should be taken. This is especially evident during wildland fire smoke events where the AQHI is above 10 and messaging is fixed to specific messages regardless of how serious the air pollution event is.

Understanding the benefits and limitations of the AQHI, ODM is currently exploring ways to integrate smoke-specific messaging into the AQHI. While some jurisdictions have utilized two separate health communication tools, an air quality index and separate wildland fire air quality scale, using two separate tools may be complicating to the public which counters the AQHI's benefit of being easy to use and understand. Additionally, the concern from the AQHI is not

from the tool itself, but the "10^{+}" health category where it can lump all serious air pollution events into one category.

A tool that can be integrated with the AQHI and utilized only during wildland fire smoke events where the AQHI is above 10 would provide the most benefit to Canadians as the AQHI has been a successful tool thus far for general day-to-day activities. ODM will continue to explore ways to integrate health messaging and guidance for decision-makers with the AQHI to ensure that health messaging during wildland fire smoke events is consistent with actions from decision-makers.

Conclusion

Climate change models suggest that conditions will likely become drier and warmer throughout much of Canada. Wildland fires can therefore be expected to increase in Canadian forests on the whole, with the area burned possibly doubling over the next century. With wildland fires in Canada expected to increase, the potential also increases for a greater number of smoke events with changes in air quality that will result in greater threats to human health and the environment.

For Canadians to deal with these events effectively, health officials and emergency managers must be able to appropriately message and communicate to them the extent of the risk during a wildland fire smoke event. Guidance, based on objective rather than subjective means, is also important as it provides an evidence-based approach for decision-makers during a wildland fire smoke event.

Manitoba Health's Office of Disaster Management will continue this work in hopes of developing an evidence-based approach to wildland fire response that can be used throughout Canada. The better prepared Canada is for wildland fire smoke events, the more can be done to mitigate their adverse health effects.

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Temporal Changes to Fire Risk in Dissimilar WUI Communities

N.C. Leyshon, C.A. Dicus, and **D.B. Sapsis**

Introduction

Despite increasing proportions of governmental budgets allocated to fire suppression resources, wildfires annually destroy great numbers of homes and critical infrastructure in the wildland-urban interface (WUI). Since 2002, the largest fires in the histories of California, Arizona, Colorado, New Mexico, Utah, Oregon, and Texas have occurred in spite of increased fire agency staffing, equipment, and training (National Interagency Fire Center 2013). To aid policy development that reduces these losses, we propose to evaluate how risk changes through time in communities expanding into fire-prone areas, but vary in demographics and socioeconomic status.

Conventional wisdom is that escalating WUI losses are caused, in part, by an expansion of residential development into fire-prone areas. However, if new construction adheres to the mitigation policies, then expansion of the WUI (with higher-resistant development) may actually buffer the older, high-risk communities from exposure to flames and embers. Thus, expanding WUI may either increase or decrease risk of residential loss dependent upon the extent of adhering to mandated mitigation strategies. To help elucidate this seeming dichotomy, we propose to utilize various GIS and remote sensing strategies to spatially analyze changes to risk of structural ignitions through time in expanding, but demographically dissimilar residential communities in California. This research compliments and expands previous investigations by the principal investigator, which focused on how fuel treatments in the WUI simultaneously impacted wildland fire behavior and ecosystem services (including carbon sequestration and air pollution removal) at various spatial and temporal scales.

The cause of increased fire losses is related to a myriad of complex and interacting factors, the influence of each factor varies by place. Population growth into fire-prone areas has resulted in greater exposure of residential development to wildland fire. Fire managers commonly employ multiple mitigation strategies to reduce the risk of fire loss in the WUI, one example is the creation of defensible space immediately surrounding a building to reduce structural ignitions via direct flame impingement or radiant heat transfer (Cohen and Butler 1998). To that end, the California Public Resources Code Section 4291 was updated in 2006 to require 30.48 m of defensible space around structures.

Even when enforced, defensible space may not impact structural ignition from lofted embers, which is a more critical factor in residential losses than flame impingement or radiant heat (Cohen 2000). To mitigate potential residential losses, in 2008 California enacted building standards for new construction in areas in which the state has primary fire protection responsibility. California Code of Regulations Title 24, Part 2, Section 701.A now requires standards for some portions of dwellings most prone to ignition, including roofs, siding, attic ventilation, windows, decks, and others. While the new standards will likely reduce fire losses in

Figure 1—Study site locations with fire history from 2000–2012.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

future development, they will not necessarily impact the vulnerability of existing structures.

To better facilitate sustainable communities in the WUI, managers need an accurate and detailed assessment of not only the fire hazard in a given area, but also its risk to assets of value. In general, fire *hazard* is the likelihood of an area burning and how it will burn (frequency and intensity), whereas fire *risk* is the potential for damage (Sapsis 2011; Turner 2014). Many methods of WUI risk assessment involve the use of maps or spatial data (Prestemon, Pye and others 2002; Bar Massada, Radeloff and others 2009). Mapping and defining the WUI is critical for wildfire risk management because as the WUI expands, it must be monitored in order for planners to make effective policy decisions to mitigate risk (Stewart, Radeloff and others 2007). Such maps provide powerful visual images and are commonly used as tools to direct policy, which has contributed to their increasing use in the US (Radeloff and others 2005, Theobald and Romme 2007). Many studies of WUI fire risk have used Geographic Information Systems (GIS) to examine changes through time (Jain, Ravan and others 1996; Greenberg and Bradley 1997; Nourbakhsh, Sargent and others 2006), which is an effective approach because fire risk analysis commonly employs both spatial and temporal attributes (Chuvieco, Aguado and others 2010). A GIS-based model is an especially effective approach for areas in which a large part of the land is being encroached upon by development (Jaiswal, Mukherjee and others 2002).

In addition to the more traditional parameters of housing density, vegetation, and fire probability, there is a great need to develop a WUI risk assessment that more fully considers aspects of individual structure ignition (Menakis, Cohen and others 2003; Chuvieco, Aguado and others 2010; Calkin, Cohen and others 2014). For example, the inclusion of near-structure vegetation and defensible space in a remote sensing analysis would provide a better means of quantifying fire risk in WUI communities (Menakis, Cohen and others 2003; Calkin, Cohen and others 2014). Further, knowledge of a structure's location and arrangement relative to other structures or flammable materials is critical in effective risk analysis (Cohen 2000; Murnane 2006). Unfortunately, many risk analysis studies have not considered the fine-scale characteristics of vegetation immediately surrounding a home or have assumed all structures are equally flammable (Prestemon, Pye and others 2002; Menakis, Cohen and others 2003; Bar Massada, Radeloff and others 2009). Risk analysis has also traditionally emphasized the ignition and propagation potential of a wildfire, rather than potential damages (Chuvieco, Aguado and others 2010). The idea of vulnerability is an important new addition to fire risk assessment models (Calkin, Ager and others 2010; Chuvieco, Aguado and others 2012). Sound risk analysis must therefore include elements of both fire hazard and the susceptibility of assets of value (Calkin, Ager and others 2010). Because of the multitude of assets at risk during a WUI fire event, risk assessments can vary in scope and can take into account many different key factors and variables.

Methodology

The proposed research will quantify changes to risk based on characteristics of community wildfire exposure and characteristics of individual structures, including roofing materials, defensible space, and housing density. In essence, the proposed research will simultaneously (1) quantify the growth of the WUI over time in multiple, dissimilar communities, (2) analyze temporal changes to risk based on altered wildfire exposure and structural characteristics, and (3) evaluate differences in risk between multiple communities that vary in demographics and socioeconomic status.

Study Sites

Three residential communities in San Diego County, California will be assessed including Julian, Ramona, and Rancho Santa Fe (fig. 1). The area has conditions conducive to high fire hazard, including a warm climate with extended drought and regular occurrence of high-velocity Santa Ana winds, steep terrain, and flammable vegetation, which has led to several high-intensity, high-loss wildfires in the past 10 years. The three specific WUI communities represent a range of rates of development, demographics, housing density and geographic area.

Rancho Santa Fe—Rancho Santa Fe has a population of 3,100 with an average household income of over $200,000. The community has taken numerous additional measures above county and state regulations to mitigate fire hazard and lower the chance of structural ignitions during wildfires. Rancho Santa Fe can be used in the study as an example of high construction standards and structures with low fire risk.

Ramona—The city of Ramona has a population of 20,000 with an average household income of $60,000. The 2013 Corelogic Wildfire Hazard risk Report (Botts, Jeffery and others 2013) found that in San Diego County, Julian and Ramona had the most residential properties at risk.

Julian—Julian California is a census designated place with a population of 1500 and an average household income of $44,000.

Project Phases

Phase 1—Remote sensing analysis to identify areas of development in each community

Phase 2—GIS analysis of housing density changes over time across the WUI

Phase 3—Remote sensing analysis of hyperspectral aerial imagery (NASA AVARIS) to detect roof type

Phase 4—Remote sensing analysis of defensible space compliance using NAIP imagery and LIDAR data

Phase 5—Validation and ground-truthing of the remote sensing results, and collection of homeowner mitigation data in San Diego

Phase 6—Evaluation of data- We are designing a flowchart to identify risk classes for each structure with input from Dr. Steve Quarles (Senior Scientist, Insurance Institute for Business and Home Safety) on the appropriate methods for assigning risk. Fire risk will be calculated as

Fire Hazard + Mitigations = Fire Risk

We will use hazard data, collected data of structural fire mitigations and defensible space compliance to classify each structure as low, medium, or high risk. Using GIS, these risk classifications will be mapped across the three communities. We will then be able to compare the three communities in present time, and using the data for previous years, discuss how these risk levels have changed over time in the three communities. We will also analyze risk of structure-to-structure fire spread, and therefore the potential effect of new 'low-risk' housing developments on the outskirts of WUI to provide a buffer for older 'high-risk' structures.

Significance of Proposed Work

Our goal is this research will acutely illustrate that proper modification of building components and near-structure vegetation does indeed reduce risk to local communities. It is anticipated, however, that there will likely be differences between communities in implementation of these mitigation activities (and subsequent risk of loss) based upon the disparate abilities of residents to pay for modifications and jurisdictional differences in willingness to enforce existing regulations. This research will develop the concept that new development buffer zones may increase community resiliency. This has the potential to inform development practices and shape community standards for building placement and neighborhood design.

This research could influence policy by illustrating the importance of lower risk development and the factors that may influence risk. Indeed, while the research is regional in nature, it is hoped that the process developed will be utilized by scientists, land managers, and policymakers on a national scale.

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Assessing Lebanon's Wildfire Potential in Association With Current and Future Climatic Conditions

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Abstract—*The increasing occurrence and extent of large-scale wildfires in the Mediterranean have been linked to extended periods of warm and dry weather. We set out to assess Lebanon's wildfire potential in association with current and future climatic conditions. The Keetch-Byram Drought Index (KBDI) was the primary climate variable used in our evaluation of climate/fire interactions and conditions. A comparison between the average monthly values (2006-2010) of the Fire Weather Index (FWI) for Eastern Mediterranean and the monthly KBDI average values for Lebanon showed a strong correlation, indicating wildfire potential has increased during the fire season (March through September). The comparison between the relative areas of current and future wildfire potentials showed a significant increase in KBDI values (more than 50) affecting a total area of 1143 km2 (441.3 sq mi).*

Keywords: *Wildfire potential, climate change, downscaled global climate models, Keetch-Byram Drought Index*

Introduction

The severe degradation of Lebanon's forest during the past decade has been mainly attributed to an increase in number and extent of relatively large scale and intense wildfires (El Halabi and others 2014). This may be the result of land-use changes, such as rural depopulation, which results in increasing land abandonment and consequently, fuel accumulation and shrub-burning to recover areas for cattle feeding. Another possible driver is climate warming, which is reducing fuel humidity and increasing wildfire risk and wildfire spread (Salloum and Mitri 2014).

As a result of declining rural populations, management of fuels in rural areas via agriculture, construction, and fuelwood collection has decreased, resulting in an increase in the abundance of woody fuels. Fertile lands have been rapidly overgrown by garrigue. Additionally, a buffer zone between natural vegetation and residential developments has declined. There has been a rapid expansion of the vegetation in rural areas accompanied by expansion of development in the Wildland Urban Interface (WUI). This has caused a new form of danger which includes increases in both the forest wildfire danger as well as the urban wildfire danger. In addition, it was hypothesized that a changing climate is worsening the situation: 1) heat waves may increase the likelihood of large scale wildfires, 2) drought periods may lead to forest dieback, and 3) heavy and short rainfall may lead to increased soil erosion, soil water scarcity, and floods.

In this work, we assessed Lebanon's wildfire potential in association with current and future climatic conditions. The specific objectives were to 1) generate a wildfire potential index for current climatic conditions and compare it to an observed estimation of wildfire risk, 2) generate the same wildfire potential index for future climatic conditions, and 3) compare between current and future wildfire potential indices.

In this work, the Keetch-Byram Drought Index (KBDI) was the primary climate variable used in our evaluation of climate/fire interactions and conditions.

Study Area and Dataset Description

The study area comprises the Mediterranean vegetation cover of Lebanon (figure 1). Lebanon has a Mediterranean climate, with warm dry summers, and cool wet winters. Around 90 percent of the total annual precipitation falls between November and March (FAO 2006; Mitri 2009; Mitri and others 2010). Like other Mediterranean countries, fire occurrence in Lebanon is driven by the interrelationship of fuel accumulation, long summer droughts and changing patterns of temperature and precipitation (MOE/UNDP/ECODIT 2011).

The spatial climatic data needed to calculate the Keetch-Byram Drought Index (KBDI) were mostly obtained from observed, interpolated data and simulated Global Climate Models (GCM) for current and projected climatic conditions, respectively. Datasets of current averages (1950 to 2000) and future 30-year running averages (2010 to 2039) included: monthly maximum temperature, monthly precipitation and mean annual rainfall at 1x1 km (30 arcsec) of spatial resolution. The current climatic data were generated through

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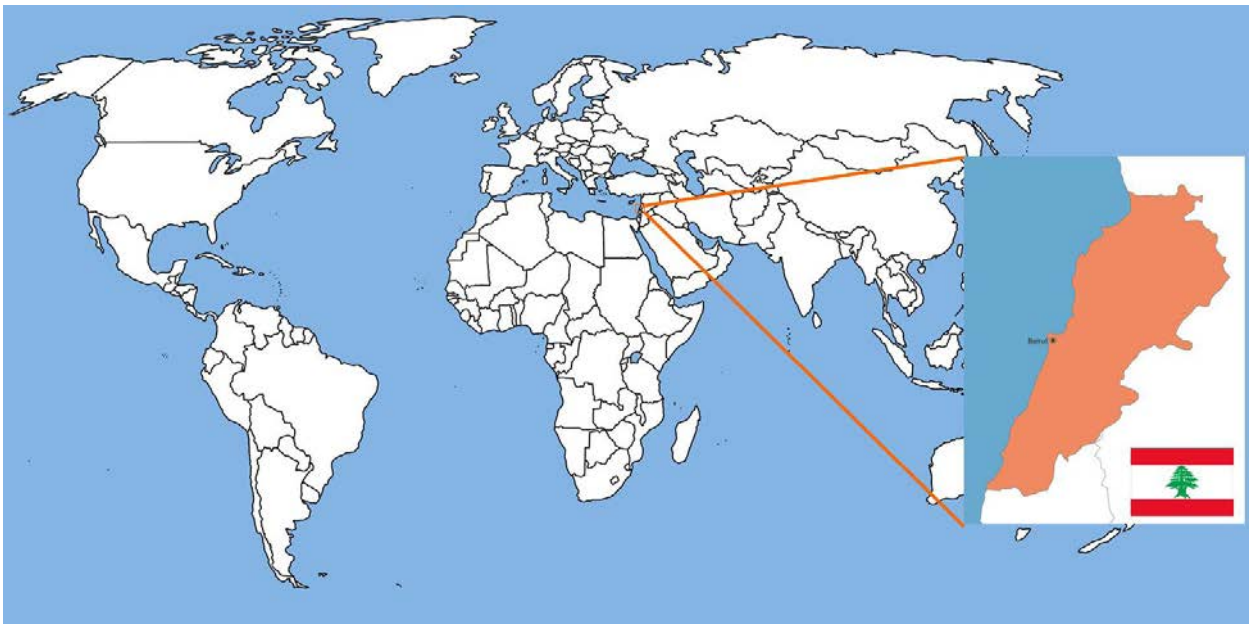

Figure 1—Study area: the Mediterranean country of Lebanon.

interpolations of representative observed data from major global climate databases, whereas, the future climatic data were referred to the 'downscaled GCM data portal' provided by the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change, Agriculture and Food Security (CCAFS) and prepared for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). The data were generated through the downscaled GCM UKMO-HADGEM1 using the Delta method for the IPCC's A1B emission scenario.

Methodology

The widely used Keetch-Byram Drought Index (KBDI), which is a part of the National Fire Danger Rating System (NFDRS) in the United States (Liu and others 2010), was selected to investigate wildfire potential in Lebanon. The KBDI is a cumulative estimate of wildfire potential based on meteorological input parameters and an empirical approximation for moisture depletion in the upper soil and surface litter levels (Keetch and Byram 1968). The drought index ranges from 0 to 800, where a drought index of 0 represents saturated soil (no moisture depletion), and an index of 800 represents absolutely dry conditions.

The KBDI was generated using the Model Maker Module in ERDAS IMAGINE software. The KBDI values of current and future conditions were calculated for each day over the average periods of the current and future datasets. Calculations were initialized when the soil was near saturation (January 1 for all Lebanon) and KBDI was assumed to be zero (Janis and others 2002). The calculations consisted of two steps (Liu and others 2010): 1) values were calculated for each day over the 30-year average periods of the current and future datasets, and 2) the same calculation was made starting from January 1 but using the KBDI values for December 31 as the initial value. The steps were repeated 30 times until the difference between two adjacent years became negligible.

The increase in KBDI values between the resulting current and future fire potentials was computed by subtracting the two spatial images using Model Maker Module in ERDAS IMAGINE software.

Results and Discussion

The monthly wildfire potential for current conditions was generated; in addition, the annual wildfire potentials for current and future climatic conditions were produced. All results were documented in spatially explicit maps.

The quality of the calculated monthly KBDI values was evaluated. A comparison between the average monthly values (2006 to 2010) of the Fire Weather Index (FWI) for Eastern Mediterranean and the monthly KBDI average values for Lebanon showed a similar trend of increasing wildfire potential between March and September (figure 2).

In a subsequent step, the spatial distribution of KBDI classes throughout the year (excluding agricultural and unvegetated areas) was investigated. This showed that the class 'Very high' (700 to 800) occurred in each month of the year with an increasing trend starting the month of March and a decreasing trend starting the month of December. The peak months of 'Very high' wildfire potential occurred in the months of September, October, and November, successively (figure 3).

Finally, the comparison between the relative areas of annual current and future wildfire potentials showed a significant increase in KBDI values (more than 50) affecting a total area of 1143 km2 (441 sq mi). At the same time, only 442 km2 (170.6 sq mi) were affected by a significant decrease in KBDI values (more than -50) (figure 4).

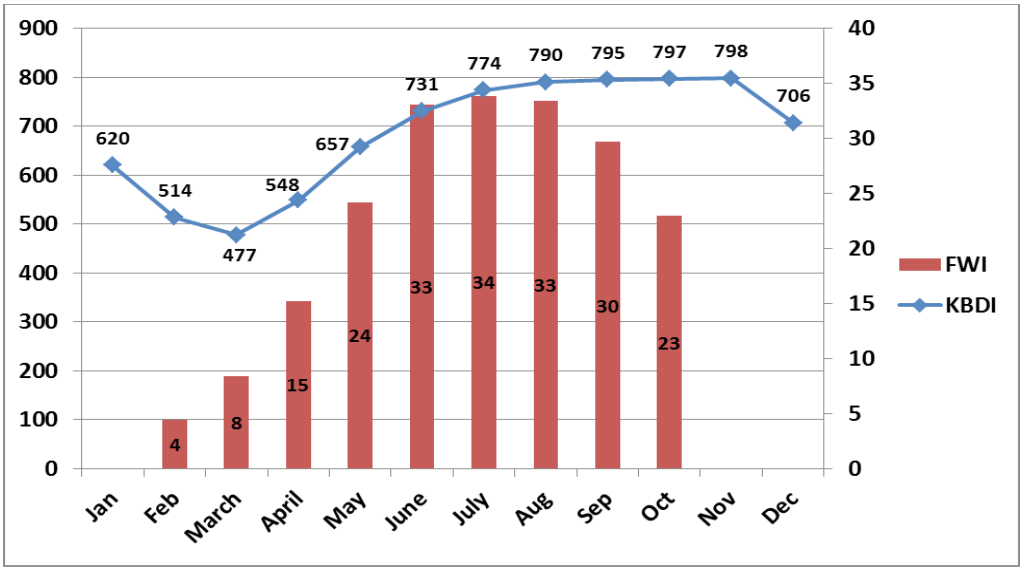

Figure 2—Comparison between monthly KBDI averages for Lebanon and monthly FWI averages for the Eastern Mediterranean

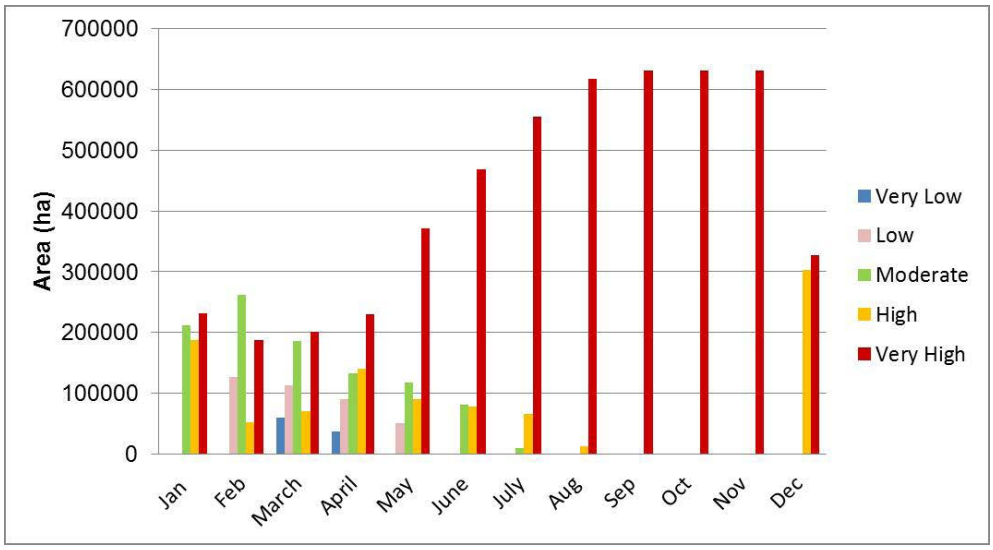

Figure 3—Spatial distribution of KBDI classes throughout the year

Conclusions

Overall, a significant increase in KBDI values (more than 50) affecting a total area of 1143 km2 (441.3 sq mi) was predicted between current and future climatic conditions. The KBDI can be viewed here as an early warning tool for fire potential and severity in Lebanon in the absence of any other national climate-based system for drought monitoring and prediction.

Although the scale of the study area is very small compared to that of other countries in the region, this study gives a preliminary indication about the increasing risk of large scale wildfires in the Eastern Mediterranean, and specifically in Lebanon.

Acknowledgments

This material was published in association with the project "Towards a better assessment and management of Wildfire Risk in the Wildland-Urban Interface in Lebanon: gaining from the US experience" supported by the Partnerships for Enhanced Engagement in Research (PEER), sponsored by USAID. The contents do not necessarily reflect the views of USAID or the United States Government.

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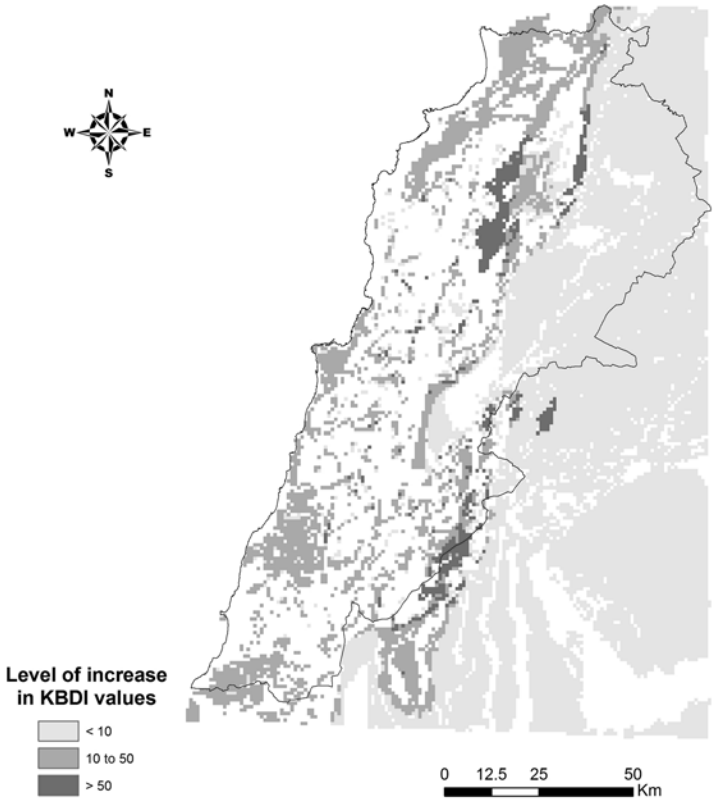

Figure 4—Future increase in wildfire potential

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Initial Results From a Field Experiment to Support the Assessment of Fuel Treatment Effectiveness in Reducing Wildfire Intensity and Spread Rate

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Introduction

Hazardous fuel reduction treatments conducted both through prescribed fire and mechanical means are a critical part of the mitigation of wildland fire risk in the United States. The US Federal Government has spent an average of $500t million each year on fuel reduction, from 2002-2012 (Gorte 2011). At present, however, rigorous experimental measurement of the effectiveness of such efforts, as they impact wildfire intensity and spread rate, has been limited. The project presented here is aimed at addressing this knowledge gap by taking a combined experimental and numerical modeling approach to quantifying fuel treatment effectiveness in the New Jersey Pine Barrens. In particular, this project deals with prescribed fire as a fuel treatment, and it involves the observation and measurement of fire spread rate, fuel consumption, and environmental conditions during two experimental prescribed fires. Given measurements of the pre-fire fuel characteristics and the environmental conditions, a detailed description of the measured fire behavior can be used to evaluate the link between the fire characteristics and the achieved fuel reduction. Such information can also be extrapolated to understand how a subsequent fire might be affected by pre-fire fuel loading.

The project objective is to then to use results of the experimental investigations to drive the use of a detailed physical Computational Fluid Dynamics (CFD) fire behavior model—The Wildland-urban interface Fire Dynamics Simulator (WFDS). The model will first be used to simulate the experimental fires. Comparison of model outputs (such as spread rate, fuel consumption, local velocities, etc.) with experimental data will provide valuable information with respect to the current capabilities of the model. Results will help pinpoint current limitations, such as physical assumptions, and guide future development. As the model is improved with such tests, it can be used to provide expanded information on different levels of fuel treatment and different environmental conditions. Combined, these experimental and numerical evaluations will aid in the understanding of fuel treatment effectiveness.

As the project is ongoing, the current focus is only on an initial description of the fire behavior in the first experimental fire. A variety of different measurements were made during this experiment, but this report focuses specifically on the range of surface fire intensities observed. A brief discussion on wind and canopy fuel consumption is provided.

Study Site

The experimental fire was conducted in the Pinelands National Reserve (PNR) of New Jersey, United States. The PNR spans approximately 445,000 ha, and is host to an active fuels management program by the New Jersey Forest Fire Service (NJFFS) and federal wildland fire managers. Prescribed fires are employed by the NJFFS with the explicit intent of reducing fuel loads and thus mitigating fire risk. These managers, for the most part, currently rely on professional judgment when planning the temporal intervals and geographic position of these fires. The climate is classified as cool temperate, with mean monthly temperatures of 0 °C in January and 24 °C in July, and a mean annual precipitation of 1159 mm. The terrain consists of plains, low-angle slopes, and wetlands, with a maximum elevation of 62.5 m. A burn block covering an area of 16.6 acres was used for the experiment. The forest canopy in the block was comprised primarily of pitch pine (*Pinus rigida* Mill.), with intermittent oaks (*Quercus* spp.). The understory contained a mixed shrub layer of huckleberry (*Gaylussacia* spp.), blueberry (*Vaccinium* spp.), and scrub oaks (*Quercus* spp.).

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Methods

The experimental fire was conducted on March 5th, 2013. Ignition was carried out with a drip torch along the northwest road, moving from northeast to southwest over a roughly 8 minute period. Due to safety concerns caused by rapid fire growth, a secondary ignition line was subsequently formed along the southwest road.

Point measurements of wind were made using 4 overstory towers, with one was positioned outside of the burn block to monitor ambient conditions (figure 1). At the top of each overstory tower (12.5 m) a 3D sonic anemometer was used to obtain velocity and turbulence measurements. 12 understory towers were also placed throughout the burn block (figure 1). While measurements from these towers are not discussed here, they serve as reference points for the locations of destructive fuel sampling and serve to facilitate discussion of local fire behavior. In addition to point measurements, sequential aerial IR images of the fire were recorded using Rochester Institute of Technology's Wildfire Airborne Sensor Program (WASP) (McKeown and others 2011). Images were time-stamped and georeferenced.

Field measurements of surface fuel loading were obtained by destructive sampling of the forest floor and shrub layer in 1 m^2 clipped plots. Thirty six of these measurements were made (three surrounding each understory tower at a roughly 14 m radius) both pre- and post-fire, to give an indication of surface fuel consumption. Measurements from the litter layer (O_t horizon) on the forest floor were divided into categories of fine fuel (such as pine needles), reproductive material (such as pine cones), 1-hr wood, 10-hr wood, and 100-hr wood. Measurements from the shrub and oak layer fuels were divided into categories of foliage (though deciduous species were leafless during the dormant-season burn), 1-hr wood, and 10-hr wood. Remote measurements of both pre- and post-fire canopy fuel loading were conducted using an airborne Light Detection and Ranging (LiDAR) technique. These data will allow the generation of a 1 m x 1 m resolution canopy height profile (Skowronski and others 2011), as well as 3D canopy bulk density (CBD) at a resolution of 10 m x 10 m x 1 m. CBD will be calibrated to profiles from an upward-sensing LiDAR unit in twelve 20 x 20 meter plots within the burn area. This unit was previously calibrated to represent profiles of CBD using equations developed through destructive harvest by Clark and others (2013). This calibration is currently ongoing, and the relative reduction in canopy fuel loading is only discussed qualitatively.

To characterize the type of fire observed, it was useful to estimate the quantity known as fireline intensity (I), which indicates the energy release rate per unit length of fire front (Byram 1959). Fireline instensity is often calculated as $I = H \cdot \Delta m \cdot R$, where R is the rate of spread [$m \cdot s^{-1}$], Δm is the mass of fuel consumed [kg], and H is the heat yield of the fuel. In this study, H is taken as 18700 $kJ \cdot kg^{-1}$ (Alexander 1982). Currently, only the physical measurements of surface fuel consumption are used. Thus, the quantity will be referred to as surface fireline intensity (I_{surf}). Only fine fuel (primarily needle litter), 1-hr forest floor wood, and 1-hr oak and shrub layer material was used to calculate surface fireline intensity. Not only do these smaller fuels tend to be the dominant contributors, but due to the inability to collocate pre- and post-fire destructive fuel samples, consumption estimates for the larger, sparsely distributed fuel elements were considered less reliable. Spread rates were determined from the IR imagery.

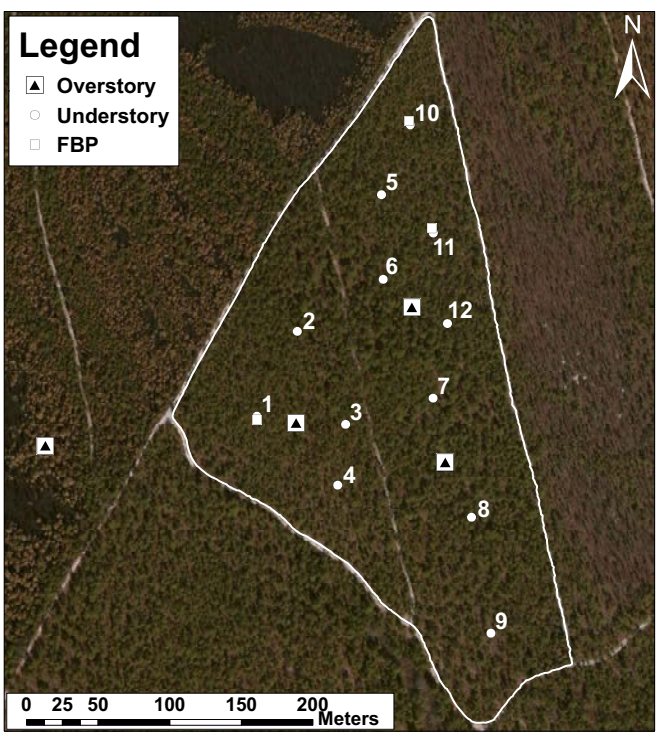

Figure 1—Layout of instrumentation in the study site with understory tower numbers labeled.

Results

IR images captured by the WASP allowed the tracing of fire contours and the mapping of fire progression (figure 2). Only seven of the sixteen available contours (P2-P8) are shown, as these represent the fire behavior of interest for this study. The primary fire front, originating from the northwest road, spread as a head fire in a southeasterly direction. It did not completely merge with the secondary (backing) fire front until sometime between fire contour P5 and P6. In a number of locations in figure 2, there appears to be a sharp dip, or discontinuity, in the fire contours. In a number of locations, this was due to a narrow track which ran along the center of the block (visible in figure 1). Vegetation in this track consisted of only a thin and scattered litter layer, causing an interruption in fire spread.

Using the fire contours to obtain spread rate, surface fireline intensity was estimated at the Understory 10, 5, and 11 towers (table 1). These sites only represent an initial investigation, but were situated in a region of headfire which was not influenced by the backfire. It can be seen that mean surface fire line intensities ranged between 500-6000 $kW \cdot m^{-1}$,

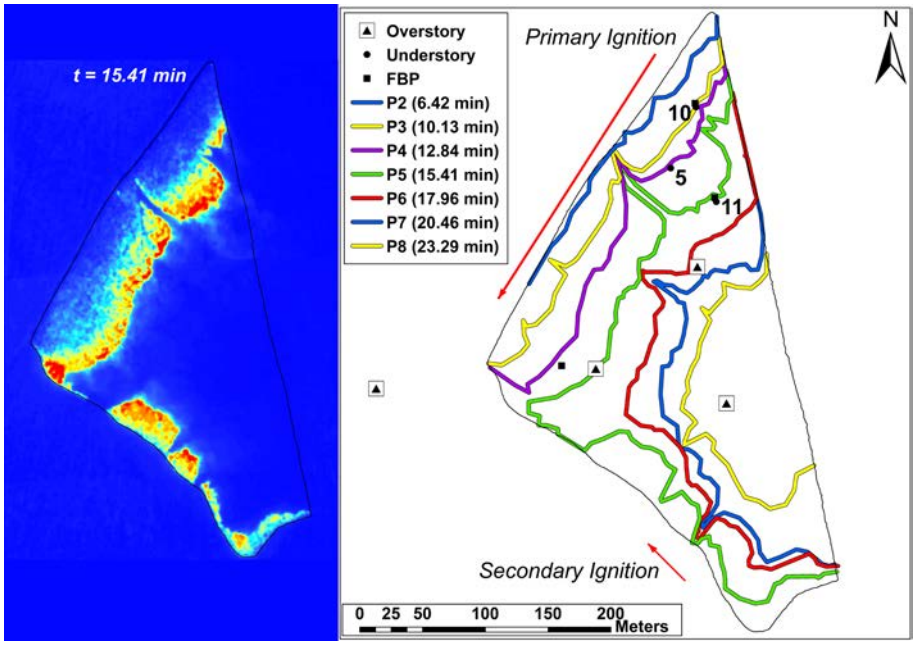

Figure 2—(Left) Example IR image from the WASP. (Right) Progression of the fire front, extracted from IR imagery. The fire progressed from West to East, with consecutive fire contours labeled P2-P8. The time of each contour is given in minutes after the start of ignition. Only the understory tower locations discussed are shown.

Table 1—Summary of Δm (± maximum relative difference in the 3 samples), R (± relative standard deviation), and I_{surf}. Values of I_{surf} are rounded to the nearest 100 kW·m^{-1} and variation is estimated using the propagation of errors.

Location	Δm [kg·m^{-2}] ± %	Contours	R [m·s^{-1}] ± %	I_{surf} [kW·m^{-1}] ± %
Understory 10	0.73 ± 41	P2-P3	0.095 ± 7	1300 ± 42
		P2-P4	0.074 ± 10	1000 ± 42
		P2-P5	0.073 ± 9	1000 ± 42
		P3-P4	0.039 ± 36	500 ± 55
		P3-P5	0.055 ± 28	700 ± 50
		P4-P5	0.074 ± 49	1000 ± 64
Understory 5	0.90 ± 9	P3-P4	0.088 ± 28	1500 ± 29
		P3-P5	0.164 ± 7	2800 ± 11
		P4-P5	0.245 ± 9	4100 ± 13
Understory 11	1.32 ± 8	P4-P5	0.245 ± 9	6000 ± 12
		P4-P6	0.222 ± 3	5500 ± 9
		P5-P6	0.191 ± 7	4700 ± 11

with the lowest values being near the Understory 10 tower, and the highest near the Understory 11 tower, resulting from variations in mass consumption and spread rate.

Of particular note in the area studied is a period of slow spread between P3 and P4 followed by an acceleration between P4 and P5 (figure 2). Ambient horizontal winds, measured at the top (12.5 m) of the exterior control tower to the west, averaged 1.8 m·s^{-1} during the fire and tended to be consistent with the direction of spread. However, the ambient wind shifted by about 60° away from the dominant direction during the period of diminished spread. During the subsequent acceleration, winds again aligned with the fire spread, and a peak magnitude of 6.4 m·s^{-1} was observed—the largest measured during the fire. Though it appears that wind played a role in this modification of fire behavior, a detailed investigation of the pre-fire ladder and canopy fuel arrangement from the LiDAR will be an important aspect of future work. With a linked analysis, these two variables will give significant insight into the observed fire behavior. A preliminary examination of canopy fuel consumption did reveal that this acceleration corresponded to a transition from a predominantly surface fire to canopy fuel involvement.

Discussion and Future Work

This first investigation helps to quantify the type of fire which was observed. Surface fireline intensities can be compared to other fires, such as those summarized by Morandini and Silvani (2010). While spread rates were within a similar range of those determined here, the upper range of reported shrubland fire intensities was eight times greater. Winds in these studies had similar or slightly higher magnitudes, though the measurements discussed from this experiment were made above the canopy, and the drag of the canopy vegetation will cause lower values at the level of the shrubs.

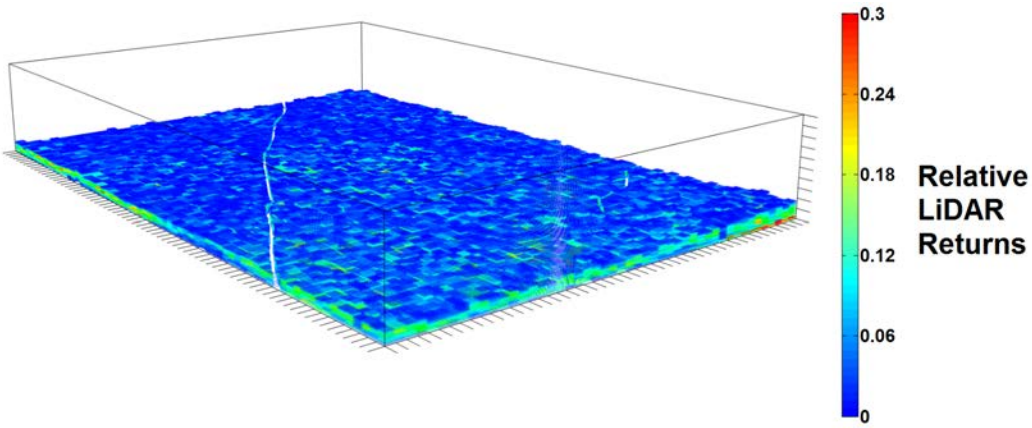

Figure 3—Example of relative canopy densities in the burn block from LiDAR data, input into the WFDS model. Colors represent the relative raw LiDAR returns along height, which will subsequently be calibrated to model the 3-dimensional CBD. View is towards the northeast, with the primary ignition road visible on the left. Axis tick mark divisions are 10 m.

Beyond the influence of wind, the high surface fireline intensities presented by Morandini and Silvani (2010) can be linked to the fuel loads. The open shrub layers of these studies tended to be denser than the shrub layer of the forested PNR environment. However, canopy fuel involvement presents a whole other challenge for fuel management which is not present in shrublands.

A continued study of the wind and fuel arrangement will aid in identifying scenarios where transition to tree crowns is a risk, and post-fire fuel loading will indicate the degree to which this fire reduced dangerous fuel configurations. In an effort to build on this information, work has begun to simulate this fire in WFDS. The model will be tested against the experimental conclusions, and will also allow the simulation of a wide variety of different environmental and fuel conditions. The first challenge lies in the adaptation of LiDAR data into model inputs, as the model requires a high spatial resolution. Potential methods include directly sampling the data at a higher resolution, using an interpolation technique to smooth the data over the high resolution cells, or using an object-oriented processing approach which would attempt to identify individual trees, or groups of trees, and estimating fuels from the LiDAR for each individual. An example of the first is given in figure 3. As the project progresses, the combination of the two experiments and the modeling will result in a clearer picture of the impact of these prescribed fires and how they can be optimized for the purposes of hazardous fuel reduction.

Acknowledgments

The authors wish to thank the Joint Fire Science Program (JFSP) for funding this research effort (project #12-1-03-11). Dr. Filkov was supported by the Tomsk State University Competitiveness Improvement Program and the Russian Foundation for Basic Research (project number 14-01-00211-a). The authors would also like to thank the NJFFS for their cooperation in the planning and execution of the experimental fires, as this was critical to the success of the project.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Near Real-Time Wildfire Mapping Using Spatially Refined Satellite Data: The Rim Fire Case Study

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Fire incident teams depend on accurate fire diagnostics and predictive data to guide daily positioning and tactics of fire crews. Currently, the U.S. Department of Agriculture—Forest Service National Infrared Operations (NIROPs) nighttime airborne data provides daily information about the fire front and total fire affected area of priority fires to the incident teams on the ground. During the peak of the fire season, NIROPs aircraft can fly over 30 incidents per night to monitor active fires. The total flight hours performed by NIROPs aircraft have increased in the last five years, highlighting the growing demand for timely and accurate active fire mapping. Despite efforts of the NIROPs team, numerous low priority fires are not monitored by NIROPs aircraft. In this context, satellite-based remote sensing of active fires may provide timely information to monitor events lacking thermal airborne data.

Remote sensing of active fires offers consistent near real-time geospatial information that has proven useful for strategic operations (Davies and others 2009). However, fire managers may require higher spatial resolution products for tactical operations. The recently developed 375 m Visible Infrared Imaging Radiometer Suite (VIIRS) active fire detection algorithm improves the current spatial resolution of active fire detection products, showing a higher level of agreement with available airborne data (Schroeder and others 2014). In addition, the improved spatial sampling of the VIIRS sensor and the 12 h revisiting time produce consistent daily data, allowing multiple observations of fires lasting several days. In this study we present the application of 375 m VIIRS active fire detection product to map the active fire front and monitor the Rim fire.

Having burned 257,314 acres (1,041.31 km^2), the Rim fire was one of the largest wildfires in California's history. The fire started on August 17, 2013 in the Sierra Nevada region, and was contained on September 27, 2013. The vegetation affected by the fire consisted mainly of chaparral, ponderosa and Jeffrey pines (*Pinus ponderosa* and *Pinus jeffreyi*), white fir (*Abies concolor*) and red fir (*Abies magnifica*).

First, we performed a qualitative assessment of VIIRS 375 m active fire detections (AFD) to map the active fire front by comparing the VIIRS 375 m AFD with near-coincident NIROPs data, VIIRS 750 m AFD, and 1 km MODIS Terra and Aqua AFD (figure 1). VIIRS 375 m showed an improved spatial agreement with the airborne data in comparison with the coarser resolution satellite active fire detection products.

We also built animated displays of the Rim fire growth using the consecutive active fire detections of VIIRS 375 m, VIIRS 750 m and MODIS-Aqua AFD products.[1] The VIIRS display showed finer spatial resolution producing a smooth transition between consecutive active fire detections. In addition, the number of observations tripled in the VIIRS 375 fire growth display in comparison with the MODIS-Aqua fire growth. VIIRS can provide two to four acquisitions each day depending on the latitude due to its 12 h revisit cycle and wide swath whereas MODIS data offer two acquisitions a day (four when Terra and Aqua are combined). In addition, the VIIRS 375 m AFD product showed higher sensitivity to fire activity than the VIIRS 750 m AFD product, as the latter missed many active fires at nighttime during the last six days showed in the display.

To evaluate the ability of VIIRS 375 m AFD to monitor fire growth, we used the total affected area mapped by NIROPs as reference data. The VIIRS 375 m AFD were aggregated consecutively to obtain a daily estimation of affected area. To perform a proper comparison between the VIIRS estimation and the NIROPs map, we used the lower time difference between NIROPs and VIIRS acquisition times to select the last VIIRS image aggregated in the burned area estimation. The period analyzed ranged from the first NIROPs data acquisition on August 20th to September 16th, when the fire perimeter had stabilized. NIROPs provided maps of affected area each day of the period studied except for August 23rd and September 5th when data were not collected.

The quantitative assessment showed how VIIRS 375 m fire-affected area followed the same trend as the total affected area mapped by NIROPs (figures 2 and 3). VIIRS 375 m produced an average overestimation of 12 percent despite the variable time difference between NIROPs and VIIRS acquisition times. The effect of larger time difference was only visible on August 21st. The high fire spread rate experienced that day tripled the fire-affected area from August 21st to August 22nd. As a result, the closest VIIRS image acquired almost five hours later than the NIROPs thermal data produced an overestimation of 48 percent.

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1 Animated display VIIRS 375 m: http://blaze.umd.edu/_img/IBand_Rim_fire_Movie_v2.mp4
Animated display VIIRS 750 m: http://blaze.umd.edu/_img/MBand_Rim_fire_Movie_v2.mp4
Animated display MODIS-Aqua: http://blaze.umd.edu/_img/MYD14_Rim_fire_Movie_v2.mp4

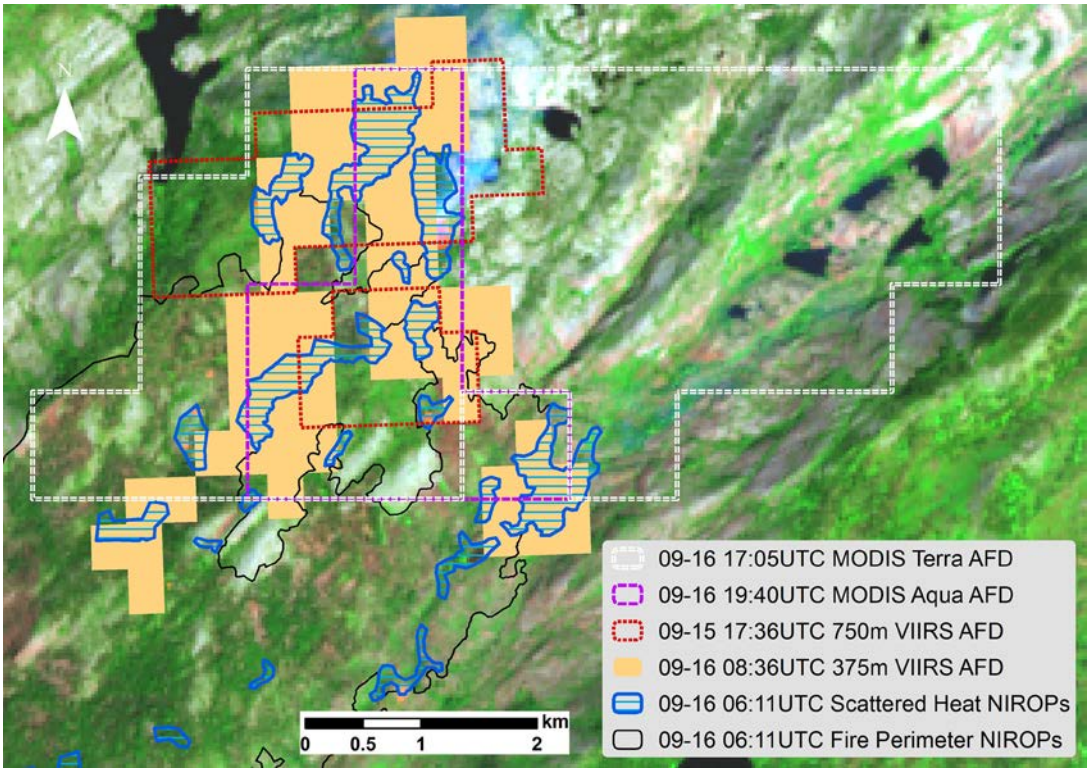

Figure 1—Visual comparison of the active fire front mapping from several active fire detection products and NIROPs scattered heat on September 16th over the northeast region of the Rim fire. The VIIRS 750 m active fire detection product did not generate detections on the morning of September 16th, therefore we used data from the previous overpass on the afternoon of September 15th. The background image is the Landsat 8 image acquired on September 16th (color composite 7-5-2).

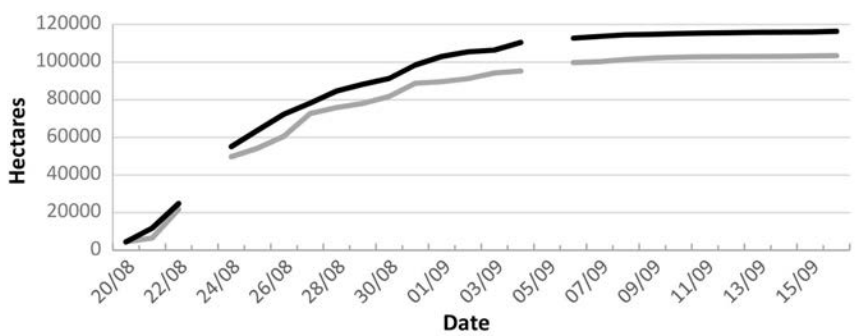

Figure 2—Daily comparison of total fire affected area mapped by NIROPs (grey line) and by aggregated VIIRS 375 m AFD (black line) in the Rim fire.

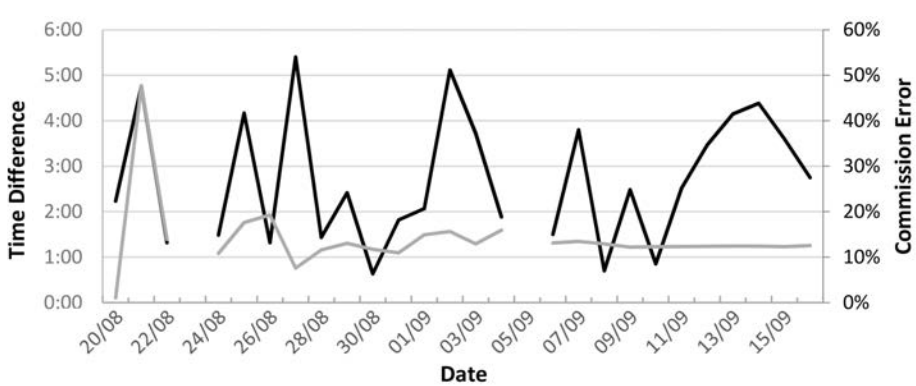

Figure 3—Representation of the time difference between the acquisition time of NIROPs data and the closest VIIRS 375 m image (black line); and the commission error produced by VIIRS 375 m fire affected area estimation (grey line). The commission error measures the overestimation produced by the VIIRS burned area estimation.

Conclusions

Results of our Rim fire case study showed that the VIIRS 375 m AFD product offers valuable information for near real-time wildfire mapping. VIIRS 375m enhanced spatial and temporal resolution enabled the production of more frequent active fire detections and at higher detail compared to existing MODIS fire product. As a result, VIIRS 375 m AFD showed an improved spatial agreement with the airborne data acquired by NIROPs producing a consistent estimation of the daily total affected area.

Consequently, VIIRS 375 m AFD could be used to supplement nighttime airborne imaging resources in support of tactical fire applications providing daytime active fire information. VIIRS 375 m AFD product may be particularly useful to monitor controlled fires and low priority fires supplementing the information provided by the airborne thermal data. In addition, the aggregation of VIIRS 375 m AFD could serve as a near real-time method to estimate burned area providing a first and timely estimation of the extent of areas impacted by fire.

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Regional Likelihood of Very Large Wildfires Over the 21St Century Across the Western United States: Motivation to Study Individual Events Like the Rim Fire, a Unique Opportunity With Unprecedented Remote Sensing Data

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Studies project that a warming climate will likely increase wildfire activity in many areas (Westerling and others 2002; Flannigan and others 2005, 2009; Littell and others 2009). These analyses are often of aggregate statistics like annual area burned, which are insufficient for analyzing changes in seasonality of fire events, the temporal resolution useful for fire management and understanding what drives individual events. Stavros and others (in press, a) show that very large wildfires (VLWFs >20,234 ha ~50,000 ac) may account for only the top two percent of all fires burned in the western contiguous United States, but they constitute a substantial fraction (approximately 33 percent) of aggregate area burned from 1984 to 2010, thus providing strong motivation for understanding what drives them. Using composite records of mean and 95% confidence interval of climate indices for individual fires within a region vs. these same indices the weeks leading up to, including, and post ignition, Stavros and others (in press, a) investigate the spatial and temporal variability of the VLWF climate space. The VLWF climate space was used to define explanatory variables for logistic regression models of the probability of VLWF occurrence with high accuracy of area under the curve (AUC) > 0.80. Assessments of this climate space show that relationships between climate and aggregate area burned may be driven by how VLWFs respond to climate, and that climate and weather both before and after ignition determine fire growth to VLWF size.

Using these models, Stavros and others (in press, b) project the likelihood of VLWF across the western United States using two representative concentration pathways (RCPs): 4.5 and 8.5. Results show a significant ($\alpha \leq 0.05$) difference between the historical modeled ensemble mean probability of a VLWF occurrence from 1979 to 2010 and both RCP 4.5 and 8.5 means during 2031 to 2060. Assessing the likelihood of VLWF exceeding a classification threshold allows analysis of how occurrence may change in the future. For example, with a classification threshold of 0.5, any week with a probability exceeding 0.5 is classified a week when a VLWF occurs. Generally, VLWFs will occur more frequently, and over longer season under both future scenarios RCP 4.5 and 8.5, with more pronounced patterns under RCP 8.5. The biggest changes in likelihood of VLWF occurence depend on whether system's fire regime is flammability-limited, fuel-limited, or mixed. Flammability-limited areas have abundant fuel and require specific conditions for ignition, whereas fuel-limited areas often have conditions suitable for ignition, but not enough fuel. General changes in probability of VLWF occurrence are more pronounced in flammability-limited areas and mixed fire regimes. Results provide a quantitative foundation for management to mitigate the effects of a changing wildfire environment across the western contiguous US, one marked by longer fire seasons with more VLWFs (Stavros and others in press, b). Furthermore, results suggest that understanding what drives VLWFs as individual events is crucial to preparing for the future.

There are a number of techniques for understanding what drives individual VLWFs, many of which include spatially comprehensive, remotely sensed satellite data, but the level of detail from this information can be a limiting factor (Kokaly and others 2007). Often studies relate fire severity, or the magnitude of environmental change caused by fire, to fire behavior, e.g. how much energy is released or flame length. A commonly used remote sensing metric of fire severity, derived from Landsat, is differenced Normalized Burn Ratio (dNBR) (Key and Benson 2006; French and others 2008). The dNBR is a normalized spectral index derived from the differences between pre- and post-fire red (0.615-0.680 μm) and shortwave infrared (SWIR: 1.750-2.400 μm) (Key

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and Benson 2006). Although dNBR is used as a fire-severity metric, it requires ecosystem-specific calibration with field data to derive biophysically meaningful quantitative estimates (French and others 2008). As an alternative to assess fire severity other studies have used spectral mixture analysis (SMA) to estimate fractional char cover (e.g., Lentile and others 2009; Veraverbeke and Hook 2013). SMA and dNBR are currently used with broadband satellite remote sensors, like Landsat, but newer technologies with finer spectral information and more complete coverage of the IR spectrum may improve data quality (Kokaly and others 2007). Technologically advanced imagers are difficult to apply, however, because they are often first heavily tested on airborne platforms before being launched into orbit. Consequently, studies have mostly focused on post-fire data alone with these advanced data sets because access to pre-fire data has been limited as a result of the unpredictable nature of wildfires.

August 2013, however, presented a unique opportunity to study unprecedented amounts of pre and post-fire remotely sensed data at particularly fine spatial (~1-40 m) and spectral resolution with bands from visible to thermal infrared. A VLWF, known as the Rim Fire, burned 104,131 hectares (257,314 acres) in Yosemite National Park and the Stanislaus National Forest before extinction on October 24th, 2013. Raw data provided by flight line came from three airborne sources: (1) the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS); (2) MODIS/ASTER Airborne Simulator (MASTER); and (3) high-resoultion, discrete-return LiDAR. These data cover 100% of the Rim Fire with a 2-km buffer after the fire, and approximately 5%, 50% and 95% before the fire for LiDAR, AVIRIS, and MASTER respectively. AVIRIS and MASTER are part of the HyspIRI airborne campaign to provide a testbed for what will be possible with these kind of datasets once these technologies are launched into orbit. Considering future applications, these data are being processed for the fire perimeter, with a 2-km buffer, into atmospherically and topographically corrected surface reflectance, surface metrics (for example, canopy surface and digital elevation model), and indices widely used by researchers and decision makers (available for download: RimFire.jpl.nasa.gov). These airborne data at high spectral and spatial resolution, unparalleled by any satellite data, provide a unique opportunity to cross-reference remote measurements collected from different technologies to assess VLWF characteristics specifically related to fire behavior and fuel dynamics.

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Characterizing Large Airtanker Use in United States Fire Management

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Abstract—*The appropriate role of large airtankers (LATs) in federal fire suppression in the United States has been the source of much debate and discussion in recent years as the U.S. Forest Service (USFS) has faced impending decisions about how best to address an aging fleet of contracted aircraft. Questions of fleet efficiency are complicated by inadequacies in historical data on airtanker use. A need for improved data collection systems for LATs was a key recommendation to come from a 2013 U.S. Government Accountability Office (GAO) investigation into actions made by the USFS and the U.S. Department of Interior (DOI) regarding fleet modernization. Our research has also identified deficiencies in data collection regarding LAT use in federal fire suppression, particularly with respect to capturing the objectives and outcomes of individual retardant drops. Using spatially-explicit drop location data from 2010 and 2011 for the conterminous U.S., we linked retardant drops to fire occurrence and resource ordering records to identify whether LATs were used during initial attack (IA), and if so, whether or not the fire was contained at the IA phase. Our analysis showed that despite federal policy stating that the priority for use is on IA, 43% of drops from 2010 and 2011 occurred during extended attack (EA) operations. In addition, containment rates of fires associated with LAT use are low; 75% of all IA drops were on fires that escaped IA containment efforts. We expand on this by incorporating drop data from 2012. Further, in order to qualify where and when drops occur, we explicitly characterize the conditions of use for all drops, particularly with respect to terrain, fuels, time of day, weather, and proximity to identified values at risk and areas of restricted retardant use. Preliminary results suggest that approximately 35% of drops occurred in late afternoon (1500 – 1800 hours) and over 30% of all drops intersect with timber fuel models from the LANDFIRE dataset. Here we will elaborate on these results and discuss the potential implications related to the use of LATs in fire management operations.*

Introduction

Large airtankers (LATs) are the highest profile fire suppression tool available to fire managers in the United States. These aircraft are ingrained in the public perception of effective fire suppression, due in part to the publicity and visibility of airtankers involved in suppression operations of wildland-urban-interface fires. In spite of this public sentiment, many unknowns remain regarding the specific conditions of LAT use (for example, what fires received drops, drop locations, and how much retardant per drop) and the effectiveness of retardant application under the range of mission objectives and spatial and temporal conditions under which they operate (Calkin and others 2014; Thompson and others 2013). In this abstract, we extend the work presented in Calkin and others by evaluating an additional year of LAT use (2012) and providing further detail regarding the specific characteristics of the drop environment.

Federal guidance on the use of aviation resources states that the priority for airtanker use is in initial attack (IA; Artley 2005, National Interagency Fire Center 2014), generally, the first 24 hours following operational engagement. This is because they are rapidly deployable and can quickly reach inaccessible areas, often before helicopters or ground crews can be dispatched, to limit fire spread before the fire grows large (Ganewatta and Handmer 2009; National Wildfire Coordinating Group 2014; Plucinski and others 2007). LATs are also used in extended attack (EA), or operations that occur after the fire escapes initial containment efforts, although EA operations can span a range of missions beyond direct suppression (for example, indirect suppression and point protection of values or personnel). Calkin and others (2014) manually linked multiple data sources to provide a coarse summarization of LAT use for 2010 and 2011. However, because federal agencies have not systematically recorded the location, objective, or outcome of retardant drops from federally contracted LATs in the United States, the full historical extent of LAT use in IA versus EA is largely unknown, as is the volume of use tied to specific missions and the outcomes related to individual retardant drops.

The appropriate role of LATs in federal fire suppression in the United States has been the source of much debate and discussion in recent years as the U.S. Department of Agriculture, Forest Service (USFS) has confronted decisions to address an aging and dwindling fleet of contract LATs. Questions of fleet efficiency are complicated by inadequacies

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in historical data on airtanker use. A need for improved data collection systems for LATs was a key recommendation from a 2013 U.S. Government Accountability Office (GAO) investigation into actions made by the USFS and the U.S. Department of Interior (DOI) regarding fleet modernization (U.S. Government Accountability Office 2013). Our research has also identified deficiencies in data collection regarding LAT use in federal fire suppression (Calkin and others 2014; Thompson and others 2013). As a necessary step moving toward fleet efficiency, we pieced together historical datasets to link retardant drops to unique incidents, then incorporated dispatch and spatial data to associate the drops with temporal and spatial characteristics of drop conditions.

Characterizing Airtanker Use

To first characterize conditions of historical airtanker use, we used door-opening events, logged by aircraft sensors designed to monitor airframe stress, to identify retardant drop locations from 2010 to 2012 for the conterminous United States. We then manually linked retardant drops to fire occurrence and resource order records from the Resource Ordering and Status System (ROSS) to identify whether LATs were used during IA, and if so, whether the fire was contained at the IA phase. Our analysis shows that despite federal guidance stating that the priority for use is in IA, 45 percent of drops from 2010 to 2012 occurred during EA. In addition, containment rates of fires associated with LAT use are low; 75 percent of all IA drops were on fires that escaped containment efforts. This containment rate is in stark contrast to the general initial attack success rate of approximately 97 percent for all fires on USFS and DOI lands (Tidwell 2012; U.S. Department of Interior, Wildland Fire Management 2012).

To describe where and when drops occur, we employed a variety of geospatial datasets to explicitly characterize the conditions of use, particularly with respect to terrain, fuels, time of day, and proximity to human populations and identified values at risk. It is generally accepted that retardant effectiveness from LAT drops diminishes with increasing flame length, fire intensity, canopy cover, slope, and wind speed (National Wildfire Coordinating Group 2014). Preliminary results show that LATs are frequently used under conditions where they are thought to be less effective. Approximately 35 percent of drops occurred in late afternoon (1500 – 1800 hours), which is generally the hottest period of the day with potentially the most active fire behavior. Only 14 percent of all drops occurred before noon. When intersecting drops with 30 m fuel model data from the LANDFIRE 2010 dataset (U.S. Department of Interior, Geological Survey 2013), drops intersected timber fuel models (38 percent) almost as frequently as grass fuel models (43 percent). Fourteen percent of drops were in timber in the late afternoon. Slope steepness at the drop location was derived from 10 m digital elevation models (Gesch 2007; Gesch and others 2002), and slopes were categorized according to general land use and zoning regulations defining slope steepness. From this, 45 percent of drops occurred on the steepest slopes (extreme slopes category, greater than 25 percent). When comparing time of day to slope steepness, the highest category of use was in late afternoon on extreme slopes. Finally, drops also occurred most frequently on fires in close proximity to human populations. For example, median distance to the mapped wildland-urban-interface (SILVIS Lab, 2012) was 2.8 mi and median distance to a major highway (U.S. Department of Transportation, Federal Highway Administration 2013) was 4.7 mi.

Discussion

The airtanker modernization strategy (U.S. Department of Agriculture, Forest Service 2012) highlighted cost-effectiveness as the fundamental principle guiding both the replacement strategy and the use of aerial firefighting resources; however, an understanding of LAT usage conditions is a prerequisite for any cost-effectiveness analysis. Our efforts provide a detailed picture of the historical conditions and frequency of use for 2010 to 2012. Unfortunately, the nature of the available data precludes automation of the methods for additional years, and the absence of data on drop objectives and outcomes prevents analysis of the effectiveness of suppressants in meeting stated objectives. The Agency is recognizing this critical need for enhanced data collection to move toward cost-effectiveness and has increased support for the ongoing Aerial Firefighting Use and Effectiveness (AFUE) study. This project will document objectives and outcomes of suppression missions, through field observation and remote sensing of a sample of actual retardant and water delivery operations on active wildfire incidents. AFUE will initially focus on airtankers, but will eventually include data from helicopter and water scooper drops. The data from the AFUE efforts will improve our ability to assess the range of conditions of LAT use and the effectiveness of meeting objectives under specific conditions.

Currently, aviation costs account for approximately 25 percent of USFS fire expenditure (Calkin and others 2014) and aviation accidents are responsible for roughly half of all federal and federally contracted wildland fire related fatalities from 2000 to 2012 (National Wildfire Coordinating Group 2000 to 2012; Stonesifer and others, accepted). Despite guidance stating priority of use in IA, our analysis shows that only half of drops occur during IA, and that for the fires with those IA drops, escape is the typical containment outcome. This suggests that managers are restricting the use of LATs in IA to only those fires with the highest potential to escape. Unfortunately, at this time we do not have the ability to identify how many of these drops resulted in containment of fires that would have otherwise escaped in the absence of aviation use. It is important to note that we are not suggesting that retardant drops under challenging fire environments are ineffective; however, given the high-risk, high-cost nature of aviation missions in fire suppression, it is critical to utilize LATs in the most effective manner possible. To ensure effective use, information regarding the

effectiveness of LATs in meeting a range of objectives under variable conditions could be incorporated into improved resource allocation models, particularly for use during periods of high resource demand.

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The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Decision Making Under Uncertainty: Recommendations for the Wildland Fire Decision Support System (WFDSS)

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Abstract—*The management of wildfire is a dynamic, complex, and fundamentally uncertain enterprise. Fire managers face uncertainties regarding fire weather and subsequent influence on fire behavior, the effects of fire on socioeconomic and ecological resources, and the efficacy of alternative suppression actions on fire outcomes. In these types of difficult decision environments, even well-trained and experienced individuals can become susceptible to cognitive limitations and decision biases, as indicated by several recent analyses of fire manager decision making. This extended abstract focuses on fire management decision making under uncertainty, in relation to current decision support provided by the Wildland Fire Decision Support System (WFDSS), offering several recommendations to improve decision content and process.*

Introduction

Management of wildfires presents myriad sources of uncertainty (Thompson and Calkin 2011). These uncertainties are manifest across a variety of decision contexts including fuel treatment planning, incident response planning, and incident response (Figure 1). The natural variability surrounding the locations and timings of unplanned ignitions, along with fire weather conditions driving fire behavior, are perhaps the most obvious sources of uncertainty, typically quantified probabilistically through the use of stochastic wildfire simulation systems (Finney and others 2011a; Finney and others 2011b). Addressing uncertainties surrounding the quantification of socioeconomic and ecological consequences of fire can be even more challenging (Venn and Calkin 2011), although some combination of expert judgment and multi-criteria decision analysis is often used (Thompson and others 2013a). Further, fire managers face uncertainty regarding partial control and the relative efficacy of alternative suppression actions and other wildfire management strategies (Thompson 2013).

When faced with such complex, dynamic and uncertain decision environments, humans tend to fall prey to a number of cognitive biases and heuristics that can lead to suboptimal decisions (Thompson 2014). Thus there is interest in expanding the role of risk and decision analysis to help support high quality decision making, and in identifying opportunities for improving decision support functionality within the Wildland Fire Decision Support System (WFDSS). Critically, attention on improved decision support needs to focus on both decision content and decision process (Thompson and others 2013b).

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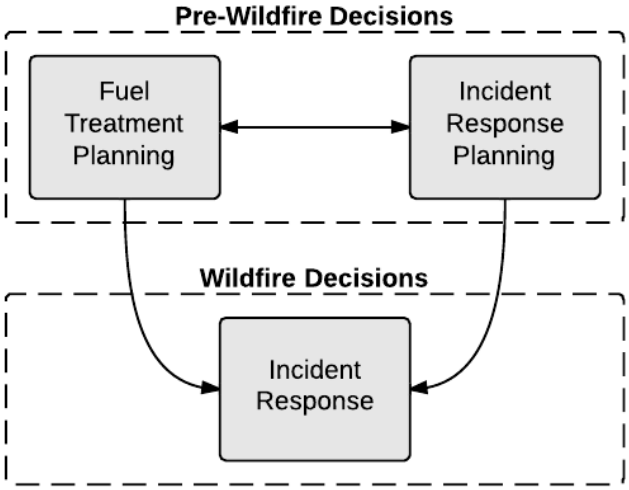

Figure 1—Pre-wildfire and wildfire decision contexts. Ignition prevention, although important, is not considered here because of a focus on planning for large wildfire.

- **Decision content:** Characterization of the risks posed by wildfire, as well as the potential ecological and economic costs and benefits associated with various fire management actions, leading to a more complete understanding of options and tradeoffs.
- **Decision process:** Characterization of the complexities and uncertainties faced in wildfire management, leading to delivery of targeted decision support tools and approaches, and promotion of frameworks for systematic, structured, and risk-informed decision making.

WFDSS currently provides a structured format for information management, risk assessment, and decision documentation, and has likely helped fire managers arrive at and justify risk-informed decisions (Calkin and others 2011; Zimmerman 2012). Recognizing the importance of decision process, however, suggests that decision support efforts

need to extend into the pre-fire environment to set the stage for good decisions before smoke is in the air. Successful decision-making is largely premised on clearly framing a decision, articulating objectives, and identifying performance measures (Marcot and others 2012). In the next section several suggestions are presented for how to better integrate principles of risk and decision analysis into WFDSS.

Implications for WFDSS

Potential improvements and implications for future directions with WFDSS center around three hierarchical premises:

1. The linkages between fuel planning, incident response planning, and incident response need to be strengthened (Figure 1).
2. In support of #1, there is a need to expand application of spatial wildfire risk assessment frameworks (Scott and others 2013) that consider the likelihood and intensity of wildfire along with the susceptibility of resources and assets (Figure 2).
3. In support of #1 and #2, the possible benefits from wildfire need to be better recognized and quantified from an ecological perspective in the context of fire-adapted ecosystems, and also from a fuel treatment perspective wherein wildfires can exert controls on the extent and severity of future fires (Parks and others 2014). Similarly, the role of suppression actions in transference of risks to the future needs to be better acknowledged.

Recommendations for Establishing Stronger Planning Linkages

The recommendations below outline steps to help establish stronger linkages across fire planning contexts to support risk-informed decision making.

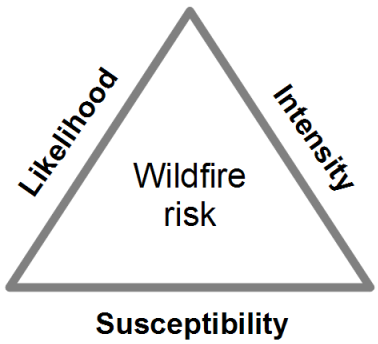

Figure 2—The three primary components of wildfire risk (Scott and others 2013) are wildfire likelihood (i.e., probability of occurrence) and intensity (i.e., heat release per unit length or flame length), along with resource or asset susceptibility (i.e., potential for loss/benefit due to exposure to wildfire).

Fuels Planning & Incident Response Planning

- Treatment strategies should be designed in concert with response planning to identify and evaluate how different spatial treatment patterns could improve the safety and effectiveness of suppression operations. This could, for instance, entail the creation of "low hazard fire containers" where aggressive suppression may be unnecessary, or conversely "high hazard fire containers" where fuel breaks along roads and other natural barriers afford opportunities for restricting fire growth (Ager and others 2013).
- The scope of treatment strategies could extend to the landscape-scale in order to increase the likelihood that treatments actually interact with fire and the likelihood that treatments can measurably influence landscape-scale fire behavior.

Fuels Planning & Incident Response

- Spatial information on treatment location should be integrated into WFDSS to provide fire managers with improved situational awareness (currently underway).
- Auxiliary information on treatment age, treatment type, and treatment objectives could be succinctly characterized, and simulation exercises on pre-treatment and post-treatment landscape conditions (Ager and others 2010; Cochrane and others 2012) could help fire managers to better anticipate fire behavior within treated areas.

Incident Response Planning & Incident Response

- Spatial fire management plans should more clearly characterize objectives within various fire management units, including fundamental objectives (what are we trying to accomplish) along with means-based objectives (how can we accomplish it). Early efforts characterizing strategic response categories (Thompson and others 2013c) at the national scale identified issues with missing or unclear objectives, highlighting a need for more thoughtful locally-based input. Current spatial fire planning efforts within WFDSS that allow fire managers to spatially characterize strategic objectives and management requirements could provide refined information to support development of risk-informed strategies and tactics.
- In support of developing spatial fire management plans with variable management objectives, and potentially delineating these areas at a smaller resolution than the size of some fire management units, spatial risk assessment efforts could be expanded. This could include not only identification of patterns of likely benefits and losses across the landscape (Scott and others 2013), but also the delineation of areas where ignitions pose significant risk transmission threats (Scott and others 2012; Thompson and others 2013d). Spatial risk assessment efforts could integrate complementary information such as the FIRESEV Severe Fire Potential map (Dillon and others 2011).

Summary

The basic thesis of this document is that risk-based wildfire management will succeed only to the degree that pre-fire planning efforts incorporate risk-based information, with feedback loops and information sharing across planning contexts. Key recommendations are to more strongly link pre-fire planning and assessment with actual incident response, to use spatial risk assessments to inform planning efforts, and to more comprehensively evaluate the short-term and long-term risks and benefits of wildfire. Many of the analyses as part of these planning efforts are outside of the WFDSS environment itself, but nevertheless could yield improvements in both decision content and decision process when fire managers find themselves managing an active incident and analyzing risks and documenting decisions within WFDSS. Work is ongoing from partners within the National Fire Decision Support Center and elsewhere to expand availability of data layers and functionality within WFDSS to more clearly define and delineate fire management objectives, to more explicitly recognize opportunities for ecologically beneficial fire, and to support a broad range of management options.

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Applying the Wildland Fire Decision Support System (WFDSS) to Support Risk-informed Decision Making: The Gold Pan Fire, Bitterroot National Forest, Montana, USA

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Abstract—*In response to federal wildfire policy changes, risk-informed decision-making by way of improved decision support, is increasingly becoming a component of managing wildfires. As fire incidents escalate in size and complexity, the Wildland Fire Decision Support System (WFDSS) provides support with different analytical tools as fire conditions change. We demonstrate the application of WFDSS information and tools to assess risk management cycle elements by using a case study wildfire from the 2013 fire season; the Gold Pan Fire, Bitterroot National Forest, Montana, USA. Examples of the scalability of the WFDSS, its ability to gain quick situational awareness, and an evaluation of fire behavior potential and burn probability with respect to Highly Valued Resources and Assets, is shown for the Gold Pan Fire as an emerging incident that evolved into a complex wildfire, supported with sophisticated analyses to assist decision-making.*

Introduction

Documenting a deliberate, risk-informed decision is emphasized with recent national policy guidance (USDA-USDOI 2009) regarding the management of wildfires on federal lands. Additionally, specific protocols for making risk-informed decisions on wildfires exists in the Forest Service 2014 Wildland Fire Risk Management Protocols (USDA Forest Service 2014). Decision-makers have traditionally used the Wildland Fire Decision Support System (WFDSS—Noonan-Wright and others 2011) to document a wildland fire decision since 2009, but there are numerous ways a user can engage with the WFDSS to inform the risk management cycle. We applied the risk management cycle as described by Taber and others 2013 (Figure 1) and demonstrated: (1) how the WFDSS was used to assess and inform risk throughout the life of the Gold Pan Fire, and (2) the adaptability of the WFDSS to respond to changing fire complexities.

Figure 1—The Risk Management Cycle. The six parts of the risk management cycle are not always followed in a linear fashion, but typically start with Situational Awareness (Taber and others 2013).

Gaining Situational Awareness for an Emerging Fire

There are six parts to the risk management cycle: (1) situational awareness, (2) assessment, (3) risk control, (4) decision, (5) implementation, and (6) evaluation (Taber and others 2013). The completions of all parts are dependent upon each other and require iteration, deliberation, and the use of the best available science (Figure 1). Situational awareness requires decision makers to identify risks and opportunities for mitigation by defining the Highly Valued Resources and Assets (HVRAs), the hazard, and the probability those important values will be positively or negatively impacted by wildfire. A decision-maker gains situational awareness regarding values, hazard, and probability, to inform a preliminary risk assessment.

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Category	Value
Building Clusters: Idaho, ID	0
Campgrounds	3
Class 1 Airsheds	27,503 acres
County: Idaho, ID	90,860 acres
Est Ground Evac Time: 1-2 Hrs	4,066 acres
Est Ground Evac Time: 2-4 Hrs	23,472 acres
Est Ground Evac Time: 4-6 Hrs	17,287 acres
Est Ground Evac Time: 6+ Hrs	46,009 acres
Habitat: Bull Trout	45.0 miles
Habitat: Steelhead	49.0 miles
Jurisdictional Agency: USFS	90,860 acres
Responsible Agency: USFS	90,860 acres
USFS Buildings	9
Wilderness: Frank Church-River of No Return Wilderness	63,306 acres
Wilderness: Selway-Bitterroot Wilderness	25,118 acres

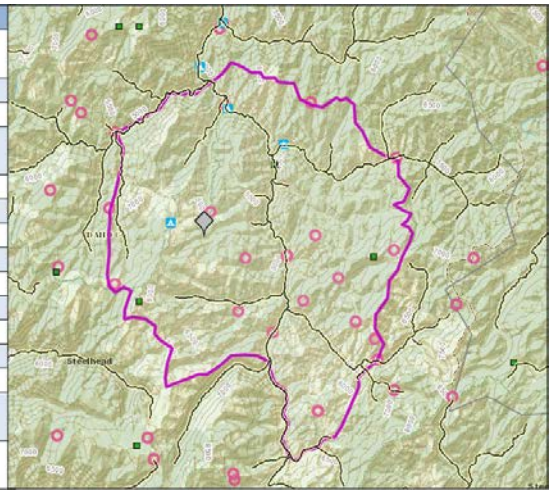

Figure 2—Planning Area Spatial Inventory Table and Planning Area. In WFDSS, the Incident >Situation tab is shown with Infrastructure (campgrounds—white tents/blue background; Forest Service buildings—green squares; and outfitter locations and camps—pink circles). Natural resource spatial data like bull trout habitat is displayed (linear yellow and black polygons on streams and rivers). The pink line delineates the planning area. The table summarizes spatial and non-spatial data, including highly valued resources and assets, which could support decision-making.

Identifying HVRAs (what infrastructure, natural and cultural values are adjacent to the location of the fire) helps decision-makers gain situational awareness to begin informing the preliminary risk assessment. In WFDSS, users draw a planning area polygon that will automatically populate a table of values, called a Planning Area Spatial Inventory (Figure 2). In addition, a user can manually click data sources on and off to isolate and identify specific values of interest or concern. For the Gold Pan Fire area, HVRAs included a cabin, a fire lookout tower, and a rural community east of the fire.

Hazard

During the initial phases of a risk assessment, decision-makers have a range of tools and data to evaluate hazard, including the continuity, amount, and configuration of surface and canopy fuels; fire behavior; and potential for fire growth. Fire danger graphs for the Bitterroot National Forest comparing current and historic Energy Release Component (ERC) trends were automatically generated for most Remote Automated Weather Stations (RAWS) and suggested that the ERC index was below the 90th percentile after the fire was detected. Fire history spatial data layers helped to quickly evaluate recently burned areas that could retard fire spread, and a large unburned area was noted between the Gold Pan Fire and the concentration of HVRAs to the east, suggesting greater hazard of unburned fuel in this area.

Probability

For a quick, qualitative risk assessment, probability refers to the likelihood of a fire becoming an active event with potential to reach HVRAs. Users address the potential for fire spread, barriers that would limit fire spread, and the current fire danger. For the Gold Pan Fire, much of the area had been historically managed to allow wildland fires to burn for enhancement of natural and cultural resources; subsequently there were old fire scars that could limit spread potential. Within the first few days of fire detection, two Fire Spread Probability (FSPro) runs were used to simulate two-dimensional fire spread for 2,000 fires lasting 14 days, using historical weather and wind observations from the Hells Half Acre RAWS (No. 101019). The first simulation used minor modifications to surface and canopy fuels to represent less spread potential from historical fire scars, and the other simulation used barriers and fire scars to limit fire spread. To evaluate the probability of a fire becoming an active event, the mean fire size from the first run (12,000 acres) was compared to a mean fire size of 4,800 acres for the alternative run using the fire size table generated from each FSPro run (Figure 3). Displaying a range of outputs rather than one single analysis can be useful to address modeling uncertainty. Both outputs were considered and discussed with the decision makers during the preliminary situation awareness phase.

RISK Assessment for a High-Complexity Fire

Situational Awareness and Assessmentt

Within a few weeks of the detection of the fire, two significant spread events grew the Gold Pan Fire to 8,000 acres and an Incident Management Team (IMT) was called to manage the fire. WFDSS tools were used to reassess the Situational Awareness and Assessment phases of the risk management cycle. At that time, fire danger set a new record for maximum ERC (ERC=76), the peak of the season was still several weeks away, a season-ending event to naturally extinguish the fire was not expected until late September, and there were few barriers between the head of the fire and the HVRAs 12 miles northeast of the fire. An updated FSPro run with associated values helped the IMT gain some perspective on the fire's potential to burn outside of the Selway-Bitterroot wilderness area in the next two weeks, reinforcing the need for a long-term strategy that included consideration of both backcountry and front-country values.

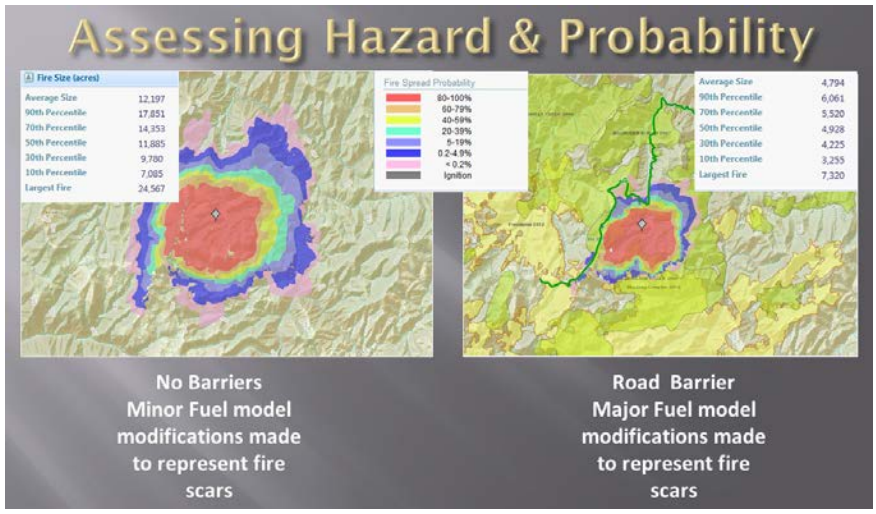

Figure 3—Assessing Hazard and Probability Using FSPro. Fire spread potential was evaluated with two separate runs to understand the uncertainty associated with using FSPro when very little information is available. The first run shows a much larger average fire size (>12,000 ac) in the fire size table, when no barriers to surface fire spread were used as inputs to the model; and only minor fuel model modifications were made to represent less spread potential for historical fire scars. The second run is much smaller (<5,000 ac) when these modifications were fully implemented. Fire Spread Probability is represented spatially ranging from very low probability (< 0.2 percent) to high probability (80-100 percent) that the location of a HVRA could be impacted sometime within the time frame of the model (in this case, 14 days).

Risk Control

Before the long-term plan was finalized, strategies and tactics were identified by the IMT to control risk and comply with incident objectives during the next operational period, including committing firefighters along a road to prepare for a burnout operation. However, the IMT reconsidered these actions after using the WFDSS Near-term fire behavior modeling tool to assess the potential fire behavior and fire spread over the next 72 hours. The analysis suggested that the safety of the firefighters was likely to be compromised before the work would be completed.

Bitterroot National Forest staff, local stakeholders, and a subset of the IMT were assembled to begin the long-term planning effort, assembling expertise in operations, policy, safety, and desired conditions. WFDSS outputs were used to focus efforts where fire was most likely to spread in the next several weeks and plan "Management Action Points" (MAPs) that, if breached, would initiate specific actions to be implemented. For example, MAP 11 was a north-south line between the fire and the urban interface that would consider home evacuations and a burnout operation if encountered by wildfire (Figure 4). Fifteen MAPs were developed over the life of the fire in the areas where the fire could potentially spread and impact values.

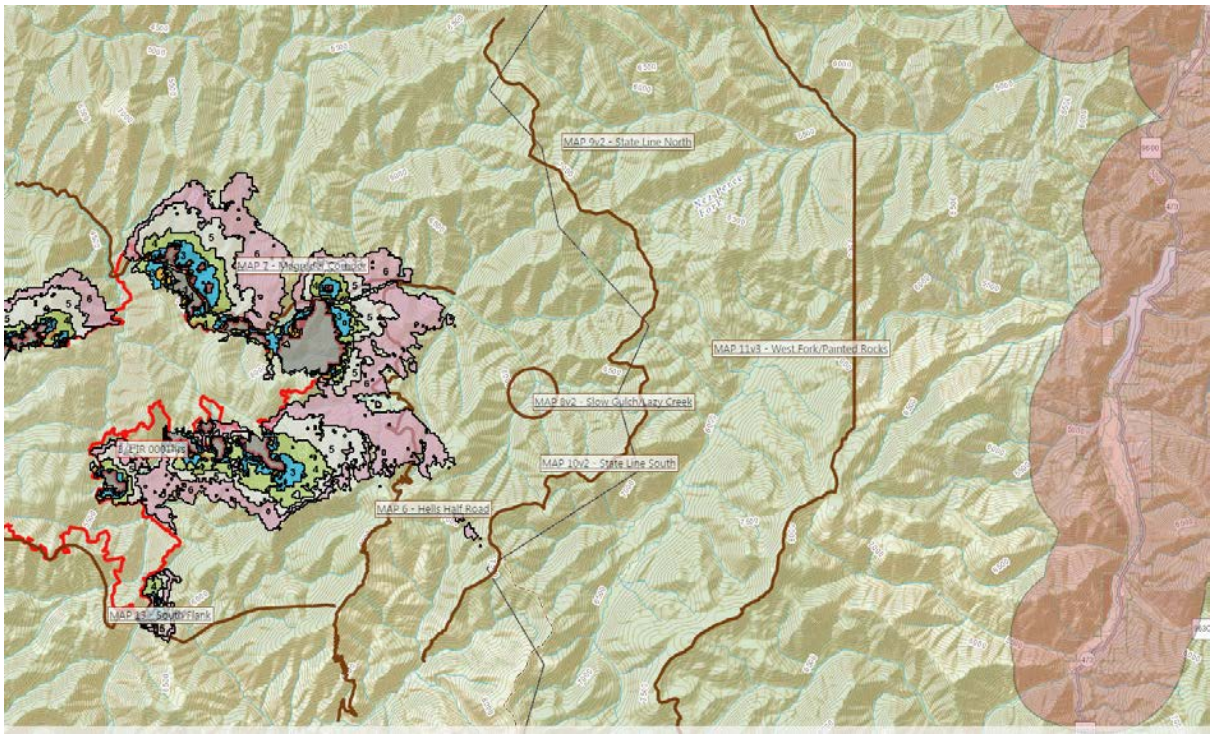

Figure 4—Six day simulated fire progression of the Gold Pan fire using Near-term Fire Behavior (NTFB). The Gold Pan Fire (perimeter in red) was modeled for a 6-day period (multi-colored polygons) to predict the fire progression given forecasted wind and weather and using the intense heat from the August 1st infrared and heat detection flight information as an ignition. Outputs display the potential for the fire to reach Management Action Points (brown lines). Management Action Points were developed in the long-term plan to protect highly valued resources and assets and the wildland urban interface (shown in pink).

Decision

Once the MAPs were identified and fire behavior was modeled, the risk management cycle moved to the Decision phase where the decision-makers validated the course of action (actions to manage the fire tiered from land management plan and the fire objectives) and acknowledged the risks. The tools in the WFDSS supported this phase by allowing the decision maker to easily see the products like fire danger rating graphs, season ending event graphs, and probabilistic fire spread. Additionally, a Near-term Fire Behavior output demonstrated expected fire behavior over the next several days. These graphics and descriptions, when assessed with the MAPs, gave the decision maker confidence in approving a sound course of action.

Implementation and Evaluation

The Implementation and Evaluation phases of the risk management cycle include carrying out the course of action and revising it as needed throughout the life of the fire. MAPs identified in the long-term plan along with daily reassessments of fire spread projections were used by the IMT and decision maker at daily planning meetings. The long-term analyst listed all MAPs that could be impacted in the next 24, 48 and 72 hours so the IMT could plan actions accordingly and implement the plan successfully. Additionally, a daily assessment for impacts to the planning area or closure area boundaries was made to ensure the planning area remained relevant and public safety was addressed. This daily reassessment using WFDSS fire behavior tools allowed the decision makers to continually evaluate the Decision to ensure it remained relevant.

Conclusion

The risk management cycle used for the Gold Pan Fire demonstrates how initial fire decision making can be quickly informed by geospatial information and analysis. As the fire's complexity escalated, an IMT was able to use WFDSS products to continually assess risk and inform the planning process. WFDSS is not just a place to document a decision that is compliant with National Fire Policy, but a powerful collection of data, tools and processes that can provide quick, scalable, relevant support to decision making at all levels of the Risk Management Cycle.

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Abstracts

Anatomy of the Las Conchas Fire, Jemez Mountains, New Mexico

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Abstract—*New Mexico has experienced a prolonged drought, with increasing temperatures and decreasing snowpack, since the late 1990s. This has coincided with significant increases in wildfire activity, resulting in the state's largest and most destructive fires occurring since 2000. The winter and spring prior to the Las Conchas Fire in 2011 were among the driest on record. Less than 1 mm of total precipitation was recorded in the burn area the 30 days prior to fire ignition. Fuel conditions were very dry, with 1 hour fuels at <1 percent fuel moisture and 1000 hour fuels at <6 percent fuel moisture. The Las Conchas Fire began at 1300 hours on June 27, 2011, from a tree that fell onto a power line. It burned on multiple land ownerships, including U.S.F.S., National Preserve, private, and National Park Service property. Fire intensity and spread were driven by the combination of high topographic and vegetation diversity, fuel conditions, and wind. Deep extensive canyons dissect the burned area and are surrounded by steep mountain slopes and open expansive grasslands that allowed the fire to spread in multiple directions at varying speeds and intensities. The vegetation within the burned area was characterized by montane forest, grasslands, and shrublands in higher elevations, and shrubland, grassland, and woodland at lower elevations. Within the first two days of the fire, spread occurred in multiple directions extending south, east, and north; typical directional spread was to the northeast, driven by usually southwest winds. During the first five days of the fire, maximum temperatures averaged 28°C and minimum temperatures averaged 7°C; humidity ranged from 15 to 67 percent throughout the 5-day period (including evenings). Average wind speeds were 2.7 ms^{-1} and maximum winds averaged 12.5 ms^{-1}. At the time of ignition, atmospheric conditions were unstable, resulting in strong winds at both the surface and aloft (40 mph gusts at 20 ft); the temperature was approximately 32°C with very low humidity. During the first 14 hours, fire behavior was erratic and fast-moving, burning approximately 43,000 acres at a rate-of-spread of about 1 acre per second. Flame lengths were >300 ft., including during evening hours. Over two weeks, it grew to 156,000 acres and was New Mexico's largest fire until 2012. The fire was largely wind-driven over the first two days, becoming more plume-dominated thereafter. Two critical burn events took place that were characterized by extreme plume formation and collapse, and extreme fire behavior in an upper watershed. The high severity of both these episodes later resulted in severe post-fire flood events. Based on observed intensity, severity, and behavior, the Las Conchas Fire was out of the historic range of variability when compared to other large fires.*

Keywords: *Las Conchas Fire, Behavior, Fuels, Flame*

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Understanding Post-Wildfire Vegetation Trajectories in Pine-Oak Woodlands

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Abstract—*The Lost Pines of central Texas are the westernmost stands of loblolly pine (*Pinus taeda*) in the United States, a portion of which is found in Bastrop State Park (BSP). These pine-oak woodlands support a diverse native plant community and are the designated critical habitat of the endangered Houston toad (Bufo houstonensis). In September 2011, wildfires burned much of the Lost Pines and BSP during a record drought, which together killed most of the trees and much of the understory vegetation. A primary goal of BSP managers is to return BSP to pine-oak savanna, in part because this was likely the predominant landscape prior to European settlement in the early 19th century. Furthermore, a more open canopy with fewer surface fuels will reduce the risk of future high-intensity wildfires. However, other vegetation trajectories leading to oak woodland, pine woodland, or other unknown plant communities are possible. In collaboration with Texas Parks and Wildlife staff, we are investigating how post-wildfire vegetation trajectories are affected by pre-wildfire species composition, short-term vegetation dynamics, wildfire severity and spatial patterns. Fifty-six permanent plots have been surveyed for 12 years pre-wildfire and three years post-wildfire.*

*Early successional herbaceous species, including Canadian horseweed (*Conyza canadensis*) and numerous species of rosette grass (*Dichanthelium *spp.), are the most common post-wildfire herbaceous species across all burn severity classes. A preliminary survey along roads and power lines in BSP showed that invasive species remain rare, although some highly invasive species are becoming more widespread, most notably Chinaberry (*Melia azedarach*) and King Ranch bluestem (*Bothriochloa ischaemum*).*

*In much of BSP, pre-wildfire thickets of yaupon (*Ilex vomitoria*) with dried pine needle drape contributed to high wildfire intensity and crowning, especially in areas that burned during the daytime. Yaupon cover has increased in both 2012 and 2013 through basal resprouting. From the wildfire through summer 2012, pine regeneration was greatest in low to moderate burn severity plots. The absence of pine seedlings from high burn severity plots may have been due to pine seed shortage, unsuitable seedbeds, or both. In 2013, pine seedlings began to colonize severely burned plots, possibly due to wind-dispersed pine seeds or the formation of more suitable seedbeds from post-wildfire accumulation of organic matter. Oaks (primarily* Quercus marilandica *and* Q. margaretta*) resprouted in both 2012 and 2013 in plots of every burn severity class, and increased in number and height more rapidly than pine seedlings.*

Our findings through 2013 suggest that oaks may out-compete pines, shifting plant communities in BSP towards oak woodland. However, as oak resprout numbers decrease and more pine seedlings become established, vegetation trajectories may continue towards the restoration goal of pine-oak savanna. Continued monitoring will aid in the early detection of the spread of invasive species and clarify likely potential post-wildfire vegetation trajectories in BSP and similar pine-oak woodlands.

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The Las Conchas Fire, New Mexico, in Historical Context

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Abstract—*Wildland fires have been increasing in spatial extent and severity in recent decades across the western US. Our research team has spent the past two and a half years researching the broad range of fire effects from one large, predominantly severe wildfire in the southwest region, the Las Conchas fire (2011) located in the Jemez Mountains of New Mexico (approximately 56% of the fire area was classified as moderate or high severity). Our study sites are located in the Valles Caldera National Preserve, which was not impacted by fire retardant during suppression activities, and was not directly rehabilitated post-fire. Fortunately, several fire history studies have been conducted near our study area, providing us with information about historic fire regimes and climate-fire interactions. For the lower elevation ponderosa pine dominated forests, fire scars indicate that low severity surface fires burned relatively frequently (5 to15 years). In the higher elevation mesic mixed-conifer dominated forest, fire return intervals were longer (15 to 30 years). Fire scarring and recruitment dates indicate that both surface fire and patchy crown fires occurred in this forest type. Fires historically burned between the months of April and September, with the largest fires burning in June before the monsoonal moisture typically arrived in July. Large fire years were often synchronous with dry years that followed two years after a significantly wet winter/spring in the ponderosa pine forests. Fuel moisture, rather than fuel availability, was found to determine fire occurrence in the mesic mixed-conifer forests. The once-frequent surface fires ceased around 1890 A.D. in this region of the Jemez Mountains due to coupling of several landscape-level change agents: livestock grazing, fire exclusion and a reduction in fuels through logging efforts. Intense sheep grazing began in the grassland areas on the Valles Caldera around 1748 A.D. After a decline in wool prices in 1940 A.D., cattle and horse grazing increased. Grazing practices reduced the fine fuels that would have carried historic surface fires, and prompted fire suppression in the area to protect both grazing and timber profits. Logging operations began in 1926 A.D. and continued until around 1975 A.D., resulting in large areas of second-growth forest with tree densities of 800 to 2000 trees/acre. Historic reference conditions for ponderosa pine in the southwest are 11.7 to124 trees/ac, and for mixed-conifer are 20.9 to99.4 trees/ac. Additional studies at the Valles Caldera suggest that between 1935 A.D. and 1965 A.D. the grasslands decreased in size by 18 percent due to encroachment and infilling by conifers, leading to an overall increase in fuel density and ladder fuels. These drivers of change partially explain the departure from the historical range of variability in vegetation and fire regimes, and thus partially explain the fire severity and behavior of the Las Conchas Fire.*

Keywords: *Fire History, Valles Caldera, Change Agents, Historic Range of Variability, Wildland Fire*

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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The Combustion of Large Downed Wood: Initial Impacts of Burn Intensity on Soil Nutrients and Ectomycorrhiza Communities of Ponderosa Pine Seedlings

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Abstract—*Climate shifts in conjunction with fuel accumulation are predicted to increase the frequency of high-severity fires in the ponderosa pine forests of central Oregon. Exposure of soils to intense heating from high-severity fire alters soil properties and causes mortality of soil microbes. This outlook has created a need to comprehend the potential ecological and timber resource impacts. Ectomycorrhizal fungi (EMF) are considered essential for conifer seedling growth and survival by aiding seedlings in water and nutrient uptake. Previous studies showing EMF improve ponderosa seedling establishment after fire did not compare EMF communities at different levels of soil heating intensity in a field setting. For this study, burn intensity impacts on soil nutrients and EMF species composition were compared in a thinned ponderosa stand at Pringle Falls Experimental Forest, La Pine, Oregon. A total of twelve replicate sites were used, each with three treatments applied using a prescribed burn: high intensity burn (HB), low intensity burn (LB), and unburned control (UB). HB treatments were created by the combustion of downed logs stacked together and LB treatments were applied through the broadcast burning of pre-existing ground fuels. Thermocouple probes were used to record burn temperatures at multiple depths within the soil. Ponderosa pine seedlings planted post-burn were harvested after four months and analyzed for EMF species richness, constancy, and relative abundance using morphotyping and molecular techniques. Preliminary results show: a) lower soil nutrient concentrations were present in HB soils compared to UB soils; b) EMF species composition differed significantly between HB and UB soils but not between LB and UB soils or LB and HB soils; c) there were no detectable differences in EMF species richness across treatments; and d) correlations exist among burn treatments, pH, carbon, and organic matter content when compared with species composition. These results suggest fire-related alterations to the physical and chemical environment influence EMF species composition. Changes to soil nutrients and EMF species composition detected in high intensity burned soils were otherwise undetectable in low intensity burned soils. Despite lethal temperatures throughout the depths of soil commonly occupied by EMF, HB soils were recolonized within four months with nearly the same number of species though species dominance was altered. This research aims to advance our understanding of EMF primary succession and its role in fire ecology. The importance of mixed-severity fire in providing soil refugia for EMF species may influence fuel reduction practices in ponderosa pine forest management.*

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Soil Characteristics Across Burn Severities in the Las Conchas Fire

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Abstract—*Climate change is currently one of the major drivers of increasingly severe wildland fire behavior throughout the Southwest. The Las Conchas fire in the Jemez Mountains, New Mexico, burned during the summer of 2011. It was the largest recorded fire in the state until it was surpassed in size the following year by the Whitewater-Baldy complex. Las Conchas provided an excellent opportunity to study fire effects on soil nutrient concentrations in differing fire severities, as small fluctuations in nutrients can have major implications on water quality and vegetation recovery. We collected and analyzed soils for texture, potassium (K), aluminum (Al), manganese (Mn), ammonium (NH4), iron (Fe), copper (Cu), pH, nitrate-nitrogen (NO3-N) and orthophosphate (PO4). Soil samples were collected from five plots in each of the four fire severities types: control (unburned) and low, moderate, and high. Each of the sites is similar in parent material and vegetation. We analyzed soil texture using the bouyoucos hydrometer method, and nutrient levels [excluding (NO3-N) and (PO4)] were analyzed using LaMotte Soil Nutrient Kits. NO3-N and PO4 levels were measured using an Analytical FS 3100 Automated Chemistry Analyzer following USEPA method 353.2. The soil texture at all four sampling sites was classified as a sandy loam. There were no significant differences between any of the fire severity sites or the control for K, Al, Mn, NH4, Fe, Cu or pH using the LaMotte Kits. Our findings suggest that NO3-N and PO4 concentrations in soil decreased with an increase in fire severity. Low concentrations of NO3-N and PO4 were found at all study sites: low severity (1.5 (µg/g) NO3-N; 0.27 (µg/g) PO4), moderate severity (1.3 (µg/g) NO3-N; 0.22 (µg/g) PO4, high severity (0.6 (µg/g) NO3-N; 0.12 (µg/g) PO4) and control (unburned)(3.0 (µg/g) NO3-N; 0.11 (µg/g) PO4). Heavy monsoonal precipitation events after the containment of the Las Conchas fire initiated major movement of soil especially in the severely burn areas. This mass movement of soil partially explains the low concentrations of NO3 –N in the burned area, and may have facilitated the availability of PO4 due to the unearthing of parent material. In the unburned site, the decreased concentration of PO4 as compared to the burned plots could likely be explained by utilization through biological processes. Higher concentrations of NO3 –N in the unburned control site compared to the burned sites may also be explained by summer rain facilitating mineralization through microbial processes. Additional research examining soil nutrient dynamics post fire needs to be undertaken in uncharacteristically large, severe fires to better understand the impacts on vegetation recovery.*

Keywords: *Soil, NO3, PO4, Fire, Las Conchas, Climate Change, Fire Severity*

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Fuel Treatment Effectiveness During the 2013 Rim Fire, Stanislaus National Forest, California

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Abstract—*The 2013 Rim Fire started on the Stanislaus National Forest (NF) in the Central Sierra Nevada Mountain Range of California and burned on land managed by several federal and state agencies and private land owners. The Rim Fire grew to a final size of 257,314 acres and became the largest documented fire in the Sierra Nevada Range. Fuel treatment objectives in the preceding two decades for the National Forest System land within the 2013 Rim fire included protection of the wildland urban interface and recreation sites, managing for forest resilience, and reducing hazardous fuels. Fuel treatment activities either removed or mechanically rearranged vegetation and fuels, used fire to consume fuels, or some treatments combined both fuel removal/alteration and prescribed fire. About 36,000 acres of treatments, many with overlapping treatment footprints, occurred on the Stanislaus NF between 1995 and 2013. Over half of the treatments implemented by the Stanislaus NF within the Rim fire perimeter were impacted by the two-day period of rapid growth (34 percent burned on Aug. 21-22, 2013), which burned under 97th percentile weather conditions. Treatments are typically designed for 90th percentile weather conditions.*

The purpose of the national fuel treatment effectiveness monitoring program is to help answer the following questions: 1) Are fuel treatments affecting fire behavior by reducing the fire intensity and/or rate of spread; 2) Does wildfire management improve by enhanced firefighter safety and/or reduced potential fire damage; and 3) What are the lessons learned that are important to help improve the hazardous fuels program? The Rim Fire fuel treatment effectiveness assessment attempted to quickly answer these questions through field visits, eyewitness accounts, and spatial analyses.

Within the Rim fire, over 200 treated areas were first identified using a combination of historical spatial data describing treatments and the Forest Service Activity Tracking System (FACTS) database, and then field visits were completed on a subset of sites. Additionally, the preliminary vegetation severity data was utilized as a composite burn index from the Rapid Assessment of Vegetation Condition after Wildfire process based on the immediate post-fire imagery. When possible, interviews were conducted with incident staff that witnessed fire behavior and management actions in or near the treatments. Initial assessments found that treatments exhibited variable success in altering fire behavior, and the treatments that burned outside the two large progression days more clearly altered fire behavior. Additionally, treatments that implemented a combination of mechanical thinning with prescribed fire or were recently completed were most successful at altering fire behavior and subsequent immediate post-fire severity. Some treatments aided firefighter safety, such as where they were easily accessed, located near priority values at risk, or located where tactics were planned for this incident. Some treatments reduced fire damage or severity compared to nearby untreated sites. Fires the size of the Rim fire present challenges to assessing fuel treatment effectiveness, particularly when they burn under conditions that are outside of the treatment design.

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Fire Behavior Assessment Team (FBAT)—Measurements During Active Wildfires

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Abstract—*Fire behavior and fire effects models are used frequently to inform fire and land management decisions despite their limited evaluation with field measurements, particularly from active wildland fires. The Fire Behavior Assessment Team (FBAT), under the coordination of the Adaptive Management Services Enterprise Team (AMSET, U.S. Forest Service1) and in collaboration with land managers and research groups, is focused on collecting fire behavior data on active wildfires to advance three objectives:*

1) Provide pre-, active-, and immediate post-fire data and active fire video useful for improving firefighter safety and public information;

2) Measure fire behavior and effects on fuel treatments, past disturbances, and on archeological, botanical, and biological resources; and

3) Build datasets useful for calibrating fuel consumption, smoke production, and fire behavior and fire effects models.

In coordination with incident management teams, sampling sites are located opportunistically ahead of fires accounting for expected fire behavior, safe access, and operational tactics. Measurements at each site consist of fuel consumption estimated from pre- and post-fire inventories, as well as wind, temperature, and fire behavior data derived from heat-resistant equipment left on-site prior to, during, and following passage of the active fire front. Fuel moisture data are collected, time-permitting, prior to the fire. Thermocouple arrays are used to estimate fire spread rates and flame front residence times, and heat flux sensors measure radiant and total energy transport. Video imagery is used to estimate flame heights and describe general fire behavior (e.g., flame depth, spot fire ignition) and cup anemometers measure wind speed at a height of five feet above the ground surface. Several fire severity measures (e.g., crown scorch percentage and bole char heights, understory vegetation and soil severity, and fuel consumption) are recorded post-fire.

Since the inception of the FBAT module in 2002 (Vaillant and others 2014), the full data complement has been collected on 17 wildfires (109 sites) and two prescribed burns (32 sites). Collection of data under wildfire conditions is challenging but has proven to be useful. Data collected by FBAT have been reported in wildfire-specific case studies of fuel treatment effectiveness and incorporated in a California study assessing modeled fuel consumptions as related to wildfire emissions (Lydersen and others 2014). Conversations with the scientific and fire management communities are ongoing about methods and applications for FBAT data relative to improving smoke modeling and remotely sensed fire severity maps, assessing fire behavior models, and informing fuel treatment effectiveness evaluation and planning. This presentation outlined data collection methods, described measured variables, and demonstrated the utility of these data for fire managers and scientists. Data collected from the 2008 Clover and 2011 Lion Fires were compared to the BehavePlus fire modeling system's flame length and rate of spread outputs which indicated further adjustments are needed for models to better predict active fire spread as captured in the field data.

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Fire Management Lessons Learned—Evolving Fire Management Programs on the George Washington and Jefferson National Forests and Sequoia National Forest

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Abstract—*The innovative and evolving fire management programs on the George Washington and Jefferson and the Sequoia National Forests were documented in a 2013 Wildland Fire Lessons Learned Center case study1. These fire management programs, with the support of Forest Service leadership, are taking proactive steps to address agency direction in developing and maintaining fire-resilient forests while assuring firefighter and public safety and economic efficiency. Historical fire and GIS data, case study information, and interviews with key fire program and Forest Service leadership were used to inform this study, which was organized into four themes: organizational culture, safety, economics, and natural resource effects and data modeling. While these two National Forests represent vastly different ecological systems with contrasting fire regimes, several common practices have allowed these National Forests to become progressive fire management leaders, such as:*

- *Acknowledgement by leadership that existing practices were not compatible with maintaining functioning ecosystems, based on past significant fire events or current forest conditions.*
- *Embracing management of fire-adapted systems by National Forest leadership, and using fire as a tool to improve overall forest health. Critical habitat was enhanced by managing wildfires for integrated objectives.*
- *Acknowledgement that wildfires managed for both human or infrastructure protection and resource benefit objectives improved firefighter/public safety and ecosystem health.*
- *Tailoring incident actions/operations to the threats and opportunities presented, which resulted in a cost-per-acre reduction for incident management.*
- *Establishing that agency and National Forest direction exists through land management plans to utilize a wide variety of fire management practices to meet land management and public safety goals.*
- *Recognition that larger burned areas under these evolving strategies are resulting in landscape-level improvements in fuel conditions, allowing available fuels funding to be focused on key locations closer to communities and developments.*

Wildfires managed for human or infrastructure protection and resource objectives have benefits beyond ecosystem restoration, including reduced needs for large numbers of ground-based and aviation resources associated with incident-specific safety improvements. These strategic shifts in fire management come with leadership support. Key human factors and commonalities were seen in these fire management programs including: insightful leaders who are responsible for driving the organizational change; support from key partners and stakeholders which is critical to sustain these programs through time; resistance to organizational change decreased as program successes became obvious; and shared risk management between line officers and incident or local fire staff is necessary for the long-term success of resilient landscapes. The four keys to the future success of these programs were: engraining successful fire management practices into day-to-day incident or National Forest operations; remembering the seminal events that lead to the organizational paradigm shift; assuring that policy and enabling documents support resilient or integrated land management practices; and maintaining strong partnerships with stakeholders and the public. Each National Forest has unique challenges in meeting the goals of developing and maintaining healthy, fire-resilient ecosystems, while simultaneously ensuring firefighter and public safety. The George Washington and Jefferson and the Sequoia National Forests have demonstrated that, through the thoughtful use of existing agency authorities, these goals are within reach.

[1]*full report available online at: http://www.wildfirelessons.net/viewdocument/?DocumentKey=de0bb7ad-1010-4b88-8dbd-658ddbc811b8&tab=librarydocuments*

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Fuel Mapping and Fuel Treatment Alternatives for Large Fire Mitigation in the Sage-Steppe

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Abstract—*Large fires (1000 acres +) occur about every seven to ten years in the vegetation types located at US Army Garrison Camp Williams (AGCW) practice range located near South Jordan, Utah. In 2010 and 2012, wildfires burned beyond the Camp's boundaries into the wildland urban interface. Due to fervent public and political reaction, researchers at Utah State University were asked if a spatially organized system of fuel treatments could be developed to prevent future escapes. Using a combination of empirical and model based methods, fire behavior was predicted for the dominant vegetation types at AGCW. Results suggest the need for a removal of woody vegetation within 20 m of firebreaks and a minimum firebreak width of 8 m in grassland fuels. In juniper (Juniperus osteosperma (Torr.) Little), a canopy coverage of 25 percent or less is recommended. In Gambel oak (Quercus gambelii Nutt.) stands along the northern boundary of the installation, a fuelbreak width of 60 m for secondary breaks and 90 m for primary breaks is recommended. Final results will be reported in a M.Sc. thesis to be completed by the senior author.*

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Short Term Fire Impacts on Aquatic Macroinvertabrate Community Structure in the San Antonio Creek, Jemez Mountains, NM

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Abstract—*In June 2011, the 156,593 acre Las Conchas fire burned 30,000 acres (55 mi^2) of the Valles Caldera National Preserve (VCNP), located in the Jemez Mountains, NM. The day after the fire was contained, the monsoonal precipitation runoff carried large amounts of debris and water that impacted the San Antonio Creek located in the Valle Toledo within the VCNP. This study assessed the short term impacts that fire-induced precipitation runoff had on the aquatic insect community at various distances downstream from the fire within the San Antonio Creek headwater sub-basin. Pre- and post-fire aquatic insect samples were collected (June 2011 pre-fire, October 2011, June 2012, and October 2012 post-fire) at three different locations (Toledo Well Heads, San Antonio Cabin, and San Antonio Hot Spring) along the San Antonio Creek at increasing distances from the source of post fire surface runoff. Quantitative aquatic insect samples were collected from riffle areas in triplicate from each site on each sampling date using a circular Hess sampler. After samples were sorted, counted, and identified to family, indices for the following metrics were calculated: taxa richness; Jaccard's coefficient of similarity; community loss, Simpson's diversity, Shannon-Wiener Diversity; EPT; EPT+C; and the Family Biotic Index (FBI) to assess fire impact. Results indicate that all measures declined significantly post-fire with a gradual recovery towards pre-fire conditions one year later. As expected, sites closest to burned areas experienced the largest impact to community structure and water quality when comparing pre and post fire data. The pre- and post-fire (June to June) comparison for both the Toledo and Hot Spring sites respectively resulted in a declining density (653>463 individuals^{-1}M^2) and (487>186 individuals^{-1}M^2); Shannon-Wiener index (2.34>1.87) and (2.31>2.27); taxa richness (24>16) and (23>22); and EPT (949>326) and (1320>917). The FBI rating pre and post fire for the June 2011 to June 2012 comparison indicated very little change in score where the pre- and post-fire rating did not change from "Fair" and "Good" respectively. Based on these results we can conclude that, one year after the fire, recovery of community structure (richness, percent similarity and diversity) to pre-fire conditions has not occurred at sites closest to the burned area. Based on these metrics, the recovery that has occurred in the richness and diversity indices is due to the increased number of tolerant species moving into the impacted areas. Overall, the San Antonio Hot Spring site (furthest downstream from the burned area) appears to have fully recovered to pre-fire conditions when using both the community structure and water quality measures. This study illustrated that runoff from a forest fire had a significant short term effect on aquatic insect community structure and, based on the FBI rating, also on stream water quality.*

Keywords: *Aquatic Insects, Diversity, Richness, Impact, Water Quality, Fire, Valles Caldera*

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Operational Test Results and Technical Description of the Xiomas Airborne Wide Area Imager

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Abstract—*The Airborne Wide Area Imager for Fire Mapping and Detection (WAI) has been developed by Xiomas Technologies under the NASA Small Business Innovation Research (SBIR) program. Xiomas worked with NASA and USDA Forest Service personnel during the development process to incorporate both operational requirements and the latest technologies in the design of the WAI.*

The overall goal of the WAI SBIR project is the development of an airborne sensor, which could increase the efficiency of the National Interagency Fire Center (NIFC)—National Infrared Operations (NIROPS) by fielding a sensor that covers more ground in less time and with higher spatial resolution. We estimate that this technology will reduce the NIROPS flight time over fires significantly (by approximately a factor of 2).

As of this report, the WAI has flown about twenty flights, including a number of engineering tests, calibration flights, several flights for a commercial imaging project, and the fire mapping flights detailed here.

A multi-day Test and Evaluation mission was conducted during July 23-26, 2013, to operate the WAI sensor over active fires. High-resolution (3 foot) two-band thermal infrared imagery of active wildfires was collected and provided to the USFS for evaluation to determine the operational usability of the WAI imagery for deriving standard tactical fire mapping/geospatial products. WAI imagery was collected within 1 hour of the Forest Service Phoenix system imagery over the same fires.

Flight operations generally occurred between 10:30 pm and 2:00 am. Immediately following the flights Xiomas delivered the orthorectified imagery to the USFS, briefed the USFS personnel on the flight and any items of interest in the imagery, and participated in the evaluation of the imagery by Forest Service personnel.

Results in brief:

- *Registration of the WAI imagery to the National Agriculture Imagery Program (NAIP) reference base imagery was very good. Most of the WAI imagery lined up almost perfectly with the NAIP. There are a few areas with registration errors of up to 10 meters.*

- *Spatial Resolution of WAI imagery was very good with small features such as drainages, structures, and roads, clearly visible.*

- *Fire detection was very similar to the USFS Phoenix system.*

Based on previous engineering flight test results, Xiomas has shown that the WAI is capable of detecting a 6 inch by 6 inch fire from an aircraft altitude of 35,000 feet above ground. Acquisition rate will vary based on altitude above ground and speed. As an example, the WAI can be configured to operate at 17,000 feet above ground and at typical cruise speed of 210 knots, the system will map approximately 680,000 acres per hour.

The presentation includes detailed results of the fire mapping flights in addition to an overview of the engineering test flights and commercial imaging projects. A technical overview of the sensor is presented as well as a discussion of ongoing activities to further develop the technology for space-based operation, and for persistent/staring operation.

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Forest Fires, Climate Change and Community Based Fire Management in Bolivia

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Abstract—*Bolivia is one of the most biologically diverse countries in the world, with nearly half of its territory covered by forest. Yet, in the last decade, forest fires have become a major threat to biodiversity and human livelihoods. Fires have burned around 24.5 million hectares of forest and grassland over the past 13 years, showing an increasing trend in burned area and a cyclical pattern of extreme fire seasons which occur every two to three years with devastating consequences for the entire country.*

The main causes of forest fires in Bolivia are related to human activities, such as traditional slash-and-burn agriculture, grassland burning for livestock management and the burning of piled biomass from mechanized agriculture. Climate change adds to these threats, with warmer and drier conditions that increase the risk of forest fires.

Facing this situation, Fundación Amigos de la Naturaleza (FAN) works together with local authorities since 2011 on a pilot initiative of community-based fire management and climate change adaptation around protected areas in the Chiquitano Dry Forest ecoregion in the department of Santa Cruz. This initiative is currently being replicated in the Northern Bolivian Amazon region in the department of Beni.

These initiatives have increased the level of participation and coordination among local communities to address forest fires and climate change through the establishment of inter-community fire management committees, which include indigenous and peasant communities, neighboring ranches and Mennonite colonies. Communities are adopting best practices of fire use in their agricultural activities and are actively involved in the planning and implementation of actions to prevent and combat forest fires. Controlled burns are scheduled and conducted in a coordinated way with the community, and fire-fighting brigades have been created to strengthen capacity for quick response of communities to prevent larger fires.

An early warning system of fire risk is being implemented at regional and community level, enabling to conduct agricultural burnings during days with lower risk to reduce probabilities of uncontrolled fires. Also, institutions involved in forest fire management are able to take better informed decisions, as they are provided with near real time information on fire risk, active fires and burned areas, as well as historical information, which is available on a web-based system.

Additional Keywords: *fire risk early warning system, controlled burns, fire management committees*

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A 'Leopoldian' Fire Ethic to Empower Ecological Fire Management

Timothy Ingalsbee, Executive Director, Firefighters United for Safety, Ethics, and Ecology, Eugene, OR

Abstract—*Firefighters United for Safety, Ethics, and Ecology (FUSEE) is a national nonprofit organization promoting safe, ethical, ecological wildland fire management. FUSEE members include current, former, and retired wildland firefighters; fire managers, scientists, and educators; forest conservationists; and other interested citizens who support FUSEE's holistic fire management vision.*

FUSEE's primary mission is to provide public education and policy advocacy in support of the 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 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 of workers and citizens able to work safely and live sustainably with wildland fire.

Inspired by Aldo Leopold's "Land Ethic," FUSEE advocates for a new "Fire Ethic" in fire management policies and practices:

> *"A thing is right when it contributes to the safety of firefighters and the public, ethical use of public resources, environmental protection of fire-affected landscapes, and ecological restoration of fire-dependent ecosystems. It is wrong when it tends otherwise."*

This poster will display FUSEE's philosophy, mission, research, education, and advocacy projects. Elaboration of some key FUSEE concepts will be featured, including: the FUSEE triad of safety, ethics and ecology; re-identifying firefighters as fire rangers; promoting community fire preparation; creating fire-compatible communities, restoring fire-permeable landscapes, and the fire ethic for ecological fire management.

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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Hydrologic Impacts of Burn Severity on Nutrient Concentrations in Surface Water, Jemez Mountains, NM

Anita Lavadie, Sara Brown, Joseph Zebrowski, Edward Martinez, New Mexico Highlands University, Las Vegas, NM

Abstract—*Climate change is currently intensifying wildfire behavior and thus fire severity in the Southwest. After a fire, surface water runoff may contribute high concentrations of nutrients to water bodies, which may potentially impair surface water quality in the receiving aquatic systems. Although there is a considerable amount of research on the effects of nutrients in streams following fire, conditions on nutrient levels transported from various fire severity classes on a small scale is not well researched. The purpose of this study was to investigate the contributions of total suspended solids (TSS), nitrate-nitrogen (NO_3-N) and orthophosphate (PO_4) concentrations in surface water runoff originating from high, moderate, low, mixed, and control (unburned site) fire severity types from the Las Conchas fire in the Jemez Mountains, New Mexico. Prior to surface water runoff sampling, fire severity classification was determined for four (Control-unburned, Low, Moderate, and High) sub-drainages within the Cerro del Medio area in the Valles Caldera Preserve using fuel load measurements and remote sensing imagery. Once fire severity classification was confirmed, ISCO automated water samplers and buried single stage water-samplers were used to collect surface water runoff from ten precipitation events at each severity collection location during the 2012 monsoon season. Total suspended solids were measured from surface runoff collected at a mixed severity (inclusive of all severities) site as well. TSS, NO_3-N, and PO_4 concentrations were determined following standard Environmental Protection Agency (EPA) methodology. TSS was determined using a gravimetric method and nitrogen and phosphate concentrations were determined using colorimetric methods using an OI Analytical Auto Analyzer. Preliminary results show that TSS were highest from the mixed severity site and increased with fire severity from Low to Moderate, to High severity burn. Additionally, NO_3-N concentrations in surface runoff also increased with fire severity. TSS concentrations ranged from 3 mg/L to 28 mg/L; NO_3 concentrations ranged from 3.1 mg/L at the Control site to 7.8 mg/L at the High severity site. PO_4 concentrations decreased with fire severity, ranging from 0.35 mg/L at the Control site to 0.1 mg/L at the High severity site. Data from all burned severity classes were collapsed and a t-test analysis determined that the average NO_3-N, and PO_4 nutrient concentrations between burned and unburned (Control) sites were significantly different ($p<.001$). Results from the Las Conchas fire illustrate the potential for nutrient loading in runoff that may result from high severity wildfires. Our findings suggest that large wildfires or "mega-fires" experience amplified nutrient modifications and can pose negative water quality effects on receiving aquatic systems. Additionally, removal of nutrients from the landscape by surface runoff can result in nutrient-poor soils and may prolong regeneration of vegetation, especially in areas burned at high severity. Quantifying the removal of nutrients from the landscape via TSS and surface runoff and their contribution to aquatic systems will provide scientists, land managers, and policy makers with the empirical information to make well-informed land management decisions in regard to the impacts and recovery from large wildfires.*

Keywords: *Las Conchas fire, Total suspended solids, Nutrients, Surface runoff, Fire severity*

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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A Synthesis of The Las Conchas Fire: How Does it Compare?

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Abstract—*As wildfires have been increasing in extent and severity throughout the Southwest, so have the fire effects. Unlike many other big fires, the 156,593 acre Las Conchas fire of 2011 uncharacteristically burned more than 61,000 acres in a 24hr period on June 27 where over 50 percent of the total area burned at moderate and high severity. Its severity and extent provided the opportunity to develop better tools to understand and classify severity and its impact on ecological processes, natural resources, and human communities. As a means to contextualize the significance of the Las Conchas fire, the fire effects produced were compared to other recent, regionally relevant large fire events such as the Whitewater-Baldy (2012; 297,845 ac) and Silver fires (2013; 138,705 ac). Furthermore, the impacts to both natural resources and communities based on findings from our studies of the Las Conchas fire were synthesized. The Whitewater Baldy fire was two times larger than the Las Conchas fire and burned an area characterized by mixed-conifer, ponderosa pine, piñon-juniper and grasslands. The Silver fire was the largest fire of 2013 in the southwest. The burned area was characterized by mixed-conifer, ponderosa pine, piñon-juniper, and woodlands. Compared to the over 30 percent area burned at high severity of the Las Conchas, the area burned at high severity was 15 percent and 13 percent respectively for the Whitewater Baldy and Silver fires. Additionally both of these fires burned within their historical range of variability unlike the Las Conchas, where fire behavior was not characteristic of a frequent fire regime. The precipitation after the containment of the Las Conchas fire initiated major movement of soil especially in the high severity burned areas. This mass movement of soil resulted in low NO_3-N and PO_4 concentrations in soil collected from the high severity study site. Results indicated that NO_3-N and PO_4 concentrations in soil decreased with an increase in fire severity. Both of these relationships were opposite (nutrient concentrations increased with severity) for NO_3-N and PO_4 concentrations in surface water runoff collected from the control and the various burn severity sites. A significant negative correlation was determined for presence of vegetation with burn severity and bare ground, i.e., as bare ground and burn severity increased, presence of vegetation (biomass, diversity, and seed bank regeneration) decreased. Similarly, the impact of surface water runoff and debris flows entering the San Antonio Creek was evident in the decreased aquatic insect community structure when comparing pre- and post-fire aquatic insect data. The Las Conchas fire was out of the historic range of variability when we compare it to other large, regional fires. Based on climate change model projections of increased temperatures and increased drought conditions, as well as current forest management policies and fire suppression activities we can speculate that the Las Conchas fire is an excellent representation of future fires in the southwest. It is imperative that fire scientists and fire managers collaborate to develop policies that will allow for the creation of resilient forests that will minimize ecological and social costs of future fires similar to Las Conchas.*

Keywords: *Synthesis, Las Conchas Fire, Nutrients, Vegetation, Soil, Impacts*

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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Vegetation Response to the Las Conchas Fire, 2011

Richard McNeill, New Mexico Forest and Watershed Restoration Institute, Las Vegas, NM; **Sara Brown, Edward Martinez,** New Mexico Highlands University, Las Vegas NM

Abstract—*The Las Conchas fire burned in the Jemez Mountains of northern New Mexico in 2011, and was the largest fire in New Mexico's history until the Whitewater-Baldy fire surpassed it the following year, 2012. The Las Conchas fire exhibited intense fire behavior that burned 178 km^2 (44,000 acres) in the first 13 hours, and a total of 634 km^2 (156,593 acres). The intense fire behavior led to severe first and second order fire impacts across the landscape. This study describes the vegetation response to the Las Conchas in the mixed-coniferous forest of the Valles Caldera Preserve, New Mexico. Four study areas were delineated based on fire severity classification: high, moderate, low and unburned (control). Four factors were evaluated across these fire severity types: vegetation cover, diversity, biomass and seed bank. Vegetation cover, biomass and diversity data were collected for two years post-fire and seed bank data were collected one year post-fire. Cover and diversity were estimated using the line point intercept method, along five 50 m transects within each severity class in May, June and July in 2012 and in August/September 2013. Biomass was collected using four, 0.25 m^2 quadrats along the same 50 m transects at the peak of the growing season in July 2012 and September 2013. The seed bank was evaluated by collecting four soil samples from each of the 20 plots in July 2012 and identifying species that germinate for one year in a controlled greenhouse. Canonical discriminant analysis showed clear and significant separation between the vegetation response in the different fire severities and between the different sampling dates. For the field transect data, the mean number of species across fire severities were: Control, 6.47; Low severity, 6.4; Moderate severity, 6.1; and High severity, 3.57. The seed bank experiment produced 18 species in the Control site, 15 species in Low severity, 11 species in Moderate severity and 5 species in High severity. The Control site had a mean of 9.93 gm^{-2}of biomass, Low severity had 69.18 gm^{-2}, Moderate severity had 59.54 gm^{-2}, and High severity had 48.16 gm^{-2}. The Control had a mean herbaceous canopy height of 7.77 cm, Low severity was 11.53 cm, Moderate severity was 8.67 cm, and High severity was 4.08 cm. One primary metric examined was bare ground; this has a strong influence on second order fire effects such as mass movement of earth downslope. The control site had a mean bare ground amount of 2.93 percent; Low severity, 13.20 percent; Moderate severity, 11.37 percent; and High severity, 34.93 percent. Considering the unusually large amount of area categorized as high severity, this could have resulted in as much as 99.18 km^2 (24,507acres) of bare ground immediately following the Las Conchas fire.*

Keywords: *Vegetation, Response, Fire, Severity, Bare Ground, Las Conchas, Valles Caldera*

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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Wildfire Interactions With Fuel Treatments in Sierra Nevada Forests: Consequences for Forest Structure and Understory Plant Diversity

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Abstract—*Wildfires in the Ponderosa pine (Pinus ponderosa Laws.) and mixed-conifer forest belt of the Sierra Nevada Mountains in California are increasing in size and severity. These increases are due to forest structural changes and accumulated fuel loads associated with past management practices after a century of fire exclusion. The most common management strategy in these forests is to implement fuel treatments to reduce canopy fuel loads and decrease subsequent wildfire severity. We present results from a large statewide study of fuel treatment-wildfire interactions, with specific focus on the ecological effects of these two disturbances on forest structure and understory plant diversity. We sampled forest vegetation plots from twelve wildfires that burned into previously implemented fuel treatments, as well as adjacent unburned fuel treatments and controls. We show that wildfire severity is dramatically reduced by fuel treatments, with tree mortality decreasing by up to 75%, and that the degree of structural change caused by wildfire is much less in treated stands than in untreated, high tree density stands. Effects of fuel treatments on patterns of shrub and tree regeneration in response to wildfire are contingent upon whether stands had previously been treated, with post-wildfire shrub recruitment highest in untreated stands and post-wildfire tree recruitment highest in treated stands. We found strong evidence that the extent of forest canopy disturbance affects the diversity and composition of the understory plant community. Intermediate levels of forest disturbance, which we largely found in treated forests that subsequently burn in wildfire, had the highest stand-level understory plant diversity, relative to unburned forests or untreated forests that burned at high-severity. We used information on species' evolutionary histories and traits to demonstrate that the proportion of the understory flora with evolutionary origins in mesic climates decreases with increasing fire severity, and that increased water stress in open-canopy forests following high-severity fire may filter understory species composition on the basis of leaf traits.*

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The Impacts of Wildfire on Amphibian Populations in Northern New Mexico and Southern Colorado

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Abstract—*Climate models suggest that the planet is becoming hotter and drier. As a result, natural disturbance cycles, such as forest fires, have been altered across many ecosystems in the American Southwest. Wildfires are becoming increasingly larger and are burning more severely, affecting wildlife habitat, especially amphibian habitat. One of those large forest fires was the Track Fire, which burned 11,247 ha in 2011 on the border of New Mexico and Colorado. This fire burned with unusual severity through the riparian areas, fully consuming all aboveground vegetation.*

The purpose of this study was to investigate the impacts of the Track Fire on amphibian population dynamics, vegetation and water quality within northeastern NM and southern CO. Field data was collected during the spring of 2013 at both an unburned control location along the Sapello River (Prizlaff Ranch), and two sections of river burned during the Track Fire. Three methods were used for sampling amphibians including minnow trap deployments, day and night visual surveys, and frog call transect surveys. Additionally, line-point intercept transects were used to measure the changes in vegetation, and analysis of water nutrients using sondes, temperature probes, and collecting total organic carbon (TOC) from the stream bottoms.

Our results suggest the burned areas have far fewer amphibians (zero animals per 50 meter reach) than the control (at least two animals seen per 50 meter reach) and were found to be statistically significant (visual day surveys ($U = 172.5$, $Z = -11.2$, $p = 0.00$), visual night surveys ($U = 196.0$, $Z = -6.9$, $p = 0.00$), call surveys ($U = 96.0$, $Z = -4.8$, $p = 0.00$), and minnow trap surveys ($U = 478.5$, $Z = -2.3$, $p = 0.02$); this is likely related to differences found in several vegetation parameters including the number of points with a canopy height above zero, the percent of woody cover, and the percent of shrubs as well as TOC at both sites. Amphibians still were not recovered two years after a large high severity fire. We expected that amphibians will take several additional years to recover after a severe wildfire; however, additional work is needed to determine what environmental factors are ultimately impacting the amphibian populations. It can be inferred that under climate change predictions, more frequent and severe could significantly influence amphibian populations in the southwest.

Keywords: *amphibians, fire severity, habitat, water quality, vegetation, Climate change*

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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Characterizing Post-Fire Vegetation Conditions in a Small Watershed Using High Resolution Color Infrared Imagery and LiDAR

Joe Zebrowski, New Mexico Highlands University, Las Vegas, NM; **Patti Dappen,** New Mexico Forest and Watershed Restoration Institute, Las Vegas, NM

Abstract—*In the summer of 2011 the Las Conchas fire burned over 60,000 hectares in the Jemez Mountains. This study examines a method used to assess the fire's impact on vegetation in a small 137 hectare Cerro del Medio watershed in the Valles Caldera. Shortly after the fire, New Mexico Highlands University researchers began a study of the relationship of different burn severities on surface water runoff nutrient levels. The resolution of Landsat-derived differenced Normalized Burn Ratio (dNBR) data is too coarse to adequately delineate burn severity and vegetation conditions for such a small area. To better assess the vegetation conditions of the drainages above each surface water runoff sample site, the team turned to Light Detection and Ranging Data (LiDAR) collected in 2010 and high resolution color infrared (CIR) aerial photography collected in October 2011. LiDAR derived height and canopy data were used to broadly classify the vegetation (tree, shrub, grass, bare ground) of the watershed. This was combined with Normalized Difference Vegetation Index (NDVI) data derived from post-fire CIR imagery. The result is an estimate of area burned by vegetation class and a more accurate delineation of the total area burned above each surface water runoff sampling site. This improved delineation will be combined with ground observations and the Landsat dNBR data to describe the burn severity in the drainages.*

Keywords: *Watershed, LiDAR, Imagery, Las Conchas Fire, Runoff, Infrared, Valles Caldera*

In: Keane, Robert E.; Jolly, Matt; Parsons, Russell; Riley, Karin. 2015. Proceedings of the large wildland fires conference; May 19-23, 2014; Missoula, MT. Proc. RMRS-P-73. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 345 p.

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