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Proceedings of the Fire Continuum—Preparing for the Future of Wildland Fire

Missoula, Montana May 21-24, 2018

THE FIRE CONTINUUM
MAY 21-24, 2018 • MISSOULA, MT
PREPARING FOR THE FUTURE OF WILDLAND FIRE
CONFERENCE

Forest Service
Rocky Mountain Research Station
Proceedings
RMRS-P-78
July 2020

Hood, Sharon M.; Drury, Stacy; Steelman, Toddi; Steffens, Ron, [eds.]. 2020. Proceedings of the Fire Continuum—Preparing for the future of wildland fire; 2018 May 21-24; Missoula, MT. Proceedings RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Abstract

The Fire Continuum Conference, co-sponsored by the Association for Fire Ecology and the International Association of Wildland Fire, was designed to cover both the biophysical and human dimensions aspects of fire along the fire continuum. This proceedings includes many of topics covered during the conference—including pre-fire planning and management, strategies during an incident, and post-fire effects and management options. It contains extended abstracts and full papers based on some of the presentations as well as field trips.

Keywords: wildland fire, prescribed fire, planning, response, recovery, wildland urban interface, disturbance, ecology, behavior, diversity, fire effects, fuels and fuels management, air quality, smoke management

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Cover photos

Upper left: Field trip leaders discuss the 2017 Lolo Peak Fire. Center left: Some conference attendees participated in a group hike to the “M” to enjoy the Missoula sunset. Bottom left: Panelists share ideas about ways to advance fire behavior science. Center right: Field trip participants learn and discuss aspects of prescribed fire while observing a burn at Lubrecht Experimental Forest. Bottom right: Field trip participants learn and discuss aspects of fuel treatments and challenges to forest management in the wildland urban interface on the Lolo National Forest.

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Acknowledgments

The Association for Fire Ecology and the International Association of Wildfire would like to thank the conference committee and all the sponsors that that contributed funding and support to make the Fire Continuum Conference and Proceedings happen.

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Preface

Wildland fire science and management are defined by continuums. There is the continuum of fire experience from the rookie firefighter to the seasoned fire manager. There is a continuum of succession from the post-burn environment to development of vegetation to an eventual return of fire. There is the continuum of education from basic fire courses to advanced degrees offered by universities and certifications offered by professional societies. And most importantly, there is the continuum of fire management from pre-wildfire activities, such as prescribed fire and mechanical treatments, seasonal wildfire planning and fire danger prediction, to the actual wildland fire occurrence, followed by post-fire rehabilitation of burned areas and affected communities.

The Fire Continuum Conference was designed around all the fire management continuums that exist today, including pre-fire planning, management during a wildland fire, and post-fire activities. It brought together experts in wildland fire from more than 20 countries around the world. Co-sponsored by the Association for Fire Ecology and the International Association of Wildland Fire, the event had the tagline “Preparing for the Future of Wildland Fire.” The conference was a platform for formal knowledge-sharing through over 400 oral and poster presentations and 16 training workshops, as well as experiential learning through 6 field trips that allowed participants to learn about and discuss science and management activities that occur along the fire continuum—before, during, and after wildland fires. Keynote speakers and panelists discussed the latest thinking on long-term fire planning, wildland fire behavior, post-fire ecology, human dimensions, and other management activities. Vicki Christiansen, Chief, US Department of Agriculture, Forest Service opened the conference with a keynote presentation. The conference also featured 25 sponsors and exhibitors representing Federal agencies, universities, nonprofits, companies, and consultant groups.

The timing and location of the Fire Continuum Conference in May 21-24, 2018 was apt. Unknown to conference organizers in 2015 when Missoula was chosen as the meeting location, the 2017 wildfire season in Montana would become one burned into its residents’ memories. Over one-million acres burned in the State that year, producing some of the worst air quality conditions ever reported. Missoula was the perfect setting to convene an international conference of over 500 wildland fire experts less than a year after that epic 2017 season. But Missoula is also a natural choice for such a conference for other reasons. The city is small, but it is home to the University of Montana and its College of Forest Resources and Conservation and many offices of the U.S. Forest Service. In Missoula alone, the Forest Service locates its Northern Regional office, the Lolo National Forest Supervisor office, the Lolo National Forest Missoula Ranger Station, a smokejumper base, a technology and development center, and three research laboratories of the Rocky Mountain Research Station—including the Fire Sciences Lab—which focuses solely on wildland fire research. The majority of land in western Montana is publically owned by the U.S. Forest Service, the Bureau of Land Management, the Montana Department of Natural Resources and Conservation, all of which are within the ancestral homelands of several federally-recognized tribes including the Confederated Salish and Kootenai Tribes and Pend d’Oreilles. Many adjacent nations including the Confederated tribes of Colville, Blackfeet, and Nez Perce occupied the lands known today as western Montana. Scattered amidst public lands are private inholdings, population centers like Missoula, and numerous small towns—in other words lots of wildland urban interfaces to consider when fires occur. This diversity in land ownership and plethora of people working in the fields of wildfire and natural resource management offered the perfect setting for dialog about wildland fire issues.

This proceedings is the distilled version of the topics covered during the conference. It contains extended abstracts and full papers based on some of the presentations. The “me-too” movement loomed large in 2018, and the conference included a panel on the need for diversity and inclusivity in all fields of wildland fire. There is a full paper devoted to this important topic. Four of the six field trips are summarized through collaboration with the Joint Fire Science Program’s Northern Rockies Fire Science Network. As a companion to the formal proceedings and to see the full gamut of topics covered, all oral and poster presentation abstracts can be viewed at https://fireecology.org/fcc-abstracts. What readers can’t see in this proceedings is the huge value gained by the in-person experience of the conference. In a world of webinars, tweets, and floods of digital information, this conference allowed invaluable opportunities for face-to-face conservations, relationship building, manager-researcher communications, and getting to know the aspects of fire from around the world. Such golden opportunities stimulate research and cutting-edge management strategies by introducing people to new ideas. It is our hope that ideas shared during the Fire Continuum Conference provide a lasting imprint on the global fire community for better stewardship of our natural resources and better protected communities in fire-prone environments.

Proceedings Technical Editors,

Sharon Hood
Stacy Drury
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CONFERENCE ABSTRACTS

As a companion to the proceedings, all oral and poster abstracts delivered during the conference are available at https://fireecology.org/fcc-abstracts. Abstracts are grouped by how they were presented during the conference: special session abstracts, concurrent session abstracts, micro-talk abstracts, and poster abstracts.

Inclusivity Paper

On the Need for Inclusivity and Diversity in the Wildland Fire Professions

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INTRODUCTION AND BACKGROUND

Inclusivity and diversity are being increasingly recognized as important factors in the production of scientific knowledge, not only for the sake of equal opportunity, but as necessary to the best quality research (e.g. Feliú-Mójer et al 2018; Poster 2018; Smith et al 2018). However, lack of diversity persists in many if not all scientific fields to varying degrees (e.g. Pérez 2018; Poster 2018), and affects various facets of research and education including the underrepresentation of women in leadership at universities (Smaglik 2018; Hamburg et al. 2018), in the peer-review process (Lerback 2017), and in publication in high-impact journals (Shen et al 2018; Woolston 2018).

As such, inclusivity remains a challenge in the field of wildland fire science and management (Smith et al. 2018). Inclusivity and diversity are stymied by a number of factors, but sexual harassment, gender discrimination, and implicit bias are most prevalent. Sexual harassment is conduct of a sexual nature in a workplace or social situation that affects an individual's employment or work performance (EEOC 2016; Hamburg et al. 2018). Sexual harassment can take the form of requests for sexual favors, obscene remarks, or unwelcomed sexual advances. Gender discrimination occurs when someone is treated unfairly due to their gender (Association for Fire Ecology 2016). It can manifest in unequal pay and/or inequitable opportunity for promotion, benefits, or other professional rewards. Discrimination can be deeply embedded in institutional cultures, so that people may be unaware they are participating in discriminatory practices (Flood and Pease 2009). Implicit bias occurs when individuals unconsciously attribute characteristics to social groups, including women and minorities, based on stereotypes.

The International Association for Wildland Fire (IAWF) and the Association for Fire Ecology (AFE) are two nonprofit organizations working to improve the understanding of wildland fire as an ecological process as well as to increase the safety and effectiveness of the management of wildland fire. As such, AFE and IAWF are working to increase inclusivity in this field. These two organizations were the sponsors of the Large Fires Conference in Missoula, Montana, in May 2014, and the Fire Continuum Conference in Missoula, Montana, in May 2018 (the proceedings of which this paper is included). At the Large Fires Conference, a board member of AFE learned of an assault against a female conference attendee. This incident spurred an AFE effort over the next few years to survey members of

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the wildland fire professions to gain an understanding of the scope and prevalence of gender discrimination and sexual harassment in this field. As the issue gained a national profile, AFE was invited to submit written testimony on the survey to the Full House Committee on Oversight and Government Reform hearing on Examining Sexual Harassment and Gender Discrimination at the US Department of Agriculture in December 2016 (Kobziar 2016).

In the winter of 2017, AFE and IAWF received a letter signed by over 50 wildland fire professionals ranging from those working in research to land management to the non-profit sector in at least three countries. The letter stated that, "Over the past several AFE and IAWF conferences, a disproportionate number of plenary speaking roles have been awarded to non-minority male scientists. For example, at the recent AFE Orlando conference, only 4 of 19 plenary speakers were women, and minority scientists were strikingly underrepresented. Our profession is growing, and many distinguished colleagues are not being recognized at these conferences…As ecologists, we understand that strength and capacity exists in diversity, not only in ecosystems, but also in societies and associations."

An examination of the gender ratio in recent AFE and IAWF conferences indicated that this ratio (approximately 1 in 5) was not an aberration. A plenary session on inclusivity was added to the program of the Fire Continuum Conference as a first step in this campaign, with the speakers comprised of Sara Brown, Karin Riley, Diego Pérez Salicrup, and Toddi Steelman (many of the authors of this manuscript). In this manuscript, we discuss the scope and prevalence of the problem, examine some of the effects, and discuss steps IAWF and AFE are taking to monitor and address the problem.

Defining the Problem

The AFE survey found that sexual harassment and gender discrimination are prevalent in the wildland fire vocation (Association for Fire Ecology 2016). Out of the 342 respondents, 24 percent reported experiencing sexual harassment in their workplaces, with 32 percent having witnessed it. One respondent recounted, "The engine captain had me ride alone with him and spoke in great detail about my breasts." Gender discrimination was more widely reported, with 44 percent having experienced it in their workplaces while 54 percent had observed it. A respondent reported, "Women have to fight to be included in group discussions, planning strategy and tactics." Because sexual harassment and gender discrimination are often underreported (McDonald 2012), these proportions might be lower than the proportion in the population at large. Indeed, the majority of survey respondents who were affected by sexual harassment or gender discrimination didn't report it (64% and 60% respectively). Of those who did report, their workplaces supported them a little over half the time, with their manager being supportive only 58 percent of the time and the broader organization only 53 percent of the time. Legal intervention and external agencies were rarely of assistance in resolving the reported issues.

As noted above, gender discrimination can also result in the underrepresentation of some groups in prestigious positions. For example, the approximate ratio of 1 woman in 5 speakers applies to the plenary speakers in several recent wildland fire conferences. The ratio of plenary speakers from ethnic minorities and from various countries has not yet been effectively tracked or tabulated in AFE conferences, but is also likely to be underrepresented. For recent IAWF conferences, women and diversity speakers held a combined 28 percent of plenary speaking slots, with white males holding the other 72 percent.

Because fire is an ecosystem process present worldwide, research on fire should reflect the participation of scientists working in different countries to capture socio-ecosystem differences and understand not only the diverse effects of fire on vegetation, but the ways in which cultures manage fire. However, some countries are clearly underrepresented. In a bibliometric search, using the words "fire" and "forests", Ibero-American countries contributed 3,004 research manuscripts during the period 2000-2018, of which 2,575 contributions came from only six countries: Spain, Brazil, Mexico, Portugal, Argentina and Chile (fig. 1). Yet, as unbalanced as this number seems, it is overshadowed by the contributions produced in the United States and Canada, with a total

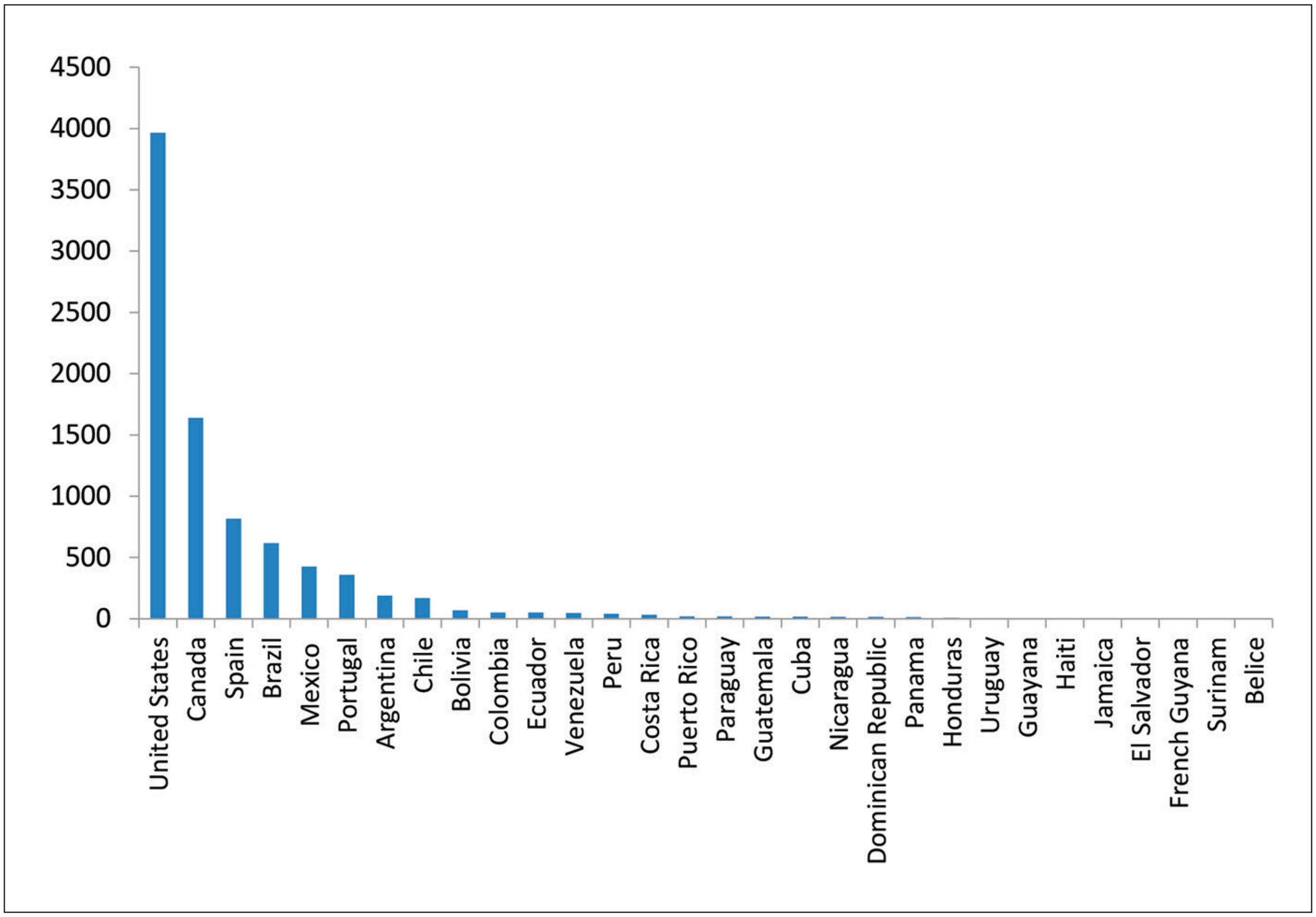

Figure 1—Heterogeneity in the amount of literature concerning forest fires in Ibero-American countries, plus the United States and Canada. The number of publications was generated by searching in Scopus using the words “Fire,” “Forest,” and “Country Name” for the years 2000-2018 (search conducted on May 19, 2018).

of 5606 (fig. 1). Promoting fire research in diverse cultural contexts will benefit the whole scientific community, and would broaden our perspective on the relation between humans and forest fires.

This pattern of underrepresentation is also visible within countries. For example, in Mexico, where the proportion of urban inhabitants has been increasing, legislation regarding forest fires is clearly biased against rural inhabitants (Martínez-Torres and Pérez-Salicrup 2018). Yet, rural inhabitants have used and managed fires historically, and may contribute to avoiding atypically severe large wildfires. By incorporating traditional fire knowledge from rural communities, fire scientists and fire managers would benefit from empirical knowledge that would otherwise be lost.

This is particularly true for the perspectives of women, who are not only underrepresented in all fire-related work (research, management, and planning), but who have been traditionally marginalized. In Mexico, there are only 58 women out of 1,731 individuals in Federal forest fire fighting brigades. Currently, the Federal Government (CONAFOR) and Organizations of the Civil Society (Mexican Fund for the Conservation of Nature) are making an effort to incorporate more women in fire related jobs, yet the greatest challenge is to include women from minorities such as indigenous communities. Implicit bias and gender discrimination appear to be present in Mexican universities as well. Though women in Mexican universities are often perceived as being less productive than their male colleagues due to implicit bias, in fact they are on average 8 percent more productive (León et al 2016).

However, women are less likely than their male peers to be rewarded, with significant barriers to success, including being 35 percent less likely to be promoted at public research centers and with only 11 percent of senior-ranking positions being occupied by women (León 2017).

While working as a wildland firefighter, a traditionally hyper-masculine culture, female firefighters may feel the need to change their personalities to fit in. Sara Brown reported that, " 'fitting in' with the firefighter culture is essential for safety and a positive work environment", which she accomplished by creating "a masculine version of myself" (Brown 2017). When other women attempted to join the fire crew, Brown found that she actively eschewed them. In retrospect, she attributed her actions to two theories. The first is tokenism: in a study conducted in the early 1980s, when women in male-dominated firms felt that only a limited number of them would be promoted, they actively competed with each other (Ely 1995). The second theory is that of the Queen Bee: in explaining the near absence of women in the upper echelons of academia, Naomi Ellemers found that women coped with gender discrimination by emphasizing their differences from other females (Ellemers et al 2004). Conditions that foster the Queen Bee syndrome are present on the fireline: women are marginalized, large sacrifices have been made for career, and women may not identify strongly with their gender.

Effects

The AFE survey found that gender discrimination and sexual harassment in the workplace caused numerous impacts to the respondents, who reported negative effects on their career such as needing to change jobs, emotional impacts ranging from depression to anxiety to anger and even "major mental breakdown", and substance abuse ("I drink a lot!"). Because women had "to fight" to be included in discussions about strategy and tactics, their perspectives were often missing and perhaps discounted when they were allowed to join. Sara Brown reported that while working as a firefighter, she was not able to contribute "many of the positive characteristics that females typically possess", including "alternative perspectives on risk taking" and accomplishing fireline tasks, and providing emotional support (Brown 2017). This dynamic leads to domination by some groups and marginalization of other groups, resulting in the omission of some perspectives that could inform better land management, increase firefighter safety, and produce better science, among other things. Thus, perspectives are limited and diversity is stifled, especially in the hyper-masculine culture present on the fireline and in fire camp. Simply put, this matters because ignoring diversity and inclusivity in the practice of scientific research and discovery as well as operational implementation means that access to the full spectrum of talented, creative, problem-solving, and innovative minds that wildland fire management demands is lacking.

Furthering Inclusivity

As a result of the survey findings and the letter regarding plenary session underrepresentation, IAWF and AFE passed resolutions during spring 2018 stating that diversity and inclusivity across gender and a variety of ethnicities and countries of origin shall be a priority in all that the two organizations undertake, including leadership, membership, programs, and activities including recruiting Board members, Associate Journal Editors, and reviewers. The two organizations are currently forming Inclusivity Committees to recognize and monitor the problem, to implement effective actions, and to report to the association Boards regarding accomplishments and status. The goal of the initiative is to begin to shift the culture of harassment and exclusion that prevails not only on the fireline but in other parts of the wildland fire ecology profession. The committees will participate in conference planning to ensure diversity when speakers are selected, monitor diversity in the authors and reviewers of manuscripts for the journals of the two organizations, identify organizational constructs that result in exclusion, and recommend corrective actions.

As leaders of these two organizations work to implement and foster the intent of the resolutions, they are also sensitive about unintended perceptions and outcomes. As Karin Riley, Vice President of AFE, noted in the Fire Continuum Conference plenary session, "We also want to be clear about a few things that this initiative is not. It's not about blaming any one group or person for the situation. It is about all of us coming together to shine a light on how conscious and unconscious biases harm our profession. It is about ensuring that differences are embraced, all community members are welcomed, included, and valued, and that we have participation from the widest and most diverse range of wildfire professionals possible.”

The positive outcomes of the initiative are expected to be numerous. As Toddi Steelman, Vice President of IAWF, said during the plenary session, “These values of diversity, inclusivity and equity increase our strength, promote learning, develop our capacity and provide a much-needed example for the next generation of wildland fire managers, professionals and scientists. We do not value diversity, equity and inclusivity for their own sake. We value it because it makes us better in what we do. Greater equity in management will make for better management. Greater diversity in science will make for better science. Greater inclusivity in all we practice will make us better practitioners.”

CONCLUSION

As society continues to grapple with issues of inclusivity and diversity, the wildland fire science and management fields are working toward acknowledging, understanding and tackling these issues directly. Boldly recognizing the critical need for diverse perspectives in the wildland fire profession has led to gaining a better understanding of the challenges the community faces through survey work and other efforts. AFE and IAWF are leading in this arena by passing resolutions that prioritize increasing diversity and inclusivity and establishing working committees to sustain focus, attention, and accomplishment in this area. These efforts are intended to spark a positive and permanent cultural shift that spreads throughout the larger wildland fire profession.

REFERENCES

Association for Fire Ecology. 2016. Sexual harassment and gender discrimination in wildland fire management must be addressed. https://fireecology.org/resources/Pictures/AFE%202016%20position%20paper%20on%20discrimination%20final%2011-25.pdf. [Accessed 2018 September 19].

Brown, Sara. 2017. Let’s unpack an “uncomfortable” question: Why don’t women in fire universally encourage more women to join fire? Southern Fire Exchange and Association for Fire Ecology: 2017 Fire Congress Research Highlight. https://fireecology.org/resources/Documents/Research%20Highlight_Brown.pdf.

Ellemers, N.; van den Heuvel, H.; De Gilder, D.; Maass, A.; Bonvini, A. 2004. The underrepresentation of women in science: Differential commitment or the queen bee syndrome? British Journal of Social Psychology. 43: 315–338.

Ely, R.J. 1995. The power in demography: Women’s social constructions of gender inequity at work. Academy of Management Journal. 38: 589–634.

EEOC [Equal Employment Opportunity Commission]. 2016. Discrimination by type. https://www.eeoc.gov/laws/types/index.cfm. [Accessed 2016 November 22].

Feliú-Mójer, Mónica I.; Griffin, Nina; Kirschner, Elliot. 2018. Rethinking the narrative of diversity in science. Scientific American. https://blogs.scientificamerican.com/voices/rethinking-the-narrative-of-diversity-in-science/. [Accessed 2018 September 19].

Flood, M.; Pease, B. 2009. Factors influencing attitudes to violence against women. Trauma, Violence, and Abuse. 10(2): 125-142. doi: 10.1177/1524838009334131.

Kobziar, Leda. 2016. Statement of Dr. Leda Kobziar, President, Association for Fire Ecology, Submitted for the Full House Committee on Oversight and Government Reform, Hearing on Examining Sexual Harassment and Gender Discrimination at the US Department of Agriculture, December 1, 2016, 9:00 AM. https://fireecology.org/resources/Pictures/_Congressional%20committee%20testimony%2011-25-2016_final.docx.pdf. [Accessed 2018 September 19].

Hamburg, M.; Hockfield, S.; Chu, S. 2018. Address harassment now. Science. 361: 1167.

León, Lorena Rivera; Mairesse, Jacques; Cowan, Robin. 2016. An econometric investigation of the productivity gender gap in Mexican research, and a simulation study of the effects on scientific performance of policy scenarios to promote gender equality. United Nations University and Maastricht Economic and Social Research Institute on Innovation and Technology Working Paper #2016-072. https://www.merit.unu.edu/publications/working-papers/abstract/?id=6327. [Accessed 2018 September 26].

León, Lorena Rivera. 2017. Women aren't failing at science—science is failing women. Naturejobs. http://blogs.nature.com/naturejobs/2017/03/20/women-arent-failing-at-science-science-is-failing-women/. [Accessed 2018 September 26].

Lerback, Jory; Hanson, Brooks. 2017. Journals invite too few women to referee. Nature. 541: 455-457.

Martínez-Torres, L.; Pérez-Salicrup, D.R. 2018. El papel del campesino ante la regulación de los incendios forestales en México: Consecuencias inesperadas. Perspectivas Rurales, nueva época. DOI:10.15359/prne.16-31.5.

McDonald, Paula. 2012. Workplace sexual harassment 30 years on: a review of the literature. International Journal of Management Reviews. 14(1): 1-17 doi: 10.1111/j.1468-2370.2011.00300.x.

Perez, Debra J. 2018. Perspective: Women in science—making the invisible, visible. Gordon and Betty Moore Foundation News. February 2018. https://www.moore.org/article-detail?newsUrlName=perspective-women-in-science---making-the-invisible-visible&tagToFilterBy=ab660061-a10f-68a5-8452-ff00002785c8.

Poster, Winifred R. 2018. Cybersecurity needs women. Nature. 555: 577-580.

Smaglik, Paul. 2018. Fewer women lead top universities. Naturejobs. http://blogs.nature.com/naturejobs/2018/03/22/fewer-women-helm-top-universities/. [Accessed 2018 September 19].

Smith, Alistair M.S.; Kolden, Crystal A.; Prichard, Susan J.; Gray, Robert W.; Hessburg, Paul F.; Balch, Jennifer K. 2018. Recognizing women leaders in fire science. Fire. 1, 30; doi:10.3390/fire1020030.

Shen, Yiqin Alicia; Webster, Jason M.; Shoda, Yuichi; Fine, Ione. 2018. Persistent underrepresentation of women's science in high profile journals. bioRxiv. doi: https://doi.org/10.1101/275362.

Woolston, Chris. 2018. Where are the female first and last authors? Naturejobs. http://blogs.nature.com/naturejobs/2018/03/14/where-are-the-female-first-and-last-authors/. [Accessed 2018 September 26].

Full Papers

Sharing the Road: Managers and Scientists Transforming Fire Management

Craig Bienz, The Nature Conservancy, Klamath Falls, Oregon;

Russell Parsons, USDA Forest Service, Rocky Mountain Research Station, Missoula, Montana;

Nancy Grulke, USDA Forest Service, Pacific Northwest Research Station, Western Wildlands Environmental Threats Assessment Center, Prineville, Oregon;

and **Katie Sauerbrey**, The Nature Conservancy, Klamath Falls, Oregon

Abstract—The Nature Conservancy and the Forest Service, Department of Agriculture have long-term goals to reintroduce fire into U.S. ecosystems at ecologically relevant spatial and temporal scales. Building on decades of collaborative work, a Master Participating Agreement was signed in March 2017 to increase overall fire management capacity through training and education. In October 2017, The Nature Conservancy hosted a cross-boundary fire training, education, research, and restoration-related event for 2 weeks at Sycan Marsh Preserve in Oregon. Eighty people from 15 organizations applied prescribed fire on over 1,200 acres (490 ha). Managers and scientists participated in the applied learning and training exercise. The exercise was a success; operational and research objectives were met, as indicated by multiagency, multidisciplinary fire research, and effectiveness monitoring. This paper describes a paradigm shift of fire-adapted, cross-boundary, multiagency landscape-scale restoration. Participants integrated adaptive management and translational ecology so that applied controlled burning incorporated the most up-to-date scientifically informed management decisions. Scientists worked with practitioners to advance their understanding of the challenges being addressed by managers. The model program has stimulated an exponential increase in landscape-scale and ecologically relevant dry forest restoration in eastern Oregon. Collaboration between managers and scientists is foundational in the long-term success of fire-adapted restoration. Examples of effects of prescribed fire on ecosystem services in the project area, such as increased resilience of trees in drought years, are also provided.

Keywords: active fire regime, all-lands, cross-boundary, fire training, forest restoration, interorganization

INTRODUCTION

Fire has shaped human societies. Conversely, societies have shaped fire regimes. Fire defines the persistence of carbon in nature and the distribution of resources. Inherent in the use of fire are some social feedback mechanisms through which these fire-use practices include adaptations for the generation, accumulation, and transmission of knowledge; the use of local institutions to provide leaders and stewards and rules for social regulation; mechanisms for cultural internalization of traditional practices; and the development of appropriate world views and cultural values. How people relate to fire—the observable effects of their beliefs—can be seen live on the land.

Conditions in forests have become more hazardous due to accumulation of abundant flammable vegetation, in many cases a result of disrupted traditions of indigenous fire management, practices of

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

fire exclusion and suppression, establishment of weeds and other flammable plants, and a warming climate (Moreira et al. 2011; Nagel et al. 2017; Williams 2013). Length of fire seasons and extent of land area burned with high severity have increased, as have economic losses from wildfire and expenditures on fire suppression (Jolly et al. 2015). Population change has also affected fire risk. In some regions, such as the western United States, expansion of exurban areas has increased the probability of ignitions and placed more assets at risk in forested fire-prone areas. Accompanying demographic shifts have engendered new social values, policies, and decisions that favor reduction of short-term fire risk to homes and other structures at the expense of long-term risk to forest landscapes (Williams 2013).

Ongoing research into the complex interactions between forest ecosystems, socioeconomic changes, land uses over space and time, and ongoing climate change has demonstrated major alterations in large-scale disturbance patterns (Allen 2007; Barbier et al. 2010; Lambin and Meyfroidt 2010; Ravenscroft et al. 2010; Spies et al. 2014). Wildfires are out of control. Many lack appreciation of the changes in fire use that have brought us to this situation. Social and ecological regimes have undergone a subtle transition from fire adapted, to fire excluded, to fire-intolerant so that today we have a high wildfire risk for people and the environment (Fischer et al. 2016; Spies et al. 2014). The nearly intractable problem of wildfire risk in forests can be characterized as a socioecological pathology (Fischer et al. 2016): the science of the causes and effects of a set of interrelated social and ecological conditions and processes that deviate from what is considered healthy or desirable.

Most often we seek to solve societal problems through governance (Canton-Thompson et al. 2008; Fischer et al. 2016). Acknowledging the remedy to the wildfire risk pathology is a governance system that transforms maladaptive feedbacks into adaptive feedbacks (Duit and Galanz 2008). Creating such a governance system requires policies that influence human–land–forest and fire-management behaviors and that account for socioecological interactions at multiple scales: spatial (ownership, landscape, ecoregion), temporal (short- and long-term), and organizational (individuals, groups, institutions).

Components of a framework for addressing the pathology of wildfire risk in fire-prone temperate forests include broad human engagement in complex thinking about multiscalar policies, and adaptive planning and management. The Fire Learning Network is an example of network that has built connectivity among land management organizations to further the restoration of fire-dependent ecosystems through landscape-scale collaborative planning (Butler and Goldstein 2010). The Network process has identified institutional innovations to reduce temporal and spatial scale mismatches. Risks of social exchange mismatch can best be resolved through trust.

In 2009, the National Cohesive Wildland Fire Management Strategy was developed as a strategic push to work collaboratively among all stakeholders and across all landscapes, using best science, to make meaningful progress toward three goals: 1) resilient landscapes, 2) fire adapted communities, and 3) safe and effective wildfire response. The National Strategy establishes a vision for wildland fire management, defines three national goals, describes the wildland fire challenges, identifies opportunities to reduce wildfire risks, and establishes priorities focused on achieving these goals.

Objectives

In the Big Coyote Fuels Reduction project, the goals of the partnership between the Forest Service, Department of Agriculture (hereafter, Forest Service) and The Nature Conservancy (TNC) were exemplified when TNC hosted a collaborative training, education, research, and restoration-related event for 2 weeks at Sycan Marsh Preserve in Oregon. The objectives of the workshop were to 1) increase overall fire management capacity, through training, research, and education; 2) increase knowledge of prescribed burning techniques targeted at achieving specific effects; 3) build trust, and facilitate communication between managers, citizens, and scientists; and 4) provide the means to promote an increase in landscape-scale ecologically relevant restoration. Outside of the agreement, TNC and the Forest Service would continue monitoring the effectiveness of fuels reduction monitoring begun in 2014 for fire behavior and forest health. The objectives of this paper are to document strategies of the Big Coyote project that have provided social acceptance of prescribed fire use through cutting-edge scientific understanding of fire behavior and that have contributed to successful and long-lasting collaborations between managers and scientists. Effectiveness monitoring has revealed how implementation may be improved. In combination, and with national-level support, these concepts have contributed to an increase in cross-boundary projects in eastern Oregon.

BACKGROUND

The Nature Conservancy and the Forest Service have long-term goals to reintroduce fire into U.S. ecosystems at ecologically relevant spatial and temporal scales. Both the Forest Service and TNC have recognized that excluding wildland fire from fire adapted ecosystems, once thought to protect valuable natural resources as well as people and communities, has instead often had detrimental effects. The lack of fire as a natural disturbance has also contributed to uncharacteristic fuel loadings and fuel profiles. These conditions, coupled with management activities, changing climatic conditions, and drought, as well as the ever-increasing wildland-urban interface, very likely contribute to higher complexity fires and more extreme fire behavior. As a result, many fires are having catastrophic effects. Building on decades of collaborative work, a Master Participating Agreement (MPA) (FS Agreement No. 17-PA-11132543-013) was entered into in March 2017 to increase overall fire management capacity, through training and education. The MPA was intended to enhance the longstanding relationship, particularly around prescribed fire. The purpose of this agreement was for the parties to cooperate and exchange resources in various aspects of prescribed fire management and fuels management, including training and development, planning, and implementation of prescribed fire and mechanical fuel treatments. The MPA will help to enhance training and educational opportunities; increase overall fire management capacity; facilitate restoration of fire adapted ecosystems; improve community safety; enhance training and education opportunities; facilitate sharing of science, traditional ecological knowledge related to fire in a contemporary context, expertise; and increase overall fire management capacity. The projects performed under the MPA will work to restore, protect, or enhance natural resources and make communities safer.

A national Cooperative Agreement, "Promoting Ecosystem Resilience and Fire Adapted Communities Together" (PERFACT), #14-CA-11132543-094, has been executed between the parties. Supplemental project agreements under this MPA will round out the field element of the project described in the PERFACT Cooperative Agreement. In October 2017, TNC and the Forest Service began the Big Coyote Fuels Reduction project, FS Agreement No. 18-PA-11060200-001, completing the administrative means to implement PERFACT through cross-boundary fuels treatments.

To conduct cross-boundary fire management, the two parties agreed to follow standard operating procedures outlined in national, regional and local dispatch center mobilization guides for dispatching of resources and equipment. We complied with standard planning and implementation procedures as described in the Interagency Prescribed Fire Planning and Implementation Procedures Guide (National Wildfire Coordinating Group 2017 www.nwcg.gov/tags/pms-484). One burn plan was written for the cross-boundary burn area. There was one Burn Boss each day, with an overall Incident Command for the burn operations. Monitoring plans included pretreatment and post-treatment monitoring, evaluation of activities, and an ongoing assessment of ecosystem services.

Past Collaboration and Research with the Forest Service

In 2002, TNC and the Forest Service began a before-after-control-impact (BACI) study (Green 1979; Stewart-Oaten et al. 1986) to evaluate the effects of fuels reduction on habitats and populations of birds in ponderosa pine (*Pinus ponderosa*) forests throughout the Interior West. Due to the dependence of bird responses on fire severity, effects of prescribed fires on bird communities may differ from the effects of wildfire. Low severity fire, such as prescribed fire, generally consumes the ground-layer vegetation and duff without killing large overstory trees, while leaving the structure of the dominant vegetation intact (Saab et al. 2005). In contrast, high severity fires cause changes in forest structure by killing the aboveground vegetation (Smith et al. 2000). Sycan Marsh Preserve had two study-site pairs, which were formed by splitting a large area into control and burned units. The current project was one of the control sites of the Birds and Burn research project initiated in 2002.

SITE DESCRIPTION

Sycan Marsh Preserve is in the Modoc Plateau and East Cascades Ecoregions in the headwaters of the Klamath Basin, on the divide between the Great Basin and Klamath Basin. The Upper Sycan Watershed is composed of seven watersheds (six field Hydrologic Unit Codes) from Sycan Marsh to the headwaters (84,511 ha). Average annual precipitation at the marsh is 47.8 cm, with 90 percent of the total falling between October and May. Mean annual air temperature is 5.6 °C.

There are 15 different soil series found in the Big Coyote Fuels area. The most common soil type is Andyfan (60A–64A), followed by the Andyfan-Shakecreek series (66A–67A). These soils occupy much of the dry prairie and marsh area. Most of the forested areas occur on soil series 016B, Lapham. This series consists of very deep, somewhat excessively drained soils that formed in volcanic ash over lacustrine deposits derived from volcanic rocks, such as basalt and tuff-breccia. Lapham soils are on lake terraces.

The Upper Sycan Watershed is a mixed ownership of Forest Service lands (56 percent), TNC (15 percent), and industrial forest lands (29 percent). Three streams, Coyote, Long, and Pole, traverse the project area from west to east, transmitting water from forested areas west of the marsh. Pole Creek rises as a spring within the project area, then flows east.

Low elevations are predominantly ponderosa pine and lodgepole pine (*Pinus contorta*), while higher elevations on and around Yamsae Mountain contain mixed conifer stands consisting of ponderosa pine, white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), and an occasional western white pine (*Pinus monticola*). Smaller inclusions of aspen (*Populus tremuloides*) clones and juniper (*Juniperis occidentalis*) woodlands also exist in the project area. Historically, most of the Big Coyote forested areas consisted of ponderosa pine that averaged 12 trees ha^{-1}, with 24 percent of the trees in clumps with more than 15 trees, and 20 percent as isolated trees. Clump spacing was based on 6 m between trees. The single-storied stands had small openings between the clumps. Average tree diameter was over 68 cm diameter breast height (d.b.h.). The natural fire interval ranged from 3 to 37 years, with a median of 10.7 years over the past 400 years based on fire scars (Bienz, unpublished).

In 2005, we treated 142 ha of forest land with mechanical harvest (fig. 1). Pretreatment density was 10.1 m^2 ha^{-1} (71 trees [>10 cm d.b.h.] ha^{-1}), plus 103 saplings ha^{-1} (59 percent). Ponderosa pine was dominant (66 percent) and structure was uneven-aged. Harvest yielded 17.8 m^3 ha^{-1}. We included 71 ha of the mechanical harvest area in prescribed burns in 2006, 2013, and 2017. In 2008, another 162 ha, consisting of 130 ha of forest land and 32 ha of grassland, was treated with prescribed fire only. Forest structure in these two areas was uneven-aged, with lodgepole pine being the predominant tree (51 percent). Average gross volume was 39 m^2 in lodgepole pine and 70 m^2 in ponderosa pine. The density was 5.3 m^2 ha^{-1}; there were 42 trees ha^{-1} with d.b.h. greater than 10 cm and 16 saplings ha^{-1} (29 percent of the number of trees). In 2016, 110 ha was restored to historical spatial patterns, and a basal area of 6 m^2. Tree density post-harvest was 17 trees ha^{-1} (fig. 2). Harvest was 20.6 m^3 ha^{-1}.

METHODS

Cooperation (e.g., jointly planning and implementing fire management) has the potential to increase the economy of scale of operations and, potentially, the collective impact of practices. The Nature Conservancy received a grant (March 28, 2017) under the authority of the Cooperative Forestry Assistance Act of 1978 for the Big Coyote Fuels Reduction project 17-DG-10062765-705. Despite the potential ecological and social benefits of cooperating on forest management on landscape scales, and over 15 years of prescribed fire treatments with resource monitoring and research, we have found that such approaches are uncommon in practice among public and private land managers.

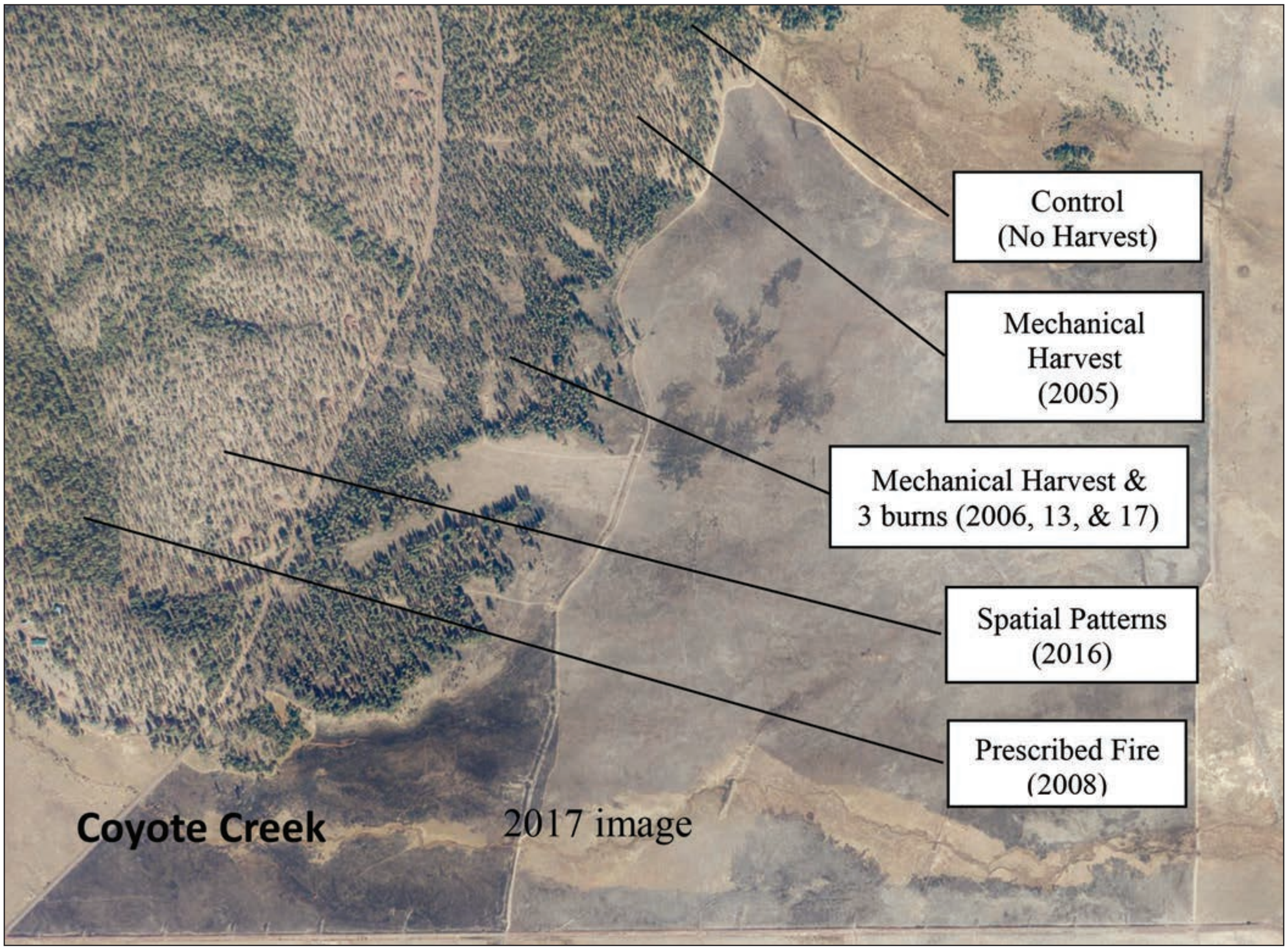

Figure 1—Image of the Big Coyote Fuels Reduction area in Oregon, post-burn, October 2017. Labels identify the types of project activities and years by area.

Figure 2—Before (left) and after (right) a prescribed burn to reduce basal area, increase quadratic mean diameter (QMD), retain fire- and drought-resistant trees, and establish plant architecture (spatial heterogeneity). Pretreatment basal area was 24.4 m^2 ha^{-1}; posttreatment basal area was 9.9 m^2 ha^{-1}, with 12 trees ha^{-1} and a QMD of 149 cm^2. The arrows point to the same tree pre- and post-treatment.

In anticipation of cross-boundary prescribed burning, TNC and the Forest Service began coordination in January 2017 to develop burn plans, identify contractors and collaborators, and proposed schedule of activities. Contractors were employed to prepare fire lines. In addition, contractors were hired to participate in the burn activities. Perhaps one of the most vital contractors was the caterer. Good food is critical to the success of a multiday fuels reduction project. The Fire Learning Network (FLN) provided logistical and financial support. The research team, composed of faculty and students, and Federal agencies, made several visits to the preserve to coordinate and plan for their activities. Monthly phone calls facilitated coordination.

On October 11, 2017, 80 people from 15 organizations engaged in constant two-way communication between the fire cadre and scientists. Unique to this project was the goal of advancing knowledge and application of fire science. Participants had the opportunity to learn lessons from their peers in TNC's FLN cadre, and advance their skills by completing task book requirements. The application of these skills has enhanced their knowledge of fire behavior, and fire use skills were advanced, and provided enthusiasm to apply prescribed fire.

RESULTS

The ways in which individuals observe and experience environmental change, including hazardous conditions and wildfires, have bearing on their responses. To understand the factors that shape values, beliefs, and behaviors of individuals across the full spectrum of stakeholders in wildfire risk mitigation within our region, we must include resource users, landowners, members of community organizations, and participants in task forces, as well as decisionmakers in nongovernmental organizations, Federal and State agencies, and other formal organizations.

Our objective to reduce wildfire risk, and significantly expand the area restored through collective actions, is dependent on sound science, case studies that illustrate ecosystem services and how well we can identify appropriate collaborators, work out collaborative agreements, and ensure that the behaviors of others are beneficial. Our scientific understanding of the processes and impacts is essential to guide our discussions. We also recognize how these activities impose transaction costs on collaboration, which may vary depending on how well individuals can draw upon their experiences or social and organizational network affiliations. Likewise, transaction costs may depend on characteristics of the surrounding natural environment, which may influence the difficulty of observing whether a partner follows through on risk mitigation agreements.

In one example, one of the neighbors adjacent to this project was opposed to the use of controlled burning in early October 2017. This landowner's institutional knowledge and the increased fear from extensive wildfires ongoing in California made our proposed controlled burning unacceptable to her (or him; gender not disclosed to protect the landowner's privacy). After extensive discussions over a 4-day period, the level of fear moderated. Mostly based on our history of working as neighbors, our listening to this individual's concerns, and trust in our scientific approach, this person provided endorsement. Upon reflecting on the methodical process that we followed and seeing the positive ecological benefits after the fire, the landowner asked whether we would include her (or his) lands when next we applied controlled burning.

In our situation, the value of cross-boundary fuels treatments expands beyond restoring ecological process to the human relations developed. During our training, participants learn from each other and share experiences while conducting controlled burns. The FLN cadre experiences the world of fire with a diversity of people along the spectrum of individuals, agencies, experience, and wonder. Participants are able to climb the professional ladder more quickly as more highly skilled resources and have greater opportunities because of cross-boundary training.

Collaboration in Fire and Forest Science

Understanding fire ecology and management and managing adjustments in our existing applications are essential to our learning processes. Current methods of data collection and the process to validate next-generation models that are relevant at operational and ecological scales are foundational. Working with the Forest Service's Missoula Fire Sciences Laboratory and the University of Montana, provided the most up-to date, physics-based fire behavior models. The Nature Conservancy's work with the Forest Service's Western Wildlands Environmental Threats Assessment Center, led by the third author of this paper, has provided needed information on the physiological basis of tree and stand health, and the net long-term effects of fuels reduction treatments, including fire effects, on forest health. Results from the research team have contributed to documentation of effects of fire on ecosystem services.

Ecosystem Services

Fuels reduction treatments are prioritized on public lands to reduce wildfire hazard and spread, while improving forest health, wildlife habitat, aesthetics, and other cultural values. The projects being implemented as part of the Big Coyote Fuels Reduction effort were initiated with an emphasis on BACI research design, so we have continued to monitor results and report here some of the other findings. Ecosystem services, the benefits that nature provides to people, are one approach for emphasizing the importance of conservation and restoration. These benefits can be defined in a variety of ways but are often categorized as provisioning services, regulating services, cultural services, and supporting services (Millennium Ecosystem Assessment 2015).

Provisioning services are goods directly enjoyed or consumed, such as food, water, medicines, timber products, and nontimber forest products. Through the Big Coyote Fuels project and associated cross-boundary treatments, provisioning services have been enjoyed in food, water, timber, and recreation. Timber harvest has provided local employment and forest products to sustain local mills. Mule deer (*Odocoileus hemionus*) populations are an important resource for recreation and Klamath Tribal subsistence. Populations were monitored throughout the year to determine animal density, annual production, and physiological condition for specific habitat conditions. Multiple regression analysis found a significant relationship between carrying capacity and annual production and animal condition ($r^2 = 0.94$, $P < 0.001$). The relationship between carrying capacity and animal density and annual production was also significant ($r^2 = 0.76$, $P = 0.01$) (Bienz and Dunsmoor 1992).

Monitoring of populations by using radiotelemetry was conducted in 2006 and 2007 by the Oregon Department of Fish and Wildlife and the Klamath Tribes. Does with fawns used the treatment areas disproportionately to other habitats (fig. 3).

Regulating services are recognized as beneficial outcomes from regulation of processes such as flood control, water storage, erosion prevention, air and water purification, and climate stabilization. Without forest resilience, all other ecosystem components and values are not sustainable, at least over the long term. We have provided discussion on the merits of incentives and agency structures that facilitate

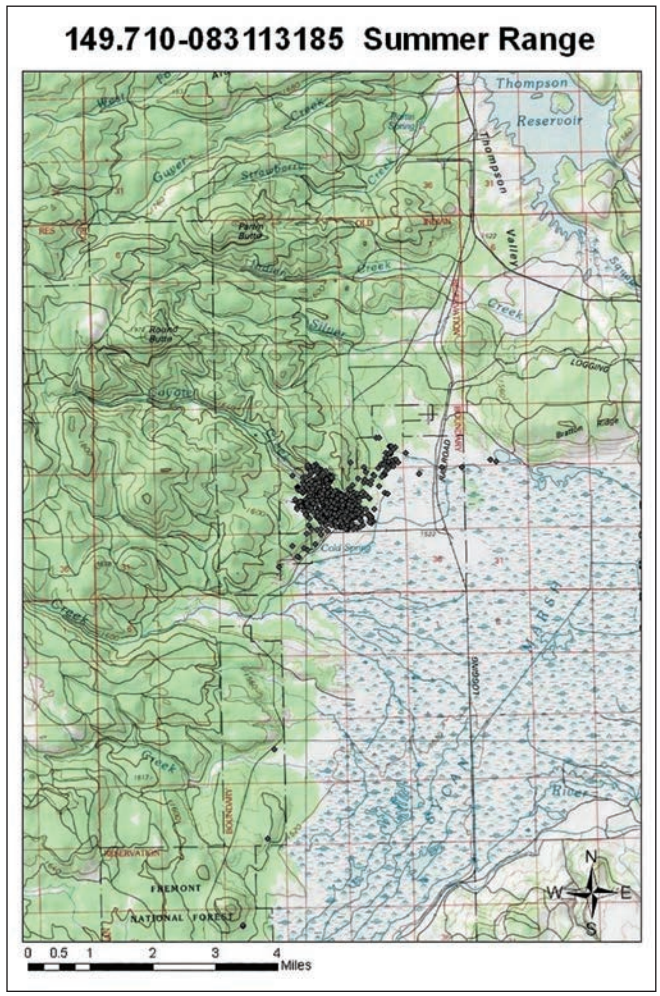

Figure 3—Locations of one female mule deer with radio transmitter 149.710 near Sycan Marsh Preserve, Oregon. Locations of the transmitter are concentrated in the areas of the Big Coyote Fuels Reduction project. This deer successfully raised two fawns each year during the radiotelemetry study conducted by the Oregon Department of Fish and Wildlife.

restoration of wildland fire and ecologically based fuels treatment to forest landscapes. Here we provide an example of forest resilience to fire, insects, and climate change.

We investigated the responses of ponderosa pine to stand basal area manipulations at Sycan Marsh. Stand basal area was manipulated to four replicated levels in 2005, and additional stands in 2008 and 2016 (see Site Description). Three treatments with prescribed fire were applied in 2006, 2013, and 2017 in one of the stands that received mechanical harvest in 2005. We measured basal area increment (BAI) to assess the response and sustainability of wood growth, carbon isotope discrimination inferred from annual rings to assess the response of crown gas exchange, and ratios of leaf area to sapwood area to assess longer term structural acclimation. We assessed aboveground productivity from tree ring analysis of BAI. After trees were felled, we removed stemwood cross-sections from a height of 1.3 m from each stump with chainsaws. Ring widths were converted to BAI from 1980 to 2017 using tree-specific cross-sectional radii (inside bark) and assuming concentric circularity. We found that mechanical harvest and mechanical harvest with three treatments of prescribed fire had similar increases in growth following treatments. Results for BAI are presented at the individual plot level (fig. 4). Treatments of reducing basal area and prescribed fire increased tree resilience during drought years, and increased carbon sequestration (see also Supporting Services).

Cultural services include intangible or spiritual connections with nature, including heritage, sense of place and recreation experiences. In our location, members of the Klamath Tribes exercise treaty-protected subsistence use on public lands. Their continued use of subsistence resources maintains their health and well-being physically and spiritually. In 2016 and 2017 tribal members were included in the fire training. Members of the tribes have been included in other forest restoration working sessions, and trainings.

Supporting services are foundational building blocks of ecosystems, including nutrient cycling, pollination,

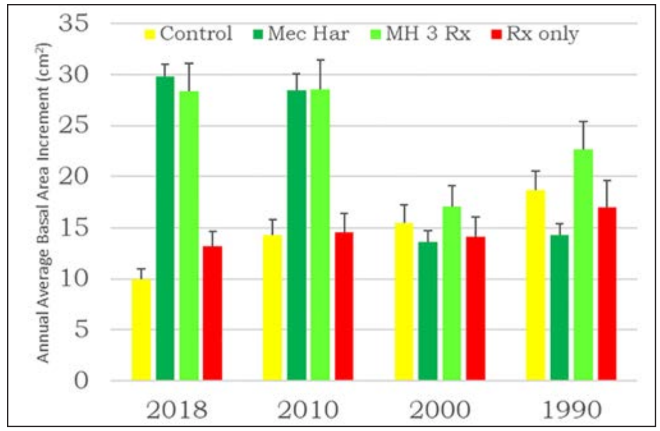

Figure 4—Annual average basal area increment (BAI) (cm^2) for the period 1980 through 2018 by decade in the Big Coyote Fuels Reduction project at Sycan Marsh Preserve, Oregon. Growth in the control was generally the same as the treatment areas for decades 1980 to 1990 and 1991 to 2000, and with prescribed fire (Rx) only through 2010. Mechanical harvest (Mec Har) in 2005 released the residual stand to more than double rates of growth through 2017. Prescribed fire applied in 2006, 2013, and 2017 to an area with mechanical treatment in 2005 (MH 3 Rx) had similar growth to the Mec Har. Prescribed fire (Rx only) in 2008 has led to a general downward trend in BAI, but not as significant as in the control. Data are averaged for 30 trees per treatment.

and photosynthesis. Whole-tree and canopy attributes (measured from the ground) were used to assess the level of tree drought stress and health in the current year. Tree condition is categorized as above average, average, or below average. Average age of trees and tree diameters were not significantly different between treatment types. In general, above-average trees had the largest diameters; the exception was the mechanical harvest with two prescribed fires (now three fires), where the above-average trees had an average diameter of 40.3 cm, and average-condition trees had an average diameter of 42.7 cm. In the control area, tree diameters averaged 48.6 cm for above-average trees, 36.9 cm for trees in average health, and 38.3 cm for trees in below-average health. We concluded that 1) fuels reduction treatments not followed by prescribed fire had a greater proportion of trees in poor health than unmanaged stands; 2) harvest followed by prescribed fire eliminated all poor-health trees; and 3) harvest followed by three prescribed fires within 11 resulted in 62 percent of the population in above-average condition (fig. 5).

Figure 5—Comparison of proportion of sampled trees in each of three health conditions after fuels reduction treatments conducted in the dry pine forest type. Treatments: No treatment (control), mechanical harvest with no fire (Harvest, nF), mechanical harvest with prescription to create spatial complexity (Heterogeneous, nF), and Mechanical Harvest with prescribed fire in 2006, 2013, and 2017 (Harvest, 2xF). Tree health was quantified within each treatment aspoor, average (ave), or above average (AA). Fuels reduction treatments followed by three prescribed fires in 11 years improved the proportion of above-average trees by 60 percent. Harvest with three fires had 1.4 times greater diameter growth than other treatments, and diameter growth in the control and harvest with no fire were similar. Managing forest structure by increasing spatial heterogeneity increases resilience in drought; 62 percent of the trees were in above-average condition. Source: Grulke and Bienz (2014–2017).

Water supply has been quantified for the Upper Sycan Watershed through rate and timing of streamflow collected by TNC starting in the summer 2000 field season. The data have been used to determine the surface flow components of a hydrologic budget. Data collection by the Forest Service had begun at some of these sites in 1993, with some changes and data gaps occurring over time. The Klamath Tribes, and Oregon Water Resources Department (OWRD 2019) continue to collect and report on streamflow data. We have found an immediate, short-term increase in streamflow following prescribed fire during each treatment. This has allowed more continuous surface flow and longitudinal connectivity, which also can help establish subsurface pathways (Ward and Stanford 1995).

Water supply is enhanced by increased connectivity, given that it is expected to drive groundwater supply recharge. Information on groundwater elevations is used to assess seasonal changes in groundwater levels at Sycan Marsh, rate and direction of groundwater fluxes, and relationships to annual precipitation and evapotranspiration. Beginning in 1995, piezometers (groundwater wells) were installed at the preserve, and more wells were added each year through 2012. We observed an immediate response in groundwater elevations following prescribed fire. Wells located within burn areas have increased in elevation as much as 1 cm within 24 hours of burning. Groundwater level is important for attenuation and base flow maintenance, which in turn offsets climatic water deficits (Mayer and Naman 2011).

Several streams at Sycan Marsh have been listed on the Clean Water Act 303(d) list for failing to meet State water quality standards for stream temperature. Data are collected to: 1) validate the influence of restoration management on water temperature with respect to Clean Water Act regulations; 2) provide a baseline of environmental conditions on aquatic species (habitat quality vs. degree-days); and 3) guide adaptive management for future restoration projects.

CONCLUSIONS

Sycan Marsh Preserve provides the facilities and environmental conditions needed to address landscape-scale implementation and analysis. Watershed-scale treatments and evaluation of the responses require large field sites in which surface and canopy fuels are mapped in three-dimensional space at high resolution (Parsons et al. 2018) and where medium- and long-term fire effects on community composition, structure, and fuel accumulation are measured. Prior to this project we collected data on large, spatially explicit forest plots referenced to historical reconstruction plots. Collection of these historical collection was a key investment needed to meet one of the most pressing research challenges in fire science.

Historical forest conditions based on extensive forest inventory plots (Hagmann et al. 2013), along with data collected shortly after initiation of the fire-prevention era combined with 5-ha reference plots (Churchill et al. 2013), provided historical reference information. Management that incorporates ecological processes as well as spatial patterns requires inventory plots greater than 5 ha (Churchill et al. 2013, 2018). Our large plots with tree health data provide consistent methods to accurately assess impacts from treatments, fire, and climate (fig. 5). These types of data may assist in guiding future research and management.

The high frequency, low and moderate severity fire regime forest types are the most appropriate ecosystems for investment in large, spatially explicit forest plots. Recent modeling studies illustrate the effects of fine-scale differences in stand structure on fire behavior (Parsons et al. 2017), with the finding that aggregated fuel patterns, which may be established from spatially aggregated tree patterns (Larson and Churchill 2012), increase the variability of fire behavior (Churchill et al. 2018). These initial results suggest a promising pathway for testing conceptual models for forest dynamics and the generation of spatial heterogeneity in frequent-fire forests (Platt et al. 1988), and for the design and evaluation of fuels reduction, restoration, and climate change adaptation treatments in frequent-fire forests (Churchill et al. 2013; Ziegler et al. 2017).

Active management in the form of forest thinning, prescribed fire, and the combination of the two has been shown to increase forest resilience (Clyatt et al. 2016; D'Amato et al. 2011; Nagel et al. 2017) and decrease wildfire severity in dry forests (Hessburg et al. 2016; Lyderson et al. 2017; Moritz et al. 2014). To restore ecological resilience to significant areas of national forests and ensure socioeconomic viability of communities, the pace and scale of restoration projects need to significantly increase. The Fremont-Winema National Forest developed an Accelerated Restoration and Priority Landscape Plan (Lehman and Markus 2015) and a Ten Year Integrated Natural Resource Plan which provides a strategy to double restoration on the forest over the next 10 years. We have taken steps to exceed the goals, as the current schedule will restore over 1 million Federal forest acres (405,000 ha) by 2028. And the all-lands approach will achieve the National Cohesive Strategy objectives.

Reforming the approach to amend the socioecological interactions to expedite forest restoration was addressed at multiple scales: spatial (ownership, landscape), temporal (short- and long-term), and organizational (individuals, groups, institutions). We provided leadership, administration of programs, and people, training, and feedback from the learning experiences. Our model was flexible in both engagement and implementation, making necessary adjustments daily. One example was when the test fire exceeded the comfort level of the Burn Boss, who then called off that day's burn. The experience was perhaps most valuable to the cadre members who were eager to begin the day's fire activities, only to learn that each situation needs careful and experienced evaluation of fire response to environmental conditions. Though this call was not popular with the cadre members, who were prepared to burn, the decision was a necessary step to illustrate the precautions required for using controlled fire.

Prescribed fire science tools help managers understand how different types of fire behaviors may affect ecosystem services and resulting negative effects, such as smoke movement. Information on wildfires may not apply to prescribed fire situations. Fire managers need better fire models to predict fire behaviors under moderate conditions. We are still learning how the fire will behave in different ignition scenarios and with backing and flanking fires.

Quantifying the importance of fire to ecosystem services provides a framework to better understand values and interconnected services. We have included a framework to advance the discussions on how to incorporate these values into future forest restoration programs.

Providing a landscape where individuals can observe and experience a resilient forest and its myriad ecosystem services changes perceptions and opinions. In the social engagement of discussing these systems, people experienced new avenues for scientific discovery that expand the scope of the social–ecological system under inquiry. Ultimately this engagement enriches understanding of how biophysical processes play out in today's world. This points out many of the social and psychological processes that influence the communication and implementation of science in practice. Our results show the importance of considering predominant wildfire experience types in a community before developing a wildfire mitigation program. The findings of this study may have relevance for other communities that have experience with wildfires.

Support garnered from the training has exceeded expectations for outcomes. Commitments have been made from agencies, contractors, universities, and research associates to continue to participate in future burning projects at Sycan Marsh Preserve. Through our collaborative learning process, team concepts, and increased capacity, we have found individuals and agencies accepting the importance of fire for nonindustrial and commercial forest lands. Data and teamwork have been valuable to evaluate impacts on tree health and seedling establishment (Smith et al. 2016b). A Prescribed Fire Council Chapter has now been formed for Klamath and Lake Counties in Oregon to provide for the socioecological "firescapes" (Fischer et al. 2016; Smith et al. 2016a). Cross-boundary fuel and wildfire risk reduction are being developed in these two counties of Oregon. A manual to guide future cross-boundary projects has been published through collaboration with the Forest Service's Pacific Northwest Research Station (Leavell et al. 2018).

Data collected during the fuels treatments have been used to adjust plans for future burning (fig. 1). The benefits of hazardous fuels reduction are being increasingly recognized, and the importance of expanding fuels reduction activity across property lines has achieved valuable social acceptance. Collaborative groups such as the Klamath Lake Forest Health Partnership have now developed cross-boundary projects for over 30,000 acres (12,000 ha) (Leavell et al. 2018). This is in addition to the 10,000 acres (4,000 ha) associated with the Big Coyote Fuels Reduction project. Within Klamath and Lake Counties, non-Federal forest restoration is being planned on over 100,000 acres (40,000 ha) to increase human safety and reduce risks of severe wildfire. Since the Master Participating Agreement was signed in 2017, cross-boundary forest restoration has been implemented on more than 4,000 acres (1,600 ha). The Klamath Lake Prescribed Fire Council has been formed. Over $2 million has been secured to expanded community engagement with Learning Networks for Fire, Forests, and Community Risk Reduction and Resilience.

There is still a lack of holistic understanding of how fire management enables the provisioning of ecosystem services in a range of forested ecosystems. We have briefly discussed the types of ecosystem services and the value of incorporating them into planning and management. We will continue to incorporate these values into future restoration discussions. The extension of research into the measurements of fire behavior, forest health response, effects on water and nutrient balance and dynamics, and long-term interactions over time and space will be critical to understanding how vertical connectivity relates to priority ecosystem services. However, the Sycan Marsh model has provided a community of learning that has the training and space to apply ecological insights more effectively in improving forest resilience and meeting societal needs.

REFERENCES

Agee, James K. 1998. The landscape ecology of western forest fire regimes. Northwest Science. 72: 24–34.

Allen, Craig D. 2007. Interactions across spatial scales among forest dieback, fire, and erosion in northern New Mexico landscapes. Ecosystems. 10: 797–808.

Barbier, Edward, B.; Burgess, Joanne C.; Grainger, Alan. 2010. The forest transition: Towards a more comprehensive theoretical framework. Land Use Policy. 27: 98–107.

Bienz, Craig S.; Dunsmoor, Larry K. 1992. Quantification of mule deer carrying capacity in south-central Oregon. In: Brown, Robert D., ed. The biology of deer. New York: Springer.

Butler, William Hale; Goldstein, Bruce Evan. 2010. The US fire learning network: Springing a rigidity trap through multiscalar collaborative networks. Ecology and Society. 15: 21.

Canton-Thompson, Janie; Gebert, Krista M.; Thompson Brooke; [et al.]. 2008. External human factors in incident management team decision making and their effect on large fire suppression expenditures. Journal of Forestry. 106: 416–424.

Churchill, D.J.; Seager, S.T.; Larson, A.J.; [et al.]. 2018. Ecological functions of spatial patterns in dry forests: Implications for forest restoration. Portland, OR: The Nature Conservancy. 7 p.

Churchill, Derek J.; Larson, Andrew J.; Dahlgreen, Matthew C.; [et al.]. 2013. Restoring forest resilience: From reference spatial patterns to silvicultural prescriptions and monitoring. Forest Ecology and Management. 291: 442–457.

Clyatt, Kate A.; Crotteau, Justin S.; Schaedel, Michael S.; [et al.]. 2016. Historical spatial patterns and contemporary tree mortality in dry mixed-conifer forests. Forest Ecology and Management. 361: 23–37.

Cooperative Forestry Assistance Act of 1978, Pub. L. 95-313, July 1, 1978, 92 Stat. 365 (16 U.S.C. 2101 et seq.). Available at https://www.law.cornell.edu/topn/cooperative_forestry_assistance_act_of_1978.

D'Amato, Anthony W.; Bradford, John B.; Fraver, Shawn; Palik, Brian J. 2011. Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. Forest Ecology and Management. 262: 803–816.

Duit, Andreas; Galanz, Victor. 2008. Governance and complexity—Emerging issues for governance theory. Governance. 21: 311–335.

Fischer, A. Paige; Spies, Thomas A.; Steelman, Toddi A.; [et al.]. 2016. Wildfire risk as a socioecological pathology. Frontiers in Ecology and the Environment. 14: 276–284.

Green, Roger H. 1979. Sampling design and statistical methods for environmental biologists. New York: Wiley Interscience. 272 p.

Grulke, Nancy; Bienz, Craig. 2014–2017. Dataset for Big Coyote Fuels Reduction project, Sycan Marsh Preserve, Oregon. Data on file at: Prineville, OR: USDA Forest Service, Pacific Northwest Research Station, Western Wildlands Environmental Threats Assessment Center.

Hagmann, R. Keala; Franklin, Jerry F.; Johnson, K. Norman. 2013. Historical structure and composition of ponderosa pine and mixed conifer forests in south central Oregon. Forest Ecology and Management. 304: 492–504.

Hessburg, Paul F.; Spies, Thomas A.; Perry, David A.; [et al.]. 2016. Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. Forest Ecology and Management. 366: 221–250.

Jolly, W. Matt; Cochrane, Mark A.; Freeborn Patrick H.; [et al.]. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications. 6: 1–11.

Lambin, Eric F.; Meyfroidt, Patrick. 2010. Land use transitions: Socio-ecological feedback versus socio-economic change. Land Use Policy. 27: 108–118.

Larson, Andrew J.; Churchill, Derek. 2012. Tree spatial patterns in fire-frequent forests of western North America, including mechanisms of pattern formation and implications for designing fuel reduction and restoration treatments. Forest Ecology and Management. 267: 74–92.

Leavell, Daniel; Markus, Amy; Bienz, Craig; [et al.]. 2018. Planning and implementing cross-boundary landscape-scale restoration and wildfire risk reduction projects: A "how to" guide to achieve the goals of the National Cohesive Strategy. PNW 707. Oregon State University; University of Idaho; Washington State University. 117 p.

Lehman, J.; Markus, A. 2015. Request for pilot authority of the Fremont-Winema National Forest. USDA unpublished report. On file at Winema National Forest, Lakeview, OR.

Lyderson, Jamie M.; Collins, Brandon M.; Brooks, Matthew L.; [et al.]. 2017. Evidence of fuels management and fire weather influencing fire severity in an extreme fire event. Ecological Applications. 27: 2013–2030.

Mayer, Timothy D.; Naman, Seth W. 2011. Streamflow response to climate as influenced by geology and elevation. JAWRA Journal of the American Water Resources Association. 47: 724–738.

Moreira, Francisco; Viedma, Olga; Arianoutsou, Margarita; [et al.]. 2011. Landscape – wildfire interactions in southern Europe: Implications for landscape management. Journal of Environmental Management. 92: 2389–2402.

Moritz, Max A.; Batlloria, Enric; Bradstock, Ross A.; [et al.]. 2014. Learning to coexist with wildfire. Nature. 515: 58–66.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: Synthesis. Washington, DC: Island Press.

Nagel, Linda M.; Palik, Brian J.; Battaglia, Michael A.; [et al.]. 2017. Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. Journal of Forestry. 115: 167–178.

National Wildfire Coordinating Group. 2017. Interagency prescribed fire planning and implementation procedures guide. PMS 484. National Wildfire Coordinating Group, Fuels Management Committee. Available at www.nwcg.gov/tags/pms-484. [Accessed 2019 June 19].

Oregon Water Resources Department. 2019. Klamath Tribal Instream Claim dashboard. https://apps.wrd.state.or.us/apps/wr/klamath_sif_dashboard/Charts.aspx. [Accessed 2019 June 22].

Parsons, Russell A.; Linn, Rodman R.; Pimont, Francois; [et al.]. 2017. Numerical investigation of aggregated fuel spatial pattern impacts of fire behavior. Land. 6: 43.

Parsons, Russell A.; Pimont, Francois; Wells, Lucas; [et al.]. 2018. Modeling thinning effects on fire behavior with STANDFIRE. Annals of Forest Science. 75: 7.

Platt, William J.; Evans, Gregory W.; Rathburn, Stephen L. 1988. The population dynamics of a long-lived conifer (*Pinus palustris*). The American Naturalist. 131: 491–525.

Ravenscroft, Catherine; Scheller, Robert M.; Mladenoff, David J.; White, Mark A. 2010. Forest restoration in a mixed-ownership landscape under climate change. Ecological Applications. 20: 327–346.

Saab, Victoria A.; Powell, Hugh D.W.; Kotliar, Natasha B.; Newlon, Karen R. 2005. Variation in fire regimes of the Rocky Mountains: Implications for avian communities and fire management. Studies in Avian Biology. 30: 76–96.

Smith, Alistair M.S.; Kolden, Crystal A.; Paveglio, Travis B.; [et al.]. 2016a. The science of firescapes: Achieving fire-resilient communities. Bioscience. 66: 130–146.

Smith, Alistair M.S.; Sparks, Aaron M.; Kolden, Crystal A.; [et al.]. 2016b. Towards a new paradigm in fire severity research using dose-response experiments. International Journal of Wildland Fire. 25: 158–166.

Smith, Stanley D.; Huxman, Travis E.; Zitser, Stephen F.; [et al.]. 2000. Elevated CO_2 increases productivity and invasive species success in an arid ecosystem. Nature. 408: 79–82.

Spies, Thomas A.; White, Eric M.; Kline, Jeffrey D.; [et al.]. 2014. Examining fire-prone forest landscapes as coupled human and natural systems. Ecology and Society. 19(3): 9.

Stewart-Oaten, Allan; Murdoch, William W.; Parker, Keith R. 1986. Environmental impact assessment: "Pseudoreplication" in time? Ecology. 67: 929–940.

Ward, J.V.; Stanford, J.A. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research & Management. 11: 105–119.

Williams, Jerry. 2013. Exploring the onset of high-impact mega-fires through a forest land management prism. Forest Ecology and Management. 294: 4–10.

Ziegler, Justin Paul; Hoffman, Chad; Battaglia, Mike; Mell, William. 2017. Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests. Forest Ecology and Management. 386: 1–12.

Comparison of Three Methods for Quantifying Coarse Surface Fuel Loading

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Abstract—We compared three commonly used sampling methods for estimating coarse woody surface fuel (>7.62 cm diameter) loading: fixed-area plot, planar intersect using one transect, and planar intersect using two transects. Sampling occurred in ponderosa pine/Douglas-fir (*Pinus ponderosa*/*Pseudotsuga menziesii*) dominated stands in the northern Rocky Mountains, USA. These methods commonly have tradeoffs in execution and accuracy that managers must consider. We found fixed-area plot sampling was more likely to capture log occurrence; planar intersect methods estimated zero loading on 23 to 47 percent of plots, but fixed-area sampling always captured some loading. Adding a second transect did not improve accuracy of sampling estimates at either high or low log loading when compared to fixed-area log loading. The three sampling techniques produced similar results at the unit level, but on an individual plot, the planar intersect method tends to overpredict log loading when actual loading is very low (<1.0 kg m^{-2}) and underpredict values as loadings increased beyond that level. These results suggest that planar intersect sampling can accurately be used to estimate log loading if numerous transects are installed. If sampling is constrained to one transect per stand, then fixed-area plot sampling is recommended.

Keywords: Brown's transects, fixed-area plot sampling, hazardous fuels, line intersect sampling, *Pinus ponderosa*, planar intercept, planar intersect sampling, monitoring, *Pseudotsuga menziesii*

INTRODUCTION

Evaluating the impacts and effectiveness of forest fuel reduction treatments commonly includes monitoring of surface woody debris loadings (Brown et al. 2003; Crotteau et al. 2016; Strom and Fulé 2007; Waddell 2002). Dead coarse woody surface fuels (i.e., logs >7.62 cm in diameter) influence intensities and residence times of fires and can have important ecological functions (Brown et al. 2003; Harmon et al. 1986; Schoennagel et al. 2012). Several fuel sampling methods exist to quantify coarse woody fuel loading, each with advantages and disadvantages, depending on fuel particle size (Keane and Gray 2013; Sikkink and Keane 2008). Two common methods for measuring dead downed surface fuels are planar intersect transects and fixed-area plot sampling (Keane 2015).

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Planar intersect sampling along linear transects was refined by Brown (1971, 1974) as a two-dimensional modification of Van Wagner's (1968) line intersect sampling for estimating dead and down woody surface fuels. In the planar intersect sampling method, woody debris pieces more than 7.6 cm in diameter that cross a vertical plane along a linear transect are tallied by diameter and decay class at the point of crossing (Brown 1974). From those intersect recordings, fuel loading is calculated on a mass per unit area basis. Planar intersect transects are adjustable to length and orientation and are generally quick to measure (Keane 2015). As such, they have become standard for many forest and fuel monitoring programs to measure both fine and coarse woody surface fuels (<7.62 cm and >7.62 cm diameter at point of intersect, respectively), as well as other live and dead fuels (e.g., Busing et al. 1999; Lutes et al. 2006; USDI National Park Service 2003).

While planar intersect transects are easily taught and learned, they have some major disadvantages. If transect direction is not adjusted throughout a stand, sampling may produce biased estimates of log loading if fuels are similarly oriented upslope or downslope (Brown 1971; Van Wagner 1968). Additionally, stands with highly variable downed woody fuel loading may require prohibitively large sample sizes or transect lengths for an accurate estimate of loading and its variability (Keane 2015; Lutes 1999; Woldendorp et al. 2004). On the other hand, the planar intersect transect sampling technique is adaptable to both management and research requirements and allows estimation of all woody fuel size classes.

Alternatively, fixed-area plot sampling is an equal probability sampling technique that uses a fixed sample area to estimate fuel loading. Fuels can be removed for weighing in the laboratory or fuel dimensions can be measured on-site (and loading later calculated from log volume and wood density). The fixed-area plot method may capture spatial variability more accurately than the planar transect method (Woldendorp et al. 2004), depending on plot size, size class of woody debris, and distribution of fuels (Keane 2015; Sikkink and Keane 2008), but fixed-area plots can be time-intensive to sample and are not always practical for resource-limited monitoring programs. For logs, fixed-area plot sampling may require plots as large as 0.04 ha to capture spatial variability (Keane 2015).

In this study, we compared planar intersect transect and fixed-area plot sampling methods for quantifying dead coarse woody surface fuel loading (kg m^{-2}). Fuels are intrinsically variable in distribution and abundance; either sampling method may produce significantly different results compared to the true mean. Greater sampling intensity, as a rule, should reduce error, but sampling costs are always a concern; balancing these two factors is key. This study had two objectives: 1) compare log loading by measurement method at a plot level, and 2) determine whether stand-level log loading estimates differed between fixed-area plot sampling and planar intersect transects. In this paper, we use the term "logs" to describe dead coarse woody surface fuels with a diameter over 7.62 cm at the point of intersect for planar intersect pieces or at the small end for pieces measured inside a fixed-area plot. The study's findings will help fire and fuels managers evaluate the tradeoffs associated with these sampling methods, and choose the method most informative for their project.

METHODS

Study Site

We sampled logs at the Lick Creek Demonstration Research Forest (Lick Creek) on the Bitterroot National Forest in southwestern Montana (46°5'N, 114°15'W). Lick Creek is predominantly on 10- to 30-percent south-facing slopes at an elevation of 1,300 to 1,500 meters AMSL (Gruell et al. 1982). This study is located in the Interior Ponderosa Pine forest cover type (Eyre 1980), consisting mainly of ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *ponderosa* C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.)). On the upper slopes, the habitat types (h.t.s) (Pfister et al. 1977) are *Pseudotsuga menziesii/Calamagrostis rubescens* h.t., *Pinus ponderosa* (Douglas-fir/pinegrass h.t. ponderosa pine) phase, and *Pseudotsuga menziesii/Symphoricarpos albos* h.t. *Calamagrostics rubescens* (Douglas-fir/snowberry h.t., pinegrass) phase (Gruell et al. 1982). On the lower slopes, the habitat types are *Pseudotsuga menziesii/Vaccinium caespitosum*

(Douglas-fir/dwarf huckleberry), and *Pseudotsuga menziesii/Vaccinium globulare* h.t. *Arctostaphylos uva-ursi* (Douglas-fir/blue huckleberry h.t., kinnikinnick) phase (Gruell et al. 1982).

There are 24 total units in this study containing 1- to 2-ha treated and control units that are part of a 1992 long-term experiment evaluating combinations of restoration-focused cutting and burning strategies (Smith and Arno 1999). Each of two sites contains a network of 0.04-ha fixed-area circular plots across 12 units, with 6 plots per unit, except for 1 unit with 4 plots (total = 142 plots). We used these treated and untreated units as representative of this common forest type and for the diverse range of fuel loads that they contain in one compact space. One site (72 plots total) had been treated with a thinning, followed by broadcast burn and no-burn treatments. The second site (70 plots total) had been treated with a retention shelterwood cutting, followed by broadcast burn and no-burn treatments. No management had been conducted at either site since 1994. We emphasize that the purpose of this study was simply to utilize this study area to compare sampling methods within these known contexts, and not compare sampling methods among specific treatments within this study or describe typical or desirable levels of coarse woody surface fuels.

Data Collection and Analysis

We remeasured the original (established 1993) planar intersect transects (Brown 1974) established within fixed-area plots in 2015 using the initial methods. Transects originated at plot center and extended 15.24 m, alternating either upslope or side-hill in orientation. To test whether doubling sampling intensity affected log loading estimate, we added a second 15.24 m planar intersect transect 90° clockwise from the original (producing two estimates of loading per plot: one estimate using only the first transect and a second estimate based on the average of both transects). Using the original 0.04-ha circular fixed-area plots from the study, we measured all logs over 7.62 cm in diameter within the plot area. We measured small-end diameter, large-end diameter, and log length and recorded whether the log was sound or rotten. Only the portion of the log occurring within the plot boundary was measured, and logs or log portions were sampled when the central axis was lying in or above the litter layer.

One- and two-transect log loading for each plot were estimated using the FEAT/Firemon Integrated (FFI) software program (Lutes et al. 2006), which uses Brown's (1974) formulas to calculate log loading. Wood density of sound material was 0.40 g cm^{-3} for sound logs and 0.30 g cm^{-3} for rotten logs. For fixed-area plot log loading, we calculated log volume (m^3) at the plot level using Smalian's formula (Avery and Burkhart 2002):

$$\text{Cubic volume: } \frac{(B+b)}{2} L$$

where B and b are the cross-sectional areas (m^2) of the log at the large and small ends, respectively, and L is the log length (m).

Volumes of logs on the plot were multiplied by wood density and then adjusted for plot area to estimate loading (kg m^{-2}). The wood density values for sound and rotten material were the same as used in FFI for calculating the load of logs sampled on transects. The sum of log load per plot was expressed on a per unit area basis.

To determine how measured loadings for fixed-area plots compared to transect estimates at the plot level, we used the loading from the planar intersect transect sampling method as the predictor variable and applied separate simple linear regression models to compare plot-level log loading from both one and two transects per plot. We compared these models against the measured log loading to determine how well planar intersect transect sampling compared to fixed-area plot sampling.

We calculated the average unit-level log loading using each method. We used analysis of variance (ANOVA) to test for differences in log loading estimates between the three sampling methods at the unit level ($\alpha = 0.05$). Because the unit-level estimates were right-skewed in all sampling methods, we log-transformed the data for the ANOVA test to satisfy normality.

Normality was tested using the Shapiro-Wilk normality test (Royston 1982) and assessed with quantile-quantile plots and histograms of the residuals. All tests were conducted using the R software program (R Core Team 2016).

RESULTS AND DISCUSSION

Plot-level fuel loadings sampled using the three methods ranged from 0.0 to 15.640 kg m^{-2}. Log loadings were similarly distributed among methods, though the planar intersect method failed to detect logs on many plots (fig. 1). Mean log loading ranged from 0.773 kg m^{-2} to 0.872 kg m^{-2} across sampling methods, but median log loading ranged from 0.232 kg m^{-2} to 0.430 kg m^{-2} (table 1). The lowest measured fixed-area plot log loading was 0.039 kg m^{-2}, whereas no logs were sampled on 61 plots (47 percent) using one transect and 33 plots (23 percent) using two transects.

At the unit level, there was no difference ($F2, 69 = 0.161$; $p = 0.852$) in log loading estimates between the three methods. Measuring fuels using one planar intersect transect produced the lowest overall estimate; two planar intersect transects produced nearly equal means and standard errors as fixed-area plot (fig. 2). The overall estimate of log loading was 0.645 ± 0.104 kg m^{-2} for fixed-area sampling, 0.581 ± 0.093 kg m^{-2} using one planar intersect transect per plot, and 0.653 ± 0.105 kg m^{-2} using two planar intersect transects per plot. Comparisons of each method by unit demonstrated a lack of patterns or bias, but there were some cases where either one or two transects estimated much higher loading (fig. 3). Across all units, there was a great deal of overlap between each method's measured values, indicating that when six plots are used to calculate the average loading at the unit level, the three methods produced equivalent results.

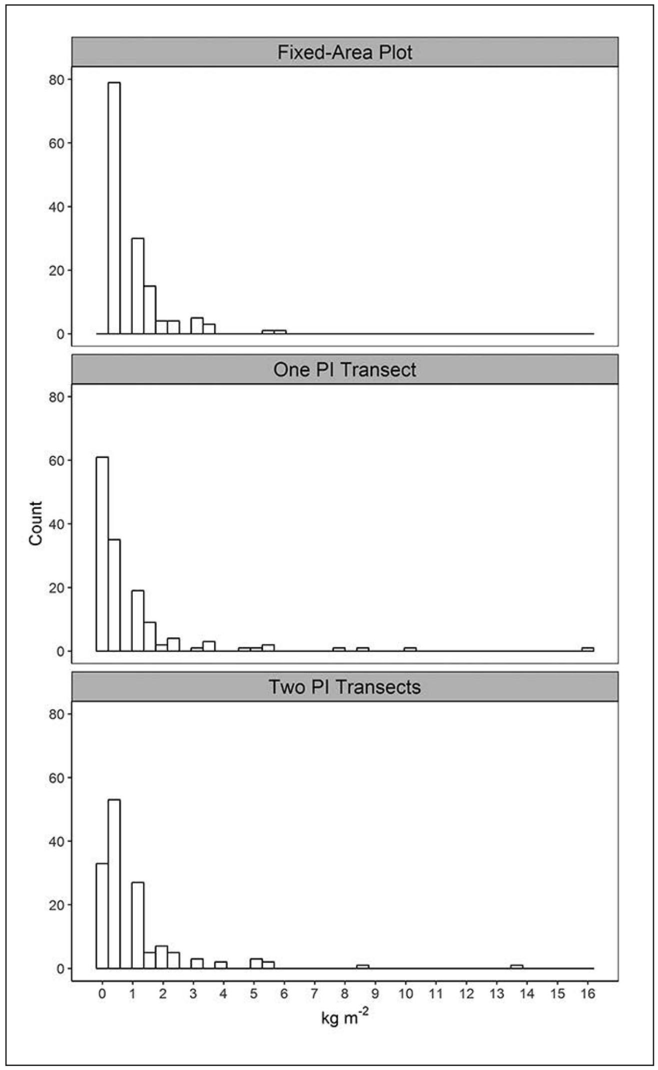

Figure 1—Distribution of plot-level (n = 142) log loading estimates by the three compared methods: fixed-area plot sampling, one planar intersect (PI) transect per plot, and two planar intersect transects per plot. Note: At the plot level, the lowest measured fixed-area plot loading was 0.039 kg m^{-2}, whereas 61 plots estimated zero loading using one PI transect, and 33 plots estimated zero loading using two PI transects.

Table 1—Log loading summaries (kg m^{-2}) at the plot level by sampling method: fixed-area plot, one planar intersect (PI) transect, and two PI transects per plot.

Sampling method	Mean	Standard error	Median	1st quartile	3rd quartile
Fixed-area plot	0.773	0.189	0.430	0.204	0.947
One PI transect	0.841	0.401	0.232	0.000	0.685
Two PI transects	0.872	0.336	0.336	0.091	0.803

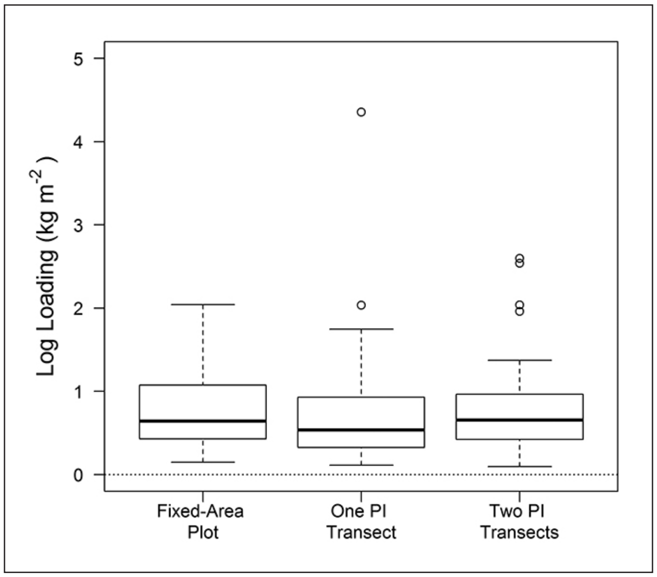

Figure 2—Unit-level (n = 24) log loading (kg m-2) estimates by method calculated from 6 plots per unit. Methods: fixed-area plot sampling, one planar intersect transect (PI) per plot, and two planar intersect transects per plot.

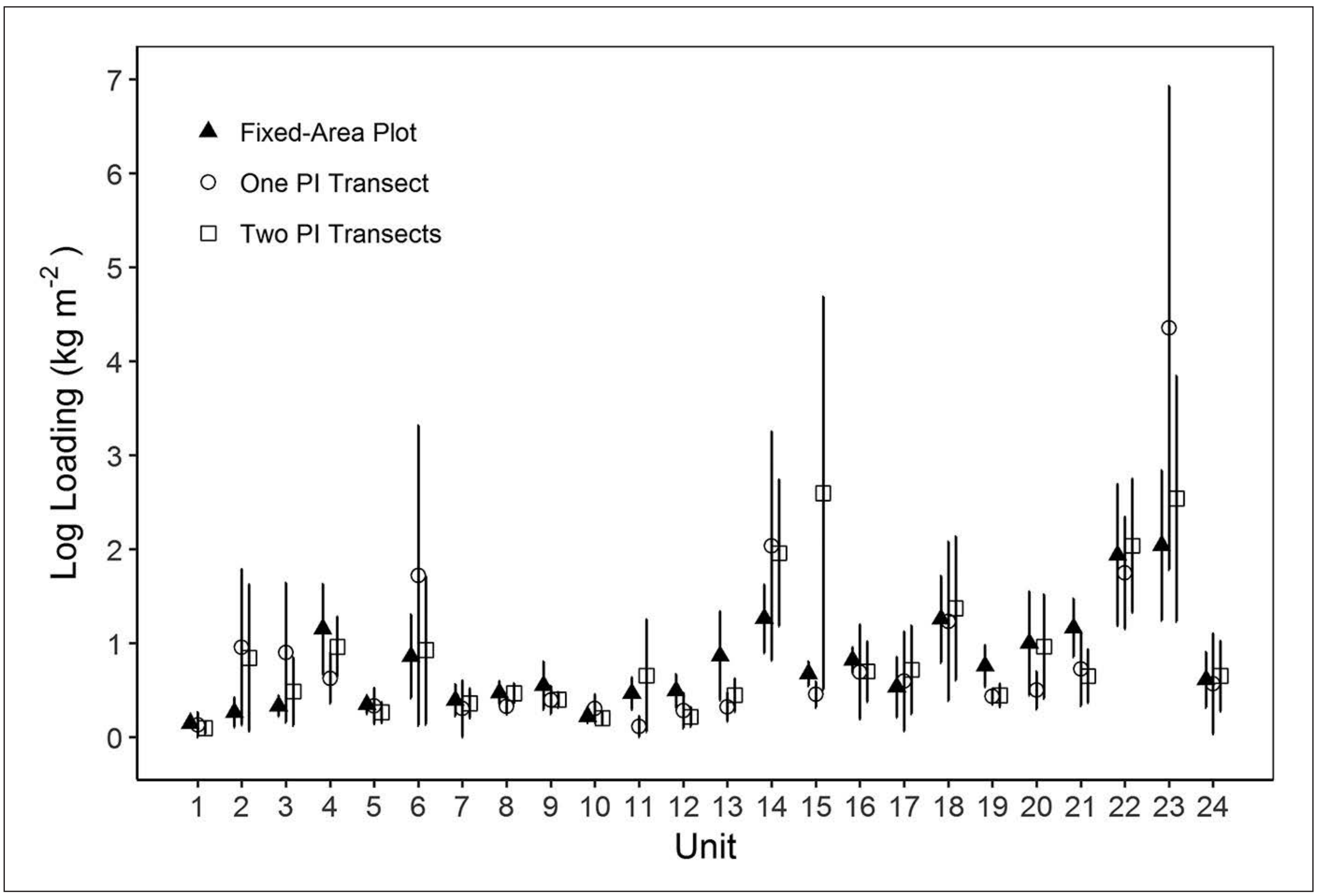

Figure 3—Comparison of mean log loading and one standard error at each unit by method. Methods included fixed-area plot sampling, one planar intersect (PI) transect per plot, and two planar intersect transects per plot.

At the plot level, model estimates of fixed-area log loading estimated from the measured loading using one planar intersect transect (equation 1) and two planar intersect transects (equation 2) are:

$$\textit{Log loading} = 0.541 + 0.275 \times \textit{Transect loading} \quad (1)$$

$$\textit{Log loading} = 0.485 + 0.329 \times \textit{Transect loading} \quad (2)$$

Compared to fixed-area plot sampling at the plot level, planar intersect transects captured only 33.8 percent (model 1) and 34.2 percent (model 2) of the variability in log loading. Transects underpredict at all fixed-area plot fuel loadings, except at the very lowest levels (<1.0 kg m^{-2}) (fig. 4).

We acknowledge that all three of our methods are estimations of fuel loadings as we did not weigh the samples. However, assuming the fixed-area plot sampling provides the most accurate estimate of log loading, planar intersect transects were a poor predictor of loading on a plot-by-plot basis. Every fixed-area plot captured at least some coarse woody surface fuels (range: 0.039–5.561 kg m^{-2}), but out of 142 plots, 47 percent of plots measured with one transect and 23 percent measured with two transects estimated zero loading (range: 0–15.640 kg m^{-2} using one transect and 0–13.049 kg m^{-2} using two transects). If only one plot is measured in a stand, our results indicate that there is a strong chance of not only incorrectly estimating log loading but estimating zero loading, when using the transect lengths used in this study.

In general, our mean log loadings were low for a northern Rocky Mountain ponderosa pine/Douglas-fir forest. Baker (2009) reported 10.44 ton ac^{-1} (2.34 kg m^{-2}) of coarse woody debris (of which 30 percent is rotten wood) in a typical Interior ponderosa pine/Douglas-fir forest, which is 368 to 403 percent greater than our observed estimates. That value was based on early Fuel Characteristics Classification System (FCCS) fuelbed loadings (Ottmar et al. 2007). The most recent FCCS estimates are 8.6 ton ac^{-1} (1.93 kg m^{-2}) of downed coarse woody fuels (also 30 percent rotten wood), which is 221 to 250 percent greater than our observed estimates (Ottmar et al. 2007). In recently treated northern Rocky Mountain ponderosa pine stands (i.e., <10 years), Keane et al. (2012) reported mean log loading ranging from 1.23 to

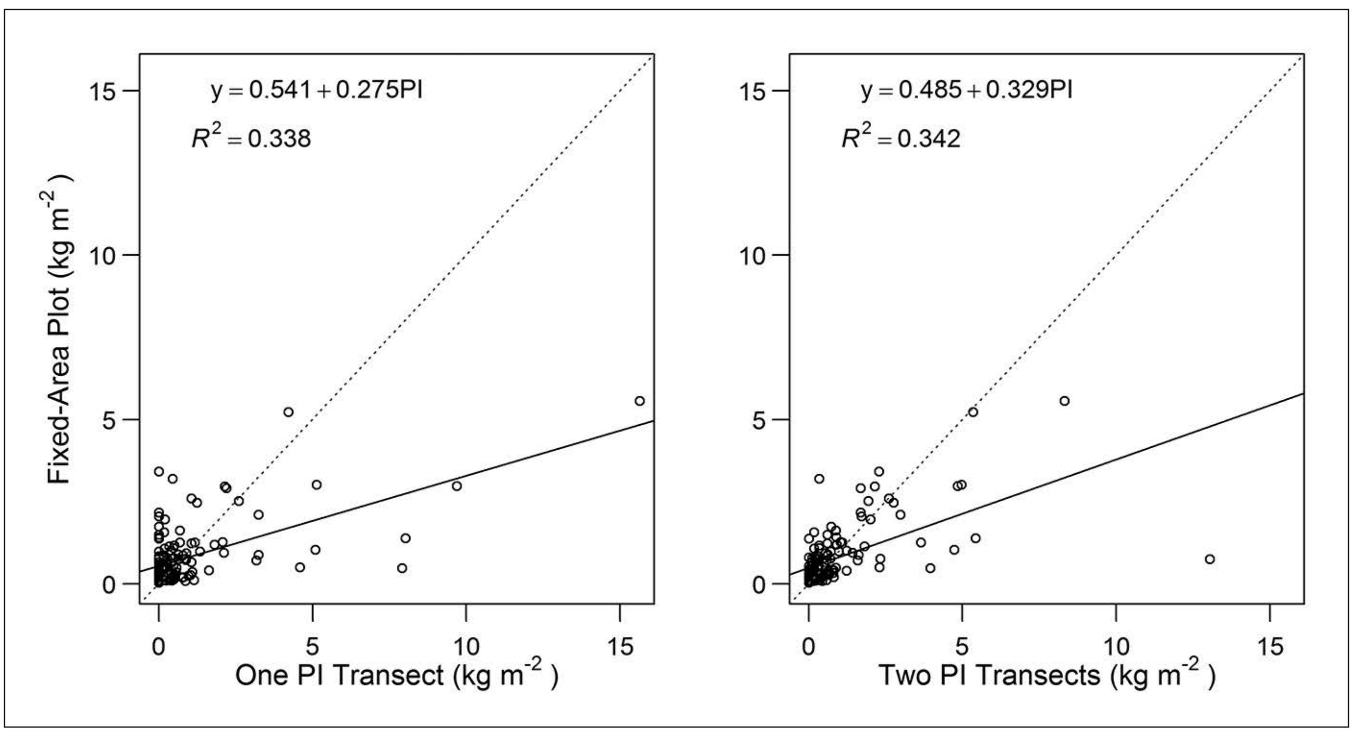

Figure 4—Observed plot-level fixed-area plot sampling estimates of log loading (kg m^{-2}) against planar intersect (PI) transects for one transect and two transects, with 1:1 line (dotted gray) and linear model line (black). Transects underpredict at all fixed-area plot fuel loadings, except at the very lowest levels (<1.0 kg m^{-2}).

2.92 ac-1 (0.276–0.657 kg m^{-2}), loadings similar or lower to our observations. Finally, Brown and See (1981) reported mean log loading of 5.3 tons ac^{-1} (1.18 kg m^{-2}) and standard deviation of 14.0 tons ac^{-1} (3.14 kg m^{-2}) in ponderosa pine cover types on the Bitterroot National Forest. These examples indicate the high variability of log loading in northern Rocky Mountain ponderosa pine forests. While mean log loading sampled in this study tended to be lower than other studies, it appears to fall with the typical range of the forest type. Our mean log loading likely better describes log loading in stands of this forest type that have been subjected to fuel reduction treatments within the last 25 years, but they may not represent other stands of the same forest type with different disturbance history.

Accurate coarse woody surface fuel inventorying is critical to monitor wildlife habitat, soil health, and fuel treatment effectiveness (Bull et al. 1997; Busing et al. 1999; Keane 2015; Waddell 2002). While not typically a driver of surface fire behavior modeling (Anderson 1969), coarse woody surface fuels are nevertheless an important component of fire severity: Larger logs smolder longer, leading to greater soil heating and higher severity (Albini and Reinhardt 1995).

Transect sampling is an efficient and appropriate method for measuring log volume and weight, especially with high log abundance, but transect length must be scaled accordingly (Bate et al. 2004; Lutes 1999; Sikkink and Keane 2008). Fixed-area plot sampling may be more time-consuming, but Bate et al. (2004) concluded that their measured log variables were more precise using fixed-area plot sampling. Therefore, having a good understanding of the advantages of measurement techniques is important for managers and researchers alike.

In summary, we conclude that the three sampling techniques produced similar results at the unit level, but that fixed-area plot sampling is more likely to capture the more rare occurrences of coarse woody fuels, and as such, provides a good estimate of the actual variance. On an individual plot, the planar intersect method tends to overpredict log loading at all levels except the very lowest. Additionally, doubling the number of transects per plot does not seem to avoid any sampling bias at either low or high log loading.

ACKNOWLEDGMENTS

This was a study of the Applied Forest Management Program at the University of Montana, a research and outreach unit of the Montana Forest and Conservation Experiment Station. This work was funded by the USDI Joint Fire Science Program Project #15-1-07-30.

REFERENCES

Albini, F.A.; Reinhardt, E.D. 1995. Modeling ignition and burning rate of large woody natural fuels. International Journal of Wildland Fire. 5: 81–91.

Anderson, Hal E. 1969. Heat transfer and fire spread. Res. Pap. INT-RP-69. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 20 p.

Avery, Thomas Eugene; Burkhart, Harold E. 2002. Forest measurements. 5th ed. New York: McGraw-Hill.

Baker, William L. 2009. Fire ecology in Rocky Mountain landscapes. Washington, DC: Island Press.

Bate, Lisa J.; Torgerson, Torolf; Wisdom, Michael J.; Garton, Edward O. 2004. Performance of sample methods to estimate log characteristics for wildlife. Forest Ecology and Management. 199: 83–102.

Brown, James K. 1971. A planar intersect method for sampling fuel volume and surface area. Forest Science. 17: 96–102.

Brown, James K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-GTR-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Brown, James K.; Reinhardt, Elizabeth D.; Kramer, Kylie A. 2003. Coarse woody debris: Managing benefits and fire hazard in the recovering forest. Gen. Tech. Rep. RMRS-GTR-105. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 p.

Brown, James K.; See, Thomas E. 1981. Downed dead woody fuel and biomass in the northern Rocky Mountains. Gen. Tech. Rep. INT-GTR-117. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 48 p.

Bull, Evelyn L.; Parks, Catherine G.; Torgerson, Torolf R. 1997. Trees and logs important to wildlife habitat in the Interior Columbia River Basin. Gen. Tech. Rep. PNW-GTR-391. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 55 p.

Busing, R.; Rimar, K.; Stolte, K.W.; [et al.]. 1999. Forest health monitoring: Vegetation pilot field methods guide. Vegetation diversity and structure down woody debris fuel loading. Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program. 28 p.

Crotteau, Justin S.; Keyes, Christopher; Sutherland, Elaine K.; [et al.]. 2016. Forest fuels and potential fire behaviour 12 years after variable-harvest in lodgepole pine. International Journal of Wildland Fire. 25: 633–645.

Eyre, Francis Howlett. 1980. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters.

Gruell, George E.; Schmidt, Wyman C.; Arno, Stephen F.; Reich, William J. 1982. Seventy years of vegetative change in a managed ponderosa pine forest in western Montana—Implications for resource management. Gen. Tech. Rep. INT-GTR-130. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Harmon, M.E.; Franklin, J.F.; Swanson, F.J.; [et al.]. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research. 15: 133–302.

Keane, Robert E. 2015. Wildland fuel fundamentals and applications. New York: Springer. 191 p.

Keane, Robert E.; Gray, Kathy. 2013. Comparing three sampling techniques for estimating fine woody down dead biomass. International Journal of Wildland Fire. 22: 1093–1107.

Keane, Robert E.; Gray, Kathy L.; Bacciu, Valentina. 2012. Spatial variability of wildland fuel characteristics in northern Rocky Mountain ecosystems. Res. Pap. RMRS-RP-98. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 56 p.

Lutes, Duncan C. 1999. Comparison of methods for the quantification of coarse woody debris and identification of its spatial scale: A study from the Tenderfoot Creek Experimental Forest, Montana. Missoula, MT: University of Montana. M.S. thesis. https://scholarworks.umt.edu/etd/1866.

Lutes, Duncan C.; Keane, Robert E.; Caratti, John F.; [et al.]. 2006. FIREMON: Fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. [CD included].

Ottmar, Roger D.; Sandberg, David V.; Riccardi, Cynthia L.; Prichard, Susan J. 2007. An overview of the Fuel Characteristic Classification System—Quantifying, classifying and creating fuelbeds for resource planning. Canadian Journal of Forest Research. 37: 2383–2393.

Pfister, Robert D.; Kovalchik, Bernard L.; Arno, Stephen F.; Presby, Richard C., eds. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-GTR-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

R Core Team. 2016. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Royston, J.P. 1982. An extension of Shapiro and Wilk's W test for normality to large samples. Applied Statistics. 31: 115–124.

Schoennagel, Tania; Veblen, Thomas T.; Negron, José F.; Smith, Jeremy M. 2012. Effects of mountain pine beetle on fuels and expected fire behavior in lodgepole pine forests, Colorado, USA. PLoS ONE. 7(1): e30002.

Sikkink, Pamela G.; Keane, Robert E. 2008. A comparison of five sampling techniques to estimate surface fuel loading in montane forests. International Journal of Wildland Fire. 17: 363–379.

Smith, Helen Y.; Arno, Stephen F., eds. 1999. Eighty-eight years of change in a managed ponderosa pine forest. Gen. Tech. Rep. RMRS-GTR-23. Ogden, UT: U.S. Department of Agriculture, Rocky Mountain Research Station.

Strom, Barbara A.; Fulé, Peter Z. 2007. Pre-wildfire treatments affect long-term ponderosa pine forest dynamics. International Journal of Wildland Fire. 16: 128–138.

USDI National Park Service. 2003. Fire monitoring handbook. Boise, ID: National Interagency Fire Center, Fire Management Program Center.

Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. Forest Science. 14: 20–26.

Waddell, Karen L. 2002. Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecological Indicators. 1: 139–153.

Woldendorp, G; Keenan, R.J.; Barry, S.; Spencer, R.D. 2004. Analysis of sampling methods for coarse woody debris. Forest Ecology and Management. 198: 133–148.

Structure Vulnerability to Firebrands from Fences and Mulch

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Abstract—Fences and mulch contribute to the spread of wildland-urban interface fires, acting both as ignition targets and as sources that may ignite nearby objects through direct flame contact and firebrand generation.

This paper presents the findings from outdoor experiments that investigated the spread of fire through firebrand spotting from fences and mulch beds near a structure in a wind field. A fence section, mulch bed, or combination was arranged perpendicular to a small structure, with a large fan directing wind toward the structure. After ignition, data were collected on firebrand spotting time, time for the spot fire to reach the wall, and flame spread rate over the fence and mulch bed.

Fence type, wind speed, and type of mulch were found to affect firebrand spotting. For fence and mulch combinations, spotting usually occurred within 7 minutes. Time to spotting generally decreased with increasing wind speed. Two parallel fence panels burned significantly more intensely, and spotted more quickly, than a single fence panel. In the absence of mulch, spotting from fences often occurred more slowly or not at all. The combination of a fence and a mulch bed decreased the time to spotting over either the mulch bed or the fence alone.

Keywords: fence, firebrand, mulch, structure vulnerability, wildland-urban interface (WUI) fire

INTRODUCTION

Wildland-urban interface (WUI) fires threaten an estimated 70,000 communities, 46 million homes, and 120 million people within the United States (ICC and NARCD Councils 2013). In recent years, the United States has been losing on the order of 3,000 homes per year, and the costs are rising, with $14 billion spent in 2009 alone on fire suppression and damages.

Firebrands generated by a wildfire are carried by the wind and may ignite fires in a community far downstream of the fire front. After the fire has reached the community, firebrands generated from burning combustible objects near a structure contribute to the firebrand assault. Postfire investigations have demonstrated that firebrands are a major contributor to structure losses in WUI fires.

Fences and mulch are common contributors to the spread of WUI fires within WUI communities. They act both as ignition targets and as sources that may themselves ignite nearby objects through direct flame contact and firebrand generation. The linear nature of fences gives them the capability of spreading fire over long distances. In a study of the 2011 Tanglewood Complex Fire near Amarillo, Texas performed by the National Institute of Standards and Technology (NIST) (Maranghides and McNamara 2016), 2.4 km of fences within a community of 25 homes were found to be damaged or destroyed. Combustible fences also contributed to fire spread in the 2012 Waldo Canyon Fire in Colorado (Maranghides et al. 2015). Firefighters were documented removing fences as part of their defensive strategy to contain this fire, reducing resources allocated to suppression.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

The goal of this work is to improve our understanding of the mechanisms by which fences and other combustible landscaping elements can transport fire to a home, including exposure to wind-driven firebrands. The results will be used to improve codes and standards, which in turn will provide guidance to homeowners and firefighters.

EXPERIMENTAL DESIGN

Setup

To investigate the spread of fire through firebrand spotting, a series of field experiments are being performed on fences, mulch beds, woodpiles, and other combustible landscaping elements arranged in front of a structure in a wind field.

Figure 1 shows a schematic of the experimental setup for fences and mulch beds. A wind machine, consisting of an airboat fan mounted on a trailer, was aimed toward a small structure. A flow straightener directed the wind downward slightly so the wind field would reach the ground and the base of any combustible object being tested. A fence section, with or without a mulch bed beneath, was arranged perpendicular to the wall of the structure. The fence section was 2.44 m long and 1.83 m high for privacy fences or 1.22 m high for lattice fences, attached to 0.09 m × 0.09 m pine (*Pinus* spp.) posts at each end. The fence or mulch bed was placed in contact with the wall of the structure or separated from it by some fixed distance.

To study the ability of firebrands to threaten a house, a target pan of hardwood mulch that was 0.46 m wide was arranged at the base of the structure wall. This mulch bed served as a surrogate for any combustible material next to a house. Because of its rough texture, any firebrands landing on this surface tended to stay in place.

Before being arranged in steel pans, the mulch was dried to a moisture content between 6 and 7 percent, as measured by a moisture analyzer. The mulch beds were prepared by filling the pans with an even layer of mulch and compressing it lightly by foot. The mulch beds were 0.05 m thick except for cases in which the mulch beds were reduced to half thickness (0.025 m).

The wind field was monitored by a set of bidirectional probes just upwind of the end of the fence. The ambient wind speed and direction were measured by

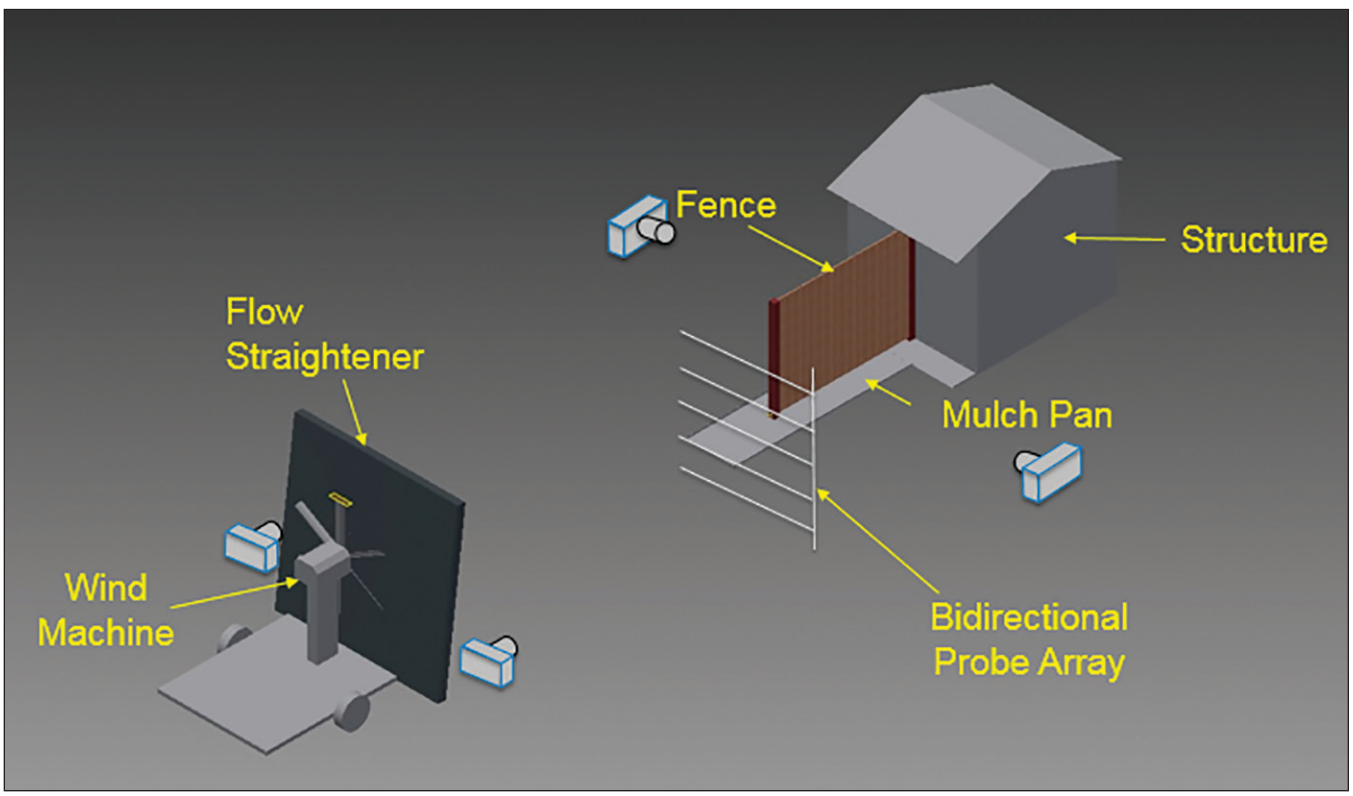

Figure 1—Experimental setup.

an anemometer mounted on a shed away from the experimental setup, and the ambient temperature was measured with a thermocouple near the test setup. Four video cameras monitored the experiment from right and left sides and from each side of the fan.

The ambient wind speed was required to be less than one-third the nominal wind speed in order to carry out the experiment. Under these conditions, the impact of the ambient winds on the wind field generated by the fan was minimal.

Procedure

A propane burner was used to ignite the fence or mulch bed at the base of the fence farthest from the structure. After 90 seconds, when the fire was judged to be self-sustaining, the fan was turned on, a timing clock was started, and the winds were brought to the speed required by the experiment. The experiment ended when a fire in the mulch bed at the base of the structure reached the wall and after fire had also reached the end of the fence or fence mulch bed. Flames at the wall from spot fires were extinguished if the fire had not yet spread over the entire length of the fence with mulch bed. At the end of the test, the clock was reset and all fires were extinguished with a water hose.

Uncertainties

The measurements of wind speed, distances, and times discussed in this paper each have uncertainties associated with them. Uncertainties generally consist of several components, which are grouped into two categories according to the method used to estimate their value. Type A uncertainties are evaluated by statistical methods, and type B uncertainties are evaluated by other means, often based on scientific judgment using all available relevant information (Taylor and Kuyatt 1994). Type B uncertainties are evaluated by estimating lower and upper limits a_- and a_+, such that the probability that the value lies in the interval a_- to a_+ is essentially 100 percent. If the value is equally probable to lie anywhere within the interval, the best estimate is $(a_+ + a_-)/2$, with standard deviation $u_j = a/\sqrt{3}$, where $a = (a_+ - a_-)/2$. Once all components have been estimated by either type A or type B analysis, they are combined using the square root of the sum of the squares (RSS) method to yield the combined standard uncertainty (estimated standard deviation), u_c. Finally, expanded uncertainties are given by $\pm ku_c$, where $k = 2$ is the coverage factor for a confidence level of 95 percent.

Table 1 shows the components of uncertainty for the measurements given in this paper. The extensive data collection on wind speed enables the evaluation of type A uncertainties; most other uncertainties on this list are type B, either estimated through scientific judgment or obtained from the literature.

Wind speed uncertainties involve the bidirectional probe design and the measurement statistics from the wind field. A paper by McCaffrey and Heskestad (1976) states that velocities are estimated within ±10 percent provided the approach flow direction is within approximately 50° of the probe axis. Since the variability of the fan was greatest at the lowest setting, which was close to the idle speed, statistical analysis was carried out for each wind speed level separately. Repeatability was calculated as the standard deviation of the average wind speed for each experiment (the average from five probes in the central wind field) from the average wind speed overall. The random component reflects the fluctuations in measured wind speed due to turbulence, and was calculated by the root-mean-square of the standard deviations of wind speed over all experiments at each wind speed level.

The time to spotting required identification of two events in videos taken by the camera positioned to the right or left side of the experiment. The first event was the time at which the fan was turned on. The engagement of the fan engine could be determined very accurately, although it should be noted that the wind speed was adjusted for up to 20 seconds afterwards before reaching a steady state value. The second event was the ignition within the target mulch bed of the first spot fire that eventually reached the wall of the structure. After identification in one of the videos, this spot fire was tracked backwards in time to the point at which the first sign of smoke could be detected in the mulch, which could be defined within an estimated ± 5 seconds. These sources of uncertainty are likely dwarfed, however, by the repeatability of time to spotting for multiple tests under the same conditions and the random nature of firebrand generation and ignition processes, neither of which is available for this study.

Table 1—Uncertainty in experimental data.

Measurement	Component standard uncertainty, ± u_j	Combined standard uncertainty, ± u_c	Total expanded uncertainty, ± $2u_c$
Wind speed			
Calibration	±10%		
Repeatability*			
6 m sec-1	±11%		
10 m sec-1	±6%		
14 m sec-1	±8%	6 m sec-1: ±24%	6 m sec-1: ±48%
Random*		10 m sec-1: ±15%	10 m sec-1: ±31%
6 m sec-1	±19%	14 m sec-1: ±15%	14 m sec-1: ±30%
10 m sec-1	±10%		
14 m sec-1	±8%		
Time to spotting			
Fan on	±1 sec		
Smoke detected	±3 sec	> ±3 sec	> ±6 sec
Repeatability*	Unknown		
Random*	Unknown		
Separation distance			
Placement	±0.002 m	±0.004 m	±0.008 m
Adjustment	±0.003 m		
Mulch thickness			
Variability	±0.005 m	±0.005 m	±0.010 m
Target mulch bed width			
Variability	±0.01 m	±0.01 m	±0.02 m

* Type A uncertainty (evaluated by statistical means). All other uncertainties are type B (evaluated by other than statistical means).

The separation distance between the fence or mulch bed and the wall of the structure was established by using a tape measure to adjust the location of the fence with mulch bed to the desired position. Sources of uncertainty include the placement of the tape measure and the ability to adjust the position of the fence with mulch bed accurately.

The mulch bed thickness varied over its surface due to the nature of the mulch as overlapping particles whose individual thicknesses are an appreciable fraction of the thickness of the mulch layer. The mulch bed thickness depended on the evenness of the spreading over the mulch bed and the uniformity of the compaction.

The target mulch bed at the base of the shed was not confined by a lip on the outside edge facing the fence, allowing firebrands to land on the target mulch without needing to clear a height. The width of the target mulch bed thus varied over its length.

Variations of dimensional values were estimated using scientific judgment.

Experimental Combinations

During 2016 and 2017, 111 experiments were carried out in the configuration just described. Figure 2 shows the distribution of experiments that have been performed on a variety of combinations of fences and mulch, at four separation distances from 0 m to 1.8 m, and at three wind speeds of 6 m second^{-1}, 10 m second^{-1}, and 14 m second^{-1}. The fences include privacy fences constructed of western redcedar (*Thuja plicata*) and vinyl and lattice fences constructed of redwood (*Sequoia* spp.) and pine. The mulches include shredded hardwood mulch at two thicknesses, pine bark mulch, and pine straw mulch.

RESULTS

Burning Characteristics for a Privacy Fence with Mulch Bed

Figure 3 shows an image from a typical experiment with a western redcedar fence sitting in a bed of shredded hardwood mulch. In this experiment, the wind speed was 10 m second^{-1} and the separation distance between the end of the fence and the small structure was 1.8 m. This image shows the conditions at about 4.5 minutes after the fan was turned on following ignition of the fence and mulch. At this point firebrands had ignited spot fires in the mulch bed at the base of the structure at several locations. A few spot fires can be seen at the front edge of the mulch bed, in addition to one close to the wall. The fence itself was burning along its entire length, although discoloration and other signs of deterioration show that the fire has remained low on the fence, not even reaching half of its height.

Other phenomena apparent from the video itself include pieces of mulch that moved out of the bed under the structure and rolled on the pavement toward the fence or the sides of the experiment. The smoke and flames from the combination of fence and mulch bed generally extended toward the structure, while smoke and flames from the mulch bed at the base of the structure extended toward the fence. These observations are consistent with a horseshoe vortex that occurs at the base of a structure at right angles to a flow stream (Martinuzzi and Tropea 1993). Figure 4 shows this feature in a model of the experimental

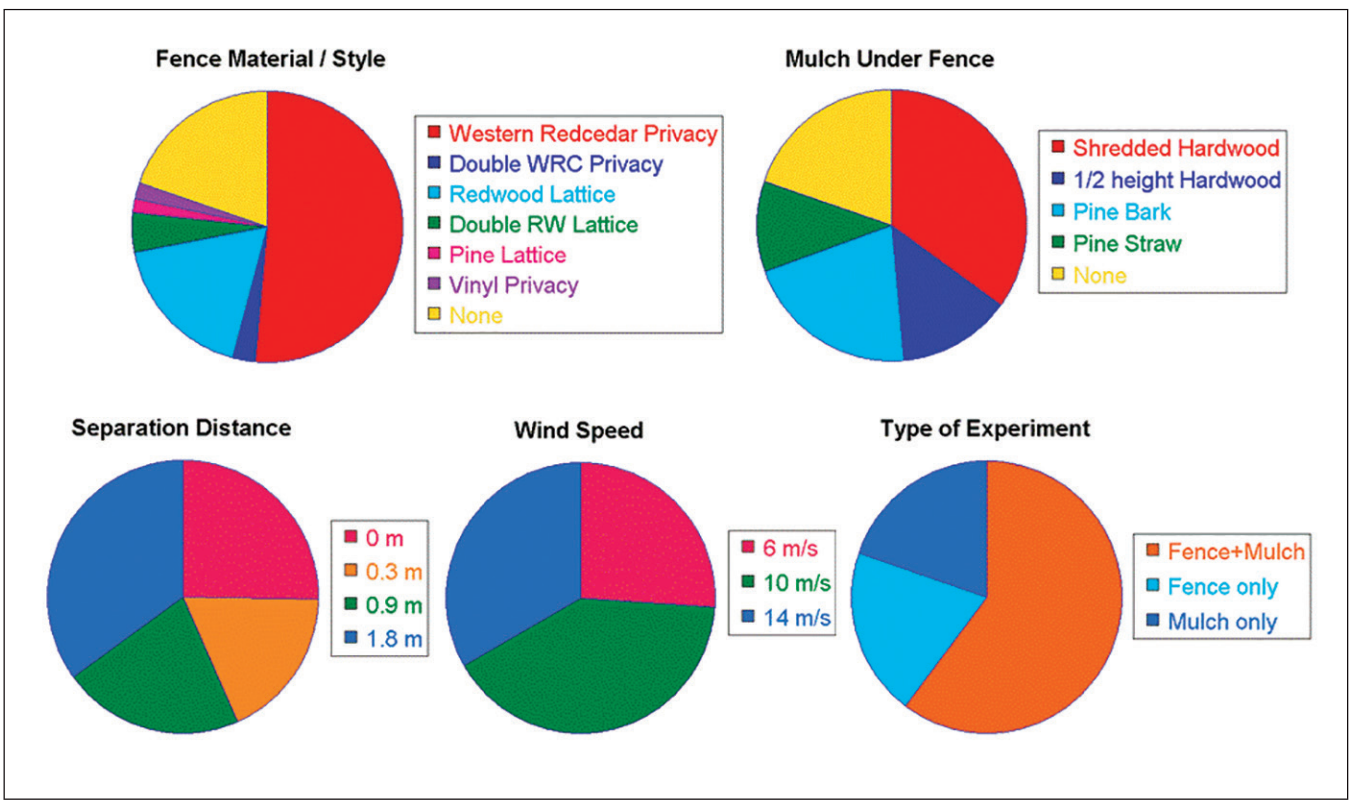

Figure 2—Distribution of experiments by fence type, mulch type, separation distance from wall, wind speed, and experiment type (fence with mulch beneath, fence only, or mulch only). WRC = western redcedar.

Figure 3—Image from video of western redcedar fence combined with shredded hardwood mulch.

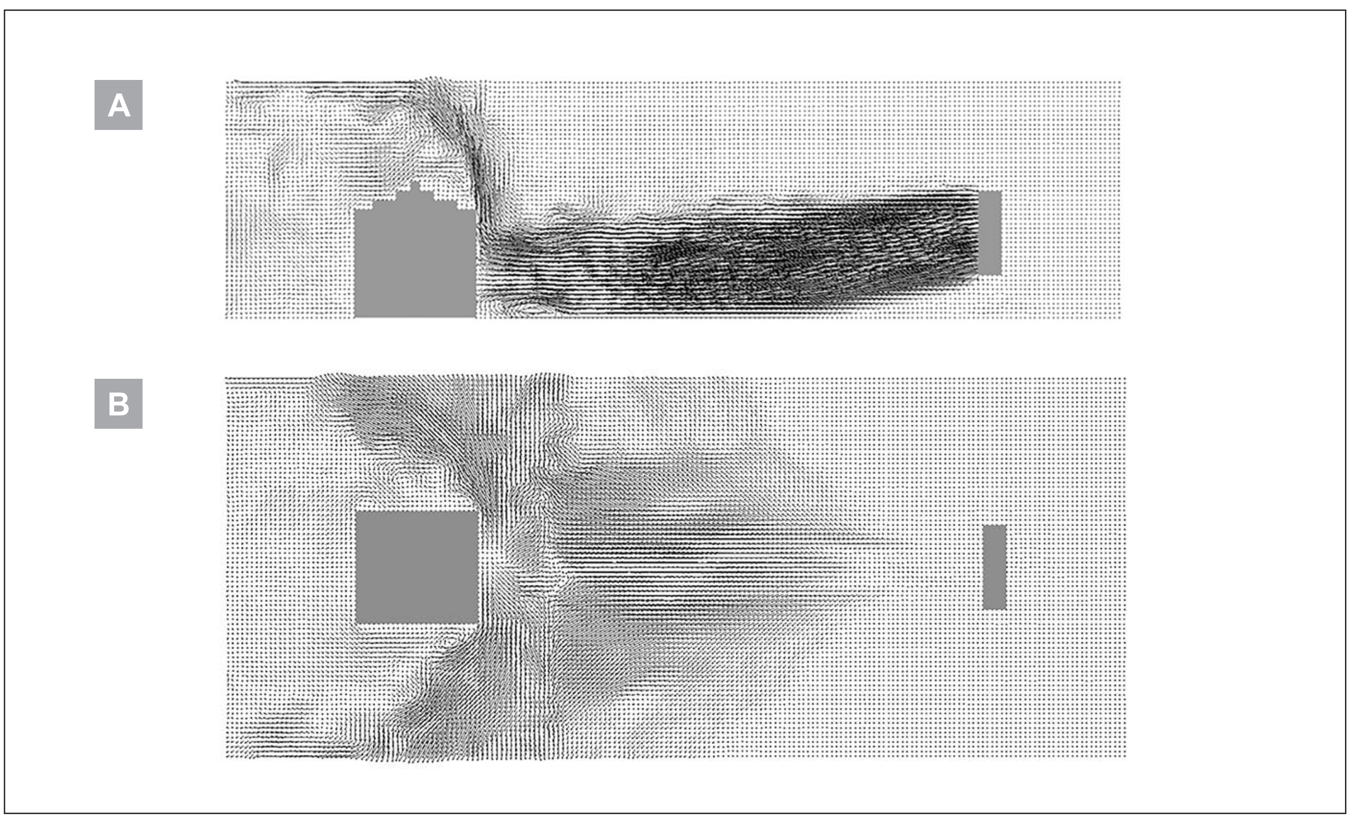

Figure 4—Instantaneous flow field from Fire Dynamic Simulator model, showing (A) side view and (B) top view in a plane close to the ground. Note the recirculation zone near the base of the structure wall.

setup using the NIST Fire Dynamic Simulator (FDS) (McGrattan et al. 2013). The vortex causes particles and smoke in the mulch bed at the base of the structure to be generally transported away from the wall and to the sides. Firebrands that are lofted, however, may be carried along the top of the vortex or drop out of the flow directed over the top of the structure, to be deposited at the base of the structure where they can ignite combustible materials close to the wall.

Spotting Time

This set of experiments represents a survey of the effects of fences and mulch on the spread of fire to a structure, directly or through firebrands and in a variety of conditions. Few experiments have been replicated, and many phenomena involved in firebrand spotting, such as generation of firebrands and ignition processes, are stochastic in nature. The analysis of this data was therefore based on uncovering trends and on discovering different modes of behavior, rather than on quantitative results.

One of the simple measures that has been determined from the video records is the length of time between turning on the fan and ignition within the target mulch bed at the base of the structure of the first spot fire that eventually reached the wall. Ignition was detected by the first sign of smoke.

Effects of Wind Speed and Separation Distance

In figure 5, the time to spot is plotted as a function of the nominal wind speed of the fan. The experiments represented in this plot are the 22 experiments performed on mulch alone and 67 experiments on fence and mulch combinations that are included in the pie charts of figure 2.

Figure 5 demonstrates several trends. First, the time to spot generally decreases as a function of wind speed. Second, the spotting times for fences in combination with mulch beds tend to be shorter than for mulch alone. Third, the spotting times are on the order of minutes. For 6 m second-1 winds, spotting occurs in 30 minutes or less, while for 14 m second^{-1} winds, spotting occurs in less than 7 minutes in every case. If a home is undefended during a WUI fire, these firebrands pose a serious threat to the home.

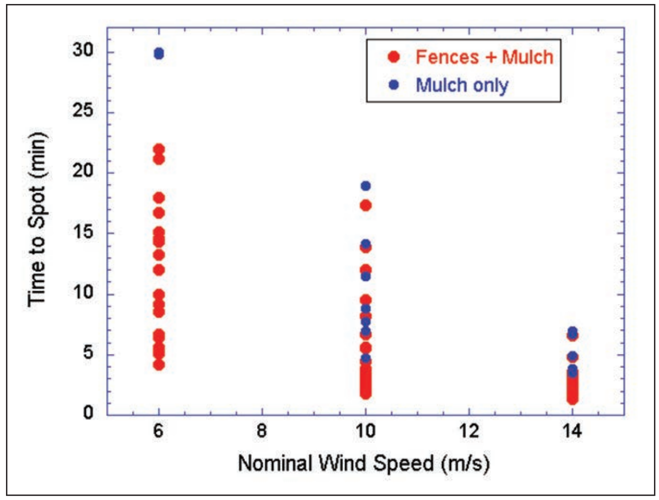

Figure 5—Spotting time as a function of nominal wind speed for experiments on mulch beds only (blue) and combinations of fence and mulch bed (red).

Firebrand spotting consists of three mechanisms: firebrand generation, firebrand transport, and ignition of the surrounding fuels (Koo et al. 2010). High speed winds break off and loft firebrands more readily. They also transport firebrands faster and farther. The ability of firebrands to ignite a spot fire in the mulch bed depends on many factors, including the characteristics of the firebrand and mulch bed, the contact between firebrand and mulch, and the local environment at the location of the firebrand. Higher speed winds deliver more oxygen to the ignition site and support smoldering (Filkov et al. 2016). However, if a critical wind speed is exceeded, the firebrand may be quenched by the cooling effect (Song et al. 2017).

Figure 6 shows that there is not a strong relationship between the time to spot and the separation distance between the end of the fence or mulch bed and the wall of the structure. This suggests that the spotting time is controlled by either firebrand generation or ignition, and that transport is not an important factor in this set of experiments, where the distance between fence and structure was relatively short.

In these experiments, spot fires appeared to be ignited by single firebrands. Not every firebrand landing in the target mulch bed found conditions favorable for ignition. Typically, a handful of spot fires (seldom more than 10) were ignited in the time period before 1 of those fires reached the wall.

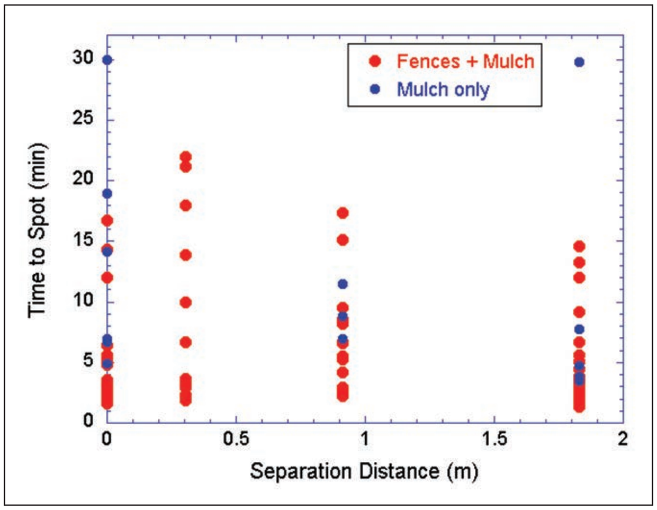

Figure 6—Spotting time as a function of separation distance for experiments on mulch beds only (blue) and combinations of fence and mulch bed (red).

Fences Without Mulch

In the absence of mulch beneath the fence, firebrand spotting was generally considerably slower, if it occurred at all; spotting occurred in only 8 of the 22 experiments with fences alone. The times to spot for these experiments are shown in figure 7.

Without mulch, the ignited fences tended to smolder rather than flame. This was a slow process that in the majority of cases did not result in spot fires. An exception is shown in figure 8, in which a smoldering piece of the fence has broken off at high wind speeds and ignited a spot fire near the wall.

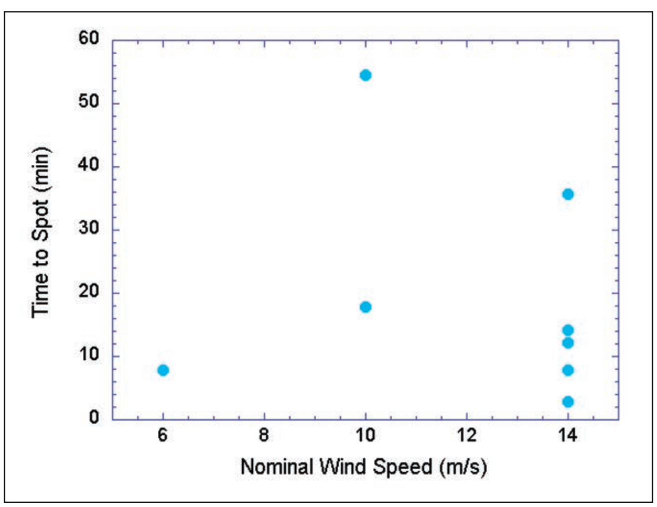

Figure 7—Spotting time as a function of nominal wind speed for experiments on fences only in which spotting occurs.

Exceptional Cases

This set of experiments demonstrated some special cases for which the fire behavior differed significantly from similar experiments.

Double Lattice Fences

A single redwood lattice fence combined with a shredded hardwood mulch bed burned with flames staying close to the ground, as shown in figure 9. This image was taken 12 minutes into the experiment. The behavior is similar to that seen with the privacy fence in figure 3.

Compare this to figure 10, in which redwood lattice fence panels have been attached to both sides of the end posts, with a spacing of 0.09 m between them. This image was taken 3 minutes into the experiment, at which point the double lattice fence is fully engulfed. The space between the fences is partially shielded from the wind field, which promotes flame attachment and spread. The changes in convective heat transfer introduced by the second fence, plus the radiative exchange between the fences, act to intensify the fire.

The time to spotting was 15 minutes in the case of the single lattice fence and 7 minutes for the double lattice fence, after the peak fire behavior in each case.

The fire behavior of the double lattice fence is sufficiently enhanced that the mulch bed beneath the fences is not necessary. Figure 11 shows a double lattice fence without mulch beneath, at 4 minutes into the experiment. Spotting in the target mulch bed occurred at 7 minutes, after the fence had collapsed into a burning pile on the ground.

Parallel Privacy Fences

The addition of a second western redcedar privacy fence parallel to the first changed the fire behavior in a similar way to the double lattice fence. Figure 12 shows a single privacy fence with hardwood mulch beneath after 20 minutes. In figure 13, a second privacy fence was arranged at a spacing of 0.20 m from the first. This could occur, for example, if two neighbors decided to build privacy fences on the property line of their respective parcels. This configuration greatly enhanced the fire behavior. Figure 13 shows the conditions 5 minutes into the experiment.

Figure 8—Firebrand spotting for western redcedar privacy fence with high wind speed (14 m second^{-1}) and at 1.8 m separation distance from wall.

Figure 9—Single redwood lattice fence in hardwood mulch at low wind speed (6 m second^{-1}).

Figure 10—Double redwood lattice fence in hardwood mulch at low wind speed (6 m second^{-1}).

Figure 11—Double redwood lattice fence without mulch at low wind speed (6 m second^{-1}).

Figure 12—Single western redcedar privacy fence in hardwood mulch at low wind speed (6 m second^{-1}).

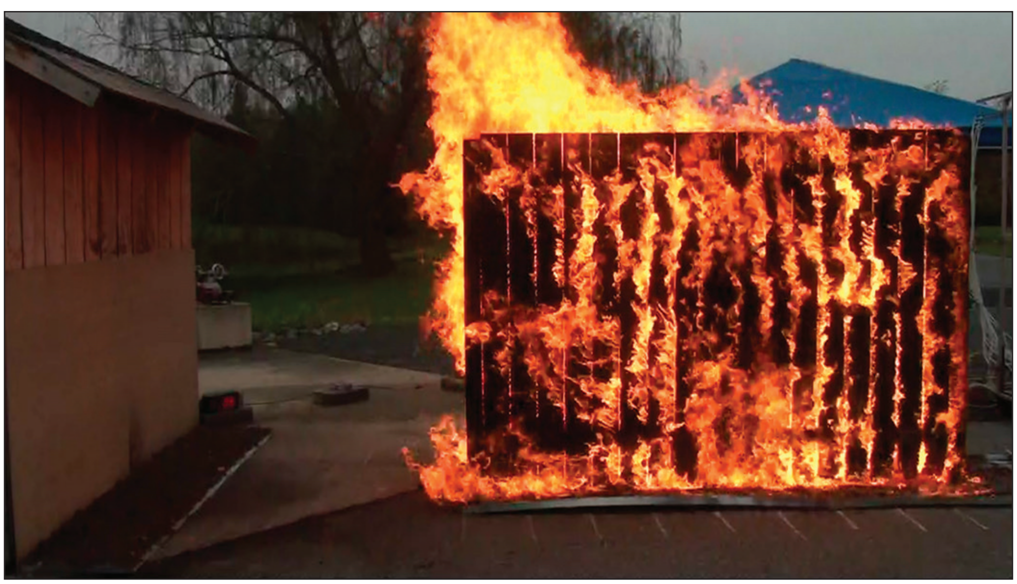

Figure 13—Parallel western redcedar privacy fences separated by 0.20 m in hardwood mulch at low wind speed (6 m second^{-1}).

The time to spotting was 13 minutes for the single privacy fence and 5 minutes for the parallel privacy fences.

Unlike the double lattice fences, a mulch bed beneath the parallel privacy fences was necessary for enhancing the fire behavior. Figure 14 shows that without the mulch bed the parallel fences smoldered slowly, similar to the behavior seen in figure 8 for a single privacy fence without a mulch bed beneath.

Pine Straw Mulch

A final example of unusual fire behavior was encountered with a bed of pine straw mulch. This mulch burned intensely and rapidly. However, the firebrands produced by pine straw mulch were too fine to ignite the target mulch bed. Figure 15 shows a pine straw mulch bed in direct contact with the target hardwood mulch bed at the base of the structure. Although the flames have reached the target mulch bed, no ignition took place.

If the pine straw mulch bed was combined with a western redcedar privacy fence, however, the pine straw quickly ignited the whole bottom of the fence, and spot fires were ignited in the target mulch bed by firebrands from the fence.

Figure 14—Parallel western redcedar privacy fences without mulch at low wind speed (6 m second^{-1}).

Figure 15—Pine straw mulch bed in contact with target hardwood mulch bed.

Removing the Structure

An additional three experiments were performed in which the small structure was removed from the area downwind of the firebrand source, the target mulch bed was moved to a distance 23 m from the source, and the burning source was subjected to a wind field of 14 m $second^{-1}$. The space between the source and target was asphalt and concrete, representing a worst case (i.e., favorable) scenario for transport of the firebrands over the ground. Roads and driveways make this a realistic condition for a WUI neighborhood. Figure 16 shows the experiment in which a double lattice fence has been ignited. A bed of shredded hardwood mulch and a woodpile were used in the other two long-range experiments. In each case, spot fires ignited in the target mulch bed 23 m from the firebrand source within 5 minutes after the wind machine was set to deliver high wind speeds. It should be noted that most of the spot fires occurred in the middle of the target mulch, indicating that the firebrands were lofted at some point rather than simply moving over the surface of the ground.

CONCLUSIONS

This limited series of field experiments on ignited mulch beds, fences, and combinations of fence and mulch bed in a wind field in front of a structure demonstrates that firebrand spotting may occur within 2 to 20 minutes of ignition. Spotting often occurred after peak flaming and was affected by wind fields near the structure.

For this set of wind velocities and approach angle, fence configurations, and materials, the time to spotting tended to decrease with increasing wind speed, but it did not show a strong relationship with separation distance. This is consistent with the wind having important effects on firebrand generation and on the local ignition environment.

For this series, the combination of a fence and a mulch bed appeared to decrease the time to spotting over either the mulch bed or the fence alone.

In the absence of a structure, firebrand spotting can occur within a few minutes even at long range.

Figure 16—Double lattice fence experiment without a structure and with a mulch bed situated 23 m from the far end of the fence.

Future experiments will include effects of mitigation, including coatings and fence height above the ground, and aging on the generation and spotting of firebrands from fences.

ACKNOWLEDGMENTS

The Frederick County Fire and Rescue Training Facility in Frederick, Maryland made this work possible by allowing us to perform the experiments on its property. Discussions with Alex Maranghides have guided this work. Our thanks also go to Marco Fernandez, whose help with instrumentation, logistics, and operations has been essential to running the experiments, to Mariusz Zarzecki for his help with both experiments and analysis, and to Eric Auth, Rachel McIntyre, and Michael Pryor for their contributions as summer students.

REFERENCES

Filkov, Alexander; Kasymov, Denis; Zima, Vladislav; Matvienko, Oleg. 2016. Experimental investigation of surface litter ignition by bark firebrands. Advanced Materials in Technology and Construction; AIP Conf. Proc. 1698, 060004. https://doi.org/10.1063/1.4937859.

ICC and NARCD Councils. 2013. Communities dealing with wildland/urban interface fire; Wildfire Safe, Sound & Code Smart; WUI fact sheet. https://nanopdf.com/download/wssampcs-wui-fact-sheet-c-international-association-of-wildland-fire_pdf. [Accessed 2018 June 21].

Koo, Eunmo; Pagni, Patrick J.; Weise, David R.; Woycheese, John P. 2010. Firebrands and spotting ignition in large-scale fires. International Journal of Wildland Fire. 19: 818–843.

Maranghides, Alexander; McNamara, Derek. 2016. 2011 Wildland urban interface Amarillo Fires Report #2—Assessment of fire behavior and WUI measurement science. Technical Note NISTTN 1909. Gaithersburg, MD: National Institute of Standards and Technology. 153 p. https://doi.org/10.6028/NIST.TN.1909.

Maranghides, Alexander; McNamara, Derek; Vihnanek, Robert; [et al.]. 2015. A case study of a community affected by the Waldo Fire—Event timeline and defensive actions. Technical Note NISTTN 1910. Gaithersburg, MD: National Institute of Standards and Technology. 213 p. https://doi.org/10.6028/NIST.TN.1910.

Martinuzzi, R.; Tropea, C. 1993. The flow around surface-mounted, prismatic obstacles placed in a fully developed channel flow. Journal of Fluids Engineering. 115: 85–92.

McCaffrey, B.J.; Heskestad, G. 1976. A robust bidirectional low-velocity probe for flame and fire application. Combustion and Flame. 26: 125–127.

McGrattan, Kevin B.; McDermott, Randall J.; Weinschenk, Craig G.; [et al.]. 2013. Fire Dynamics Simulator Users Guide. Special Publ. NISTSP 1019, 6th ed. Gaithersburg, MD: National Institute of Standards and Technology. https://doi.org/10.6028/NIST.sp.1019.

Song, Jiayun; Huang, Xinyan; Liu, Naian; [et al.]. 2017. The wind effect on the transport and burning of firebrands. Fire Technology. 53: 1555–1568.

Taylor, Barry N.; Kuyatt, Chris E. 1994. Guidelines for evaluating and expressing the uncertainty of NIST measurement results. Technical Note NISTTN 1297, 1994 ed. Gaithersburg, MD: National Institute of Standards and Technology. https://doi.org/10.6028/NIST.tn.1297.

Improvements in Australia's Bushfire Rate of Spread Models Over Time

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Abstract—We analyzed the predictive accuracy of rate of fire spread models used operationally in Australia in five different fuel types (grasslands, temperate shrublands, semiarid shrublands, dry eucalypt [*Eucalyptus* spp.] forests, and conifer forests). This analysis was undertaken by comparing predictions of older models with those of newer models and noting changes in error statistics based on independent evaluation of datasets composed largely of wildfire observations. We observed the newer models to have improved prediction accuracy in four of the five cases over their previous counterparts; only in the case of the semiarid shrublands was there essentially no difference. Mean absolute errors were reduced between 56 and 70 percent. This study has highlighted the value of continuous improvement in fire behavior modeling.

Keywords: fire behavior, fire environment, fuel type, model evaluation.

INTRODUCTION

Disastrous bushfires that cause loss of human life and property are especially common in southern Australia because of its fire environment (Blanchi et al. 2014), as exemplified, for example, by the 2009 Black Saturday fires in Victoria (Cruz et al. 2012). The accurate prediction of fire propagation across the landscape is thus imperative to informing safe and effective suppression operations and is essential to advising the public with regards to appropriate safety measures and warnings (Neale and May 2018). In keeping with the theme of the Fire Continuum Conference, this presentation is largely based on a recently published study undertaken to assess improvements over time in the models currently used to predict bushfire rates of spread in Australia (Cruz et al. 2018) (for a brief summary see Commonwealth Scientific and Industrial Research Organisation PyroPage Issue #18 at https://research.csiro.au/pyropage/).

A BACKGROUND TRIBUTE

No treatment of Australian bushfire behavior research would be complete without mentioning Alan McArthur (fig. 1A). He was not only an Australian pioneer in fire behavior research, he was one of the world's leading scientists on the subject. In late 1953, McArthur (then 30 years old) accepted a position with the Commonwealth of Australia's Forestry and Timber Bureau as the country's first professional officer engaged full-time in bushfire research. For the next 15 years or so, he devoted most of his time to studying fire behavior in grasslands and native forests.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Within 5 years, McArthur had developed a model for predicting rate of fire spread in dry eucalypt (*Eucalyptus* spp.) forests (plus flame height and average spotting distance) in the form of a set of tables. He subsequently developed a series of linear and circular slide rules (fig. 1B) reflecting improvements with time based on incremental advances in fire behavior knowledge. A very similar set of developments occurred with respect to grasslands, the most widespread fuel type in the country.

McArthur, as virtually a one-man show, was able to produce more practical fire behavior knowledge over a relatively brief period of time than most in the history of wildland fire behavior research. His two seminal publications on Australian grassland (fig. 1C) and eucalypt fire behavior (McArthur 1966, 1967) are considered classics in the field of wildland fire research. Both of McArthur's fire danger meters were eventually converted to sets of equations by Noble et al. (1980). He died in 1978 at the early age of 55.

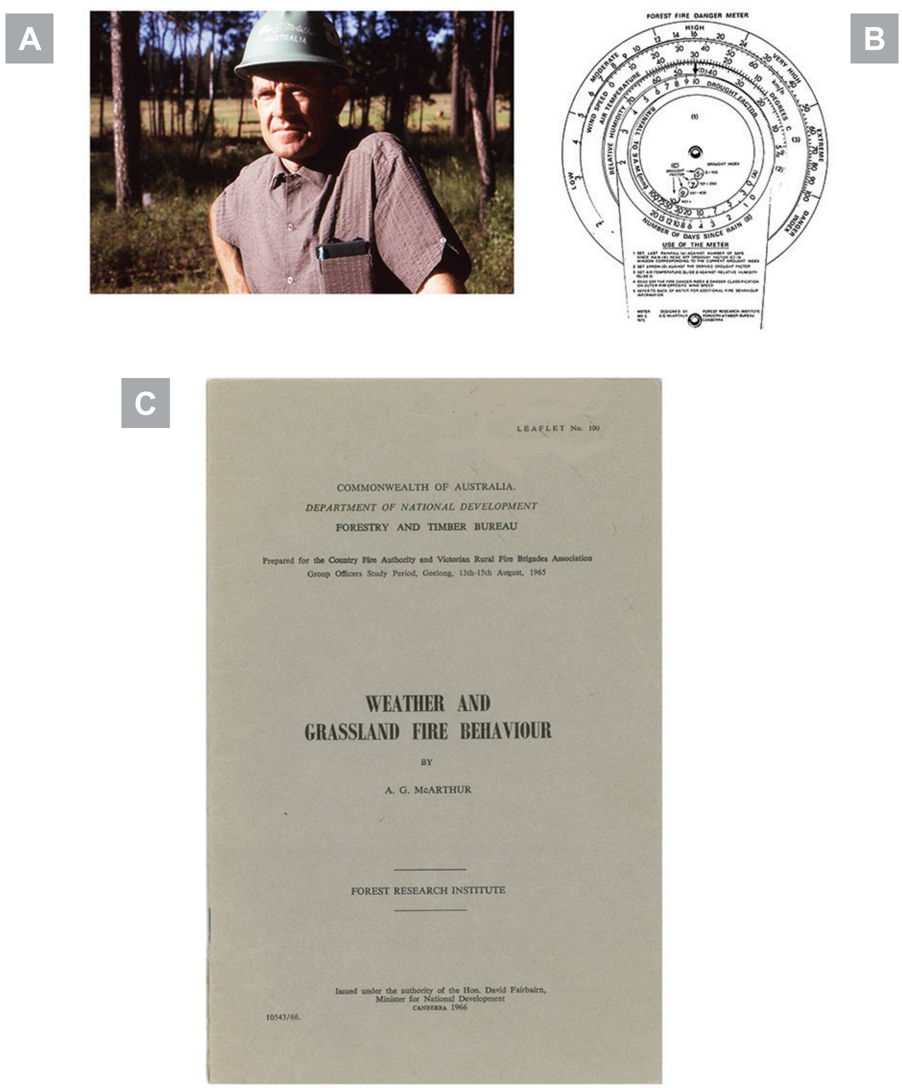

Figure 1—(A) Alan G. McArthur (1923–1978), Australian pioneer bushfire behavior researcher in 1964 (photo courtesy of CSIRO); (B) front of the McArthur Mark 5 Forest Fire Danger Meter; and (C) the front cover of McArthur's (1966) seminal publication on grassland fire behavior.

METHODS

We analyzed the predictive accuracy of five models currently used operationally in Australia to predict rate of fire spread in different fuel types and compared this accuracy with their former, older, model counterparts such as those developed by McArthur and later fire researchers (table 1). Included in these analyses were models developed in Australia for grasslands, temperate shrublands, semiarid shrublands, and dry eucalypt forests (fig. 2A–D), plus a pair of North American models for predicting crown fire spread rates in conifer forests, the most recent of which is used in part for exotic pine (*Pinus* spp.) plantations (fig. 2E) in the country (Cruz et al. 2017).

The primary inputs for all of the models, whether older or newer, are dead fine fuel moisture (or alternatively air temperature and relative humidity) and wind speed. Other inputs include fuel properties such as the degree of curing for grasslands, fuel height for shrublands, understory fuel load for dry eucalypt forests, and canopy bulk density for conifer forests. Both the older and newer rate of fire spread models are described in detail in Cruz et al. (2015).

Table 1–Listing of the older and newer wildfire rate of spread (ROS) models by fuel type and the corresponding evaluation datasets used in the present study.

Fuel type	Older ROS model	Newer ROS model	Independent dataset source
Grasslands	McArthur (1966)	Cheney et al. (1998)	Kilinc et al. (2012)
Temperate shrublands	Catchpole et al. (1998)	Anderson et al. (2015)	Anderson et al. (2015)
Semi-arid shrublands	McCaw (1997)	Cruz et al. (2013)	Cruz et al. (2013)
Dry eucalypt forests	McArthur (1967)	Cheney et al. (2012)	Kilinc et al. (2012)
Conifer forests	Rothermel (1991)	Cruz et al. (2005)	Alexander and Cruz (2006)

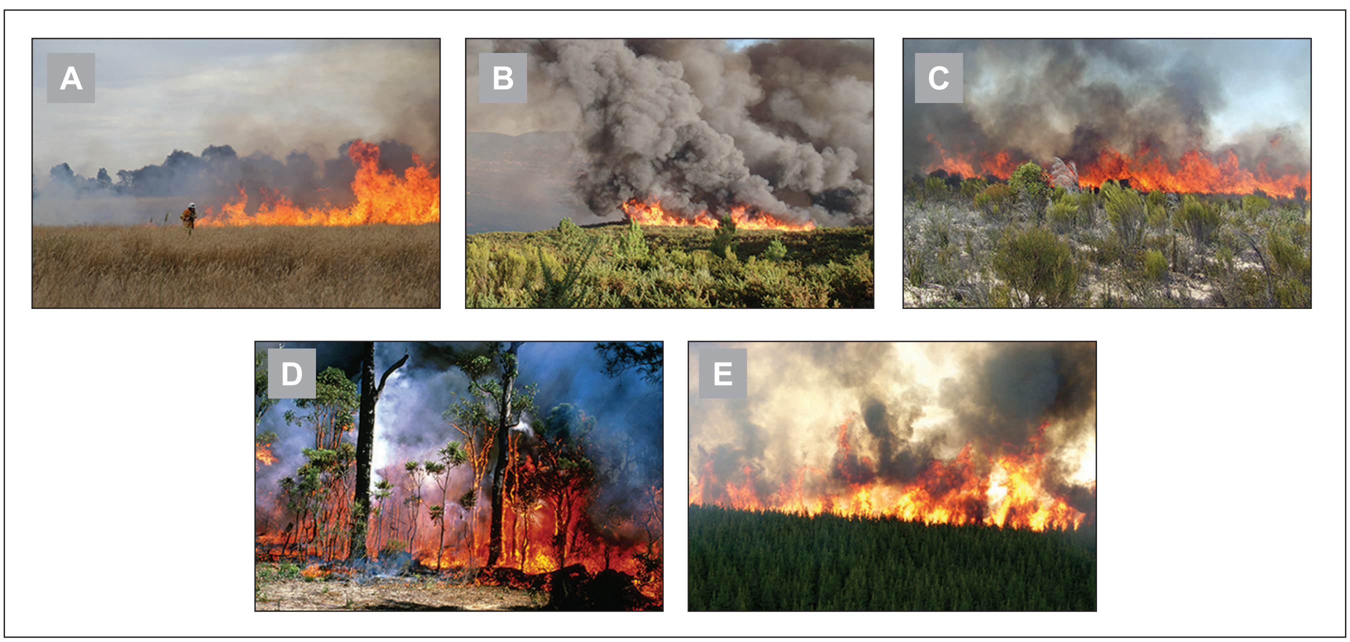

Figure 2—Representative photos of free-burning fires in five distinct fuel types: (A) grassland (photo courtesy of CSIRO), (B) temperate shrubland (photo by P. Palheiro), (C) semiarid shrubland (photo courtesy of CSIRO), (D) dry eucalypt forest (photo courtesy of CSIRO), and (E) conifer forest (photo by S. Cathcart).

Scatterplots of model predictions against observed rates of fire spread were prepared by plotting the predicted values on the x-axis for both the older and newer models against the observed values on the y-axis (Piñeiro et al. 2008) using independent datasets (table 1) composed primarily of field observations of wildfires (n = 463) and to a much lesser extent, prescribed fires (n = 7) in the case of semiarid shrublands. Linear trends were then determined for comparison with the line of perfect agreement.

Error statistics were calculated following Willmott (1982). Finally, we compared the error metrics calculated for older and newer models to assess changes in the error statistics.

RESULTS AND DISCUSSION

Model evaluation results show the current models to have improved prediction accuracy over their previous counterparts (fig. 3). The observable scatter in these plots is characteristic of wildfire data, reflecting both the temporal and spatial variability in the fire's behavior and the environmental conditions.

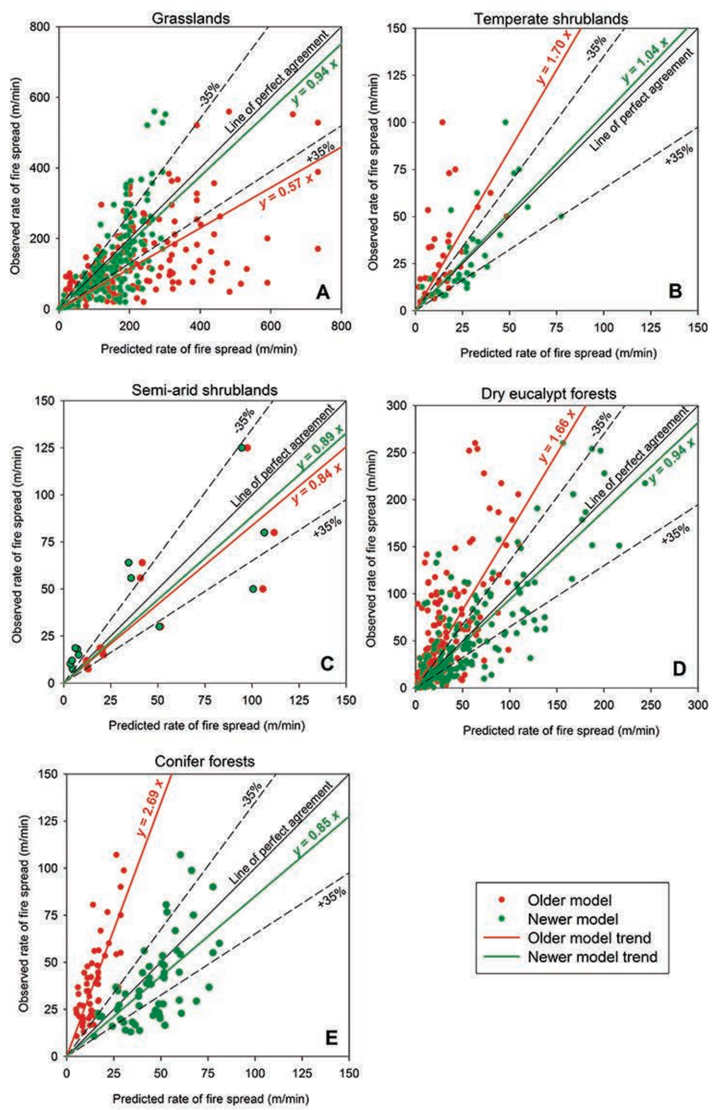

Figure 3—Scatterplots of observed rates of fire spread versus predictions from the older (red dots) and newer (green dots) models and resultant linear trends for (A) grasslands, (B) temperate shrublands, (C) semiarid shrublands, (D) dry eucalypt forests, and (E) conifer crown fires. The dashed lines around the line of perfect agreement indicate the ±35-percent error interval as per Cruz and Alexander (2013).

The mean absolute error (MAE), which is expressed in the same units as the original data (i.e., m minute^{-1} in this case), is a quantity used to express how close predictions are to the observed value. As the name suggests, the MAE is an average of the absolute error. These values were reduced by 68 percent for grasslands, 56 percent for temperate shrublands, 52 percent for dry eucalypt forests, and 70 percent for crown fires in conifer forests (fig. 4A). A minor increase in the MAE of 3 percent was noted in the semiarid shrublands. This outcome may be due in part to the small sample size of the independent dataset (n = 13).

The most significant improvement observed was the reversal or reduction of underprediction and overprediction biases achieved with four of the five newer models (fig. 4B).

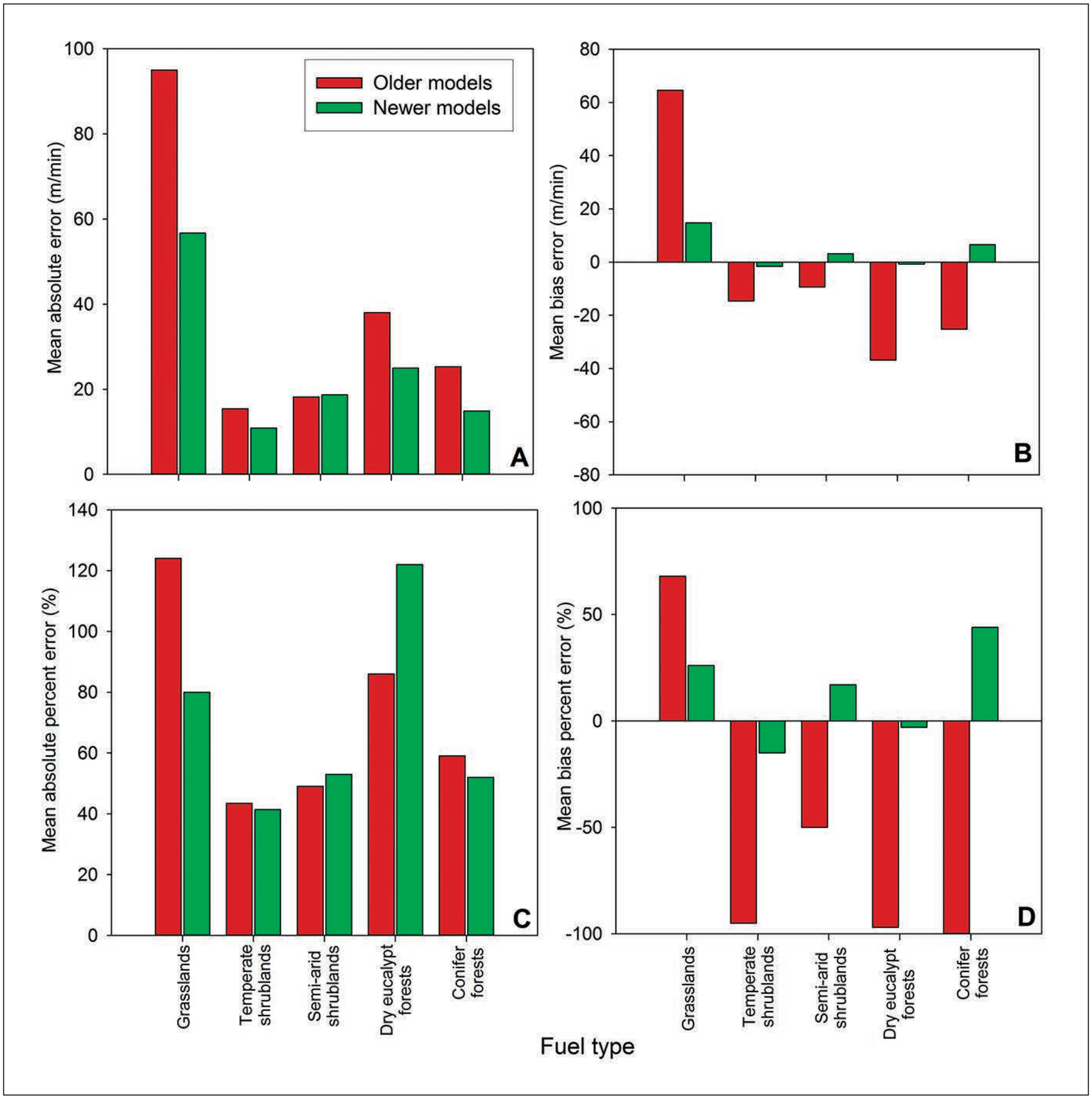

Figure 4—Change in error statistics achieved between older (red) and newer (green) rate of fire spread models.

CONCLUDING THOUGHTS

This study has highlighted the value of continuous improvement in operational wildland fire spread models, a fact that should be borne in mind when it comes to long-term planning by both senior research administrators and fire researchers. This outcome is in keeping with the tradition established by Alan McArthur before his death of carrying out revisions every 2 to 5 years; for example, between 1958 and 1977 he undertook the completion of five different editions of his grassland and eucalypt fire behavior models (Cruz et al. 2015). It also represents a good example of a wildland fire science continuum.

REFERENCES

Alexander, Martin E.; Cruz, Miguel G. 2006. Evaluating a model for predicting active crown fire rate of spread using wildfire observations. Canadian Journal of Forest Research. 36: 3015–3028.

Anderson, W.R.; Cruz, M.G.; Fernandes, P.M.; [et al.]. 2015. A generic, empirical-based model for predicting rate of fire spread in shrublands. International Journal of Wildland Fire. 24: 443–460.

Blanchi, Raphaele; Leonard, Justin; Haynes, Katharine; [et al.]. 2014. Environmental circumstances surrounding bushfire fatalities in Australia 1901–2011. Environmental Science & Policy. 37: 192–203.

Catchpole, Wendy; Bradstock, Ross; Choate, J.; [et al.]. 1998. Cooperative development of equations for heathland fire behaviour. In: Viegas, Domingos X., ed. Proceedings of the III international conference on forest fire research/14th fire and forest meteorology conference; 16–20 November 1998; Luso, Portugal. Coimbra, Portugal: Associação para o Desenvolvimento da Aerodinâmica Industrial and University of Coimbra: 631–645.

Cheney, N.P.; Gould, J.S.; Catchpole, W.R. 1998. Prediction of fire spread in grasslands. International Journal of Wildland Fire. 8: 1–13.

Cheney, N. Phillip; Gould, James S.; McCaw, W. Lachlan; Anderson, Wendy R. 2012. Predicting fire behaviour in dry eucalypt forest in southern Australia. Forest Ecology and Management. 280: 120–131.

Cruz, M.G.; Alexander, M.E.; Plucinski, M.P. 2017. The effect of silvicultural treatments on fire behaviour potential in radiata pine plantations of South Australia. Forest Ecology and Management. 397: 27–38.

Cruz, M.G.; McCaw, W.L.; Anderson, W.R.; Gould, J.S. 2013. Fire behaviour modelling in semi-arid mallee-heath shrublands of southern Australia. Environmental Modelling & Software. 40: 21–34.

Cruz, M.G.; Sullivan, A.L.; Gould, J.S.; [et al.]. 2012. Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. Forest Ecology and Management. 284: 269–285.

Cruz, Miguel G.; Alexander, Martin E. 2013. Uncertainty associated with model predictions of surface and crown fire rates of spread. Environmental Modelling & Software. 47: 16–28.

Cruz, Miguel G.; Alexander, Martin E.; Sullivan, Andrew L.; [et al.]. 2018. Assessing improvements in models used to operationally predict wildland fire rate of spread. Environmental Modelling & Software. 105: 54–63.

Cruz, Miguel G.; Alexander, Martin E.; Wakimoto, Ronald H. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research. 35: 1626–1639.

Cruz, Miguel G.; Gould, James S.; Alexander, Martin E.; [et al.]. 2015. A guide to rate of fire spread models for Australian vegetation. Canberra, Australian Capital Territory and Melbourne, Victoria, Australia: CSIRO Land and Water Flagship and AFAC. 125 p.

Kilinc, Musa; Anderson, Wendy; Price, Ben. 2012. The applicability of bushfire behaviour models in Australia. DSE Schedule 5: Fire Severity Rating Project Technical Report 1. Melbourne, Victoria, Australia: Department of Sustainability and Environment. 60 p.

McArthur, A.G. 1966. Weather and grassland fire behaviour. Leaflet 100. Canberra, Australian Capital Territory, Australia: Commonwealth of Australia, Forestry and Timber Bureau. 23 p.

McArthur, A.G. 1967. Fire behaviour in eucalypt forests. Leaflet 107. Canberra, Australian Capital Territory, Australia: Commonwealth of Australia, Forestry and Timber Bureau. 36 p.

McCaw, William Lachlan. 1997. Predicting fire spread in Western Australian mallee-heath shrubland. Sydney, New South Wales, Australia: University of New South Wales. 240 p. Ph.D. thesis.

Neale, Timothy; May, Daniel. 2018. Bushfire simulators and analysis in Australia: Insights into an emerging sociotechnical practice. Environmental Hazards. 17: 200–218.

Noble, I.R.; Bary, G.A.V.; Gill, A.M. 1980. McArthur's fire danger meters expressed as equations. Austral Ecology. 5: 201–203.

Piñeiro, Gervasio; Perelman, Susana; Guerschman, Juan P.; Paruelo, José M. 2008. How to evaluate models: Observed vs. predicted or predicted vs. observed? Ecological Modelling. 216: 316–322.

Rothermel, Richard C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. Res. Pap. INT-RP-438. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 46 p.

Willmott, Cort J. 1982. Some comments on the evaluation of model performance. Bulletin of the American Meteorological Society. 63: 1309–1313.

2017 Megafires in British Columbia: Urgent Need to Adapt and Improve Resilience to Wildfire

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Abstract—The status quo approach of addressing wildfire threat in British Columbia is not working. In 2017, wildfires overwhelmed suppression capabilities, burned 1.2 million hectares, and cost $568 million for suppression and immediate rehabilitation. From 2003 to 2017, the Provincial government spent $3.1 billion on direct fire suppression, but only $73.8 million on proactive fuels mitigation in the wildland-urban interface. A holistic, landscape view of this problem and transformative changes to wildfire and forest management are urgently needed to achieve forest and community resilience to wildfires. We propose a four-part approach to improve forest and community resilience in British Columbia: (1) increase resources for initial attack and emergency fuel reduction treatments; (2) integrate wildland-urban interface zoning and proactive landscape planning; (3) prioritize forest restoration and adaptive forest management; and (4) invest in research to inform adaptive wildfire management. Our recommendations aim to transform policies and practices to improve ecological and social resilience to wildfire. We contributed written and oral submissions to the 2018 Provincial Flood and Fire Review. The resulting report includes 108 recommendations, 44 of which are consistent with changes we proposed. Through advocacy based on our applied research, we are working toward implementation of transformative change to wildfire management in British Columbia.

Keywords: adaptive management, forest restoration, fuel mitigation, fuel reduction, landscape planning, wildland-urban interface, wildfire management

INTRODUCTION

2017 Wildfires in British Columbia

The 2017 wildfires clearly showed that forests and communities in British Columbia (BC) are not resilient to wildfire and the status quo approach of addressing wildfire threat in BC is not working. The 2017 wildfires overwhelmed suppression capabilities: more than 1.2 million ha of forests burned; and 65,000 citizens were forced from their homes during a 10-week Provincial state of emergency (Abbott and Chapman 2018). Direct costs exceeded $768 million (CAD): $568 million for suppression and approximately $200 million emergency support for evacuees. Indirect, long-term costs of human health impacts, lost cultural values, and compromised ecosystem services such as water and timber supply, livestock, biodiversity, and environmental and habitat degradation will greatly exceed direct costs (Gray et al. 2015).

BC's extreme wildfire season of 2017 was not an isolated event. It is part of a global trend of increasing megafires with tremendous social, ecological, and

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

economic costs (Stephens et al. 2014). Since 2001, wildfires in BC have been driven by record-breaking high temperatures and pronounced droughts, combined with excessive fuels resulting from fire suppression, widespread forest health problems, and forest management practices. In this essay, we argue that inadequate funding and numerous policy conflicts perpetuate hazardous conditions, leaving communities vulnerable to wildfire. We outline a holistic, landscape view of this problem and advocate transformative changes to wildfire and forest management that are urgently needed to achieve forest and community resilience to contemporary and future wildfires.

Wildfire Management in British Columbia

The western-most Province in Canada, BC, covers 94 million hectares (ha; 232.3 million acres), 95 percent of which is publicly owned or "Crown" land. The Province is geographically diverse, spanning 10 degrees of latitude and crossing the Coastal, Cascade, and Rocky Mountains. It encompasses 18 different bioclimatic zones with diverse vegetation ranging from grasslands to coastal temperate rainforests to true boreal forests. Of 62 million ha (153.2 million acres) of forests, 24 million ha (59.3 million acres) are designated for management emphasizing timber, regulated by the Provincial government. On average, 200,000 ha (494,211 acres) per year are harvested within a sustained yield framework. Another 6.2 million ha (15.3 million acres) are grasslands and dry forests, < 4,000 ha (9,884 acres) of which are restored to maintain open conditions each year.

Wildfire management is the responsibility of the BC Wildfire Service. On average (2007-2016), the Province experienced 1,692 fire starts annually, with 57 percent ignited by lightning and 43 percent human-caused (table 1). The annual area burned is strongly influenced by fire suppression policies. Until 2011, the wildfire management strategy was dedicated to protecting people, property, forests, and grasslands from fire (BC Government 2006, 2010). Reportedly, 92 percent of fires were suppressed while less than 4 ha in size and within 24 hours of detection (BC Wildfire Management Branch 2012). Paradoxically, protecting some forests from fire during the 20th century has resulted in changes to forest composition and structure and increased fuel loads (Chavardès et

Table 1—Wildfire fire summary statistics for British Columbia. The 2017 season is compared with individual years and averages of the previous decade from 2007 to 2016. (Source: BC Government 2018a)

Year	Fires (N)	Total area burned (ha)	Mean area per fire (ha)	Person-caused N (%)	Lightning-caused N (%)
2017	1,353	1,216,053	898.8	552 (42%)	773 (58%)
2016	1,050	100,366	95.6	564 (54%)	486 (46%)
2015	1,858	280,605	204.9	617 (33%)	1,237 (67%)
2014	1,481	369,168	249.3	664 (45%)	817 (55%)
2013	1,861	18,298	9.8	564 (30%)	1,297 (70%)
2012	1,649	102,122	61.9	708 (43%)	941 (57%)
2011	653	12,604	19.3	444 (68%)	209 (32%)
2010	1,672	337,149	201.6	680 (41%)	992 (59%)
2009	3,064	247,419	80.8	881 (29%)	2,183 (71%)
2008	2,023	13,240	6.5	848 (42%)	1,175 (58%)
2007	1,606	29,440	18.3	687 (43%)	919 (57%)
Average	**1,692**	**151,041**	**94.8**	**666 (43%)**	**1,026 (57%)**

al. 2016, 2018; Daniels et al. 2011; Marcoux et al. 2013, 2015), potentially resulting in a shift toward more extreme fire behavior with more severe effects than occurred historically (Stephens et al. 2014). These effects are most pronounced in low-elevation dry forests, many of which form the wildland-urban interface surrounding the 161 municipalities and 203 indigenous communities and reserves in BC (UBCIC 2018; UBCM 2018). These forests also influence drinking water supplies and provide the timber and other resources that sustain rural economies. Superimposed on changes due to fire exclusion and suppression are global warming (Flannigan et al. 2016; Wotton et al. 2017) and widespread insect outbreaks (Raffa et al. 2008) that have altered fuels in many forests. With cumulative human impacts interacting with natural disturbances enhanced by climate change, the traditional engineering approach of trying to "control" fires has proven unsuccessful in recent years.

In 2012, a new Provincial wildfire management strategy was introduced. The new mandate is to "deliver effective wildfire management and emergency response support on behalf of the government of British Columbia to protect life and values at risk and to encourage sustainable, healthy and resilient ecosystems" (BC Wildfire Management Branch 2012). This mandate has resulted in a shift toward a diversity of management strategies, with three new strategic priorities in addition to fire suppression. Fuel management aims to reduce loss and damage from wildland fires through community wildfire protection planning and fuel hazard reduction. It is complemented by landscape fire management planning to create fire-adapted communities and fire-resilient ecosystems, and by innovation in wildfire management science, practices, technology, and decision support models. Although a strong conceptual framework, implementation has been inadequate and resistance from Provincial-level public and private-sector agencies has left BC citizens and communities vulnerable to wildfire.

From 2003-2017 (table 2), the cost of direct fire suppression in BC was $3.1 billion. Over the same period, BC budgeted a total of $183 million to

Table 2—Wildland fire expenditure and area burned versus treated in British Columbia since 2003. Expenditures are in Canadian dollars and do not account for inflation. (Data provided by the BC Wildfire Service, April 2018.)

Year	Suppression expenditure ($)	Area burned (ha)	Prevention expenditure ($)[1]	Prevention area treated (ha)
2017	568,000,000	1,216,046	3,028,290	245
2016	129,000,000	100,366	14,297,105	456
2015	277,000,000	280,605	3,570,483	406
2014	297,900,000	369,168	3,723,375	653
2013	122,200,000	18,298	6,951,454	1,332
2012	133,600,000	102,122	4,622,321	1,125
2011	53,500,000	12,604	7,312,059	1,524
2010	212,200,000	337,149	7,698,877	1,361
2009	382,100,000	247,419	10,871,019	2,041
2008	82,100,000	13,240	5,090,966	657
2007	98,800,000	29,440	3,129,038	862
2006	160,000,000	139,265	2,142,072	867
2005	47,000,000	34,588	1,040,925	149
2004	165,000,000	220,518	283,361	
2003	371,000,000	265,053		
Totals	3,099,000,000	3,385,881	73,761,344	11,679

[1] Prevention expenditures were from the Strategic Wildfire Prevention Initiative, plus $11,160,000 from the Forest Enhancement Society in 2016.

proactive, preventative wildfire management, although research shows the cost of reducing wildfire extent and severity through proactive fuel management is lower than the cost of fighting extensive wildfires. Funding was allocated to three programs: $78 million to the Strategic Wildfire Prevention Initiative for treatment of the wildland-urban interface treatments starting in 2004; $85 million to the Forest Enhancement Society of BC (FESBC) for landscape treatments starting in 2015; and $20 million to the Ecological Restoration Program for ongoing management of grasslands and open forests. In 2004, the Provincial government designated a 2-km-wide zone surrounding communities as wildland-urban interface (WUI). The Province-wide strategic threat assessment of fuel hazards classified 685,000 ha as high to extreme hazard and another 970,000 ha as low to moderate wildfire hazard in the WUI (BC Forest Practices Board 2015). By 2017, only 10 percent of hazardous fuels around high-risk communities had been treated (BC Forest Practices Board 2015), 11,679 ha of which were directly funded by the Strategic Wildfire Prevention Initiative (table 2). Other treatments were by the BC Wildfire Service (5,000 ha), BC Ecological Restoration Program (33,600 ha), and harvesting in the WUI by industry (25,880 ha). Although credited as fuels mitigation, only 10 percent of industrial harvesting was specifically for mitigation. Few of the industrial harvesting treatments included mitigation of slash using prescribed burning; so, without posttreatment assessment and monitoring, efficacy remains unknown. Most communities in BC remain vulnerable to wildfire despite concerted efforts over the past decade to inform communities and engage them in mitigation.

The high cost and low return of the Strategic Wildfire Prevention Initiative program raises concerns. In 2015, BC's Forest Practices Board reported the average cost of fuels mitigation was $10,000 per hectare, although extremely high treatment costs in some communities skews this value. The median or midpoint cost was closer to $5,000 per hectare. At this cost, $3.425 billion is needed to treat the 685,000 hectares of WUI classified as high to extreme hazard in 2004; another $4.85 billion would be needed to treat the 970,000 hectares that were classified as low to moderate hazard. Increasing fuel hazards over time and expansion of the WUI exacerbate this problem. Given the necessity of fire suppression near communities, additional fuels have accumulated in the absence of treatments. Some areas that were considered low or moderate hazard in 2004 may have shifted to moderate or high hazard, increasing the urgency for immediate treatments. Moreover, the total area of WUI likely expanded since 2004, given the rapid population growth taking place in some parts of BC. For example, the population of the Central Okanagan Regional District increased by c.15,000 people between 2011 and 2016, led by the City of Kelowna that increased by 8.4 percent, according to the 2016 Canadian census (Statistics Canada 2016). Today, most BC communities remain vulnerable to adverse wildfire behavior and total area at risk is increasing, although it has been more than a decade since the implementation of funding programs to mitigate fuels.

The Need for Transformative Change and Adaptation

In response to catastrophic interface wildfires in 2003, a Provincial review was commissioned and the resulting Firestorm 2003 report provided a road-map for addressing the wildfire hazard to communities throughout BC (Filmon 2004). On the operational side, in areas of emergency response coordination and communications, there has been substantial improvement. However, in the area of fuels and forest practices, which is the largest component necessary to reduce wildfire severity and threats to communities, there has been little action. Implementation of the Filmon Report recommendations has been inadequate and resistance from Provincial-level public and private-sector agencies has left BC citizens and communities vulnerable to wildfire. A holistic, landscape view of this problem and transformative changes to wildfire and forest management are urgently needed to achieve forest and community resilience to contemporary and future wildfires.

RECOMMENDATIONS TO IMPROVE FOREST AND COMMUNITY RESILIENCE

In this paper, we propose a four-pronged approach and provide specific recommendations to improve forest and community resilience in BC. Our recommendations reiterate several from Filmon's

(2004) Firestorm 2003 report that need to be fully implemented and include new recommendations to address problems that have become apparent in the past 13 years. Below, we summarize the four approaches by identifying urgent needs, providing constructive criticism of current actions, and recommending ways that change can be effectively implemented.

1. Initial Attack and Emergency Fuel Reduction Treatments

British Columbia needs significant increases in human resources for all facets of wildland fire management, including wildfire suppression, managed wildfire, and prescribed fire. Additional seasonal staff on initial attack and unit crews are needed. Additionally, BC has a large pool of very experienced seasonal staff that should see advancement to fulltime positions doing landscape fire planning as well as prescribed fire planning and implementation. Hiring, training, and promoting local people will build capacity in First Nations communities and rural municipalities. Managed wildfire needs to be used more as a landscape-level tactic and long-term resource management strategy; however, its use must be science-based rather than guided by economics. Prescribed fire needs to be used extensively to reduce hazardous fuel accumulations in the WUI as well as the larger landscape around communities. When applied correctly, it is a highly effective fuel treatment that can reduce fuel continuity over large areas and establish a safe work environment for wildland fire fighters. Researchers have determined that prescribed fire, in combination with manual/mechanical thinning, is the most effective fuel treatment available when compared to thinning or burning as stand-alone treatments (Schwilk et al. 2009; Stephens et al. 2009, 2012). Where prior thinning is not available, prescribed burning is the best option. Prescribed fire also has substantial ecological and cultural benefits for many of BC's terrestrial ecosystems. BC faces a significant deficit in qualified, experienced prescribed fire practitioners capable of delivering the scale of burn program necessary. In order to build this capacity and address concerns over liability, we encourage the Province to adopt the following 15 recommendations.

Wildland Fire Resources

- Increase the number of full and part-time BC Wildfire Service (BCWS) staff in order to increase capacity for prescribed fire planning and operations and landscape wildfire management planning.
- Fund First Nations governments to employ and train fire management staff and planners.
- Train and certify a number of contract crews to the Provincial Type 1 crew standard.
- Hire additional unit crews during prescribed burning and wildfire seasons.

Resourcing Fuel Reduction Treatments (Including Thinning and Prescribed Burning)

- Provide prescribed fire training and extend the Provincial certification to non-agency personnel. This training and certification must not be limited to just burn bosses; it must include all support positions.
- Add fire effects and burn planning courses to the required Provincial Burn Boss Certification curriculum (e.g., adopt the Parks Canada course for burn planning and the US RX-310 Fire Effects course).
- The Province must certify and track certification currency for all prescribed fire personnel regardless of their employer.
- All burn plans on Crown land must be reviewed and approved by a certified burn boss with certification equal to or exceeding the level of the burns they are reviewing.
- The Province must develop regional multi-party prescribed fire modules in order to address the current short-fall in qualified practitioners.
- The Province must provide adequate funding to BCWS and First Nations crews for prescribed burning.
- The Province must provide timely funding for early spring prescribed burns to ensure that the timing for prescribed fire is not missed in any given year.

- The Province must address smoke constraints to prescribed burning. Either change the ventilation index (BC Government 2018b) approach to an approach focused on actual airshed pollution capacity (under PM2.5 criteria) or provide greater flexibility in ventilation index thresholds (e.g., allow burns under "fair" conditions).
- The Province must set limits on liability. For approved burn plans conducted by trained and certified personnel, there should be less liability. The Province self-insures so it can set limits on liability.
- The Province must implement a burn monitoring process based on burn objectives and scale of operations. Fire effects predicted in burn plans must be measured during burns to determine if/how desired fire behavior is being achieved. Ecological and forest effects of prescribed burns must be measured before and after burns to determine if management objectives are being met.
- The Province must implement a process of open and transparent after-action reviews of plans, operations, and efficacy of all prescribed burns. This is needed to build the knowledge base, expertise, and capacity.

2. Integrate Wildland-Urban Interface Zoning and Proactive Landscape Planning

British Columbia needs to develop a new relationship with its rural communities, including First Nations, when it comes to reducing the threat of wildfire. There have been many positive outcomes following the 2003 Firestorm report (Filmon 2004), such as increased awareness of wildfire threat and the need for proper community planning. On the other hand, several aspects of the Province's approach to solving the problem have been detrimental to relations between the three levels of government. Local government was expected to lead in the planning and operational treatment of wildfire hazard across the WUI, including hazards on Crown land. Those governments are severely hampered by existing forest and wildlife management policies that were not intended to mitigate wildfire hazard as a priority land management objective (e.g., as guided by existing Commission on Resource and Environment plans and Land and Resource Management Plans). We recommend the Province set the long-term maintenance of a low fire hazard condition in the forests and on rangelands in the vicinity of rural communities as the primary land management objective. Depending on landscape configuration and land use patterns, the maintenance of such WUI buffer zones may be required for up to 15 km from some communities. Additionally, we offer 13 specific recommendations for addressing existing policy that run counter to community resilience.

- The Province must work with local governments and First Nations to adjust spatial limits on the WUI buffer based on local forest, fuels, topography, and values at risk, as is the practice in other jurisdictions. Municipal governments, First Nations and the Ministry of Forests, Lands, Natural Resource Operations, & Rural Development (FLNRORD) must work together to determine the best way to ensure that the work is done in a way that maximizes actual fire risk-reduction and increased resilience and that it protects and enhances community values and benefits.
- All municipal lands in need of treatment must be eligible for funding regardless of where it is in the WUI. Currently, municipal land beyond a 2-km buffer is ineligible for funding from both the Strategic Wildfire Prevention Initiative and the Forest Enhancement Society of BC, even if they received prior operational treatment with funding from Strategic Wildfire Prevention Initiative.
- All Crown land outside the municipal boundary must be directly managed by FLNRORD.
- All Crown land in the WUI must be taken out of the timber harvesting land base. However, this does not preclude future fiber recovery from these lands.
- Tree restocking requirements in the WUI must be abolished. Where relevant, upper limits of stocking standards on other Crown land must be lowered to reduce risk of high-severity wildfire. As stands develop, forest companies would be required to thin overstocked stands, with the exception of deciduous species.

- Wood from fuel treatments on Crown land in the WUI must be auctioned off with the profits fed back into WUI treatment and maintenance funds managed by the community and local Resource District.
- Where necessary, the Province must subsidize the removal of low-value wood and make it available under auction to local bioenergy facilities or other users.
- The Province must provide funding to assess fuel hazards on private land in the WUI.
- The Province must provide funding programs for fuel reduction treatments on private land and for home renovations to increase resistance to wildfire in accordance with FireSmart recommendations.
- The Province must provide carbon-offset opportunities for land treated to reduce fuels in the WUI (e.g., lands on which fuels mitigation requires canopy cover less than the critical criterion used in the Zero Net Deforestation Act) or exempt the WUI from the Zero Net Deforestation Act.
- The Province must remove or modify barriers to fuel treatment and wildfire hazard reduction in the WUI (e.g., mule deer winter range constraints and old-growth management areas that constrain treatment options).
- Where wildfires have impacted treated areas, postfire research is needed to determine what elements of the prescription and its implementation have or have not worked. These treatment effectiveness monitoring opportunities should be published and provided as a resource to practicing foresters to facilitate adaptive management.
- The Province must revise existing land use plans with the requirement that WUI special management zones and other updates must be added.

3. Forest Restoration and Adaptive Forest Management

Compromised resilience of many of BC's grasslands and forests makes them vulnerable to severe wildfires, as witnessed in 2017. Ecological restoration aims to increase resilience by focusing on key processes (not stable states) to assist the recovery of degraded ecosystems (BC Government 2018c). Understanding the causes and consequences of altered forest composition, structure, and ecological processes is essential to guide effective solutions. In BC, wildfire is a primary driver of forest dynamics, with historical frequency, size, and magnitude varying among forest types (Daniels et al. 2017). Disruption of fire regimes since the late 19th century was due to colonial actions to eliminate indigenous traditional fire use, land use change, increasingly effective suppression, and forest management focused on optimizing stand-level timber production (Chavardès et al. 2016, 2017; Daniels et al. 2011; Green et al. 2017; Marcoux et al. 2013, 2015). Reduced fire occurrence and extensive timber harvesting with little attention to landscape-level impacts has decreased forest diversity (yielding uniform forest structures), contributed to widespread forest health problems (e.g., mountain pine beetle and Douglas-fir bark beetle outbreaks), and increased fuel loads across landscapes and elevational gradients. Other consequences include, but are not limited to, loss of habitat for 30 percent of BC's species at risk, increased fuel hazards surrounding many communities, and reduced carbon sequestration and storage in dense, overstocked forests. Given the many values at stake in our forests, adaptation must include transformative restoration and management informed by science and traditional ecological knowledge to counter unintended consequences of the past and increase ecosystem resilience in the future.

Proaction to Increase Resilience to Wildfire

- Reintegrate BCWS and Ministry of Forests, Lands, Natural Resources, and Rural Development to address the institutional barriers that artificially disconnect and disregard fundamental relations and feedbacks between fire and forests.
- Prioritize and fund ecological restoration of grasslands, open forests, and early-seral habitats for species at risk.

- Adjust landscape planning priorities. Allocate land to be managed for wildfire resilience rather than relying on the current “protection” approach.
- Retain and promote more land cover in deciduous species that form natural firebreaks.
- Landscape management must conform to natural firesheds. Under the current approach, managed wildfire is only permissible on parts of the landscape free from administrative constraints or resource allocations.

Reaction to Enable Ecosystem Recovery Following Wildfire

- Following wildfire, the Province must monitor for potential negative impacts on natural regeneration of trees and native plant species (e.g., invasive species and noxious weeds) resulting from seeding burned areas with nonnative plants and salvage logging that disrupts soils and seedbanks.
- The Province must encourage and support the production and use of native grass and legume seed for use in erosion control on burned areas, replacing the practice of using nonnative plant species.
- Develop and apply innovative postfire management strategies for ecosystems in the driest climates (e.g., Ponderosa Pine and Interior Douglas-fir biogeoclimatic zones) where contemporary and future climate, combined with fire damage to soils, may render sites unable to support conifer trees.
- Develop and apply postfire replanting strategies for dry forests that enhance resilience rather than optimize timber projection (e.g., adjust preferred species and reduce stocking standards). Apply silvicultural treatments such as juvenile spacing, thinning and pruning to the monocultures of dense lodgepole pine that are legacies of past forest practices and form hazardous fuels over long periods.
- The Province must consider not replanting sites that have been burned repeatedly in recent years (i.e., reburns). Research shows reburns can function as dedicated landscape fuel breaks (Prichard et al. 2017; Coppoletta et al. 2016).
- Ensure restoration and salvage logging strategies after fire reduce the risk of future high-severity fires. In locations near the WUI or in landscape fuel breaks this will include leaving large trees and snags (i.e., biological legacies valuable for wildlife) while removing all small-diameter trees, yielding forest structures similar to shaded fuel breaks. Some costs may need to be subsidized. Monitoring must be used to reduce the likelihood of substantial burn severity should the site burn again.

4. Research to Inform Adaptive Wildfire Management

British Columbia must incorporate current knowledge of fire regimes and ecosystem function into wildfire management. In the absence of empirical fire ecology evidence, policy and practices developed in the 1980s and 1990s were based on expert knowledge and observational science that did not acknowledge fire suppression impacts, and antiquated ecological concepts such as linear, directional succession and stable, climax forests (British Columbia Ministry of Forests and Ministry of Environment, Lands, and Parks 1995). We now have a much more complete picture of the complexity of BC fire regimes, their interaction with other disturbance agents such as insects, and the shifts we can expect under a changing climate (Burton and Boulanger 2018; Daniels et al. 2011, 2017; Haughian et al. 2012).

Constrained by inadequate funding for research, wildfire management in BC largely remains an exercise of emergency command-and-control, independent of new scientific knowledge. Given rapidly changing climate, the Intergovernmental Panel on Climate Change (2014) advocates adaptation to increase resilience of ecosystems and communities to extreme events such as wildfire. It is globally recognized that wildfire policies and practices must shift from control of ecosystems wrongly assumed to be stable, toward strategies to manage the capacity of ecosystems to function and adapt to cumulative environmental changes that are exacerbated by a warming climate. Effective transformation of wildfire management must be evidence-based to overcome current limitations. Fortunately, BC has outstanding universities capable of helping to lead ecosystem-specific research efforts and help guide management through these tumultuous times. Below, our eight recommendations provide a framework to facilitate research to guide effective adaptation:

- Increase and sustain funding for wildland fire research in the fields of ecology, fire science, social science, and economics to provide up-to-date science as the basis for adaptive management.
- Foster collaborations with First Nations to integrate traditional ecological knowledge with western science as a key component of successful adaptation.
- Identify priority topics based on the Blueprint for Wildland Fire Science in Canada (2018-19 to 2028-29) that is being developed by experts from across Canada, including several representatives from BC.
- Develop an unbiased framework for adjudicating proposals and allocating funds that is independent of the forest industry, which is already represented on boards such as that of FESBC (e.g., adopt frameworks used by the National Science and Engineering Research Council [NSERC] or the U.S. Joint Fire Science Program).
- Make funding available to academia. Incentivize or require collaboration with academia when allocating funds to applied research and development agencies.
- Incentivize collaborative research with academia to assess efficacy of WUI- and landscape-level fuel mitigation supported by the Strategic Wildfire Prevention Initiative and Forest Enhancement Society of British Columbia (e.g., expand the U.S. Fire Surrogate Study to BCs forest ecosystems).
- Funding must be administered in a form that is eligible for Federal matching funds under programs such as MITACS Canada and NSERC-Collaborative Research and Development programs, thereby benefiting the research community, collaborating agencies, and the Province.
- Allocate resources within government (e.g., funding, in-kind support and staff time) to enable applied research and training opportunities for postsecondary students who are developing expertise in wildfire science and management (e.g., support outreach and dissemination of results; fund mutually beneficial internships; partner on proposals to NSERC-Collaborative Research Experience and Training program).

IMPLEMENTATION OF RECOMMENDATIONS

The timing of the 2017 wildfire coincided with the first substantive change in political leadership in BC in 17 years. On July 7, 2017, dry lightning ignited more than 190 wildfires, many of which resulted in intense, fast-spreading fires near many communities and a Provincial state of emergency was declared. Ten days later, the Honorable John Horgan was sworn in as the newly elected Premier of British Columbia. The combination of the extreme wildfires and political change provided a unique opportunity to advocate for much-needed transformation of wildfire and forest management policy.

On September 26, 2017, we submitted the above recommendations as an open letter to Premier John Horgan and Mr. Doug Donaldson, the Minister of Forests, Lands, Natural Resource Operations, and Rural Development. Signatories included 20 academics from six universities in BC and 14 others from university research forests, municipalities, First Nations, and conservation groups. Our letter urged that the 2017 wildfire season cannot be just another "wake-up call." The 2017 wildfires revealed the tremendous vulnerability of our forests and communities and shortcomings of past mitigation efforts. Without immediate action, large and intense wildfires will undoubtedly burn, escalating economic, social, and ecological costs. As signatories, we urged the Province to engage with leaders from First Nations, Municipalities, Regional Districts, and expert fire and land managers to mitigate wildfire hazards and implement the recommendations to transform policies and practices to improve resilience to wildfire.

We also submitted the letter to the independent review of BC's wildfire practices and emergency management systems that was commissioned in December 2017. We met with the commission co-chairs, Chief Maureen Chapman, the hereditary Chief of Sq'ewá:lxw (Skawahlook) First Nation, and Mr. George Abbott, former Member of the Legislative Assembly and Cabinet Minister of BC. As well, we participated in a forum to develop a framework for updating the four phases of emergency management operations: planning and preparedness, prevention and mitigation, response, and recovery.

Responses to our letter and recommendations from the Provincial government have been positive. Over the past 9 months, we have met with representatives from the BCWS and Minister of Forests, Lands, Natural Resource Operation, and Rural Development to discuss ongoing policy reviews and program changes. The report on the findings of the BC flood and fire review includes 108 recommendations (Abbott and Chapman 2018), 44 of which reflect changes that we proposed. Although the review recommendations are not legally binding, they provide a framework for changes to policy and practice across local to landscape scales. We remain committed to working in collaboration with public- and private-sector forest management agencies to apply our research findings to transformative change to wildfire management in British Columbia.

REFERENCES

Abbott, G.; Chapman, M. 2018. Addressing the new normal: 21st century disaster management in British Columbia. Report on the BC flood and fire review to the Government of British Columbia, Victoria, BC, Canada.

BC Forest Practices Board. 2015. Fuel management in the wildland urban interface—update. Special Investigation FPB/SIR/43. Forest Practices Board, Victoria, BC, Canada.

BC Government. 2006. British Columbia forest service protection program strategy. BC Ministry of Forests. Victoria, BC, Canada.

BC Government. 2010. Wildland fire management strategy. BC Ministry of Forests, Victoria, BC, Canada.

BC Government. 2018a. Wildfire averages. BC Ministry of Forest, Lands, and Natural Resource Operations, Victoria, BC, Canada. https://www2.gov.bc.ca/gov/content/safety/wildfire-status/about-bcws/wildfire-statistics/wildfire-averages. [Accessed 2018 June 22].

BC Government. 2018b. Open burning smoke control regulation 145/93, including BC regulation 117/2018 amendments. Clean Air Section Environmental Standards Branch, Ministry of Environment, Victoria, BC, Canada.

BC Government 2018c. Ecological restoration. BC Ministry of Forest, Lands, and Natural Resource Operations, Victoria, BC, Canada. https://www.for.gov.bc.ca/hra/restoration/index.htm. [Accessed 2018 June 22].

BC Wildfire Management Branch. 2012. Wildfire management branch strategic plan 2012-2017. BC Ministry of Forest, Lands, and Natural Resource Operations, Victoria, BC, Canada.

British Columbia Ministry of Forests and Ministry of Environment, Lands, and Parks. 1995. Biodiversity guidebook. Ministry of Forests, Victoria, BC, Canada.

Burton, P.J., Boulanger, Y. 2018. Characterizing combined fire and insect outbreak disturbance regimes in British Columbia, Canada. Landscape Ecol 33, 1997–2011. https://doi.org/10.1007/s10980-018-0710-4.

Chavardès, R.D.; Daniels, L.D. 2016. Altered mixed-severity fire regime has homogenized montane forests of Jasper National Park. International Journal of Wildland Fire. 25: 433–444.

Chavardès, R.D.; Daniels, L.D.; Gedalof, Z.; Andison, D.W. 2018. Human influences superseded climate to disrupt the 20th century fire regime in Jasper National Park, Canada. Dendrochronologia. 48: 10–19.

Coppoletta, M.; Merrian, K.E.; Collins, B.M. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications. 26: 686-99

Daniels, L.D.; Maertens, T.B.; Stan, A.B.; McCloskey, S.P.J.; Cochrane, J.D.; Gray, R.W. 2011. Direct and indirect impacts of climate change on forests: three case studies from British Columbia. Canadian Journal of Plant Pathology. 33: 108–116.

Daniels. L.D.; Sherriff, R.L.; Yocom-Kent, L.; Heyerdahl, E.H. 2017. Deciphering the complexity of historical fire regimes: diversity among forests of western North America. In: Amoroso, M.M.; Daniels, L.D.; Baker, P.J.; Camarero J.J., eds. Dendroecology: Tree-ring Analyses Applied to Ecological Studies. Switzerland: Springer: 185-210.

Filmon, G. 2004. Firestorm 2003 Provincial review. Report to the Government of British Columbia, Victoria, BC, Canada. 100 p.

Flannigan, M.D.; Wotton, B.M.; Marshall, G.A.; de Groot, W.J.; Johnston, J.; and Jurko, N. 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. Climatic Change. 134: 59–71.

Gray, R.W.; Oswald, B.; Kobziar, L; Stewart, P.; and Seijo, F. 2015. Reduce wildfire risks or we'll continue to pay for more fire disasters. A position statement developed by the Association for Fire Ecology, International Association of Wildland Fire and the Nature Conservancy. https://fireecology.org/Resources/Documents/Reduce-WIldfire-Risk-16-April-2015-Final-Print.pdf [Accessed June 22, 2018].

Greene, G.A.; Daniels, L.D. 2017. Spatial interpolation and mean fire interval analyses quantify metrics of historical mixed-severity fire regimes. International Journal of Wildland Fire. 26: 138–147.

Haughian, S.R.; Burton, P.J.; Taylor, S.W.; Curry, C.L. 2012. Expected effects of climate change on forest disturbance regimes in British Columbia. Journal of Ecosystems and Management. 13(1): 1-24. http://jem.forrex.org/index.php/jem/article/viewFile/152/107.

Intergovernmental Panel on Climate Change. 2014. Climate change 2014: synthesis report. Contribution of working groups i, ii and ii to the fifth assessment report of the Intergovernmental Panel on Climate Change In: Pachauri, R.K.; Meyer, L.A., eds. Geneva, Switzerland: IPCC. 151 p.

Marcoux, H.M., Gergel, S.E.; Daniels, L.D. 2013. Mixed-severity fire regimes: How well are they represented by existing fire-regime classification systems? Canadian Journal of Forest Research. 43: 658–668.

Marcoux, H.M.; Daniels, L.D.; Gergel, S.E.; [et al.] 2015. Differentiating mixed- and high-severity fire regimes in mixed-conifer forests of the Canadian Cordillera. Forest Ecology and Management. 341: 45–58.

Raffa, K.F.; Aukema, B.H.; Bentz, B.J.; et al. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. BioScience. 58: 501–517.

Schwilk, D.W. [et al.] 2009. The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecological Applications. 19: 285–304.

Stephens, S.L.; Burrows, N.; Buyantuyev, S.; Gray, R.W.; et al. 2014. Temperate and boreal forest mega-fires: characteristics and challenges. Frontiers in Ecology and the Environment. 12: 115–122.

Stephens, S.L.; Maghaddas, J.J.; Edminster, C.; [et al.] 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications. 19: 305–320.

Stephens, S.L.; McIver, J.D.; Boerner, R.E.J.; Fettig, C.J.; [et al.] 2012. Effects of forest fuel reduction treatments in the United States. BioScience. 62: 549-560.

Statistics Canada 2016. Data products, 2016 census. Ottawa, Canada. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/index-eng.cfm. [Accessed 2018 April 15].

Prichard, S.J.; Stevens-Rumann, C.S.; Hessburg, P.F. 2017. Tamm review: shifting global fire regimes: lessons from reburns and research needs. Forest Ecology and Management. 396 (2017): 217–233

UBCIC (Union of British Columbia Indian Chiefs). 2018. https://www.ubcic.bc.ca/. [Accessed 2018 June 22].

UBCM (Union of British Columbia Municipalities). 2018. http://www.ubcm.ca/ [Accessed 2018 June 22].

Wotton, B.M.; Flannigan, M.D.; Marshall, G.A. 2017. Potential climate change impacts on fire intensity and key wildfire suppression thresholds. In: Canada Environmental Research Letters. 095003.

Medusahead Response 6 Years after Burning and Seeding in Sagebrush Steppe

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Abstract—A prescribed burn for western juniper (*Juniperus occidentalis*) reduction at Crooked River National Grassland in Oregon was conducted in 2011. Foliar cover by species or genus and functional group was measured every other year for 6 years to evaluate response to four treatments: unburned control, burned, burned-plus-native-seeding, and burned-plus-cultivar seeding. Additional measurements focused on expansion of medusahead (*Taeniatherum caput-medusae*) from localized patches and vegetative response to postburn grazing.

Keywords: bunchgrass, fire, grazing, medusahead, seeding

INTRODUCTION

Crooked River National Grassland (CRNG) covers 112,357 acres of sagebrush steppe in central Oregon. Administered by the Forest Service, U.S. Department of Agriculture, it is managed for public use that includes recreation, grazing, and wood-cutting, as well as for resource objectives of wildlife habitat and riparian protection. The invasion of exotic species, especially medusahead (the annual grass *Taeniatherum caput-medusae*), is of major concern to land managers, as is the expansion of western juniper (*Juniperus occidentalis*) into areas where it was excluded by fire historically. A conflict arises between the goal of restoring fire for juniper eradication and the reluctance to use fire where it may promote invasive annual grasses.

In 2011 the CRNG Coyote Hills unit was scheduled for a prescribed burn to reduce a 30-year growth of juniper. The unit had been ungrazed for 2 years and contained a healthy community of perennial bunchgrass (>2 plants m^{-2}) and sagebrush (*Artemisia tridentata* var. *tridentata* and var. *vaseyana*) with low-density medusahead and cheatgrass (*Bromus tectorum*), and scattered patches of dense medusahead thatch (patch size was 0.1–4.0 acres, average of 0.2 acre). An interdisciplinary team of managers anticipated that fire would stimulate growth of invasive annual grasses. We also perceived a time-sensitive need to eradicate junipers before the understory community was too depleted to recover, and thought the annuals could be managed later. At that time, widespread herbicide application had not yet been approved for CRNG, so we decided to investigate the effectiveness of seeding to minimize annuals by promoting perennial bunchgrasses after fire. We based our experimental design on a study by Davies (2010) that showed no increase in medusahead cover when burning was followed by seeding. (Davies' study showed a significant decrease in annual grass when fire was followed first with herbicide and then seeding, with results examined at 2 years post-burn.)

METHODS

We implemented a randomized complete block design in eight large medusahead patches in the Coyote Hills unit. All were at approximately 3,300 feet elevation on 5- to 10-percent slope with the same potential

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

natural vegetation. Average (15-year) precipitation was 8 inches. Soil pits showed 25 to 40 percent clay in the A-horizon at each block. Half of the blocks were untreated controls and the other half were in sites that would be burned. Each block contained two plots; the control plots had one linear transect in the densest part of the patch plus four circumferential transects at 50, 100, 150, and 200 feet from the plot center. The burned plots had three parallel linear transects, which were randomly assigned to burned, native, and cultivar treatment, plus the same array of circumferential transects. Each linear transect was a 75-foot tape placed in the center of a 12 foot × 90 foot treatment lane. Foliar cover was measured with a 4-foot^2 frequency frame placed at four sample points on each linear transect. Three samples were measured on the circumferential transects at 90°, 180°, and 270° from the linear transect.

The burn prescription called for summer-like conditions to maximize juniper mortality. Approximately 10 percent of junipers had been cut and left to dry during the preceding winter to achieve a hotter burn. We burned the unit on July 27, 2011, but weather that day was typical of late spring (dry bulb temperature: 72–82 °F; relative humidity: 21–26 percent). The treatment blocks were burned completely. The following December we hand-broadcasted and raked the seed mixes into their randomly assigned lanes. Seed mixes (table 1) were applied at 15 lbs acre^{-2}. Snow accumulated on the site a month later.

Plots were measured just before the burn and remeasured in June every 2 years after the burn. This report summarizes data from the preburn, 2 year, 4 year, and 6 year intervals. One of the control plots was partially burned, so that plot and one of the treatment plots were omitted from the analysis. Data were analyzed using analysis of variance (ANOVA), two-factor without replication, in Microsoft® Excel™ (2016). Significant change was accepted as $P < 0.05$. Bar graphs represent the mean of 28 samples from 7 plots and whiskers show standard error. The

Table 1—Seed mixes applied in the treatment plots, Coyote Hills unit, Crooked River National Grassland, December 2011. Mixes were applied at 15 lbs acre^{-1}. PLS = pure live seed.

Species	Code	Seeds lb^{-1}	lbs PLS lb^{-1} mix	lbs PLS acre^{-1}
Native mix				
Prairie Junegrass	KOMA	2,315,000	0.03	0.45
Bottlebrush squirreltail	ELEL5	192,000	0.29	4.42
Bluebunch wheatgrass	PSSP6	140,000	0.07	0.98
Idaho fescue	FEID	450,000	0.02	0.32
Thurber’s needlegrass	ACTH7	225,000	0.42	6.27
Lewis’ flax	LILE4	293,000	0.04	0.65
Cultivar mix				
Intermediate wheatgrass	THIN6	88,000	0.29	4.42
Crested wheatgrass	AGCR	200,000	0.21	3.1
Sheep fescue	FEOV	680,000	0.11	1.64
Sherman big bluegrass	POSE	882,000	0.11	1.66
Russian wildrye	PSJU3	175,000	0.04	1.62
Lewis’ flax	LILE4	293,000	0.04	0.65

exclosure dataset did not meet all assumptions for ANOVA, so the grazed-ungrazed bar graphs lack whiskers and *P*-values. Those bar graphs show the mean of 32 samples from 8 plots.

Grazing Exclosure Subset

We also looked at the effect of postburn grazing. A 208 foot × 416 foot block (2 acres) was laid out in an area of moderate, diffuse medusahead cover. Sixteen linear transects were arranged on a grid across the block. After the burn, a fence was built to exclude cattle from half the block. Foliar cover by species was measured pre-burn and again at 6 years post-burn with four sample points per transect. The grazing schedule is shown in table 2.

RESULTS

Medusahead cover decreased steadily over 6 years in the unburned plots ($P = 0.04$), but after the second year it increased significantly in the treatment plots ($P = 0.005$) (fig. 1). Cheatgrass initially declined, then rebounded at all sites, with no significant difference among treatments at any of the time intervals ($P = 0.7$ at 6 years). Bulbous bluegrass (*Poa bulbosa*), an invasive small perennial bunchgrass, showed no change over 6 years in the unburned sites ($P = 0.1$), but increased at the other sites ($P = 0.02$). Despite the apparent spike at 2 years in burned sites, the overall percent cover was small and all four treatments showed no difference at each time interval ($P \geq 0.07$).

Table 2—Number and timing of livestock grazing on the Coyote Hills allotment, Crooked River National Grassland.

Grazing pattern at Coyote Hills		
Year	**Grazed days**	**Stock numbers**
2011	rested	0
2012	rested	0
2013	Aug 1–Sept 15	200 cow-calf pairs
2014	June 1–July 15	110 cows
2015	June 1–July 15	250 cow-calf pairs, 10 bulls
2016	June 1–July 15	200 cow-calf pairs, 25 bulls
2017	May 15–Aug 15	200 cow-calf pairs

Invasive forbs, dominated by stork's bill (*Erodium cicutarium*), increased in all the burned sites ($P \leq 0.005$) but not in the unburned sites ($P = 0.2$).

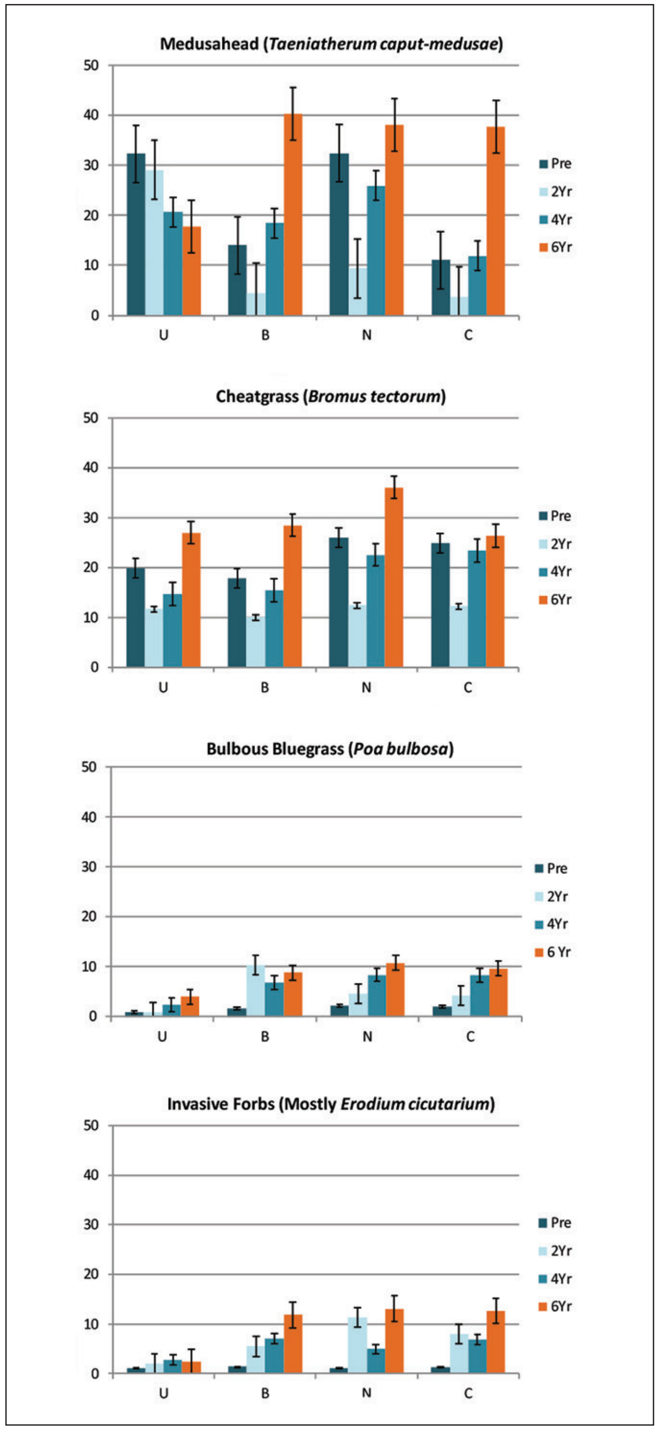

Figure 1—Mean percent foliar cover of invasive species by treatment type and time interval since the burn, Coyote Hills unit, Crooked River National Grassland. U, B, N, C = unburned, burned only, native-seeded after burn, and cultivar-seeded after burn, respectively. Colors represent preburn and 2 year, 4 year, and 6 year intervals. Whiskers show standard error.

Native large perennial bunchgrasses increased over time in the unburned plots ($P = 0.02$) but remained the same in all the burned treatments ($P \geq 0.08$) (fig. 2). Seeding had no effect, despite seed mixes that were predominantly bunchgrass (table 1). The native small perennial bunchgrass Sandberg bluegrass (*Poa secunda*) maintained the same amount of cover in all treatments at all intervals except at the cultivar sites, where it increased from preburn to 2 years ($P = 0.004$, while the others had $P \geq 0.2$ at 2 years). Native forbs increased over time at all sites regardless of treatment ($P \leq 0.006$). Mosses and lichens had no significant change between preburn and 6 years at the untreated and cultivar-seeded sites ($P > 0.07$), but decreased at the burned and native-seeded sites ($P \leq 0.05$).

There was an increase in medusahead cover on the circumferential transects, but due to greater variability with greater distance only the change at 50 feet was statistically significant ($P = 0.03$). The degree of expansion was relatively minor compared to densification within the block (fig. 3). Averaged across all samples within the burned blocks, medusahead cover increased from 19 percent pre-burn to 39 percent at 6 years ($P = 0.005$). The unburned blocks showed densification of the patch ($P = 0.03$) but no significant expansion.

Grazing Exclosure Results

At the exclosure site, the 6 year mean cover of medusahead was 18 percent in both the grazed and ungrazed blocks (fig. 4). Cheatgrass cover was 5 percent higher where grazed. Invasive bulbous bluegrass more than doubled where grazed, as did the cover of invasive forbs (predominantly *Erodium cicutarium*). Both native forbs and Sandberg bluegrass showed negligible difference in cover between grazed

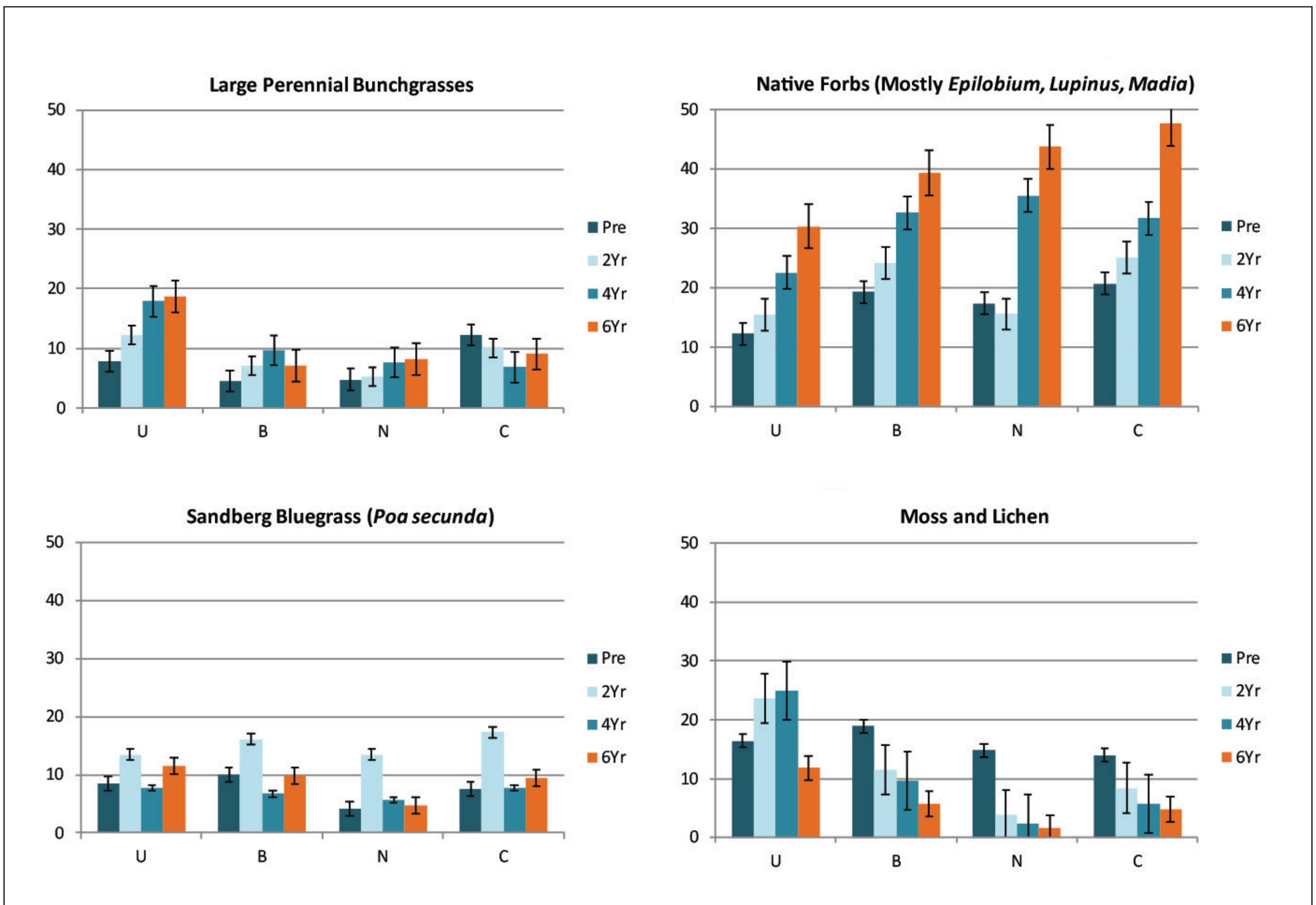

Figure 2—Mean percent foliar cover of native species by treatment type and time interval since the burn, Coyote Hills unit, Crooked River National Grassland. U, B, N, C = unburned, burned only, native-seeded after burn, and cultivar-seeded after burn, respectively. Colors represent preburn and 2 year, 4 year, and 6 year intervals. Whiskers show standard error.

and ungrazed blocks. Cryptogam cover was less than half as much where grazed, but the amounts were minimal post burn (≤ 0.10 percent). The biggest difference was in large perennial bunchgrasses, with cover less than half as much outside the exclosure (13 percent on grazed land, 39 percent on ungrazed land).

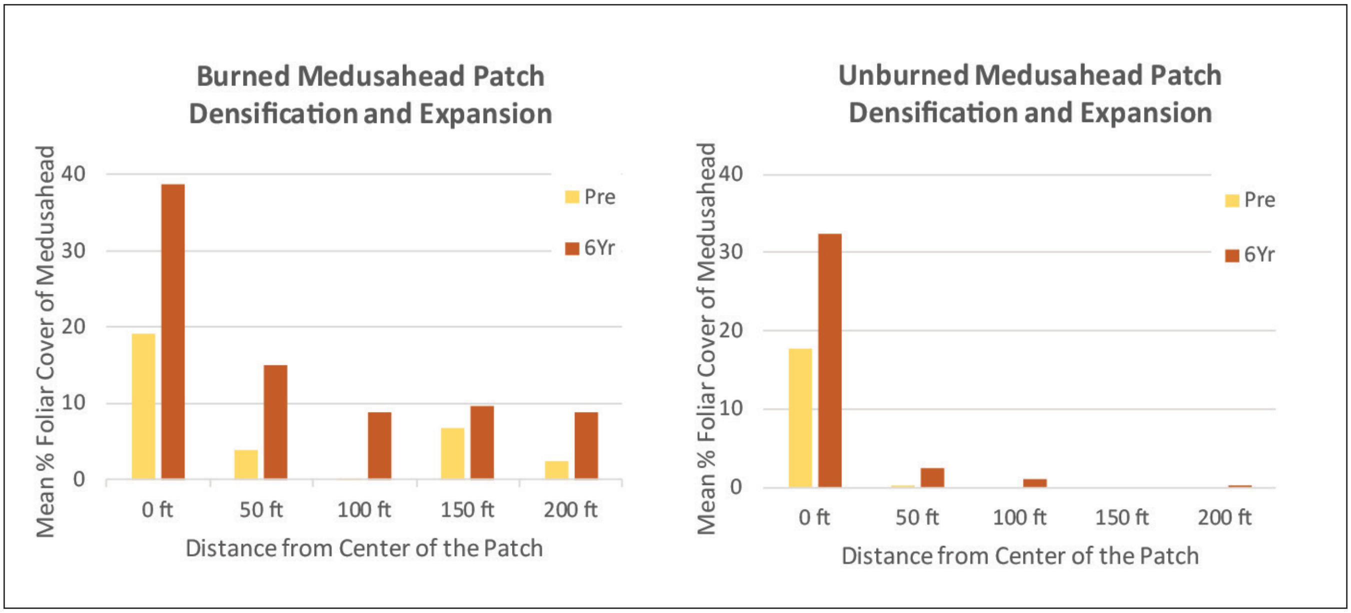

Figure 3—Densification and expansion of burned versus unburned medusahead patches at 6 years post-burn, Coyote Hills unit, Crooked River National Grassland.

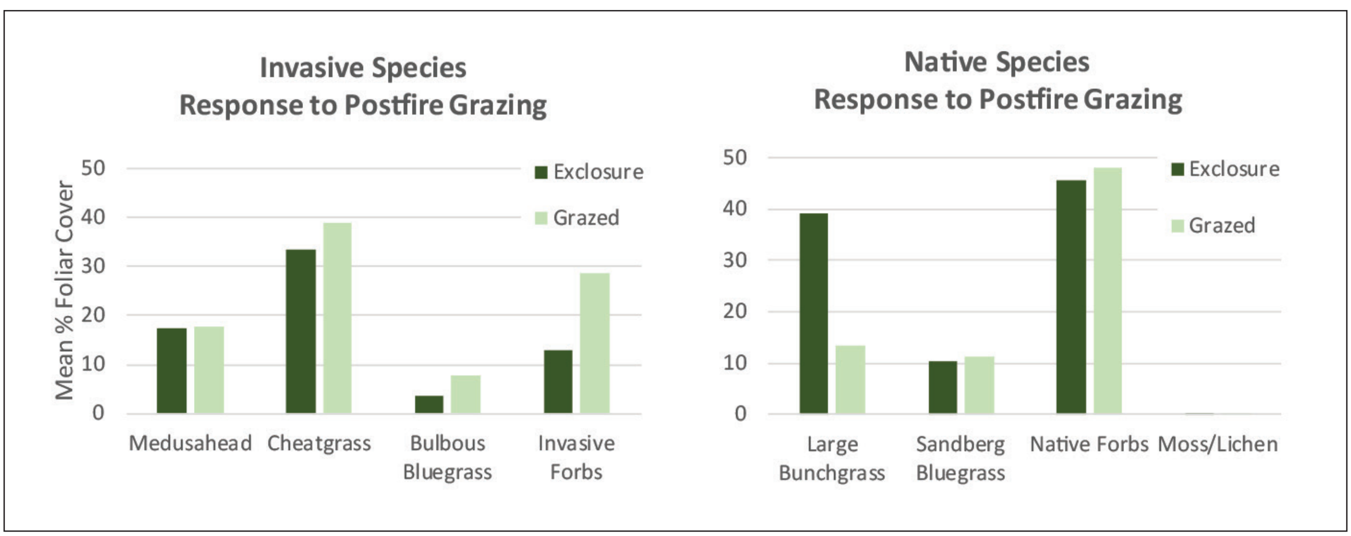

Figure 4—Invasive and native species cover in an ungrazed exclosure and equivalent grazed area, Coyote Hills unit, Crooked River National Grassland. Measurements are from 6 years post- burn with four seasons of livestock grazing (see table 2 for grazing pattern). Mosses and lichens had less than 1 percent cover overall.

DISCUSSION

Vegetative response to the burn was initially favorable but not predictive of later results. In the control and treatment blocks at the 2 year measurement we saw no increase in medusahead, a significant decrease in cheatgrass, and no change in large perennial bunchgrass density. At the 4 year interval, however, cover of nearly all the measured vegetation rebounded to the pretreatment levels. At 6 years the native forbs and all invasive species except for cheatgrass increased at burned sites compared to the unburned sites. Cheatgrass and Sandberg bluegrass remained relatively constant regardless of treatment, while the large perennial bunchgrasses increased in the unburned sites only. Mosses and lichens declined in two of the three burned treatments while remaining constant where unburned. The decline is very likely related to fire and weather, not the seed mix.

Unusually favorable weather seems to have played a role in the anomalous 2 year response. The burn occurred in July 2011, with low fire severity and phenology that probably retained a lot of seed in both the annuals and perennials. Spring precipitation in 2012 was much higher than average (fig. 5), which probably boosted the germination of perennial bunchgrasses and recovery from dormant roots. The following fall and spring were very dry, but ensuing years tracked closely with the 15 year average. Cows were back on the unit in August 2013 (after plot measurement) and then in spring and summer every year thereafter. The combination of these factors contributed to the effects seen in the 4 year and 6 year data.

Although both medusahead and cheatgrass were present before the burn at low density (<500 plants acre^{-1}), medusahead also occurred as “thatch” or high-

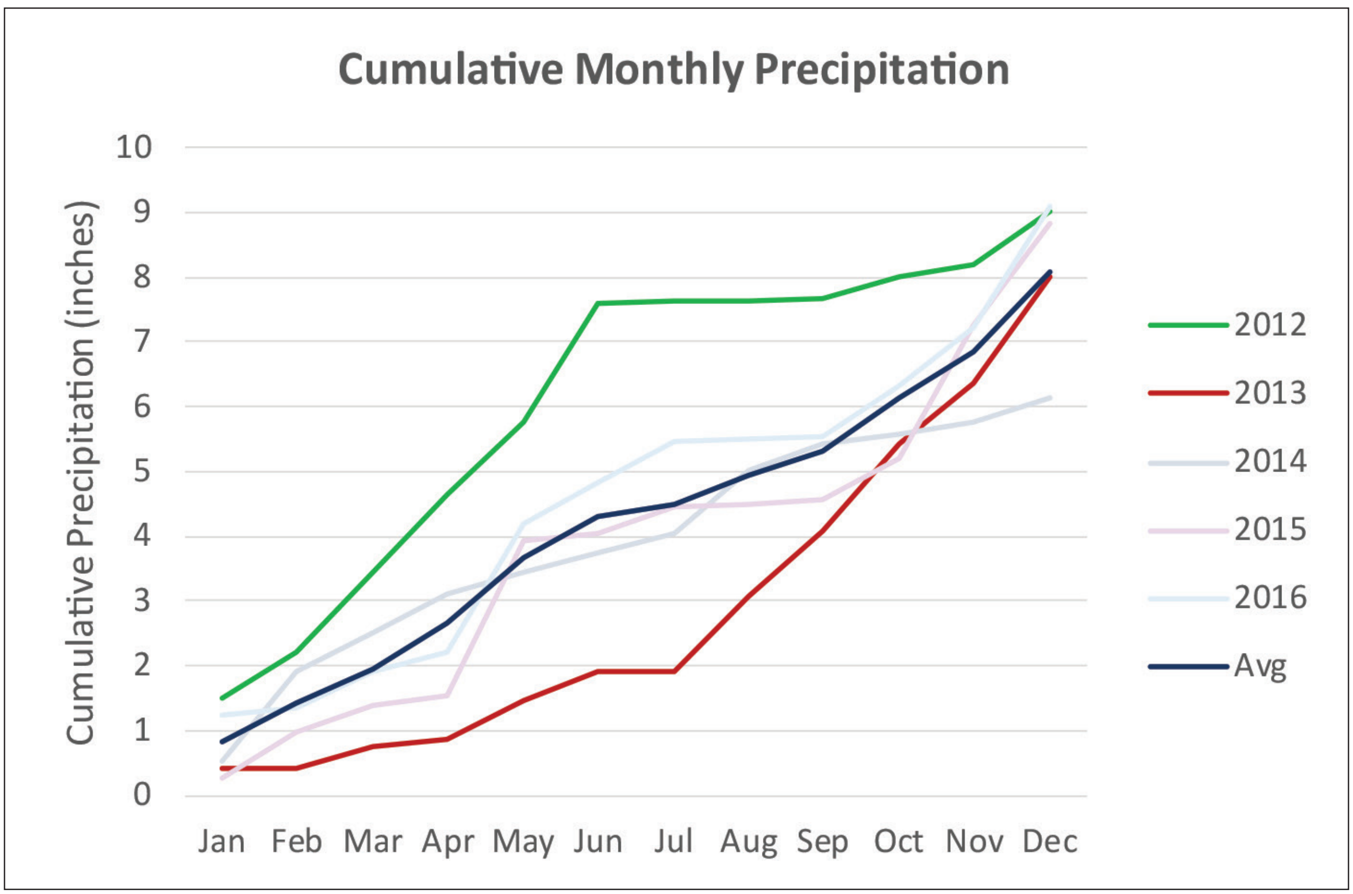

Figure 5—Cumulative monthly precipitation at the Redmond International Airport, about 20 miles southwest of the Coyote Hills burn unit, with approximately the same elevation and plant association.

density patches up to 4 acres in size with between 104 and 106 plants acre^{-1}. All of the study blocks were located in these patches. The Natural Resources Conservation Service map units were Simas cobbly silty clay loam, Lickskillet-Redcliff very gravelly loam, and Schreir-Tub Complex silt loam (USDA NRCS 2011). We dug soil pits in each block and found a clayey horizon within the upper 5 inches of all but one soil pit. Young et al. (1999) and Kyser et al. (2014) noted that clay soils strongly favor medusahead. The patchiness of the medusahead infestation is seen in a box-and-whisker diagram (fig. 6). Native perennial bunchgrasses (fig. 7) and the other cover categories tended to be distributed more evenly on the landscape.

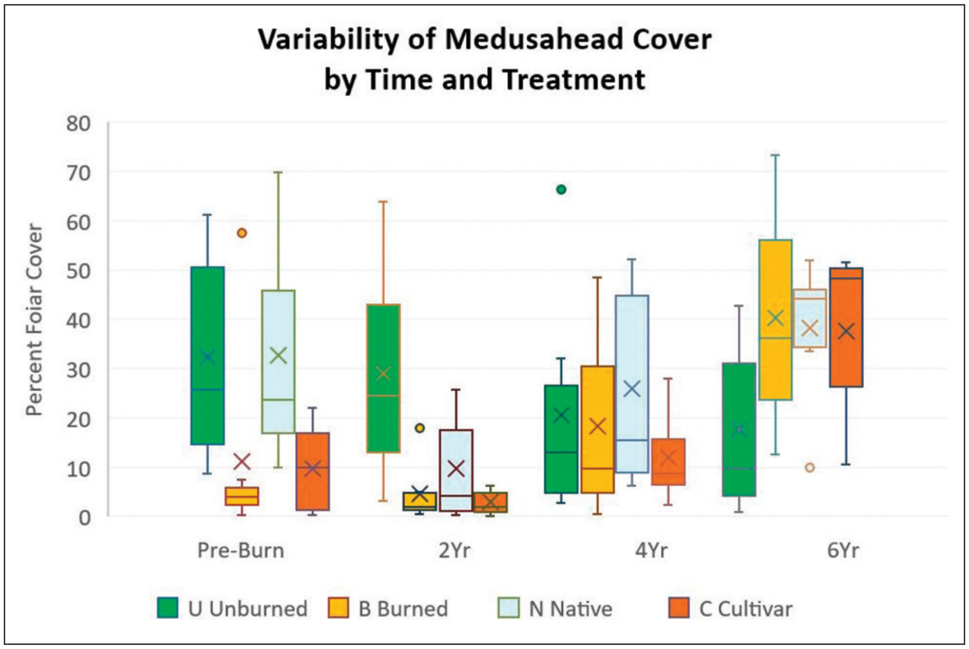

Figure 6—Uneven distribution of medusahead cover, Coyote Hills unit, Crooked River National Grassland. Each box summarizes 28 samples: X is the mean, whiskers are samples closest to 1.5 times the interquartile range, and dots are outliers.

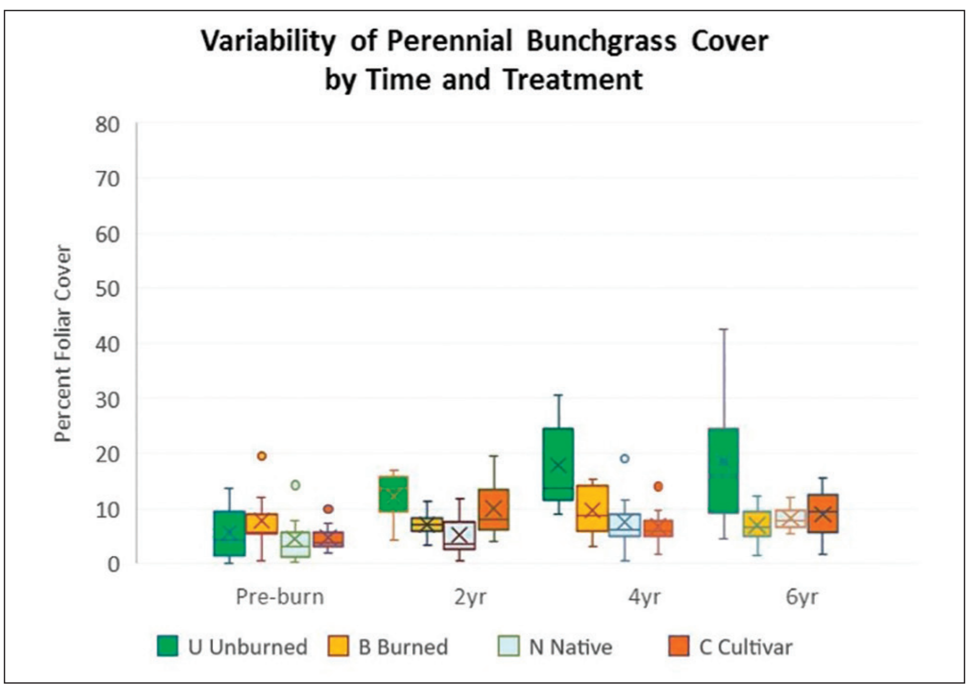

Figure 7—Relatively uniform distribution of large perennial bunchgrass cover compared with medusahead, Coyote Hills unit, Crooked River National Grassland. There is almost no difference among the burned treatment plots, but bunchgrass cover doubled in the unburned plots.

There was a lot of variability even among samples within one plot, although the means were sometimes similar across the treatments. Plot layout explains the relatively high preburn medusahead cover in the unburned and native transects compared to the burned and cultivar transects. The first transect of each plot was placed in the center of a medusahead patch, which tended to have the densest thatch. In control plots there was only the one unburned linear transect. In the other plots transects were centered in three parallel lanes 12 feet wide. After the fire three treatments (burned, native, cultivar) were randomly assigned to the parallel lanes using a random-number generator. By chance, the native-seed treatment was applied on the first transect in six out of eight plots.

Results of the exclosure portion of this project support Davies' (2018) finding that fire may have more influence than grazing on annual grass invasion. However, grazing seemed to promote invasive forbs and decrease perennial bunchgrass cover. Higher bunchgrass density is one of the key resistance-resilience indicators suggested by Chambers et al. (2014), but the foliar cover metric in this study may not be directly related. Further work at Coyote Hills may address some of these knowledge gaps.

Managers who seek to remove junipers for habitat and riparian restoration must now take into account the relative cover of invasive annual grasses and native perennial bunchgrasses (Davies 2012; James et al. 2015). Ecological site variables such as soil, precipitation, insolation, and existing plant community influence the trajectory of vegetative response to disturbance (Miller et al. 2013; Pyke et al. 2018). Our plot data suggest that medusahead easily colonizes locally clay-enriched epipedons but may be challenged to expand into less favorable sites, especially if there is competition from bunchgrass. In line with this, the grass seems more likely to densify in a clayey site than expand beyond it. Further study may determine soil-based thresholds useful for strategic management.

ACKNOWLEDGMENTS

For their assistance and contributions to this project, I would like to thank: Geoff Babb, Sarah Canham, Jim David, Kirk Davies, Louisa Evers, Steve Gibson, Barry Kleckler, Tory Kurtz, Mark Lesko, Prineville Interagency Hotshot Crew, Bryan Scholz, Slater Turner, and Gregg Riegel.

REFERENCES

Chambers, Jeanne C.; Pyke, David A.; Maestas, Jeremy D.; [et al.]. 2014. Using resilience and resistance concepts to reduce impacts of invasive annual grasses and altered fire regimes on the sagebrush ecosystem and greater sage-grouse: A strategic multi-scale approach. Gen. Tech. Rep. RMRS-GTR-326. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 73 p.

Davies, Kirk W. 2010. Revegetation of medusahead-invaded sagebrush steppe. Rangeland Ecology & Management. 63: 564–571.

Davies, Kirk W. 2012. Prescribed fire and the risk of exotic annual grass invasion in sagebrush communities and juniper woodlands. Presentation at Central Oregon Fire Science Symposium, Central Oregon Fire Management Service; April 17, 2012; Bend, OR.

Davies, Kirk W. 2018. Grazing to maintain perennial grasses and reduce nonnative annuals. Webinar presented April 11, 2018, for the Great Basin Fire Science Exchange.

James, Jeremy; Gornish, Elise S.; DiTomaso, Joseph M.; [et al.]. 2015. Managing medusahead (*Taeniatherum caput-medusae*) on rangeland: A meta-analysis of control effects and assessment of stakeholder needs. Rangeland Ecology & Management. 68: 215–223.

Kyser, Guy B.; DiTomaso, Joseph M.; Davies, Kirk W.; [et al.]. 2014. Medusahead management guide for the western states. Davis, CA: Weed Research and Information Center. 68 p. https://wric.ucdavis.edu/publications/MedusaheadManagementguide_pub_2014.pdf. [Accessed 2019 June 20].

Miller, Richard F.; Chambers, Jeanne C.; Pyke, David A.; [et al.]. 2013. A review of fire effects on vegetation and soils in the Great Basin Region: Response and ecological site characteristics. Gen. Tech. Rep. RMRS-GTR-308. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Pyke, David A.; Chambers, Jeanne C.; Pellant, Michael L.; [et al.]. 2018. Restoration handbook for sagebrush steppe ecosystems with emphasis on greater sage-grouse habitat—Part 3. Site level restoration decisions (ver. 1.1, March 2018). U.S. Geological Survey Circular 1426. Reston, VA: U.S. Geological Survey. 62 p. Available at https://doi.org/10.3133/cir1426. [Accessed 2019 June 20].

USDA Natural Resources Conservation Service [USDA NRCS]. 2011. Web Soil Survey, parts of Deschutes, Jefferson, and Klamath Counties, Oregon. Available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/tools/. [Accessed 2011 April 27].

Young, James A.; Clements, Charlie D.; Nader, Glenn. 1999. Medusahead and clay: The rarity of perennial seedling establishment. Rangelands. 21: 19–23.

New Methods for Pyrolysis and Combustion Properties of Forest Litter: Enhanced Cone Calorimetry with Longleaf Pine Needles

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Abstract—New methods are sketched for determination of pyrolysis and combustion properties used in physical modeling of wildfires involving forest litter. The physical fire models, such as the Fire Dynamic Simulator, can benefit directly from detailed pyrolysis properties such as moisture isotherm properties of foliage; surface leaf emissivity varying with moisture content; foliage heat capacity varying from ambient temperature to 440 °C; dynamic moisture losses during direct heating; extractive volatiles profiling; and detailed pyrolysis kinetics. Although various instruments and methods for these properties are mentioned, this paper focuses on the pyrolysis and combustion properties associated with enhanced heat release rate calorimetry. Data from combustion tests of foliage litter on the specialized holder in the cone calorimeter, enhanced with water vapor flow and thermocouple measurements, are analyzed to provide ignition, chemical heat of combustion, mass losses, fire emissions, combustion efficiency, fuel elemental composition, and material interface temperatures as a function of time. Further, surface temperature measurements on heated leaf samples can be used to determine thermal conductivity as the thickness, density, heat capacity, and surface emissivity are independently measured. The methods presented here focus on longleaf pine (*Pinus palustris* Mill.) needles as a prominent litter component in the southeastern United States.

Keywords: combustion properties, forest litter properties, HRR calorimetry, pyrolysis kinetics

INTRODUCTION

There is a widely expressed need to improve upon the legacy pyrolysis and combustion properties of forest litter and live foliage developed two to three decades ago (e.g., Burgan and Susott 1991; Rothermel 1972; Sussott 1980, 1982; Shafizadeh et al. 1975, 1977) to adapt to the physical fire models (i.e., Fire Dynamic Simulator [FDS]), as well as accommodate the unusual properties of live and dead vegetation involved in wildfires that suggest improving the fire physics itself. Although the Forest Products Laboratory (FPL) in the Forest Service, Department of Agriculture has been developing pyrolysis and combustion properties for wood (Dietenberger 2002, 2012; Dietenberger and White 2001; Hagge et al. 2004; Tang and Eickner 1968), there have been occasions in which attention by FPL was devoted to vegetation in collaboration with other Forest Service scientists (Dibble et al. 2007; Dickinson et al. 2016; Safdari et al. 2018; White et al. 1996) as FPL acquired various equipment and expertise. Understanding live vegetation flammability properties has proved daunting in the recent past when using the various standard methods of measurements, such as the cone calorimeter in following ASTM E1354 (ASTM International 2017), or the various attempts at pyrolysis kinetics from measurements with thermal gravimetric analysis (TGA) (e.g., Bradbury et al. 1979; Sait et al. 2012; and many others).

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

These difficulties catalyzed a movement toward the nonstandard methods as with the Forced Ignition and Flame Spread Test (FIST) (McAllister and Weise 2016; McAllister et al. 2012), or with hot gases on single live leaves (Fletcher et al. 2007). We postulate that the methods used thus far have been unable to provide the basic properties requisite for accurate fire modeling. Recognition by the fire modeling community of fundamental differences between live and dead vegetation has recently resulted in a new physically based model of ignition for live fuels (Anand et al. 2017; Lamorlette et al. 2018).

Part of the problem is an inadequate description of the live leaf compositions, as from our recent summative analysis (for later publication) we know that hemicellulose, cellulose, and lignin make up only a majority of the dried mass of foliage, and that there are significant lipids, protein, fructose, glucose, pectin, and starch within the foliage. Further differences from the wood are noted, specifically that the foliage hemicellulose lacks the mannan that is significant in wood; the foliage cellulose is all amorphous but is mainly crystalline in wood; and lignin is simplified, thus indicating a new material to test for properties. This means the legacy vegetation properties that have been based on wood as a model material, such as the heat capacity and the moisture isotherm (Burgan 1988), are only first approximations, and should be updated to take advantage of modern measurement techniques. For example, modern differential scanning calorimeters (DSCs) with a modulation heating feature on top of a continuous heating rate can greatly improve the heat capacity value estimates and provide them as a function of temperature. With a similar heating profile applied to a homogenized sample, the testing can be done with TGA to normalize the mass of the degrading material so that heat capacity values can stay reasonable. This has recently been done at FPL for various shrub species native to the southeastern United States. All this preliminary work is complementary to the ultimate material testing in the enhanced cone calorimetry method, which overcomes the deficiencies in traditional standard testing in obtaining various thermal, moisture, pyrolysis, and combustion properties.

If leaves could hypothetically be described as very simple materials, such as the standard polymers, one could use solely the enhanced cone calorimeter measurements described herein, in conjunction with a computational fluid dynamics (CFD) model of pyrolysis and combustion, to derive the heat capacity, thermal conductivity, surface emissivity, ignition temperature, pyrolysis kinetics, heat of combustion (HOC), and emissions, via an advanced inverse method. These basic properties can then provide the CFD model with the ability to predict ignition time, fire intensity, fuel consumption, and smoke production as flammability indicators in various situations. However, the foliage is typically very hygroscopic and in fact made of several compounds, each having unique thermal, moisture, and flammability properties (Jolly et al. 2012, 2016). This complexity of the organic materials would certainly benefit from alternate instruments (apart from the cone calorimeter) specialized for measuring certain properties, such as heat capacity with the modulated DSC, surface emissivity with modified forward-looking infrared (FLIR) observations, and pyrolysis mass loss with high resolution TGA, that will be discussed in future papers. These additional data on properties would assist the use of enhanced cone calorimetry testing to determine difficult-to-obtain properties such as dynamic moisture loss, thermal conductivity, fuel pyrolysis, and HOC for intact material exposed to radiant and convective heat. By deriving these properties on a consistent leaf structure to directly incorporate into physical models, the modeling consisting of pyrolysis and combustion could then predict the flammability properties such as time to ignition, mass loss rates, heat release rates, and fuel consumptions, as tailored to the particular plant species. The known high variability of flammability between certain plant species may finally be explainable, and on a practical basis.

However, as the diffusion flame characteristics change with size, such that the production of carbon monoxide (CO) and soot do not scale (Dietenberger 2002), the chemical HOC (and also the combustion efficiency) is better determined with the larger basket fires of forest litter under the heat release rate (HRR) hood, rather than with the cone calorimeter. We note that the enhanced cone calorimeter is incapable of measuring for radiant fraction, creeping flame spreading, or field emissions, as inputs to the CFD models. The properties derived for these flammability features require a larger diffusion flame, such as our basket tests of forest litter in a larger instrumented hood, which are not covered in depth in this paper. The other types of vegetation tested, but not discussed in detail in this paper, are 1) intact litter with oak (*Quercus* spp.) and maple (*Acer* spp.) on clay substrates for the cone calorimeter tests (Dickinson et al. 2016), 2) oak and maple litter in chickenwire baskets in HRR hood, and 3) various southeastern plant species for all the detailed measurements.

METHODS

Sample Preparation Approach

A local greenhouse of common species native to the southeastern United States was established to provide fresh leaves for testing. It was postulated that after a leaf is removed from the stem, it continues to undergo enzymatic hydrolysis (e.g., convert starch to sucrose, or protein to amino acids, or lipids to fatty acids) during air drying, which can negatively affect the determination of the live leaf moisture content. After experimentation, we found that the optimum drying regime for preserving live leaf properties meant heating the leaf in a vacuum oven at 45 °C. Under this drying regime the initial absorbed moisture evaporated quickly to prevent the hydrolysis modification of structural features. The leaf material was continuously exposed to a vacuum environment for several hours in order to completely evaporate the absorbed moisture that did not go into enzymatic hydrolysis. We found that for foliage with noticeably aromatic hydrocarbons (i.e., live longleaf pine [*Pinus palustris* Mill.] needles when plucked), the leaf material must be dried at temperatures much lower than the usual standard 105 °C, which is recommended for wood materials (ASTM D4442; ASTM International 2016). Indeed, 45 °C is a minimum temperature needed to avoid volatile loss while achieving a timely reasonable drying in a vacuum; it is the drying temperature in a vacuum used for standard material composition work at FPL. We recognize that there has been a longstanding discussion in the wildland fire community as to the appropriate temperature at which to dry biomass and live fuels in particular due to the presence of volatile and aromatic compounds.

Proper conditioning of the samples for further analysis included keeping them in a desiccator after vacuum drying to preserve the chlorophyll greenness, as it can also undergo enzymatic hydrolysis to a nitrogen-based acid when the leaf gains some moisture by exposure to the normal ambient humid air (typically found in a laboratory in Wisconsin, but also obviously relevant to other parts of the world). The samples were shipped in a very dry and oxygen-deprived sealed bag to commercial laboratories to prevent the leaf structure from degenerating into the various acids by hydrolysis or into carbon dioxide (CO_2) via cellular respiration.

By ensuring consistency among the samples as sourced from the live leaves, one can reduce significantly the errors related to the leaf structure degradations as described earlier. These consistent samples (by plucking a few mature leaves of a species to homogenize them and subject them to the same drying preservative method) then provided the basis for all other measurements that were needed on a dry basis with the added benefit of long shelf life for additional testing. However, there are tests that must be done on a live leaf basis, such as the solvent extraction for the lipid content (using hexane and isopropanol followed by acetone and water), and for flammability in the cone calorimeter and other fire tests of the foliage in the live state.

Our preliminary tests in the cone calorimeter at low irradiances showed a difference in pyrolysis mass loss, ignition, and combustion between the live leaf and an air-dried leaf. In companion work, Safdari et al. (2018) found differences in tar, gas, and char yields between live and dead (air dried for 1–2 weeks) samples of the same species that we are testing; however, there was no major difference in the composition of the chemical compounds observed. Indeed, our preliminary tests in the cone calorimeter at low irradiances show a difference in pyrolysis mass loss, ignition, and combustion between live leaves and leaves that have been air dried. Note that previously we outlined the process by which air-dried leaves undergo enzymatic hydrolysis of lipids, starch, and protein to simpler compounds that can then be easily pyrolyzed (with no charring) and thus more easily ignited. In contrast, the live leaves have starch, protein, and other structures that stay relatively intact after rapid drying, making the leaves more resistant to mass loss, or a high heat of combustion, and ignition. We will now outline a new technique for examining leaf drying and volatile properties more closely using an enhanced cone calorimetry test method.

Enhanced Cone Calorimetry Method

As discussed earlier, the plants were grown in the local greenhouse. When a plant was selected for live testing, only the mature leaves were collected in a preweighed petri dish. A target weight of 3 grams was harvested (some plants have multiple leaves), the petri dish cover was put on, the petri dish plus sample was weighed, and the sample was delivered immediately (1–2 minutes) to the enhanced cone holder (fig. 1A) of the cone calorimeter.

In advance of the experiment, six 36-gauge Type-K thermocouples (T/Cs) were monitored to determine whether they were reading correctly and connected to the cone calorimeter data acquisition (DAQ) board. The bottom steel mesh was on the holder and three T/Cs were laid on it; small inert tape on the side kept them in place. The approximately 3 grams of leaves was removed from the petri dish and placed in a thin bunched layer on the steel mesh, taking care to ensure a leaf was placed over each T/C. The remaining three T/Cs were placed on top of the leaves. The top steel mesh was placed on top, and pressed and hooked to the bottom mesh to keep all the leaves flat so that they would receive the same irradiance (35 kW m^{-2} selected) from the cone's heater. In the case of longleaf needles, the typical trimmed lengths were limited by the diameter of the petri dish to 80 mm, and the typical 3 grams of needles provided approximately 3 layers of needles to adequately cover an area of 80 mm × 80 mm. The cone calorimeter itself was in waiting mode to begin the test at the selected irradiance. Using a FLIR to determine the surface temperatures proved inadequate. That is, by an independent method we determined that the fresh longleaf pine needles (LLPN) had an emissivity of 0.89 while the oven-dried LLPN had an emissivity of 0.68. This means that with a typical irradiance on the leaves of 35 kW m^{-2} the reflected radiation would cause significant errors to the FLIR surface temperature estimations, such that using thin T/Cs remains the more reliable temperature measure.

In addition to the standard gas analyzers for oxygen, CO_2, and CO in the FTT iCone® (Fire Testing Technology Ltd., East Grinstead, UK) calorimeter,

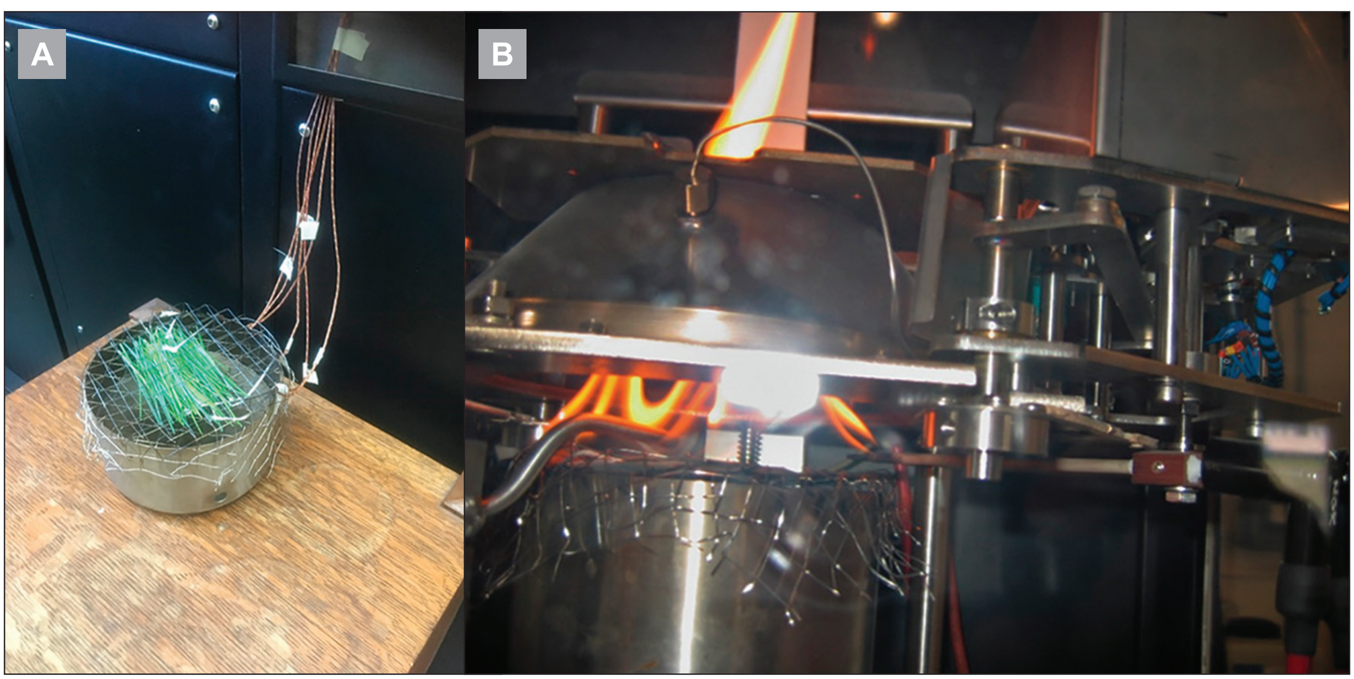

Figure 1—(A) New cone calorimeter holder with longleaf pine needles bedding constrained between wire grids, and (B) test specimen flaming as it is exposed to 35 kW m^{-2} in the cone calorimeter.

a Fourier Transform Infrared Radiation (FTIR) instrument and a fast-responding relative humidity (RH) in-line sensor (Sable RH 300; Sable Systems International, North Las Vegas, Nevada) have recently been added to the suite of instrumentation. The gas analyzers are calibrated by burning ethylene glycol instead of the usual methane. This is also helpful in the case of the RH sensor for getting the mass balance of all the gas measurements in agreement with the high accuracy weight cell mass loss, including the time responses for both delay and system dwell times. Considered along with these gas measurements is the soot extinction coefficient in the determination of the sample's "net" mass loss rate (MLR net), $\dot{m}_{net,fuel}$, via gas sampling as a comparison to weighed mass loss rate (MLR cell) in which the carbon, oxygen, and hydrogen mass flow rates provide the fuel mass flow rate as follows (Dietenberger 2012).

$$\dot{m}_{C,fuel} = \left(\frac{12}{44}\right)\dot{m}_{CO2} + \left(\frac{12}{28}\right)\dot{m}_{CO} + \dot{m}_{soot} \quad (1)$$

$$\dot{m}_{O,fuel} = \left(\frac{32}{44}\right)\dot{m}_{CO2} + \left(\frac{16}{28}\right)\dot{m}_{CO} + \left(\frac{16}{18}\right)\dot{m}_{H2O} - \Delta\,\dot{m}_{O2} \quad (2)$$

$$\dot{m}_{H,fuel} = \left(\frac{2}{18}\right)\dot{m}_{H2O} \quad (3)$$

$$\dot{m}_{net,fuel} = \dot{m}_{C,fuel} + \dot{m}_{O,fuel} + \dot{m}_{H,fuel} \quad (4)$$

The mass flow rates of oxygen, CO_2, and CO (grams second^{-1}) are provided as part of the standard equipment and the soot mass flow rate is calculated as the smoke production rate (SPR; extinction coefficient times volumetric flow rate) divided by the specific smoke area, as 8.3 m2 gram^{-1}. This in turn provides derivation of the volatile element composition (carbon, hydrogen, and oxygen) with time, as equations 1, 2, and 3 divided by equation 4. This easily translates to stoichiometric HOC with time (Dietenberger 2001) as:

$$HOC_{Stoich} = 13.23\left[\left(\frac{32\,\dot{m}_{C,fuel}}{12\,\dot{m}_{net,fuel}}\right) + \left(\frac{16\,\dot{m}_{H,fuel}}{2\,\dot{m}_{net,fuel}}\right) - \left(\frac{\dot{m}_{O,fuel}}{\dot{m}_{net,fuel}}\right)\right] \quad (5)$$

Chemical HOC due to inefficient diffusion flame combustion that produces CO and soot is determined as:

$$HOC_{chem} = HOC_{Stoich} - \left[\left(\frac{32.8\,\dot{m}_{C,fuel}}{\dot{m}_{net,fuel}}\right) + \left(\frac{10.1\,\dot{m}_{CO,fuel}}{\dot{m}_{net,fuel}}\right)\right] \quad (6)$$

In a typical experiment, the FTIR confirms that the major gases containing sulfur and nitrogen and the pure gaseous hydrocarbons are all in the parts per million range after flaming ignition, thereby improving the accuracy of equation 4 for the weight loss of the specimen. Combustion efficiency can be defined by the ratio of chemical heat of combustion to the stoichiometric heat of combustion. The other definition of combustion efficiency (Ward and Hao 1991) is also easily calculated as the moles of CO_2 divided by the combined moles of CO_2 , CO, and carbon (as soot). The spark igniter was adequate for igniting the LLPN sample after it was dried out. For some other species, an alternate pilot for igniting the white smoke after heating at the irradiance of 35 kW m^{-2} may be needed. The weigh scale is very sensitive, enough to measure the mass losses of 1-gram samples (although 3 grams was found more practical) to a small percentage error. Care must be taken to set the sample holder on and lighten the load of the six attached T/Cs with a tie to a frame to avoid a bias in the measured weight with time.

TEST RESULTS WITH FRESH LONGLEAF PINE NEEDLES

Temperature Profile of Sample

Three of the six thermocouples stayed adequately positioned and survived the test to measure the temperature as a function of time for differing depths (fig. 2). The temperature profile underneath the live needles gradually reached boiling temperature near 100 °C at 20 seconds, and was held nearly level until the point of ignition at 63 seconds. Exposed surface ignition temperature was 263 °C and the corresponding unexposed temperature was 138 °C, indicating a strong role for extractives and digestible material that pyrolyze at these temperatures in providing the volatile fuel for flaming combustion.

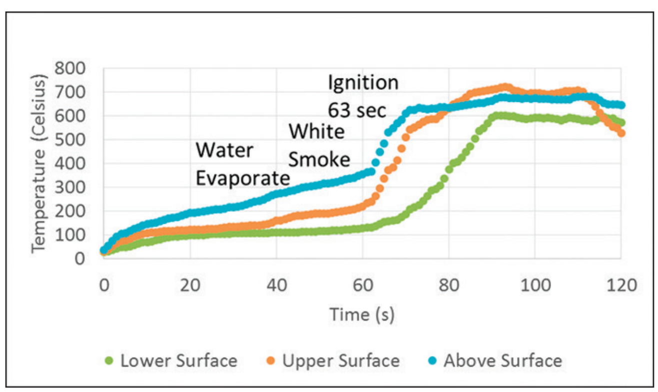

Figure 2—Temperatures measured temperatures by thermocouples on longleaf pine needles bedding on sample holder.

Our findings are similar to Susott's (1980, 1982) experiments using the catalytic oxidation feature of the evolved gas analyzer (EGA) with TGA on 5 mg of homogenized freeze-dried foliage to show the presence of extractives during pyrolysis at less than 200 °C, but which we also show with the 3.44 grams of intact live foliage. Although the exposed needles had temperature rapidly rising to 100 °C, and even rising to 200 °C prior to ignition, the temperature rise of the exposed needles was evidently constrained by the continuing water evaporation from the unexposed needles underneath the exposed needles until ignition. The delayed moisture effect has also been observed by Fletcher et al. (2007), but the effects on delayed temperature rise were observed for the first time in the current tests. Although also modeled (Shotorban et al. 2018; Yashwanth et al. 2016), the continuing refinement with the modeling will be possible with the current measurements. After ignition, the exposed needles had temperatures rapidly rising at rates of approximately 2100 °C minute^{-1}, while the unexposed and dried needles had a more delayed temperature rise due to the insulation by the exposed needles from the irradiance. The leveling out at 600 °C at 90 seconds as shown in figure 2 would be an indication that glowing combustion has been reached.

Various Mass Losses of Sample with Time

In figure 3, four significant mass losses are provided as a function of time. Of greatest relevance to pyrolysis modeling is the measured mass loss consisting of both water and the fuel. In an independent drying measurement with the vacuum oven, the moisture content is 65.7 percent green basis (192 percent dry basis), which also corresponds to total water mass loss prior to ignition in figure 3. The calculation of water vapor mass flow rate involves multiplying the water vapor mass fraction of the pyrolysis/combustion products (i.e., the increment in RH values with the in-line sensor) with the measured air exhaust mass flow rate. It is seen that the measured water vapor mass flow rate is in agreement with the measured weight loss rate in the period up to about 60 seconds after the irradiant exposure, as would be expected before ignition. After ignition, the water vapor mass flow rate is then primarily from the combustion of fuel with hydrogen composition, as the moisture content has been depleted at the point of ignition prior to ignition. The stoichiometric oxygen consumption mass rate is shown as heat release rate (as product of equations 4 and 5) divided by 13.23 (heat of combustion per mass of oxygen consumed in kJ gram^{-1}). The HRR peaking at 68 seconds corresponds to a surface temperature of 414 °C and backside temperature of 165 °C, which is much higher than what Susott (1982) observed with EGA/TGA of 5 mg of foliage heated at the very slow rate of 20 °C minute^{-1}. This would be a predicted effect of Arrhenius pyrolysis kinetics, in which the increasing of the heating rate corresponds to shifting the peak pyrolysis rates to occur at higher temperatures. Given the high rate of heating (2100 °C minute^{-1}) of the sample in the cone calorimeter test, it is then imperative to use tiny T/Cs in contact with the surfaces (unlike that in the TGA) to reflect the best accuracies with the temperature values during pyrolysis. Not shown is the similar profile of CO_2 and CO. As can be seen in figure 3, the weigh cell had an "extraneous bump" for the first few seconds while the makeshift radiant shutter was removed (the cone's shutter was inoperative so a manual shutter with a steel plate was devised).

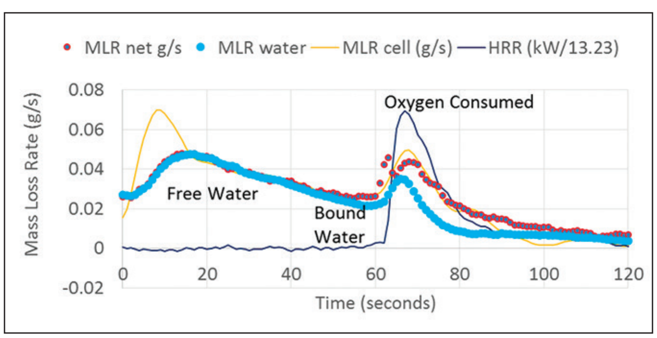

Figure 3—Mass loss rates (MLRs) for weigh cell, water, fuel, and oxygen during longleaf pine needle testing at 35 kW m^{-2}. HRR: heat release rate.

Major Combustion Emissions with Time

Four major emissions products common to all organic diffusion fires, CO_2, CO, water (H_2O), and soot, are provided as a function of time in figure 4. Emissions are calculated as the mass flow rates of CO_2, CO, H_2O, and soot divided by net mass loss rate (MLR), and therefore are dynamic emission measures. Obviously water is the major emission prior to ignition due to the live LLPN water evaporation, while the white smoke from the combustible volatiles (Yokelson et al. 1997) started to appear at 40 seconds at above 159 °C, as separate from that of the moisture. Byram (1959) calculated that the initial fuel moisture made up most of the water vapor produced in the combustion reaction when moisture content of the fuel (dry weight basis) exceeded 56 percent. This is only applicable to the green fuel as a whole, corresponding to the full 120 seconds of the current test, and provides an adequate approximation for wood stove or furnace application.

However, in a previous discussion, we determined that all of the fuel moisture in the cone calorimeter test with the thin leaf bedding has evaporated prior to ignition, at least for the LLPN, and that the water vapor after the ignition event is sourced entirely from the chemical hydrogen of the dried decomposing fuel. This provides an additional pyrolysis and combustion detail that was not available for the Byram combustion calculations. The white smoke emission measured by the laser smoke system (but not detected by the FTIR for the simpler compositions) is really about double that shown in figure 4 as the white smoke specific extinction area is about half that of black smoke (4.4 m^2 $gram^{-1}$ in Grexa et al. 2012). However, the black smoke is more important to measure than the white smoke for deriving the heat of combustion. It is seen that the CO emissions have quite low values during drying and flaming, until at the time of 80 seconds the CO mass fraction of the fuel undergoing pyrolysis reaches 0.16 while the H_2O emissions drop to 0.4, indicating the onset of glowing combustion. By 90 seconds, the sample mass was so small that errors begin creeping in, such as transient ambient RH that is responsible for the extraneous higher water vapor mass fraction at the end of the test.

Fuel Elemental Composition with Time

The trace gas emissions measured with the FTIR showed that the compounds containing sulfur and nitrogen and also the hydrocarbons were in the parts per million range, leaving the oxygen consumed, the CO_2, H_2O, and CO gases produced, and soot as solid carbon as the major measured compounds. It was possible to derive the combusting fuel elemental composition of carbon, oxygen, and hydrogen in these compounds as varying with time (equations 1, 2, and 3 divided by equation 4). We assume the initial volatile mass production is merely the water with zero carbon fraction, with hydrogen mass fraction as 0.11, and oxygen mass fraction as 0.88. Recall that figure 3 showed a small amount of volatiles in comparison to the water vapor prior to ignition. However, the white smoke as measured by the laser extinction was roughly approximated as solid carbon and is represented in figure 5 as an increasing carbon fraction while the oxygen and hydrogen fractions are decreasing. Upon volatile ignition at 63 seconds, the white smoke is converted to CO_2, H_2O, CO, and black smoke. It is evident that the leaf volatiles begin with oxygenated hydrocarbons as sourced from the extractives and digestible compounds, as indicated by carbon and hydrogen fractions (solid lines) being higher than that of reference sugar (dashed lines) and the oxygen fraction (solid line) as being lower than that of the reference sugar (dashed line).

The volatile composition then proceeded to the tar elemental compositions of carbon, oxygen, and hydrogen close to that of glucose by 80 seconds. The combusting fuel after that becomes more of solid char surface oxidation, along with the diminishing volatiles,

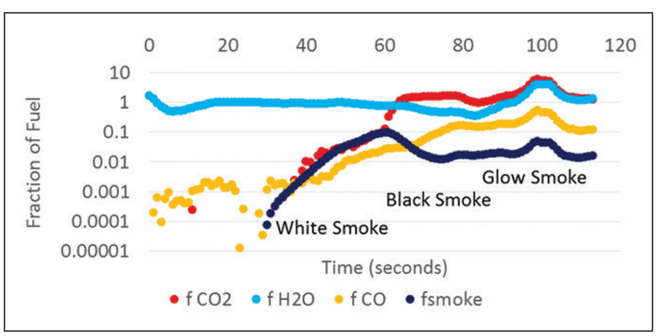

Figure 4—Major emissions of longleaf pine needles bedding during pyrolysis and combustion.

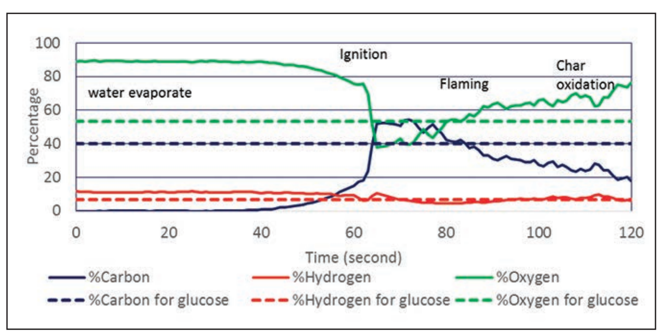

Figure 5—Estimated elemental composition of the devolved fuel for longleaf pine needles.

such that by the time of 90 seconds, the remaining mass is so small that it leads to increasing errors for the derived elemental composition of combusting fuel. We note that by integrating the fuel elemental composition over time, one can derive approximately the original dried fuel composition as the formula $C_6H_{11.7}O_{5.3}$. Then the elemental composition of the noncombusting fuel residue can be determined as a function of time by subtracting the combusting fuel composition from the original fuel composition.

Heat of Combustion Measures with Time

The availability of the combusting fuel elemental composition with time means that the stoichiometric oxygen mass consumption per fuel mass is easily calculated as a function of time. The stoichiometric HOC was estimated accurately from equation 5. It is shown in figure 6 as the upper red line starting at 40 seconds, which was when the laser extinction system began sensing white smoke. The reliability for the HOC value as measured in the cone calorimeter during flaming conditions can be assessed by comparing to the corresponding oxygen bomb measurement for the net HOC for vacuum-dried LLPN on the dry basis as the value, 19 kJ gram^{-1}. An independent gas chromatography/mass spectrometry measurement of the extractives for various lipid type compounds (e.g., terpenoids, oils, fatty acid) were found with the OH groups attached in varying amounts. This result indicates the good degree of reliability for the net heat of combustion starting at 24 kJ gram^{-1} at 65 seconds and decreasing monotonically as would be expected with the sequence of digestible material (protein has 23.6 kJ gram^{-1} for gross HOC), carbohydrates (glucose has 14 kJ gram^{-1} for net HOC), and charring lignin pyrolysis as the material temperatures continue to rise to at least 600 °C. Note that the wet basis net HOC based on the oxygen bomb calorimeter is 7 kJ gram^{-1}, indicating the serious effect of the leaf moisture content on its flammability. Also shown in figure 6 is the calculated chemical HOC due to the incomplete combustion of the diffusion flames that resulted in CO and soot as emissions.

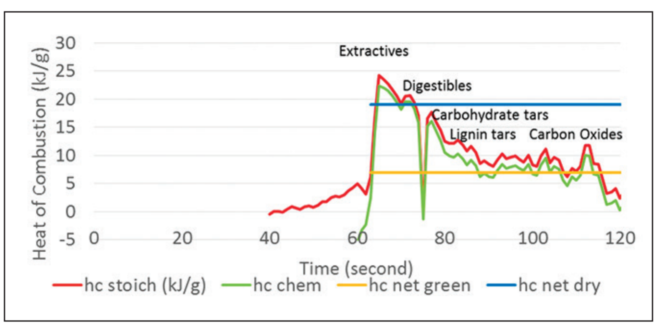

Figure 6—Heats of combustion (HCs; stoich = stoichiometric; chem = chemical) for the fresh longleaf pine litter exposed to 35 kW m^{-2}.

DISCUSSION AND CONCLUSIONS

Implications for Thermal and Moisture Properties

Some of the properties can fortunately be determined independently and perhaps better with other equipment. For example, surface emissivity of the leaves was determined with the enhanced FLIR method, the heat capacity on dried basis as a function of temperature with the modern modulated DSC, moisture characteristics with the water activity meter, and the moisture/pyrolysis kinetics with the high resolution TGA, particularly with the foliage chemistry providing various compositions. However, the thermal conductivity cannot be determined in an independent apparatus because of the rough and thin surfaces of the leaves. Further, the thermal conductivity is very dependent on the internal construction of the leaves, meaning that the samples must be intact and layered thinly. As a demonstration concerning thermal conductivity, the temperature profiles in figure 2 suggest a rough estimation for thermal conductivity as follows. The surface equilibrium temperature of the exposed surface at 100 seconds is measured at 696 °C, which provides an estimation for the effective heat transfer coefficient of the material cooling to the environment from the equation:

$$\varepsilon_s q_r = \varepsilon_s \sigma (T_{eq}^4 - T_a^4) + h_c(T_{eq} - T_a) = h_{eff}(T_{eq} - T_a) \qquad (7)$$

The point of ignition at 63 seconds in figure 2 provides a quasi-steady temperature spot in which the LLPN has just dried out and the heat being absorbed by heat capacity and water evaporation is at a minimum, leading to conductive heat losses into the triple-layered LLPN bed approximated with the equation:

$$\varepsilon_s q_r \sim h_{eff}(T_{ig} - T_a) + k(T_{ig} - T_{back})/\delta \qquad (8)$$

Using the previously mentioned values of temperatures, irradiance, and surface emissivity and with the three-layered thickness measured at $\delta = 0.85$ mm, the thermal conductivity, k, is calculated to be 0.1 W m^{-1} K^{-1}, which is often the value reported for wood in the literature. Obviously, the use of a CFD pyrolysis model can offer more refined estimation of thermal conductivity that should also include dependence on temperature and moisture content.

The moisture evaporation is also dependent on the internal construction of the leaf, as the surface layers have a cuticle composed of a waxy substance primarily composed of very long-chain fatty acids and stomata to control moisture transport to the environment (Raven et al. 1981; Yeats and Rose 2013). The material properties of heat capacity, thermal conductivity, and surface emissivity are strong functions of the moisture content. Although there are several CFD models to predict a material's thermal and moisture time responses, the profiles provided in figures 2 and 3 will challenge those models, to where perhaps only a few will succeed in predicting the profiles, or be a cause for introducing new physics in the pyrolysis model.

Implications for Pyrolysis and Combustion Properties

The foliage chemistry (methods to be discussed in another paper) for fresh LLPN litter indicates significant compositions of lipids, protein, glucose, fructose, starch, and pectin with a corresponding decrease in the celluloses in comparison to wood, while the lignin content remained similar to wood (table 1). Therefore, for the compositions aside from the lignin, there is expected to be no or minimal charring during the pyrolysis event, indicating the effective use of the TGA mass loss for the vacuum-dried leaf to define the pyrolysis kinetics of the corresponding compositions and to provide estimations for their volatile elemental composition and the corresponding stoichiometric HOC. However, the difficulties of pyrolysis in the cone calorimeter experiments include extremely high heating rates and temperature profiles existing within the thin leaf that may scuttle any attempts at a thermally thin formulation for the apparently very thin leaves. If the moisture and pyrolysis kinetics are coupled with a CFD model of heat and moisture flow, the challenge will be to reproduce the measured profiles in figures 2 to 6 with a reasonable set of properties that would allow the pyrolysis model to adapt to a variety of fire scenarios.

Table 1—Composition of fresh longleaf pine litter.

Component	Dry basis (%)
Extract (lipids)	22.3
Protein	7.4
Glucose	1.4
Fructose	0.8
Pectin	2.1
Hemicellulose	15.0
Cellulose	19.0
Starch	0.7
Lignin	26.6
Minerals	2.0
Silicates	0.6
Total	97.9
Moisture - dry basis	191.6

Concluding Remarks

In this paper we reported on fresh LLPN as a difficult material for which to derive thermal and moisture properties, and also on pyrolysis and combustion properties with an enhanced cone calorimetry test method involving a new sample holder design, attachment of T/Cs to the sample surfaces, and added gas sensors for H_2O and the FTIR. The dynamically changing profiles of various simultaneous measurements along with the complexity of the foliage material make determination of any one parameter in isolation to be difficult. Despite this difficulty, it was interesting that there were quasi-steady portions of the exposed and backside temperatures in the cone calorimeter test that provided a rough estimation of the thermal conductivity of LLPN at the point of ignition. Using a CFD model to refine the estimates of the thermal conductivity would be an improvement, particularly in that new nonstandard techniques were developed for determining other parameters such as surface emissivity and heat capacity as a function of temperature and moisture content, along with the independent physical measurements of leaf thicknesses and density. It is now possible to create detailed pyrolysis kinetics models based on a recently completed detailed profiling of dried foliage composition for extractives, protein, fructose, glucose, pectin, hemicellulose, cellulose, starch, lignin, and minerals. Data from high resolution TGA and enhanced cone calorimeter tests are being analyzed to provide an alternative to the relatively simple pyrolysis kinetics currently used in FDS. This would imply new fire physics modeling capability to be added to FDS and other CFD models. Such enhancements are expected to improve prediction of foliage degradations and combustions subjected to varying environments while providing greater speed, accuracy, and flexibility to the numerical schemes.

ACKNOWLEDGMENTS

This work was partially supported by the DOD/EPA/DOE Strategic Environmental Research and Development Program project RC-2640. We thank the staff of FPL for their support of this work. This manuscript was prepared by Federal government employees as a part of their official duties and is therefore in the public domain and not subject to copyright.

REFERENCES

Anand, C.; Shotorban, B.; Mahalingam, S.; [et al.]. 2017. Physics-based modeling of live wildland fuel ignition experiments in the forced ignition and flame spread test apparatus. Combustion Science and Technology. 189: 1551–1570.

ASTM International. 2016. ASTM D4442 – 16: Standard test methods for direct moisture content measurement of wood and wood-based materials. West Conshohocken, PA. Available at https://www.astm.org/Standards/D4442.htm.

ASTM International. 2017. ASTM E1354: Standard test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter. West Conshohocken, PA. Available at https://www.astm.org/Standards/E1354.htm.

Bradbury, Allan G.W.; Sakai, Yoshio; Shafizadeh, Fred. 1979. A kinetic model for pyrolysis of cellulose. Journal of Applied Polymer Science. 23: 3271–3280.

Burgan, Robert E. 1988. 1988 revisions to the 1978 National Fire-Danger Rating System. Res. Pap. SE-273. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 39 p.

Burgan, R.E.; Susott, R.A. 1991 Influence of sample processing techniques and seasonal variation on quantities of volatile compounds of gallberry, saw-palmetto, and wax myrtle. International Journal of Wildland Fire. l: 57–62.

Byram, George M. 1959. Combustion of forest fuels. In: Davis, Kenneth P., ed. Forest fire: Control and use. 1st ed. American Forestry Series. New York: McGraw-Hill: 61–89.

Dibble, Alison C.; White, Robert H.; Lebow, Patricia K. 2007. Combustion characteristics of north-eastern USA vegetation tested in the cone calorimeter: Invasive versus non-invasive plants. International Journal of Wildland Fire. 16: 426–443.

Dickinson, Matthew B.; Hutchinson, Todd F.; Dietenberger, Mark; [et al.]. 2016. Litter species composition and topographic effects on fuels and modeled fire behavior in an oak-hickory forest in the eastern USA. PLOS ONE. 11: e0159997.

Dietenberger, Mark. 2002. Update for combustion properties of wood components. Fire and Materials Journal. 26: 255–267.

Dietenberger, Mark. 2012. Pyrolysis kinetics and combustion of thin wood by an advanced cone calorimetry test method. Journal of Thermal Analysis and Calorimetry. 109: 1215–1228.

Dietenberger, Mark A.; White, Robert H. 2001. Reaction-to-fire testing and modeling for wood products. In: Proceedings, 12th Annual BCC conference on flame retardancy; 2001 May 21–23; Stamford, CT. Norwalk, CT: Business Communications Co.: 54–69.

Fletcher, Thomas H.; Pickett, Brent M.; Smith, Steven G.; [et al.]. 2007. Effects of moisture on ignition behavior of moist California chaparral and Utah leaves. Combustion Science and Technology. 179: 1183–1203.

Grexa, Ondrej; Dietenberger, Mark A.; White, Robert H. 2012. Reaction-to-fire of wood products and other building materials. Part 1: Room/Corner test performance. Res. Pap. FPL-RP-663. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 51 p.

Hagge, Matthew J.; Bryden, Kenneth M.; Dietenberger, Mark A. 2004. Effects of backing board materials on wood combustion performance. Proceedings, Wood & fire safety: 5th International scientific conference; 2004 April 18–22; High Tatras, Slovakia. Zvolen, Slovak Republic: Technical University of Zvolen, Faculty of Wood Science and Technology: 51–58.

Jolly, W. Matt; Hintz, John; Linn, Rodman L.; [et al.]. 2016. Seasonal variations in red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) foliar physio-chemistry and their potential influence on stand-scale wildland fire behavior. Forest Ecology and Management. 373: 167–178.

Jolly, W. Matt; Parsons, Russell A.; Hadlow, Ann M.; [et al.]. 2012. Relationships between moisture, chemistry, and ignition of *Pinus contorta* needles during the early stages of mountain pine beetle attack, Forest Ecology and Management. 269: 52–59.

Lamorlette, A.; El Houssami, M.; Morvan, D. 2018. An improved non-equilibrium model for the ignition of living fuel. International Journal of Wildland Fire. 27: 29–41.

McAllister, S.; Grenfell, I.; Hadlow, A.; [et al.]. 2012. Piloted ignition of live forest fuels. Fire Safety Journal. 51: 133–142.

McAllister, S.; Weise, D.R. 2016. Effects of season on ignition of live wildland fuels using the FIST apparatus. Combustion Science and Technology. 189: 231–247.

Raven, Peter H.; Evert, Ray F.; Curtis, Helena. 1981. Biology of plants. 3rd ed. New York: Worth Publishers.

Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-RP-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Safdari, Mohammad-Saeed; Rahmati, Mahmood; Amini, Elham; [et al.]. 2018, Characterization of pyrolysis products from fast pyrolysis of live and dead vegetation native to the southern United States. Fuel. 229: 151–166.

Sait, Hani; Hussain, Ahmad; Salema, Arshad Adam.; Ani, Farid Nasir. 2012. Pyrolysis and combustion kinetics of date palm biomass using thermogravimetric analysis. Bioresource Technology. 118: 382–389.

Shafizadeh, F.; Chin, P.S.; Degroot, W.F. 1975. Mechanistic evaluation of flame retardants. Journal of Fire & Flammability/Fire Retardant Chemistry Supplement. 2: 195–203.

Shafizadeh, F.; Chin, P.S.; DeGroot, W.F. 1977. Effective heat content of green forest fuels. Forest Science. 23: 81–89.

Shotorban, Babak; Yashwanth, Banglore L.; Mahalingam, Shankar; Haring, Dakota J. 2018. An investigation of pyrolysis and ignition of moist leaf-like fuel subject to convective heating. Combustion and Flame. 190: 25–35.

Susott, Ronald A. 1980. Thermal behavior of conifer needle extractives. Forest Science. 26: 347–360.

Susott, Ronald A. 1982. Characterization of thermal properties of forest fuels by combustible gas analysis. Forest Science. 28: 404–420.

Susott, R.A.; F. Shafizadeh, and T.W. Aanerud. 1979. A quantitative thermal analysis technique for combustible gas detection. Journal of Fire and Flammability 10: 94–104.

Tang, Walter K.; Eickner, Herbert W. 1968. Effect of inorganic salts on pyrolysis of wood, cellulose, and lignin determined by differential thermal analysis. Res. Pap. FPL-82. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 29 p.

Ward, Darold E.; Hao, Weimin. 1991. Projections of emissions from burning of biomass for use in studies of global climate and atmospheric chemistry. Paper 91-128.4 presented at the 84th annual meeting and exhibition of the Air and Waste Management Association; 1991 June 16–21; Vancouver, BC. Available at http://www.treesearch.fs.fed.us/pubs/43258.

White, Robert H.; Weise, David R.; Frommer, Susan. 1996. Preliminary evaluation of the flammability of native and ornamental plants with the cone calorimeter. In: Proceedings, 21st international conference on fire safety; 1996 January 8–12; Millbrae, CA: 256–265.

Yashwanth, B.L.; Shotorban, B.; Mahalingam, S.; [et al.]. 2016. A numerical investigation of the influence of radiation and moisture content on pyrolysis and ignition of a leaf-like fuel element. Combustion and Flame. 163: 301–316.

Yeats, Trevor H.; Rose, Jocelyn K.C. 2013. The formation and function of plant cuticles. Plant Physiology. 163: 5–20.

Yokelson, Robert J.; Susott, Ronald; Ward, Darold E.; [et al.]. 1997. Emissions from smoldering combustion of biomass measured by open-path Fourier Transform Infrared spectroscopy. Journal of Geophysical Research: Atmospheres. 102: 18865–18877.

Restoring the Fire Continuum: Restoring Fire Integrity

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Abstract—Fire is a natural environmental parameter on which the diversity of life depends. In the United States we are now engaged in sorting all remaining lands not already transformed from nature into two distinct categories of conservation. First are the lands we are committed to protect: National forests, national parks, wildlife refuges, wilderness, and other public lands, and private preserves. Second are the working landscapes found in ranches, small farms, and their woodlands, and some commercial timberlands. From the perspective of the planet, the most significant corollary of climate change is this final conversion of "natural" lands, driven by the population explosion, and portending mass species extinctions in the next three decades. Restoring fire integrity to our public and private natural lands can be reduced to a choice between embracing fire or surrendering to the forces of extinction. Emerging evidence indicates that restoring fire—the creator of habitats and sustainer of the web of life for most terrestrial species, from microbes and arthropods to birds, plants, and animals, and the broad conditioning agent of soils, fuels, and habitats—is our only countermeasure to extinction of perhaps half or all terrestrial birds, plants, and animals. When the pendulum swings our way again, the concept of fire integrity will drive funding for natural lands and the future of fire ecology. Until that time our central mission as fire practitioners, fire ecologists, and managers of natural lands consists of novel holding actions that will perpetuate the web of life.

Keywords: climate change, extinction, fire integrity, fire dependent species, HRV

INTRODUCTION

The natural continuum of fire—from the most fire-sheltered ravine in a landscape to the most fire-exposed prairie, savanna, or grassy woodland—creates the myriad habitats for the terrestrial species of North America. As fire professionals, our core mission, values, and personal commitments center on restoring the beauty and diversity of the portion of the natural world that, through our actions during the extinction bottleneck of the next three decades, we will bequeath to all future generations.

There are three striking fire continua that determine much of species diversity in nature. First is the local landscape continuum from fire-exposed to fire-sheltered sites. From this perspective, landscape factors such as fire compartment size, fire filters, topography, and pathways for fire flow, control fire frequency—not Native Americans, not lightning. Both of the latter are only ignition sources, and except for certain hotspots, fire frequency depends on what the landscape does with fire once it is ignited. Second, we find ourselves at the pinnacle of the 430 million year coevolutionary continuum of all terrestrial species with fire. Third is the distribution of organisms on the fire frequency continuum. Put another way, all terrestrial species from microbes and insects to migratory birds, have fire relations. Those species such as Venus flytrap (*Dionaea muscipula*, a threatened species) that require fire at least every 3 years, occupy one extreme; those of habitats that never burn occupy the antipode (Frost 2000). One new target of research is to be able to describe the range occupied by each species on this long gradient of fire frequency. We know this only for a handful of rare species, but with further work it will be possible to map the range occupied by every

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

species of plant or animal on this continuum. This aspect of fire dependence represents one implement for preventing extinction through use of prescribed fire.

We find ourselves participants in an unprecedented confluence of four changing paradigms of seismic proportions: Climate change, mass extinction, the population bomb, and the final planetary triage of lands, of which "nature"—the world of full species diversity and natural processes such as fire—is already the smallest.

"Climate change changes everything" is an oft-heard motif in the struggle against censorship of discourse on global warming. Climate change is just one symptom of overpopulation. We can see two ways to put climate change in ecological perspective: First, we have the socioeconomic perspective implicit in the statement above. From the anthropocentric viewpoint this is undeniable: Our culture—no matter the inevitable resistance and conflict—is destined for pervasive social change in all dimensions, including restructuring of our economic systems.

In contrast, from the perspective of a fire planet, climate change changes nothing in the fundamentals of fire ecology. A species that requires a 3- to 5-year fire interval today will still require that interval 50, 100, and 300 years into climate change, even though its range may change and frequency requirements change slightly with fuels. Failure to distinguish these two perspectives sets up a dangerous and self-defeating muddle in conservation: Seen from the first perspective, everything is off on new trajectories and the old ecology does not matter anymore (Botkin 1990; Schmitz 2016). But throwing out the baby with the bathwater is a consistent feature of paradigm change that follows the acceptance phase. From the perspective of nature, the basic processes that support species diversity, including fire, remain unchanged.

Further, as we shall see, there seems to be no supportable reason to expect that the anthric "New Ecology" and the natural ecology that evolved with fire for 430 million years, can coexist in the same landscapes. The outcome of our mission as fire ecologists depends on being clear about this dichotomy.

THE FIRST DOMAIN

The First Domain, the public and private lands that have been set aside primarily for the survival of nature, is the world of concern for fire ecology. This is the planetary reserve, the islands and archipelagoes of diversity, the intricate natural world from which we arose and whose ancient sustaining processes such as fire, predation, and herbivory we have simply not yet begun to understand. In the United States this legacy consists of the 14 percent of lands permanently committed to preservation of species diversity and natural beauty—our national parks, national wildlife refuges, wildernesses; portions of national forests and Bureau of Land Management (BLM) lands; all comparable State and local lands; and the lands of private conservation agencies. In this domain there are some 25,800 protected natural areas in the United States (World Database on Protected Areas 2015). In the United States the great triage is nearly complete; beyond a few additions, this is all we will ever have to work with. Because of the threat of mass extinction—epitomized in North America by fire dependent species—restoring fire integrity to these lands is just not optional: Nothing short of eventual full restoration of original fire frequency across these lands seems likely to provide survival for some 50 percent or more of all our native species of birds, plants, and animals, the more sensitive half of our biota, the diversity that is incompatible with human-transformed lands.

Conversely, we should be able to dispense with fire as a tool for restoration in the 86 percent of the land already appropriated for farms, ranches, grazing lands, timber plantations, and the completely transformed world of cities and the intensive agriculture and silvicultural lands that support them. These are the domain of the "New Ecology" (Botkin 1990; Schmitz 2016). As we will see from several lines of evidence in the following discussion, truly natural fire regimes, because of their obligate frequencies for species diversity, are largely incompatible with production lands.

Fire Dependent Species and Fire Integrity

Understanding this core world of conservation requires two new definitions; first is the concept of fire dependent species. By previous conceptions, never really defined, a fire dependent species was one possessing some evolutionary trick such as serotinous cones that open with the heat of a passing fire to shower seeds onto newly exposed mineral soil. Mechanistic fire dependence, however, is only the tiniest tip of the iceberg.

Fire Dependent Species

For a realistic definition, a fire dependent species is any species of plant, bird, or animal that will ultimately become rare or go extinct without fire. By this new criterion, since a large percentage of our flora, along with the arthropods, bird, and animal species that depend on plants for food and habitat, require regular fire to maintain open, sunny structure, something approaching half or more of all terrestrial species in the United States are threatened by fire exclusion. This is mass extinction in progress, almost unheeded and obscured in the smoke and conflict over climate change.

Fire is a broad conditioning agent. Understanding fire dependence hinges on recognizing the totality of the effects of natural fire as it moves through a landscape. This engenders a second new concept, fire integrity.

Fire Integrity

Fire integrity is defined as fire moving freely through a landscape, through the seasons and years, at its natural frequency; displaying its customary range of behaviors; constantly renewing vegetation; stabilizing soil chemistry; removing dead fuels; renewing the complex multidimensional mosaic of species' habitats and structure at all scales, thereby sustaining the full diversity of terrestrial species from soil microorganisms to arthropods, birds, plants, and animals as it has done for over 400 million years. Full fire integrity must also include its interactions with the dynamic equilibrium of predators and herbivores.

This may seem complex, but nature is complex; the central concept inherent in the 10 points in the preceding definition is that fire is a broad conditioning agent, interacting at so many levels that there is nothing—*no conceivable surrogate for fire*—that can perform these myriad functions but fire itself. Like it or not, we have no choice but to eventually restore fire habitats and fire frequency to the 14 percent of public and private natural lands that we have committed to the perpetuation of the natural world.

To date only a handful of studies have begun to approach the full multifactorial complexity of these interactions (Fuhlendorf and Engle 2001; Fuhlendorf et al. 2006, 2012). Restoration of fire integrity is a rich new field for research. It will require close and regular interactions between the three currently disparate fields of fire ecology, wildlife biology, and plant ecology. There are almost no well-designed multifactorial studies involving all three disciplines in the study of species diversity and species survival under the interactions of natural levels of predation, herbivory, and fire. Yet these are the very conditions underlying terrestrial species diversity and its long-term survival that is by default our responsibility and mission.

Text Box 1 lists some components of the condition of fire integrity that will underlie any success we hope to have in sustaining species diversity on committed natural lands in perpetuity.

Eight Converging Lines of Evidence for Pervasive Fire Dependence Among Species and Habitats

The pre-European United States was a frequent-fire landscape. Except for the roughly 25 percent of the contiguous lands of the United States that is desert or mountainous, the landscape had substantial areas supporting very frequent fire, with intervals between 1 and 14 years (Frost 1998; Guyette et al. 2012). These regions contained literally thousands of species dependent on those frequencies to maintain their thousands of habitats.

First Line of Evidence

In the first approximation map of pre-European fire frequencies of the United States, large areas of the south-central and southeastern United States were shown in the 1- to 3-year fire interval class (Frost 1998). As pointed out in the text, but often overlooked if one only glances at the map, this does not mean that the whole landscapes burned at the intervals shown in the polygons. For a polygon to receive the indicated frequency means that at least an estimated 10 percent of the area burned at that frequency. The intent was to point out the highest frequencies to be found in each region of the country and to begin to convey the idea that the pre-European United States was a frequent fire landscape. This theme was echoed, using an entirely different approach, in a map by Guyette et al. (2012)

Text Box 1.
The conditions and principles of fire integrity.

The concept of fire integrity recognizes that:

- Fire integrity is a condition of the landscape, not a fire regime.
- Fire integrity is measurable in terms of natural habitat structure and presence of sentinel plant species, those most sensitive to departure from natural fire frequency. These are specific for each site.
- Predation, perhaps half by Native Americans and half by animal predators, once protected vegetation diversity by maintaining a dynamic balance between predation and populations of master herbivores such as deer (*Odocoileus* spp.) and elk (*Cervus canadensis*) in a landscape with vegetation diversified and constantly reinvigorated by fire.
- Fire is a universal conditioning agent affecting soils, surface fuels, and vegetation structure, and underpins the thousand individual species habitats on each site, even as they shift in relation to climate change.
- Only fire can perform the thousand tasks—chemical, micro, and macro—that must be executed regularly in each natural area.
- There is no surrogate for fire: Nothing else comes even close.
- In Domain 1, fire, like rain, is an indispensable component of the environment and is not made irrelevant by climate change, by new trajectories of succession, or the "New Ecology."

based on the Arrhenius equation. The two maps largely agree in their broad-brush vision, but Guyette et al.'s map offers better detail.

These maps constitute the first of several converging lines of evidence that some 50 percent of all terrestrial species of birds, plants, and animals in the United States are, in the long run, dependent on fire for survival.

Second Line of Evidence

Figure 1 shows a 245-year fire exclusion chronosequence for nine 0.1-ha plots on similar silty loam soils in eastern North Carolina. The plot on the left, JO03, with 68 species, had been burned in recent years on a 3-year frequency in the Croatan National Forest, maintaining the estimated natural, pre-European fire frequency. The other plots, when sampled, had already suffered declining fire frequency through changes dating to 1772. All plots were documented, from species remnants, historical information, and their position in frequent fire landscapes, to have historically supported open, sunny longleaf pine (*Pinus palustris*) savanna with an herbaceous grass-forb understory. The red line represents fire dependent species such as wiregrass (*Aristida stricta* var. *beyrichiana*). The green line indicates fire-neutral species such as gallberry (*Ilex glabra*) that can be found in annually burned savannas as a tiny shrub 10 cm high, but also with trunks to 15 cm diameter on islands that never burned. The blue represents fire-refugia (fire intolerant) forest species. When sampled, the last two plots on the right, on a site occupied by longleaf pine when advertised for sale in 1772, were now shady, closed-canopy beech forest with white oak (*Quercus alba*) and tulip-poplar (*Liriodendron tulipifera*). In the same county there had been exploitation of longleaf pine for tar, pitch, and crude turpentine as early as 1622 (Frost 2000).

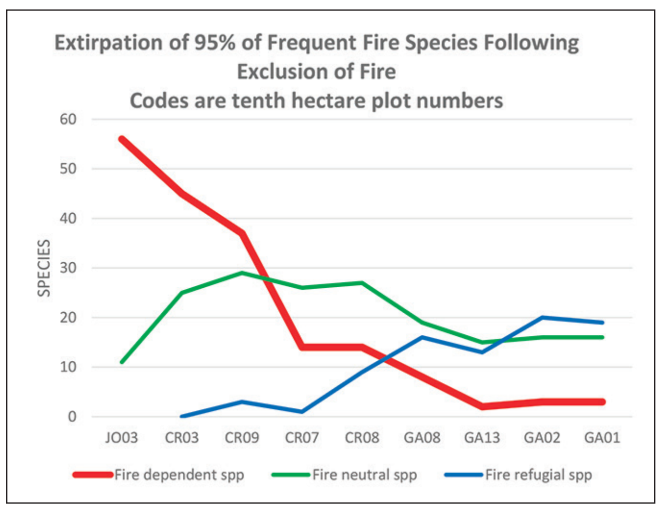

Figure 1—Number of species on plots in the southeastern Coastal Plain, North Carolina, following fire exclusion. The loss of 95 percent of fire dependent species in the southeastern Coastal Plain is a second line evidence for fire dependence and impending mass extinction. Codes identify 0.1-hectare plots.

Over the 37.6 million hectare former longleaf pine region, progressive fire deprivation has resulted in complete turnover from very frequent fire, open, sunny, species-rich communities to the uniformly dark, multistoried, species-poor forests and thickets that have taken over the eastern half of the country and many smaller areas elsewhere (Frost 2006; Nowacki and Abrams 2008). This is an ecological catastrophe the role of which in the impending sixth extinction is not yet appreciated.

Third Line of Evidence

This line of evidence lies in community response to extremely high fire frequency. In what they called the Most Frequent Fire Hypothesis, Glitzenstein et al. (2003) found that burning as frequently as fuels allowed produced the highest species richness in frequent fire longleaf pine communities. This positive fire community response to the *highest fire frequency possible* suggests that nearly annual (1–3 years) fire frequencies are natural in some landscapes and may be ancient, extending into the evolutionary past, far beyond the appearance of humankind in the western hemisphere.

Fourth Line of Evidence

This line presents itself in numerous studies and observations on pyroecology of individual species. The response of many endangered species indicates that fire deprivation underlies the increasing rarity of a previously unimagined large portion of our flora and fauna. For examples, see Venus flytrap in the Carolinas and in Florida the endangered Kissimmee grasshopper sparrow (*Ammodramus savannarum floridanus*), which rotates its nest sites into patches burned in the last year and a half, in a wet prairie landscape that experiences a 1- to 3-year fire regime driven today solely by lightning (Noss 2013).

In the Green Swamp of North Carolina a 30-year study found that the largest number of Venus flytraps per square meter occurred in plots burned annually. When mean fire frequency dropped to 2 and 3 years, numbers plunged; and when mean fire frequency dropped below 4 years, plots were overgrown with shrubs and flytraps disappeared (Frost 2000). This makes Venus flytrap the most fire dependent species known. This and its extreme evolutionary adaptions—the snap trap itself, with its triggering algorithm and its production of enzymes to digest insects for their nutrients—point again to landscapes with very frequent fire extending back millions of years.

Fifth Line of Evidence

Fire scar chronologies provide the fifth line of evidence. The existence of nearly annual fire in pre-European landscapes was first documented in Arizona from a fire scar chronology by Dieterich (1980) and more recently from Louisiana (Stambaugh et al. 2011), Florida (Huffman and Rother 2017), and other studies for a total of at least five States. At least five studies are in the southeastern United States, where a number of species dependent on this frequency have been documented.

Sixth Line of Evidence

Tracking the rate of slide of fire dependent species toward extinction is a new field and such evidence is needed to even begin to determine the percentage of species dependent on fire globally. Despite the necessity of such information for response to global extinction, this field is as yet virtually unfunded. Under the Global Strategy for Plant Conservation, Backman et al. (2018) reported current progress toward a global conservation assessment for all plants, assembled species status reports from available sources, and have assessed the status of up to 90,321 species to date. This represents 26 percent of known plant species. In the United States there is no government or private agency tasked with monitoring the overall condition of the flora and the rate of slide of all species toward extinction. The U.S. Fish and Wildlife Service responds when a single species is proposed for listing and States' Natural Heritage Programs maintain their lists of endangered and threatened species and periodically review rare species. There seems to be no place, however, where the rate of new listings over time is reported, much less any way to gauge the changing status of all species, be they plants or animals.

Seventh Line of Evidence

Similarly, there is no agency charged with monitoring the role of livestock in extinction of flora and fauna. Cattle (*Bos taurus*) can be expected to be a part of our civilization for hundreds of years. In the long run, however, because of their proclivity to dichotomizing native flora and fauna into "increasers" and "decreasers," livestock—at any commercially profitable level—are likely to be incompatible with as many as 50 percent of species native to North American grasslands.

For over a century, cattle and sheep (*Ovis aries*) ranchers have recognized that some plant species increase with grazing—these are the plants that livestock refuse to eat. They call these unpalatable, armed, or toxic species "increasers." Increasers are easier to document than decreasers because they increase. Changes in abundance of decreasers—the tasty, easily digestible, nutritious species—are easily overlooked unless they are among the dozen or so dominant forage grasses, shrubs, and showy native forbs found on a particular piece of range. In northern mixed grass prairie for example, species whose decease may raise alarm include cattle favorites such as bluebunch wheatgrass (*Pseudoroegnaria spicata*), western wheatgrass (*Pascopyrum smithii*), little bluestem (*Schizachyrium scoparium*), saltbush (*Atriplex* spp.), and purple prairie clover (*Dalea purpurea*) and standard range condition monitoring methods understandably are strongly slanted to these. Fleischner (1994) summarized the ecological costs of livestock grazing in western North America.

We can get some inkling of livestock potential for tipping the extinction scale by comparing what is known about decreasers and increasers. A few floras and plant guides across North America have begun to supply this vital information. The flora *Plants of the Black Hills* mentions palatability for 195 species, or 49 percent of the approximately 400 forbs covered in the book (Larson and Johnson 1999). Eighty-three plants or 43 percent of the 195 were considered to have some degree of palatability for cattle and 112 or 57 percent were unpalatable. So for the species for which something was known, a little less than half are negatively affected by livestock grazing and may have a long-term potential for elimination. We can infer a similar level of threat to native arthropods, birds, and animals native to the original fire-maintained North American grasslands.

Few studies of cattle grazing have taken into account that species diversity likely was maintained primarily by fire, not grazing. This is suggested by the large portion of the country—the lands west of the Continental Divide and east of the Mississippi River that had no bison (*Bison bison*) for some 9,000 years of the Holocene until the 1540 introduction of European diseases by the De Soto expedition through the Southeast and the simultaneous Coronado expedition from Mexico City to the vicinity of today's Kansas. Both explorations introduced plagues along the way, decimating Native American populations. Historical accounts of bison from these regions seem to date the expansion of bison range after diseases provided relief from hunting pressure. Prior to that event there was no cattle analog in large parts of North America, yet grasslands thrived. Despite the need for data for preventing extinction, no good multifactorial studies exist that have examined the relationships of species diversity of plants, birds, and animals under natural pre-European fire frequencies—almost universally much higher than for the last century—and the natural level of native grazers and browsers—almost universally much lower before settlement.

The unpopular, yet inescapable, conclusion for the web of life is that cattle will be a permanent part of working landscapes, as they are now, but, with portions of some agencies such as BLM excepted, livestock must eventually be excluded from most of the First Domain.

Eighth Line of Evidence

It is now possible to make fine-scale maps of pre-European fire frequency (Bailey et al. 2007; Frost et al. 2013; LANDFIRE 2018). This is another new field that should play an increasingly important role in restoring fire integrity to the First Domain.

While we are just beginning to glimpse the evolutionary world of natural fire regimes, it would be irresponsible to ignore the weight of emerging evidence summarized in the preceding discussion and the implications for species diversity. For most of the undocumented thousands of fire dependent species there is a fatal risk of not meeting their required fire frequency when planning the future of prescribed fire. Given our imperfect knowledge, the risk of omission—not burning often enough—far exceeds the risk of commission—too much fire in frequent fire ecosystems. Where these species occur on public lands and preserves, our highest obligation as land managers is to burn the most critical sites often enough to maintain full species diversity. Fire is our only practicable tool to employ against the current slide to mass extinction in North America.

HOLDING ACTIONS

If we recognize, in the current political situation, with its suppressed funding for all things natural, the impossibility in most cases of proceeding with full restoration of natural fire frequency over whole large "protected" land units, the most reasonable course should be to construct a clear plan of prescribed burn holding actions that will actualize our responsibility to ensure survival of full species diversity in each natural site we manage.

Abandon "Fire Rotations" in Favor of Ecologically Targeted Burning

Likely the most important holding action we can take is to adopt ecologically targeted burning. This is the opposite of broadcast burning or fire rotations. Heinselman (1973) coined the term "natural fire rotation" to obtain some handle on fire frequency in fire-suppressed northern landscapes, where even the natural fire intervals were longer than in most of the United States, and where ignitions were perceived as spatially random events—an invalid assumption for most landscapes other than perhaps boreal forest. It was defined further by Agee (1993) as the time needed to burn an area the size of the study area, while recognizing the critical point that some areas might burn twice or more and others not at all. This provided a rough measure that could be used to compare fire frequency between different areas, a tool that was useful with the limited data of the time. A quarter-century later we have much better fire history information (Frost 1998; Frost et al. 2013; Guyette et al. 2012) and can now make fine-scale maps of pre-European fire frequency (Frost et al. 2013).

The "fire rotations" concept has been misinterpreted in at least three ways, all of which set up situations for mismanagement and present severe threats to species diversity on public natural lands:

(a) Some users treat Heinselman's "fire rotation" as an indicator of natural fire frequency.

(b) Worse is the case discussed shortly where land managers try to burn all of a managed area one block at time and call that a fire rotation.

(c) Silviculturists sometimes use the term to refer to the cycle of burning on the arbitrary management units we set up according to roads, creeks, etc. for convenience. This might be a useful redefinition if we could drop the original, which has little application now that we have satellite imagery, geographic information systems (GIS), LANDFIRE, and new ways of getting at actual current fire footprints and historical fire frequency at fine scales.

Perhaps the best advice—since the term "fire rotation" seems to be popular in spite all of its misapplications—is to never use it in print unless it is made clear that we use it in the sense of case c.

Looking closely at case b, we can see how this most pernicious example is a clear threat to species diversity on public lands. In figure 2, the forest has the resources to burn 5,000 acres a year, so the year after the first unit is burned a second compartment is burned and so on until after 100 years all of the forest will have been burned and we will have completed one "fire rotation." Under this misinterpretation what we have done is set up a 100-year fire return interval and in the process, eliminated all of the fire dependent species and ruined the most important sites that once sustained the greatest species richness.

Ecologically targeted fire, in contrast, requires us to burn the three areas with the highest concentration of fire dependent species first, and do so as often as needed, before all else. If the three sites in the example require fire every 4 years we would burn one of them each year, and in the fourth year we have resources equivalent to burning 5,000 acres to spend elsewhere on fuel reduction, oak and hickory (*Carya* spp.) regeneration, and the like. We have to let the rest go. This seems a bitter choice but, given the current natural resources funding anomaly, we are presented

Burn compartments of hypothetical national forest of 500,000 acres

5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	**5,000**	**5,000**	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	**5,000**	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000

Figure 2—An illustration of the danger of one common misinterpretation of "fire rotation" in the eastern United States. Shown is a hypothetical 500,000-acre natural area such as a national forest, divided into 100 burn compartments. The three units in boldface represent naturally frequent fire sites with rare species and unique fire communities.

with no other option than to accept extinction of the ecologically most important species and communities. We may hope for and be prepared to use fire from lightning or other ignitions, but the core diversity—our legacy to future generations—must be preserved.

Agee (1993) distinguished two kinds of fire frequency, point frequency and area frequency. Noting that the term "point" is problematic because a single tree is rarely scarred by every passing fire, he expanded "point" to mean enough land to include enough trees to construct a composite fire scar chronology.

Site Fire Frequency

I would suggest that the most ecologically useful fire frequency be called site fire frequency, synonymous with natural fire compartment, which captures Agee's "big point." Site or fire compartment is defined as a unit of the landscape with no internal firebreaks and nearly continuous fine fuels, so that an ignition in one part would be likely to burn the whole unless there were a change in weather or fuel moisture.

Fire compartment size is the most important driver of fire frequency in most landscapes: The larger the compartment, the higher the fire frequency (Frost 1998). Further, by definition, boundaries of the fire compartment could be expected most often to correspond with boundaries of the fire footprint in landscapes with equable moisture. In many parts of the country—other than the drylands—streams, small swamps, and moist ravines divide the landscape into discernable natural fire compartments. Fire frequency, defined this way, is the most unambiguous term.

The Heinselman approach was a first attempt to provide a measure that could be used to compare fire frequency between different areas. Today, on many sites, we have 30 or more years of fire data, spatially mapped on GIS systems, as well as a growing repository of historical fire frequency in the national database represented in the International Multi-Proxy Database (IMPD) and in LANDFIRE as discussed in the lines of evidence earlier. Given that we now have far more data access—in the form of broad-brush maps (Frost 1998; Guyette et al. 2012), the IMPD, LANDFIRE, and fine-scale mapping (Frost et al. 2013), we may now focus on actual fire frequency—historical as well as modern.

It is time to honor Reed's (2006) call for abandoning the pernicious term "fire rotations" for good or to redefine it for use in case c above. Further, we should be careful with the generic term "fire cycle," always defining what we mean.

Plan to Burn the Most Ecologically Important Sites First

The best plans for prescriptive fire or fire use, where fire dependent species remain, would give such sites priority over any other uses of fire. Using the best available knowledge and with advice from regional fire, plant, and wildlife ecologists, we can choose the best historical and existing sites for active restoration and reintroduction of fire dependent grasses and forbs. While largely irrelevant for the vast working landscapes of farms, ranches, and commercial timberlands, restoring fire integrity to our protected natural lands is our only hope for avoiding loss of perhaps half of total species diversity in the United States in the impending mass extinction of the next few decades.

Poster Children

As a holding action, perhaps the most important step we can take as managers on every piece of public natural land or private preserve is to fully restore fire integrity to one or more of the sites with the highest historical fire frequency, or "exemplary sites." In most cases these would have been the sites with the highest diversity of birds, plants, and animals. With rare exceptions such sites will require reintroducing species extirpated by fire suppression and other past human disturbance and adjusting range boundaries for climate change. Reintroductions require assembling the best onsite knowledge plus expertise from regional ecologists and State heritage programs.

Such a site, made accessible to visitors, is like opening the index for a book, an index of what we are trying to achieve. Seeing is believing; be it a prairie, savanna, or forest with a grassy understory, frequent fire communities are always beautiful. Increasingly rare, an exemplary site creates a window on the natural world. Nothing is more likely to build public support for fire as a sustainer of the web of life.

The Pendulum

The pendulum of funding for conservation has gone through historical swings. Pressures from diverse sources are building and the present aberration will not last. Funding for natural resources and the environment, Budget Function 300, has declined from about 2.4 percent of the national budget in 1977 to less than half, about 1.21 percent today (CBO 2017), at the same time that environmental needs, unprecedented in the history of civilization, have risen. Many forces are building to bring funding back to rational levels. As with censorship of science and climate change, public awareness of the equivalent crisis, mass extinction, will emerge as more species vanish and the lid on media news about environmental crises lifts.

In surveys, some 70 percent of Americans consistently consider themselves conservationists. This includes groups ranging from hunter conservationists to People for the Ethical Treatment of Animals (PETA). In a recent survey of 5,550 adults, those who said that we need to increase the number of programs available for Americans to enjoy nature, the outdoors, and wildlife included respondents of whom 71 percent self-identified as conservatives and 81 percent as liberals. Measured by political affiliation, these represented 74 percent of Republicans and 81 percent of Democrats (Kellert 2017). Only 3.2 percent of all adults think these sorts of programs are overfunded. The disconnect between attitudes of the people and actions of government is striking.

In a second, encouraging, survey, younger adults are more likely (59 percent versus 35 percent of all Americans) to have taken some action to help stop the Federal government from reducing environmental protections or wildlife conservation (PGAV 2017). This survey among adults in the United States aged 18 or more, was weighted to ensure national representation across gender, region, education, income, and race or ethnicity. Both surveys suggest support for an impending swing of the funding pendulum and the future of conservation.

As the current political aberration plays out, a multitude of new careers in conservation are emerging and unrelenting land development and extinction pressure will require massive new funding in the next two decades. Our most promising action for now must lie in effective new holding actions, laying the groundwork and preparing to move when new funding appears.

CONCLUSIONS

Since the fate of perhaps half of plant species, as well as the animals that depend on them for food and habitat in the United States, requires returning fire to the First Domain, restoring fire integrity deserves to be a crucial conservation mission on a par with climate change.

History will little care nor long remember how many fires we fought or how many buildings we saved. What history will record is this era of holding actions, and the resolute and undaunted actions of those who advanced the field of fire ecology, from its very fundamentals to restoring windows on the natural world—places of beauty and species diversity, bringing the great sustaining process that is natural fire back to protected lands regardless of adversities. History will mark the turning point where we began to restore the natural processes of fire, along with its interactions with the dynamic balance of predation and herbivory, to the dedicated natural landscape. As all the remaining unprotected lands of the Earth are converted to human uses in this, the last generation of unmanaged nature, the magnitude of this gift of fire-maintained habitats with their thousands of species of birds, plants, and animals will resonate with all future generations.

REFERENCES

Agee, James K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 76 p.

Bailey, Andrew D.; Mickler, Robert; Frost, Cecil. 2007. Presettlement fire regime and vegetation mapping in southeastern Coastal Plain forest ecosystems. In: Butler, Brett W.; Cook, Wayne, comps. The fire environment—Innovations, management, and policy. Conference proceedings; 2007 March 26–30; Destin, FL. Proceedings RMRS-P-46. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 1–11.

Botkin, Daniel B. 1990. Discordant harmonies: A new ecology for the twenty-first century. New York: Oxford University Press. 256 p.

Congressional Budget Office [CBO]. 2017. Budget Function 300, Natural Resources and the Environment. Washington, DC: House Budget Committee. 6 p.

Dieterich, John H. 1980. The composite fire interval—A tool for more accurate interpretation of fire history. In: Stokes, Marvin A.; Dieterich, John H., tech. coords. Proceedings of the fire history workshop; 1980 October 20–24; Tucson, AZ. Gen. Tech. Rep. RM-81. Fort Collins, CO: U.S. Department of Agriculture, Rocky Mountain Forest and Range Experiment Station: 8–14.

Fleischner, Thomas L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology. 8: 629–644.

Frost, Cecil. 2006. History and future of the longleaf pine ecosystem. In: Jose, Shibu; Jokela, Eric J.; Miller, Deborah L., eds. The longleaf pine ecosystem: Ecology, silviculture, and restoration. Springer Series on Environmental Management. New York: Springer-Verlag: 9–48.

Frost, Cecil C. 1998. Presettlement fire frequency regimes of the United States: A first approximation. In: Pruden, Theresa L.; Brennan, Leonard A., eds. Fire in ecosystem management: Shifting the paradigm from suppression to prescription; 1996 May 7–10; Boise, ID. Tall Timbers Fire Ecology Conference Proceedings, No. 20. Tallahassee, FL: Tall Timbers Research Station: 70–81.

Frost, Cecil C. 2000. Studies in landscape fire ecology and presettlement vegetation of the southeastern United States. Chapel Hill, NC: University of North Carolina. Dissertation. 620 p.

Frost, Cecil C.; Burton, Jesse A.; Scoggins, Lillian. 2013. Historic fire regimes and presettlement vegetation of Mammoth Cave National Park. Report to the National Park Service, Mammoth Cave, Kentucky. [With 2 GIS maps]. 117 p.

Fuhlendorf, Samuel D.; Engle, David M. 2001. Restoring heterogeneity on rangelands: Ecosystem management based on evolutionary grazing patterns. BioScience. 51: 625–632.

Fuhlendorf, Samuel D.; Engle, David M.; Elmore, R. Dwayne; [et al.]. 2012. Conservation of pattern and process: Developing an alternative paradigm of rangeland management. Rangeland Ecology and Management. 65: 579–589.

Fuhlendorf, Samuel D.; Harrell, Wade C.; Engle, David M.; [et al.]. 2006. Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. Ecological Applications. 16: 1706–1716.

Glitzenstein, Jeffrey S.; Streng, Donna R.; Wade, Dale D. 2003. Fire frequency effects on longleaf pine (*Pinus palustris* P. Miller) vegetation in South Carolina and northeast Florida. Natural Areas Journal. 23: 22–37.

Guyette, Richard P.; Stambaugh, Michael C.; Dey, Daniel C.; Muzika, Rose-Marie. 2012. Predicting fire frequency with chemistry and climate. Ecosystems. 15: 322–335.

Heinselman, Miron L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quaternary Research. 3: 329–382.

Huffman, Jean M.; Rother, Monica T. 2017. Dendrochronological field methods for fire history in pine ecosystems of the southeastern Coastal Plain. Tree-Ring Research. 73: 42–46.

Kellert, Stephen R. 2017. The nature of Americans: Disconnection and recommendations for reconnection. National report. 363 p. Available at https://natureofamericans.org/research. [Accessed 2019 June 12].

LANDFIRE. 2018. Historical fire regimes. Mean Fire Return Interval layer. U.S. Department of Agriculture and U.S. Department of the Interior. https://landfire.gov/mfri.php.

Larson, Gary E.; Johnson, James R. 1999. Plants of the Black Hills and Bear Lodge Mountains. Pub. B732. Brookings, SD: South Dakota Agricultural Experiment Station. 608 p.

Noss, Reed F. 2013. Forgotten grasslands of the South. Washington, DC: Island Press. 317 p.

Nowacki, Gregory J.; Abrams, Marc D. 2008. The demise of fire and the "mesophication" of forests in the eastern United States. BioScience. 58: 123–138.

Nuttle, Tim; Royo, Alejandro A.; Adams, Mary Beth; Carson, Walter P. 2013. Historic disturbance regimes promote tree diversity only under low browsing regimes in eastern deciduous forest. Ecological Monographs. 83: 3–17.

PGAV Destinations & H2R Market Research. 2017. Communicating conservation, results of a survey. Available at https://blooloop.com/news/understanding-publics-trust-zoos-aquariums/. [Accessed 2019 June 12].

Reed, William J. 2006. A note on fire frequency concepts and definitions. Canadian Journal of Forest Research. 36: 1884–1888.

Schmitz, Oswald J. 2016. The New Ecology. Princeton, NJ: Princeton University Press. 256 p.

Stambaugh, Michael C.; Guyette, Richard P.; Marschall, J.M. 2011. Longleaf pine (*Pinus palustris* Mill.) fire scars reveal new details of a frequent fire regime. Journal of Vegetation Science. 22: 1094–1104.

World Database on Protected Areas. 2015. United States of America, North America. United Nations Environment Programme. https://en.wikipedia.org/wiki/Protected_areas_of_the_United_States. [Accessed 2015 May 2].

*k*NN vs. SVM: A Comparison of Algorithms

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Abstract—Support Vector Machines (SVM) and *k*-Nearest Neighbor (*k*NN) are two common machine learning algorithms. Used for classifying images, the *k*NN and SVM each have strengths and weaknesses. When classifying an image, the SVM creates a hyperplane, dividing the input space between classes and classifying based upon which side of the hyperplane an unclassified object lands when placed in the input space. The *k*NN uses a system of voting to determine which class an unclassified object belongs to, considering the class of the nearest neighbors in the decision space. The SVM is extremely fast, classifying 12 megapixel aerial images in roughly ten seconds as opposed to the *k*NN which takes anywhere from forty to fifty seconds to classify the same image. When classifying, the *k*NN will generally classify accurately; however, it generates several small misclassifications that interfere with final classified image that is outputted. In comparison, the SVM will occasionally misclassify a large object that rarely interferes with the final classified image. While both algorithms yield positive results regarding the accuracy in which they classify the images, the SVM provides significantly better classification accuracy and classification speed than the *k*NN.

Keywords: *k*-nearest neighbor, support vector machine, remote sensing, small unmanned aircraft system, burn extent, biomass consumption

INTRODUCTION

This paper explores whether a SVM or *k*NN classifier provides higher accuracy when mapping effects with very high spatial resolution using small unmanned aircraft system (sUAS) imagery. Support Vector Machine (SVM) and *k*-Nearest Neighbor (*k*NN) are two machine learning algorithms mentioned in the literature that outperformed other algorithms (Yang and Liu 1999) (Zhang and Ma 2008) when mapping wildland fire effects on low resolution satellite imagery (Brewer et al. 2005) (Zammit et al. 2006) (Liu et al. 2006). This study compares the classification accuracy of the two algorithms when mapping wildland fire post-fire effects with very high spatial resolution imagery acquired with a sUAS.

Wildlands provide habitat for around 6.5 million species according to the United Nations Environment Program (Mora et al. 2011). In the United States and elsewhere, wildlands provide resources for energy and material in addition to offering recreational and spiritual opportunities for humans. Wildlands also provide irreplaceable ecosystem services including clean water, nutrient cycling and pollination, in addition to habitat for millions of animals. Large expanses of the wildlands in the U.S. have evolved with fire and depend on periodic wildfires for health and regeneration (Aplet and Wilmer 2010).

Decades of fire suppression have led to the current departure of wildlands from the fire return interval characteristically experienced prior to European settlement. As a result, wildlands in the western U.S. are experiencing a much higher incidence of catastrophic fires (Wildland Fire Leadership Council 2015). Fire impacts millions of hectares of

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

American wildlands each year, with suppression costs approaching two billion dollars annually (National Interagency Fire Center 2018) (Zhou et al. 2005). High intensity wildland fires contribute to post fire erosion, soil loss, flooding events and loss of timber resources. This results in negative impacts on human communities, wildlife habitat, ecosystem resilience, and recreational opportunities. Additionally, wildland fires across the U.S. claim more lives than any other type of natural disaster, resulting in the loss of ten to twenty firefighters per year (Zhou et al. 2005).

Effective management of wildfire and prescribed fires is a critical dimension of maintaining healthy and sustainable wildlands. A quantitative understanding of the relationships between fuel, fire behavior, and the effects on human development and ecosystems can help land managers develop nimble solutions to U.S. wildfire problems. Remotely sensed imagery is commonly collected to assist in assessing the impact of the fire on the ecosystem (Eidenshink et al. 2007). The knowledge gained from remotely sensed data enables land managers to better understand the effects a fire has had on the landscape and develop a more effective management response facilitating ecosystem recovery and resiliency.

Burn Severity and Extent

The term "wildland fire severity" can refer to many different effects observed through a fire cycle, from how intense an active fire is burning, to the response of the ecosystem to the fire over the subsequent years. This study investigates direct or immediate effects of a fire such as biomass consumption as observed in the days and weeks after the fire is contained (Keeley 2009). Therefore, this study defines burn severity as the measurement of biomass (or fuel) consumption (Key and Benson 2006).

Identification of burned area extent within an image can be achieved by exploiting the spectral separability between burned organic material (black ash and white ash) and unburned vegetation (Hamilton et al. 2017; Lentile et al. 2006). Classifying burn severity can be achieved by separating pixels with black ash (low fuel consumption) from white ash (more complete fuel consumption), relying on the distinct spectral signatures between the two types of ash (Hudak et al. 2013). In forested biomes, low severity fires can also be identified by looking for patches of unburned vegetation within the extent of the fire. If a patch is comprised only of tree crowns, the analysis can infer that the vegetation is a tree which the fire passed under, and classify the pixels as low intensity surface fire (Scott and Reinhardt 2001). If the patch of vegetation contains herbaceous or brush species, then the patch is actually an unburned island within the burned area and can be classified as unburned.

Utilization of sUAS for Image Acquisition

An unmanned aircraft system (UAS) is an aircraft that is not controlled by a pilot on board the aircraft (Calkins 2017). A UAS may either be controlled by a pilot on the ground or by an autonomous flight control systems that executes a previously designated flight path. New advances in small UAS (sUAS) capabilities enable the acquisition of imagery with a spatial resolution of centimeters and temporal resolution of minutes (Laliberte et al. 2010). This hyperspatial imagery, which enables objects to be represented in the image by multiple pixels (Sridharan and Qiu 2013), results in a huge increase in the quantity of data associated with a scene. When sUAS are used for remote sensing, a set of images are taken through the course of a flight. Photogrammetry software such as Pix4D is used to stitch the set of images into a single image or orthomosaic in which perspective distortions from multiple images are resolved (Küng et al. 2011). Additionally, the photogrammetry software uses the latitude and longitude embedded in the image by the global navigation satellite system (GNSS) receiver onboard the sUAS to georeference the orthomosaic, enabling a geographic information system (GIS) to be able to identify the physical location of every object within the georeferenced orthomosaic (Rosnell and Honkavaara 2012).

Mapping Wildland Fire Effects with sUAS

Fire ecology enables managers to study temporary environmental changes by accounting for the pronounced change that wildland fire effects on an ecosystem. The emerging field of ecoinformatics promises to provide the methodologies and tools needed to acquire, analyze, and manage the growing amounts of complex ecological data available from the immense volume of data available in hyperspatial sUAS imagery. The combination of sUAS and ecoinformatics provides increasing amounts of actionable knowledge regarding wildfire management.

In order to fully utilize high resolution imagery to effectively map burn severity, it is necessary to identify black ash, white ash, surface vegetation and canopy vegetation within hyperspatial orthomosaics generated from imagery captured with sUAS. Toward this end, machine learning and image processing tools were developed which facilitate pixel-based identification of these classes of interest for mapping burn severity from hyperspatial imagery.

ALGORITHM COMPARISON: SVM VERSUS *K*NN

The recent advances in small unmanned aircraft systems (sUAS) technology promise to provide wide availability of hyperspatial imagery to users who previously did not have the ability to generate remotely sensed imagery on their own. The copious amounts of easily obtained data resulting from the acquisition of hyperspatial imagery warrant investigation into development of methods, analytic tools and metrics which enable the extraction of information and knowledge from imagery captured at much higher resolution than was previously possible. The affordability of sUAS is facilitating the dissemination of knowledge previously unattainable from lower resolution data. This paper describes a study investigating which of two machine learning algorithms—a Support Vector Machine (SVM) or *k*-Nearest Neighbor (*k*NN)—will enable mapping of burn severity with higher accuracy (Han et al. 2012; Russell and Norvig 2010).

Support Vector Machine

When classifying an image, the SVM creates a hyperplane, dividing the input space between classes, classifying based upon which side of the hyperplane an unclassified object lands when placed in the input space. The algorithm performs a pixel-based classification, labeling each pixel in the image with the postfire effects class determined by the classifier. SVM classifiers have been successfully used for image classification, including for mapping burn severity from medium resolution satellite imagery (Zammit et al. 2006) (Zhang and Ma 2008) (Liu et al. 2006) (Salimi et al. 2017). Hyperspatial imagery is defined as having a spatial resolution less than one decimeter (Hamilton, 2018). Classification starts with the training of an SVM via user-generated training data.

Training of an SVM starts with the labeling of regions in the image based on user observation of the pixels within the region. When classifying burn extent, user selected training pixels are labeled as to whether they burned or not. For training the SVM for mapping biomass consumption, or the reduction of vegetative fuels, the user labels pixels as to whether they represented black ash indicative of incomplete combustion or white ash resulting from more complete combustion.

As each training pixel is loaded from an image, the pixel values for the red, green and blue bands are placed into elements in a vector, producing a three-dimensional feature space. If necessary, any additional data for the pixel, such as texture, is included into an additional element on the vector. Assuming a binary classification, the vector is labeled with one of two classes, either +1 or -1. Each of the training pixels is placed onto an array X. The class labels for each training pixel are placed into corresponding elements of a parallel array Y. Training the SVM involves identifying a decision boundary, which separates the sets of training pixels on X. The SVM computes this class decision boundary as a hyperplane (Han et al. 2012). Two-dimensional data will be separated by a hyperplane which is shown as a line, as shown in figure 1. As the dimensionality of the data increases to three, the separating hyperplane is represented as a plane. Additional increases in data dimensionality results in separating hyperplanes that are one less dimension than the data. Unfortunately, simply selecting a separating hyperplane may not generalize well, with some candidate hyperplanes lying close to some of the training vectors (fig. 1).

SVM generalizability is improved, reducing the probability of misclassifications, by identifying the optimal separating hyperplane, which is the separating hyperplane that is the furthest from any training vectors, while still correctly separating the training vectors. Twice the distance from the hyperplane to the

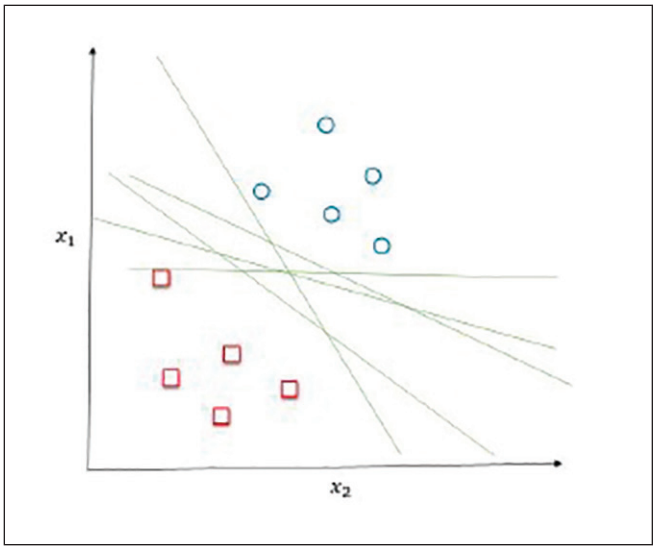

Figure 1–Hyperplanes (shown as green lines) separating classes represented by blue circles and red squares. X_1 and X_2 represent the two dimensions represented in the SVM.

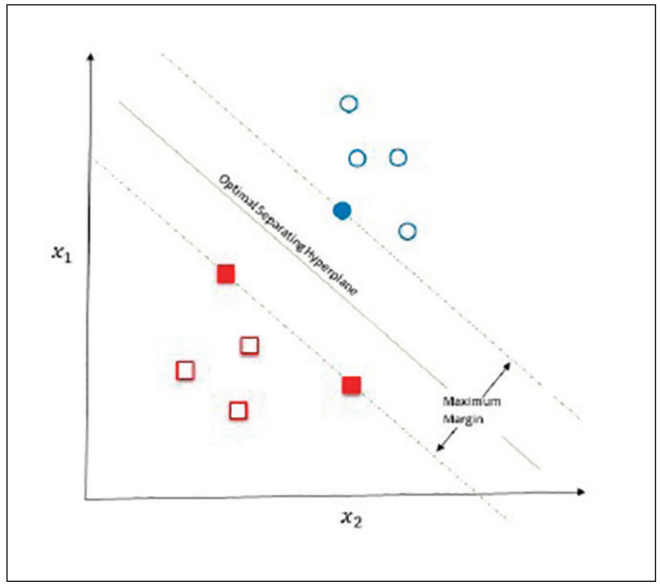

Figure 2–Support Vector Machine showing linearly separating hyperplane. The support vectors shown as solid shapes define the maximal separating margin between the two classes.

nearest training vector is referred to as the margin. The optimal separating hyperplane contains the maximum margin between training vectors of the two classes, resulting in the greatest separation between the classes. Some texts refer to the optimal separating hyperplane as the maximum margin hyperplane in reference to it having the maximum margin (Han et al. 2012). The hyperplanes that are found at the edges of the margin are parallel to the optimal separating hyperplane. The training vectors that lie on the hyperplanes on the margin edges are the support vectors, shown as the solid squares and circles as shown in figure 2. These support vectors on the edge of the optimal hyperplane margin support the placement of the optimal hyperplane. Once the optimal hyperplane has been located, none of the training vectors other than the support vectors need to be retained. SVM is a parametric model due to the need to retain the training vectors which comprise the support vectors. While it's possible that all the training vectors would need to be retained, in practice only a small number of training vectors need to be retained as support vectors, sometimes a small constant times the number of dimensions (Russell and Norviq 2010) (Hamilton, 2018).

Once the optimal hyperplane is located, pixels with unknown class are placed into a vector within the decision space, after which the pixel's class can be determined by calculating which side of the optimal hyperplane the vector lies on. Assuming there exists an optimal hyperplane that completely separates both sets of vectors on X, the classes of data are linearly separable. If the data is nearly linearly separable, with a small number of training pixels being outliers, it is possible to separate the data by allowing a minimal amount of error, resulting in the establishment of a soft margin (Russell and Norvig 2010).

Determination of Optimal Hyperplane Placement

Determining the location of the optimal separating hyperplane and maximizing the margin is an optimization problem for which there are multiple solutions. Separating hyperplanes in an SVM are defined by the equation:

$$\boldsymbol{W} \cdot \boldsymbol{X} + b = 0 \qquad (1)$$

where $\boldsymbol{W}$ is a weight vector, namely $\boldsymbol{W} = \{ w_1, w_2, \dots w_n\}$; with n is the dimensionality of the decision space (e.g. for a color image, $n = 3$), b is the intercept (Russell and Norviq 2010) or bias (Han et al. 2012) and $\boldsymbol{X}$ is the set of support vectors.

The optimal separating hyperplane can be found by searching the decision space for $\boldsymbol{W}$ and b using gradient descent optimization, searching for parameters that maximize the margin while correctly classifying the training vectors (Russell and Norviq 2010). Alternately, Equation 1 can be rewritten in an alternative dual representation as:

$$argmax_{\propto} \sum_j \alpha_j - \frac{1}{2}\sum_{j,k} \alpha_j \alpha_k y_j y_k (\boldsymbol{x}_j \cdot \boldsymbol{x}_k) \qquad (2)$$

subject to the constraints $\alpha_j \geq 0$ and $\Sigma_j \alpha_j y_j = 0$ where α_j are Lagrangian multipliers. Equation 2 is a constrained convex quadratic equation for which there are software packages that can determine an optimal solution. (Han et al. 2012) (Russell and Norviq 2010). Once the vector α has been calculated, we can derive $\boldsymbol{W}$ from Equation 1 with $\boldsymbol{W} = \Sigma_j \alpha_j x_j$. Because Equation 2 is convex, there is a single global maximum. Additionally, the weights αj associated with each of the training vectors are zero except for the support vectors, which are closest to the optimal separating hyperplane (Russell and Norviq 2010).

Recalling that the class labels associated are represented as +1 and -1, the weight vector $\boldsymbol{W}$ can be adjusted so the hyperplanes on the edges of the margin (which are parallel to the optimal separating hyperplane) are

$$H_a : \mathbf{W} \cdot \mathbf{X}_i + b \geq 1 \text{ for } Y_i = +1 \qquad (3)$$

and

$$H_b : \mathbf{W} \cdot \mathbf{X}_i + b \leq 1 \text{ for } Y_i = +1 \qquad (4)$$

Any training vector on or above H_a belongs to class +1 while any training vector that falls on or below H_b will belong to class -1. Combining Equations 3 and 4 results in

$$Y_i (\mathbf{W} \cdot \mathbf{X}_i + b) \geq 1, \forall I \qquad (5)$$

Any training vectors that lie on either H_a or H_b are the support vectors, denoted in Figure 2 as solid circles and squares (Han et al. 2012).

The support vectors are easily identifiable once the vector $\boldsymbol{\alpha}$ has been calculated, being the subset for which the weights α_j are greater than 0. The optimal separating hyperplane is defined, tuples with unknown label can be labeled with the following equation:

$$h(\boldsymbol{x}) = \text{sign}(\Sigma_j \propto_j y_j (\boldsymbol{x} \cdot \mathbf{X}_j) - b) \qquad (6)$$

where $\boldsymbol{x}$ is a vector with unknown class. $h(\boldsymbol{x})$ will return either a class label of -1 or +1, the predicted class of $\boldsymbol{x}$. Only support vectors have $\boldsymbol{\alpha_j} > 0$, therefore the trained SVM can reduce runtime by restricting j so Equation 5 runs on support vectors (Russell and Norviq 2010).

Determining Hyperplane for Training Data That is Not Linearly Separable

The inability to locate an optimal separating hyperplane without error is an indicator that the classes of training vectors are not linearly separable. If the data is nearly linearly separable, with a small number of training pixels being outliers, it is possible to separate the data by allowing a minimal amount of error, resulting in the establishment of a soft margin (Russell and Norviq 2010). While optimizing the separating hyperplane, the individual vector error is calculated for each training vector that is falls on the wrong side of the hyperplane, labeled as ε_i, subject to $\varepsilon_i \geq 0, \forall i$. The misclassification error is the summation of all the individual vector errors for all of the training vectors, giving a misclassification error for the associated separating hyperplane. A parameter, referred to as C, is added allowing tuning of an SVM controlling the weight accorded to the misclassification error, resulting in the term of $C\ \Sigma_i\ \varepsilon_i$ being added to the margin width (Cortes and Vapnik 1995) as shown in Equation 7.

$$\text{argmax}^{\propto\, \Sigma_j \alpha_j - \frac{1}{2}\Sigma_{j,k} \propto_j \propto} (\boldsymbol{x}_j \cdot \boldsymbol{x}_k) + c\ \Sigma_i\ \varepsilon_i \qquad (7)$$

Both the misclassification error and margin width are optimized together, maximizing the margin while also minimizing misclassification error. The resulting decision function is an optimal separating hyperplane with a soft margin (Cortes and Vapnik 1995). Figure 3 shows an optimal separating hyperplane that best generalizes the decision boundary between linearly inseparable classes.

Data should only be mapped to a higher dimensional decision space if the data is not already linearly separable. Fortunately, it is simple to determine whether the training data is linearly separable. By running all the training data through a trained SVM, the training data is completely linearly separable if the SVM labels all the training pixels with the same label as specified by the user. In the event that the user and SVM labels are not in agreement for all the training pixels, it is possible to calculate the degree of linear separability of the training data as

$$\sigma = \frac{\textit{Correctly predicted support vectors}}{|x|} * 100 \qquad (8)$$

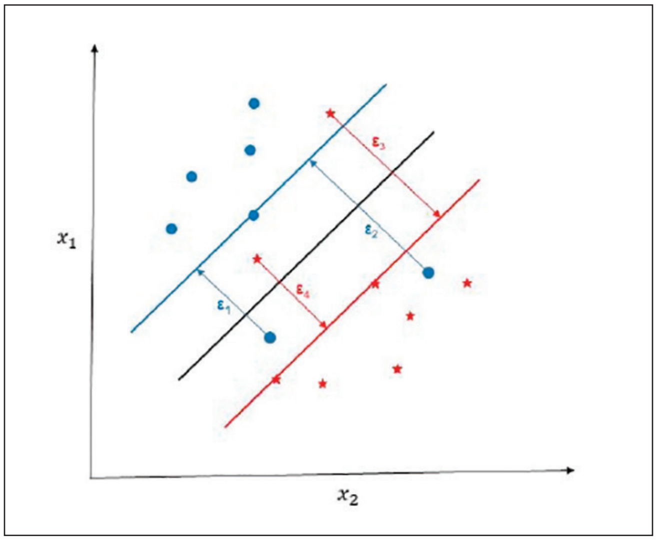

Figure 3–Optimal separating hyperplane defining decision boundary between linearly inseparable blue circles and red stars.

SVM Implementation

For this study, we used the SVM implementation that is available in OpenCV (OpenCV 2017), which used the LibSVM implementation which is very widely used by machine learning practitioners (Chang and Lin 2011). When users selected training pixels, it was common for there to be very small spatial spectral clusters of pixels in the training regions that did not match the class label assigned by the user. To compensate for this noise, the SVM used a soft margin when searching for the optimal separating hyperplane. Consideration was given to what value of C (defined in section 2.3) should be used while searching for the optimal separating hyperplane using a soft margin. Assessment of C allowed the determination of the most effective weight to be assessed for the error resulting from noisy training pixels. Additionally, we investigated the degree of linear separability of the training data in order to determine whether the original decision space was adequate for classification or if it was necessary to map the decision space to a higher dimensionality. In the situations where the original space was not adequately linearly separable, the RBF, Chi Squared and Histogram Intersection Kernels were evaluated.

k-Nearest Neighbor

The SVM is an eager learner, determining the decision boundary from the training data before considering any pixels with unknown class. Conversely, the k-Nearest Neighbor (kNN) is a lazy learner, just storing training pixels and waiting until it is given an unknown pixel before determining the decision criteria for the pixel.

*k*NN learns by analogy, comparing an unknown pixel to its most closely neighboring pixels in the decision space. Each pixel is described by n attributes, the proximity between pixels in the decision space being determined by the similarity between their attributes. Attribute similarity is defined in terms of a distance metric such as Euclidean distance. The Euclidean distance between points X_{j1}, $X_{j2}, \ldots X_{jn}$) and $\boldsymbol{X}_j = (X_{j1}, X_{j2}, \ldots X_{jn})$ is defined as

$$\text{Dist } (x_i x_j) = \sqrt{\Sigma_{k=1}^{n} \left(x_{ik} - x_{jk}{}^2\right)}. \tag{9}$$

*k*NN works best if the attributes are numeric values that have been normalized (Han et al. 2012). When working with pixels from a color image, each pixel has attributes for the red, green and blue bands. Each value represents the spectral reflectance recorded in the associated spectra for that pixel. Color images acquired with the digital cameras on board sUAS have radiometric resolution of 8 bits, resulting in integer values between 0 and 255. Normalized values are very important for not allowing one attribute to dominate the distance metric (Han et al. 2012).

Classifying an unknown pixel is conceptually simple for a *k*NN classifier. Once the unknown pixel is located in the decision space, the k nearest pixels in the decision space are located. The unknown pixel is assigned the most common class occurring between the nearest neighbors. If the *k*NN is performing a binary classification, the pixel is assigned based on a simple majority between the two classes of training pixels (Russell and Norviq 2010).

Tuning *k*

The selection of a value for k is very important when classifying with a *k*NN. As k is increased, the decision boundary is smoothed, resulting in increased generalization (Russell and Norviq 2010). Typically, k is selected through experimentation, iteratively running the classifier while increasing k, assessing classification accuracy at each iteration. The k value from the iteration resulting in the highest classification accuracy can be selected for use in that decision space (Han et al. 2012).

A related approach uses an iterative n-fold cross-validation using a single set of training pixels for both training and assessing accuracy for each value of k evaluated.

Implementation of the *k*NN Algorithm

An investigation of the OpenCV *k*NN implementation (OpenCV 2017) found that it was not capable of achieving the runtime efficiency required for this project. The classification of a 12 MP sUAS image was found to take about 10 minutes with the *k*NN. Image acquisition over a burned area that is hundreds of hectares in size was found to require multiple flights by a sUAS, with hundreds of photos taken. The largest orthomosaic created as part of this study exceeded two gigapixels (2,000 MP) in size. Classification of that orthomosaic with the OpenCV implementation of the *k*NN would have required ten hours. Consequently, a *k*NN was built around a customized n-D tree. Run time optimizations on the *k*NN were achieved by:

1. Pruning the tree so that training pixels with identical attributes were stored on a single node, which tracked how many training pixels existed with those attributes.
2. Balancing the tree once all the training pixels were loaded.
3. Implementing a recursion-less search of the tree for classifying unknown pixels.
4. Parallelizing classification of pixels with unknown class.

These customizations were successful in reducing classification runtime, resulting in a reduction of the time required to classify a 12MP image from 10 minutes with the OpenCV *k*NN implementation to 14 seconds with the custom *k*NN implementation computer with a dual-core CPU, a 42-fold decrease in runtime. Running the *k*NN on a server with even more physical cores will result in an even larger decrease in time required for classification due to the speedup resulting from dividing the classification of unknown pixels between even more processors (Cormen 2009).

Algorithm Comparison Hypothesis

In testing whether an SVM or *k*NN classifier can map wildland post-fire effects more accurately, a null hypothesis (H_0) was specified along with an associated alternate hypothesis (H_1). If H_0 was rejected, then H_1 would be accepted in its place. For this experiment, the independent variable was the algorithm selection between SVM and *k*NN. The dependent variable was burn severity mapping accuracy. The null and alternate hypotheses were:

H_0: Support Vector Machines and *k*NN have equal accuracy when mapping burn severity classes using hyperspatial color imagery.

H_1: Support Vector Machines have different accuracy than *k*NN when mapping burn severity classes using hyperspatial color imagery.

H_0 was tested by comparing algorithm accuracy, which was calculated from confusion matrices generated by validating an image classification by each of the algorithms against user labeled pixels. A two-tailed Student's t-test established the statistical significance of the accuracy results on the difference in accuracy between the SVM and *k*NN classifications. A p-value below a significance level of 0.05 rejected H0 in favor of H_1 which established that the mean accuracy of the SVM is different from the *k*NN. Once H_0 was rejected in favor of H_1 , the more accurate algorithm was identified by selecting the algorithm that was found to have the highest accuracy results. The statistical analysis was again conducted with a single-tailed Student's t-test establishing the statistical significance of the accuracy results from the classifier with the higher accuracy against the classifier with the lower accuracy as shown in Algorithm 1.

```
For each burn image
        classify with SVM & kNN
        calculate accuracy (SVM & kNN)
                AE = (TBu +TU) / px
                AT = (TBl + TW) / Bu

For {AE, AT}      //Extent and AshType Accuracy
        t-test ← SVM vs kNN accuracies
```

Algorithm 1–SVM vs *k*NN experiment workflow. A = accuracy, E = extent, T = true, Bu = burned, U = unburned, px = pixels, Bl = black ash and W = white ash, A_E = extent accuracy and A_T = ash type (black vs. white) accuracy.

Algorithm Comparison Experiment Methodology

In order to assess the accuracy of both the SVM and *k*NN for mapping burn extent and biomass consumption, a set of orthomosaics acquired with sUAS over fires across the Boise National Forest (BNF) and Bureau of Land Management—Boise District (BLM-B) were hierarchically classified using both SVM and *k*NN classifiers. The first stage classified on burn extent, segmenting the image into burned and unburned regions. The second stage classified the burned regions of the image by black ash (indicative of partial combustion) versus white ash (indicative of more complete combustion).

Creation of Training Data

Training pixels were selected from post-fire imagery acquired with a sUAS over burned areas across the BNF and BLM-B. Training pixels were selected by the user identifying regions in the image which consisted of a set of homogeneous pixels, for which the user provided a class label. This process was aided by the Training Data Selector (TDS), a graphic tool developed through this research effort which assisted the user in identifying, selecting and labeling homogeneous regions of the image. Figure 4 shows an example of user labeled regions from the TDS denoting burn extent, where pixels in the green polygons are unburned pixels and red polygons denote black ash pixels. Figure 5 shows user labeled regions denoting burn severity, where pixels in the

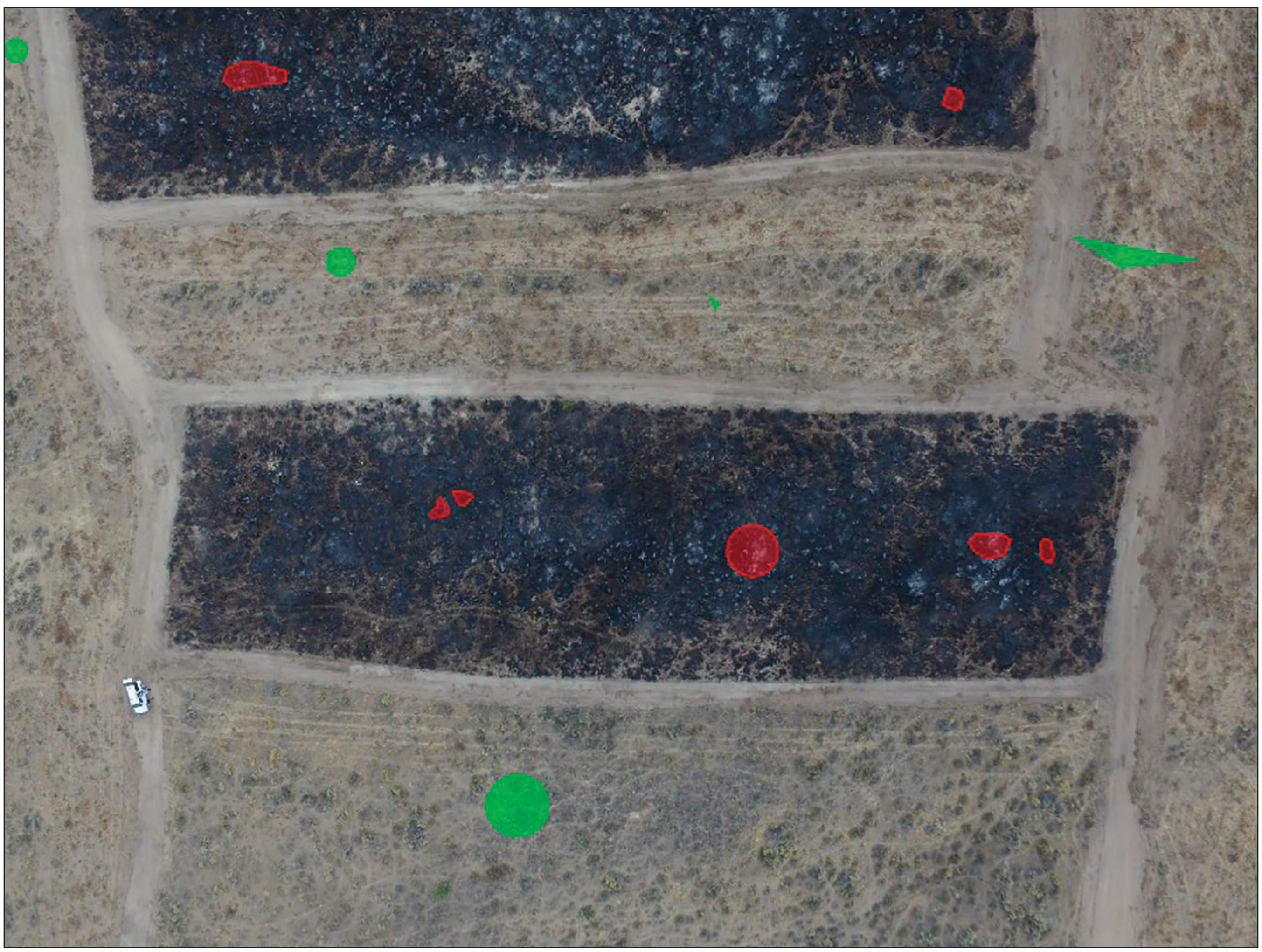

Figure 4–Training pixel regions for training burn extent as denoted by the user using the Training Data Selector. Green polygons are unburned pixels, red polygons denote black ash pixels.

blue polygons are labeled as white ash while the red polygons denote black ash.

When designating training regions in the image, it was advantageous to have approximately the same number of training pixels in each of the classes in order to ensure that the training data contained balanced amounts of both classes, which resulted in more accurate classifications. This criterion applied more to the *k*NN than the SVM, but since we were using the same training regions for both classifiers, the training data had to accommodate the implementations of both algorithms. It was also discovered that restricting the size of the training sets to under 1,000 pixels assisted the implementations of both algorithms in not over fitting the decision boundary to the data, providing for greater generalization. In order to allow the training regions to cover an adequate range of variability within a class, the TDS provided the user with the ability to select a sampling of pixels within a region. When the training pixels were extracted from the regions, only a user specified percentage of the pixels in the regions were placed in the training pixel set and labeled with the user specified class for the associated training region. Typically, when extracting pixels from a training region, only one to two percent of the pixels within the training regions were retained in the training sets by the TDS. This subsampling of the training regions provided for adequate representation of the variation within the training region while reducing the size of the training data.

Image Classification With SVM and *k*NN

The objective of classifying a post-fire image is to determine the extent of the burn as well as the level of biomass consumption within the burned area. To achieve that end, the image was first classified into burned and unburned regions. The classification of burn extent was facilitated by the spectral separability between burned and unburned vegetation as demonstrated previously in this research effort (Hamilton et al. 2017). Toward that end, the user selected burned and unburned regions within the training image using the TDS (fig. 5). Pixels within these regions were used for training the classifiers. The image was then classified into burned and unburned training pixels by either SVM or the *k*NN. With both classifiers, iterative 5-fold cross-validation (Han et al. 2012) was used to determine the optimal classifier parameter values as shown in table 1. Once the image was classified into burned and unburned pixels, a size filter was applied to the classified output using image processing morphological functions including dilation,

Figure 5–Training pixel regions classifying biomass consumption as denoted by the user using the Training Data Selector. Blue polygons are white ash, red polygons denote black ash.

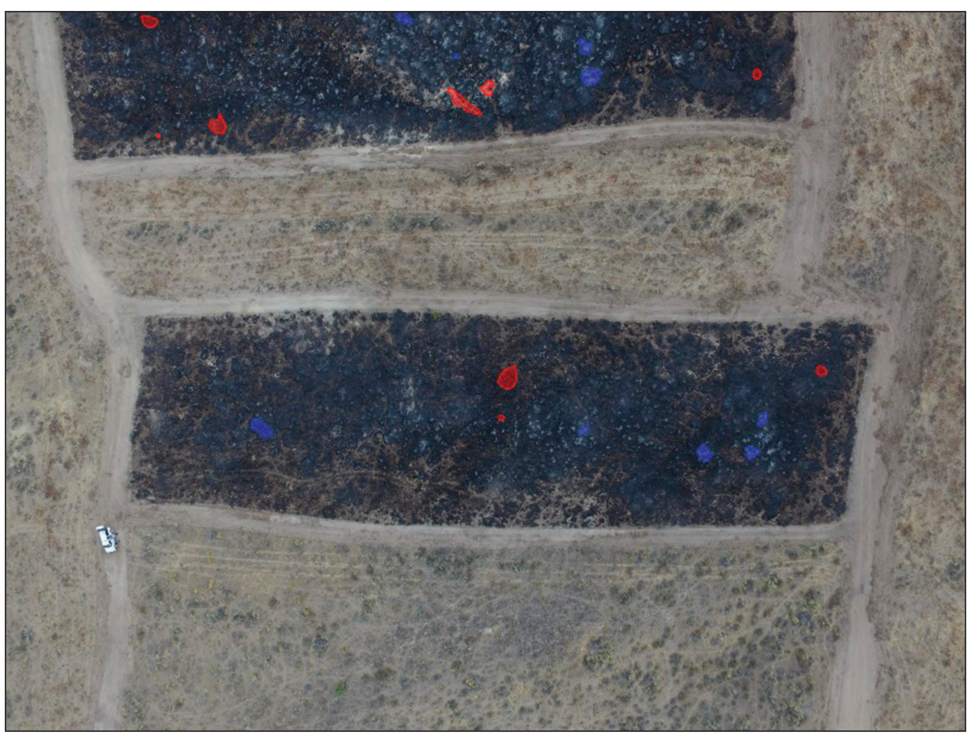

Table 1—Optimal classifier parameter values.

Algorithm	Parameter	Classification type	Optimal value
SVM	Kernel	Burn extent	None (linear)
		Ash type	None (linear)
	C	Burn extent	0.1
		Ash type	0.1
*k*NN	*k*	Burn extent	3
		Ash type	3

erosion and the detection of very small connected components (Gonzalez and Woods 2008). Dilation is the process of gradually enlarging the boundaries of foreground pixels, while erosion has the opposite effect of eroding the boundaries of foreground pixels. These functions were used to remove spatial clusters of homogeneous pixels that were sub-object in size, filtering out clusters of pixels that are smaller than the objects being classified. For example, clusters of unburned vegetation smaller than a sagebrush that were surrounded by burned vegetation were merged into the surrounding black ash class. These misclassified clusters were commonly caused by small patches of herbaceous vegetation that were too sparse to carry adequate fire, or to adequately produce enough charred vegetation to be detected. In unburned regions of the image, misclassifications were commonly caused by shadows. (Misclassifications due to shadows were found to be reduced by conducting image acquisition flights as close to solar noon as possible, or by flying on cloudy days and slowing the shutter speed.) The size filter was also found to smooth the boundary between the burned and unburned classes in the classified image.

After cleaning the burn extent classification, the image was hierarchically classified with the burned region classified by biomass consumption using a binary classification between white ash (high consumption) and black ash (low consumption) using training pixels created as described above. An iterative five-fold cross validation was used to determine the optimal classifier parameter values as shown in table 1.

Validation of Classified Output

Accuracy was assessed on each of the classification types (burn extent, ash type and vegetation type) for both the SVM and *k*NN. Validation regions were created for each classification type in the same way as the training data was selected. The resulting validation pixel sets were loaded into a tool that compared the user specified class against the class predicted by the classifier, creating a confusion matrix (Han et al. 2012). Accuracy was calculated from the confusion matrix as discussed in Section 2.8.

Establishment of Statistical Significance

Statistical significance was assessed between the SVM and *k*NN classification accuracy results using the Student t-test as described in Section 2.8. H_0 states that there is not a difference in the accuracy with which the fire effects land cover classes can be classified using either SVM or *k*NN. Since we are using a hierarchical classification, we assessed the difference between accuracy results for the two algorithms with each of the classification types. This allowed us to have a finer scale assessment, allowing us to evaluate the difference in accuracy for both algorithms with each classification type. The two-tailed t-test p-value for a classification type fell below the previously stated significance level of 0.05, so we rejected H_0 (no difference in classification accuracy) in favor of H_1 (there is a difference in classification accuracy). We accepted the alternate hypothesis that one algorithm results in a more accurate classification, so a one-tailed t-test with a significance level below 0.05 was used to determine which algorithm was more accurate. Results of the algorithm comparison experiment are shown in the next section.

ALGORITHM COMPARISON

Assessment of the benefits of mapping wildland fire post-fire effects using Support Vector Machine (SVM) versus *k*-Nearest Neighbor (*k*NN) classifiers was accomplished by training an SVM and *k*NN with the same training regions, then classifying on the same post-burn orthomosaic, allowing for the comparison between classification outputs from both algorithms from a common training set. The assessment of both algorithms was explored over a set of burn orthomosaics from 16 fires, the results of which were tested with a two-tailed t-test. The resulting p-values fell below the significance level, thus rejecting the null hypothesis that mean accuracy was the same for both algorithms in favor of the alternate hypothesis that the algorithms classify burn extent and biomass consumption with different accuracies. An observation of the SVM and *k*NN results showed that the SVM had a higher mean accuracy for both burn extent and biomass consumption. A one-tailed, paired t-test was then conducted to establish the statistical significance of the accuracy results to show that burn extent and biomass consumption can be classified with higher accuracy using the SVM algorithm.

Algorithm Comparison Accuracy Results

Evaluation of the capability with which the SVM and *k*NN were able to classify burn extent and biomass consumption was accomplished by assessing the accuracy of the output classifications of both classifiers. Accuracy is calculated as the number of samples correctly predicted by a classifier divided by the total number of samples (Han et al. 2012). To assess accuracy, both the SVM and the *k*NN were trained on a set of burn extent (burned and unburned) and biomass consumption (black ash and white ash) training regions within an image (fig. 6). The classifiers first performed a burn extent classification, labeling the pixels in the image as either burned or unburned. The image regions classified as burned were then classified by biomass consumption, labeling burned pixels as either white ash or black ash as shown in figure 7 (a-c).

Validation data sets for each of the images were selected as user labeled regions of pixels within the image, then the pixels from each validation dataset

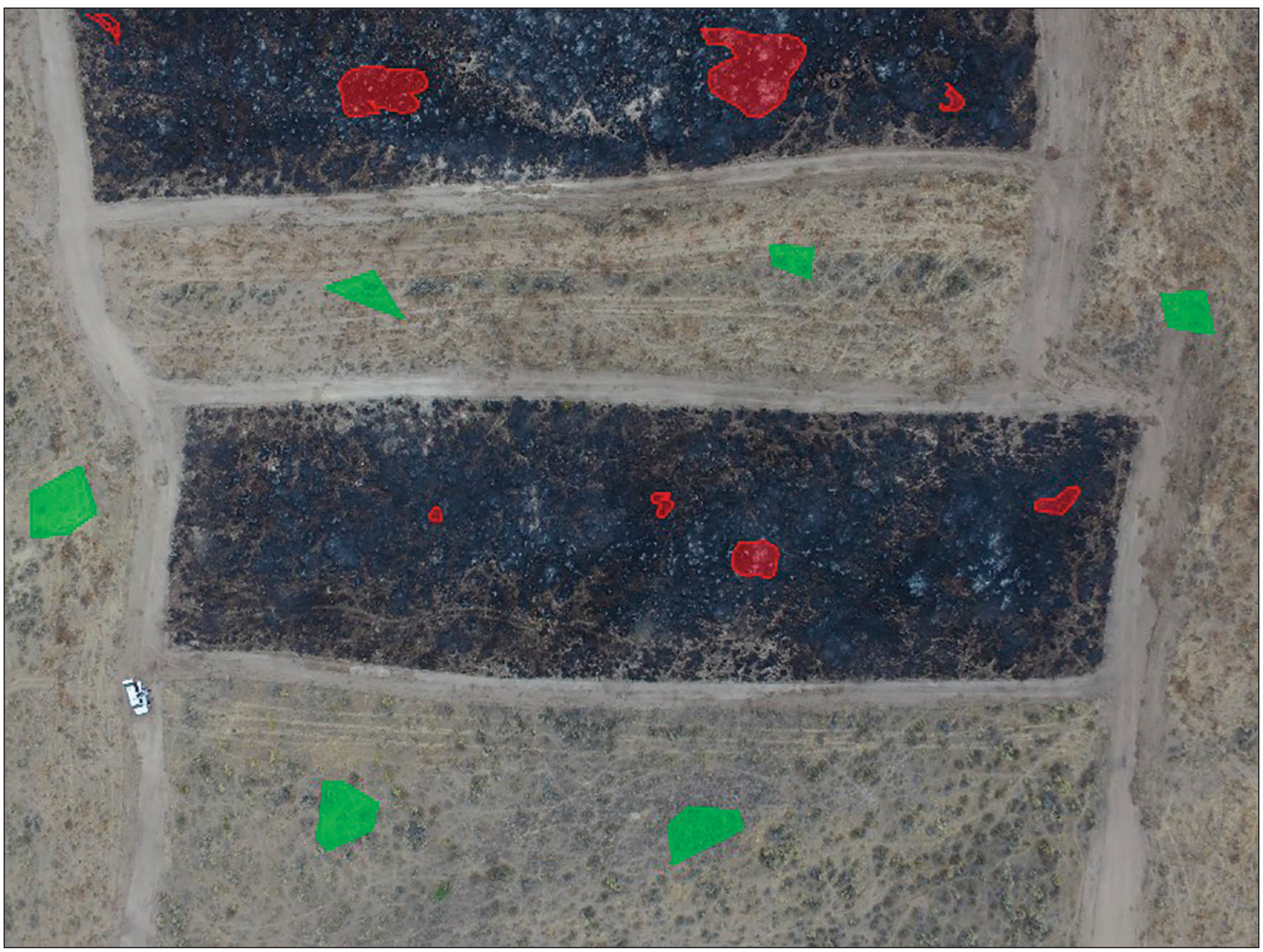

Figure 6–Example of validation data used for measuring classifier accuracy of figures 7(a) and 7(b).

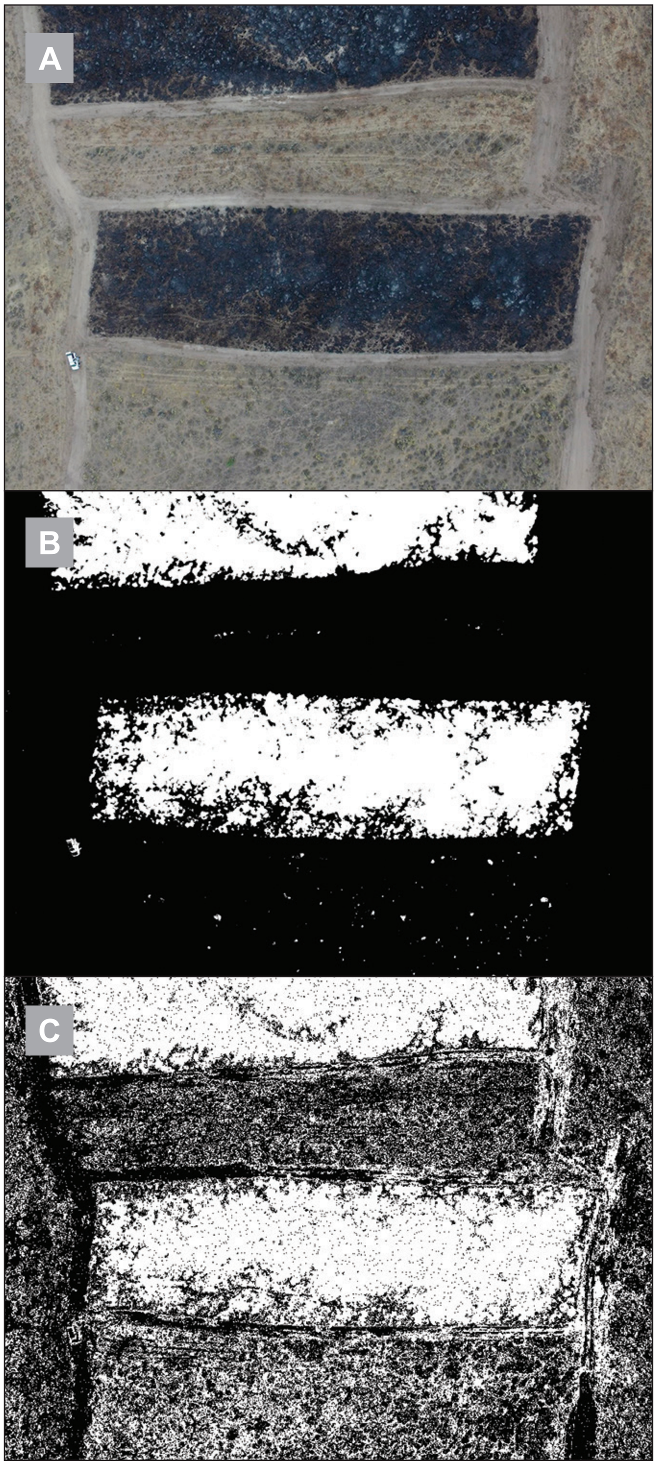

Figure 7–(a) Unclassified image of Reynolds Creek Prescribed burn; (b)–SVM classification result; (c)–NN classification result.

were run through the SVM and then again through the *k*NN. Accuracy for each validation data set was calculated for each algorithm, determining the percentage of validation pixels from a classifier which were classified the same as were labeled by the user. User labeling of validation data was based on visual observation of the image by the user, supplemented with ground observations recorded during image acquisition flights with the sUAS. Accuracy was calculated as the number of pixels correctly predicted by the SVM divided by the total number of pixels in the validation data set multiplied by 100. In order to obtain a more complete assessment of the accuracy of a set of classifier inputs, accuracy was evaluated based first on burn extent (ash vs unburned pixels) followed by assessment of biomass consumption (black ash versus white ash) accuracy. Accuracy results for each of the validation sets for burn extent and biomass consumption classifications from both classifiers on each fire are shown in table 2.

Classification accuracy for both burn extent and biomass consumption was averaged for both the SVM and *k*NN, then multiplied by 100. The resulting Mean Classification Accuracy are listed in table 3 for both SVM and *k*NN.

Table 2—SVM vs. *k*NN burn extent and biomass consumption classification accuracy.

	Burn extent		Biomass Consumption	
Fire	**SVM**	***k*NN**	**SVM**	***k*NN**
Jack	99.8	96.7	99.1	96.9
Northside	95.7	86.1	98	92.5
Reynolds Creek	99.59	79.51	98.7	96.85
Kane Fire	98.96	91.52	96.66	48.83
Deer Flat	99.99	72.62	99.86	78.06
Hoodoo 1	99.29	71.68	95.22	94.07
Hoodoo 2	89.23	50.36	99.25	92.88
Lucky Peak	97.61	74.62	99.85	96.17
mm107 (clip)	97.72	88.76	99.03	89.8
Camp	99.48	94.98	99.74	97.53
Oyhee plot	88.75	79.9	90.57	89.43
Immigrant (clip)	99.48	90.19	95.66	83.96
Elephant	95.08	91.44	99.15	96.68

Table 3—SVM vs. *k*NN mean classification accuracy.

Algorithm	Burn extent	Biomass consumption
SVM	96.97	97.75
*k*NN	82.18	88.74

A comparison of the Mean Classification Accuracy between the SVM and *k*NN showed that SVM had higher accuracy for both the burn extent and biomass consumption classifications.

Algorithm Comparison Accuracy Statistical Significance

The statistical significance of increased accuracy between the SVM and *k*NN across the validation sets for the burn images was established by using two-tailed paired t-tests. The null hypothesis is that the SVM and *k*NN classify burn extent and biomass consumption with equal accuracy. By contrast, the alternate hypothesis is that the SVM and *k*NN do not classify with equal accuracy. The t-test was run on the accuracy results for both the SVM and *k*NN, first testing burn extent, then biomass consumption. The significance level that the t-test passed is 0.05, which gives it 95 percent certainty to reject the null hypothesis in favor of the alternate hypothesis.

The burn extent accuracy tests rejected the null hypothesis with a p-value of 0.0005.

Likewise, the biomass consumption accuracy tests rejected the null hypothesis with a p-value of 0.031. In both cases, the null hypothesis was rejected, supporting the alternate hypothesis which shows that the SVM and *k*NN do not classify either burn extent or biomass consumption with equivalent accuracy.

The SVM was shown in table 3 to have a higher Mean Classification Accuracy for both burn extent and biomass consumption. Additionally, table 2 shows that the SVM had higher accuracy for each of the fires. To establish the statistical significance of the increase in accuracy over the *k*NN for both burn extent and biomass consumption, the accuracy values of both the SVM and *k*NN were run through a one-tailed t-test to establish that the SVM has a measurable increase in accuracy over the *k*NN.

The burn extent accuracy one-tailed t-test had a p-value of 0.0003, showing that the SVM has a measurable increase in mean accuracy over the *k*NN when classifying burn extent. Likewise, the biomass consumption one-tailed t-test had a p-value of 0.014, showing that the SVM had a measurable increase in accuracy over the *k*NN when classifying biomass consumption. This analysis shows that SVM classifies burn extent and biomass consumption with greater mean accuracy than *k*NN.

In addition to mapping post-fire effects with greater accuracy, the SVM implementation in this study also had a shorter execution time when classifying images, running in 20 to 25 percent of the time required by the *k*NN implementation to classify the same image. The comparison of the Support Vector Machine (SVM) and *k*-Nearest Neighbor (*k*NN) algorithms showed that both classifiers mapped burn extent and biomass consumption from hyperspatial sUAS imagery with high accuracy. The SVM outperformed the *k*NN in classifying burn extent as well as biomass consumption with the SVM mapping burn extent with average accuracy of 96.81 percent and biomass consumption with average accuracy of 97.74 percent on the fires studied. While the *k*NN did not map fire effects as accurately as the SVM, it still averaged 81.37 percent accuracy for burn extent and 88.74 percent for biomass consumption. The SVM outperformed the *k*NN, classifying burn extent and biomass consumption with higher accuracy when mapping post-fire effects from hyperspatial imagery acquired with sUAS.

CONCLUSION

The comparison of the Support Vector Machine (SVM) and *k*-Nearest Neighbor (*k*NN) algorithms showed that both classifiers mapped burn extent and biomass consumption from hyperspatial sUAS imagery with high accuracy. The SVM outperformed the *k*NN in classifying burn extent as well as biomass consumption with the SVM mapping burn extent with average accuracy of 96.81 percent and biomass consumption with average accuracy of 97.74 percent on the fires studied. While the *k*NN did not map fire effects as accurately as the SVM, it still averaged 81.37 percent accuracy for burn extent and 88.74

percent for biomass consumption. The inclusion of Second Order Entropy as a classifier input along with the three color bands was found to increase burn extent mapping accuracy with an SVM to 94.4 percent from 91.71 percent accuracy achieved using only color imagery. Likewise, the inclusion of Second Order Entropy increased the biomass consumption mapping accuracy to 83.8 percent from the 77.3 percent accuracy achieved using only the color bands as input to the SVM. While the inclusion of Second Order Entropy was able to increase fire effects mapping accuracy, that increase in accuracy must be weighed against the run-time computational complexity of calculating Second Order Entropy.

FUTURE WORK

Improve the SVM algorithm in both efficiency and accuracy. Apply research method to identifying prostate cancer. Apply research method to identifying and mapping archeological items of interest. Gather more data for testing and validating results. More data is required for determining statistical significance for white ash.

ACKNOWLEDGMENTS

This publication was made possible by an Institutional Development Award (IDeA) from the National Institute of General Medical Sciences of the National Institutes of Health under Grant #P20GM103408 and the National Aeronautic and Space Administration through the Idaho Space Grant Consortium. We acknowledge the guidance and mentorship of Dr. Gregory Donohoe, Professor Emeritus of Computer Science at The University of Idaho as well as Dr. Eva Strand, Assistant Professor of Landscape Fire Ecology at The University of Idaho. We also acknowledge the assistance of undergraduate research assistants in the Computer Science program at Northwest Nazarene University including Zach Garner, Nicholas Hamilton, Llewellyn Johnston and Greg Smith.

REFERENCES

Aplet, G.H.; B. Wilmer, B. 2010. Potential for restoring fire-adapted ecosystems: Exploring opportunities to expand the use of wildfire as a natural change agent. Fire Management Today. 70(1): 35–39.

Brewer, C.K.; Winne, J.C.; Redmond, R.L.; Opitz, D.W.; Mangrich, M.V. 2005. Classifying and mapping wildfire severity. Photogrammetric Engineering and Remote Sensing. 71(11): 1311–1320.

Calkins, A.T. 2017. Unmanned aircraft systems (UAS) and photogrammetrics as a tool for archaeological investigation in 19th Century historic archaeology. Thesis. Reno, NV: University of Nevada. 122 p.

Chang, C.-C.; Lin, C.-J. 2011. LIBSVM: A library for support vector machines. ACM Transactions on Intelligent Systems and Technology. 2(3): 27.

Cormen, T.H. 2009. Introduction to algorithms. Cambridge, MA: MIT Press. 1292 p.

Cortes; C.; Vapnik, V. 1995. Support-vector networks. Machine Learning. 20(3): 273–297.

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

Gonzalez, R.; Woods, R. 2008. Digital image processing. Upper Saddle River, NJ: Pearson Prentice Hall. 945 p.

Hamilton, D.; Bowerman, M.; Collwel, J.; Donahoe, G.; Myers, B. 2017. A spectroscopic analysis for mapping wildland fire effects from remotely sensed imagery. Journal of Unmanned Vehicle Systems. DOI:10.1139/juvs-2016-0019

Han, J.; Kamber, M.; Pei, J. 2012. Data mining: Concepts and techniques, third edition. Waltham, MA: Morgan Kaufmann Publishers. eBook.

Hudak, A.T.; Ottmar, R.D.; Vihnanek, R.E.; Brewer, N.W.; Smith, A.M.; Morgan, P. 2013. The relationship of post-fire white ash cover to surface fuel consumption. International Journal of Wildland Fire. 22(6): 780–785.

Keeley, J.E. 2009. Fire intensity, fire severity and burn severity: A brief review and suggested usage. International Journal of Wildland Fire. 8(1): 116–126.

Key, C.H.; Benson, N.C. 2006. In: Lutes, D.C.; Keane, R.E.; Caratti, J.F.; Key, C.H.; Benson, N.C.; Sutherland, S.; Gangi. L.J., eds. FIREMON: Fire effects monitoring and inventory system. General Technical Report RMRS-GTR-164-CD. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station: LA-1-LA-51.

Küng, O.; Strecha, C.; Beyeler, A. [et al.]. 2011. The accuracy of automatic photogrammetric techniques on ultra-light UAV imagery. Presented at: UAV-g 2011: Unmanned Aerial Vehicle in Geomatics, Zürich, CH, September 14-16, 2011.

Laliberte, A.S.; Herrick, J.E.; Rango, A.; Winters, C. 2010. Acquisition, orthorectification, and object-based classification of unmanned aerial vehicle (UAV) imagery for rangeland monitoring. Photogrammetric Engineering and Remote Sensing. 76(6): 661–672.

Lentile L.B.; Holden, Z.A.; Smith, A.M.S.; Falkowski, M.J.; [et al.]. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire. 15(3): 319–345.

Liu, D.; Kelly, M.; Gong, P. 2006. A spatial–temporal approach to monitoring forest disease spread using multi-temporal high spatial resolution imagery. Remote Sensing of Environment. 101(2): 167–180.

Mora, C.; Tittensor, D.P.; Adl, S.; Simpson, A.G.; Worm, B. 2011. How many species are there on earth and in the ocean? PLoS Biology. 9(8): p. e1001127, 2011.

OpenCV, vol. 3.2, no. Computer Program, 2017. Available online at: www.opencv.org.

Rosnell, T.; Honkavaara, E. 2012. Point cloud generation from aerial image data acquired by a quadrocopter type micro unmanned aerial vehicle and a digital still camera. Sensors. 12(1): 453–480.

Russell, S. Norvig, P. 2010. Artificial intelligence: A modern approach. Third edition. Upper Saddle River, NJ: Prentice Hall. eBook.

Salimi, A.; Ziaii, M.; Amiri, A.; Zadeh, M.H.; Karimpouli, S.; Moradkhani, M. 2017. Using a Feature Subset Selection method and Support Vector Machine to address curse of dimensionality and redundancy in Hyperion hyperspectral data classification. Egyptian Journal of Remote Sensing and Space Sciences. 21(1): 27-36.

Sridharan, H.; Qiu, F. 2013. Developing an object-based hyperspatial image classifier with a case study using WorldView-2 data. Photogrammetric Engineering and Remote Sensing. 79(11): 1027–1036.

Yang, Y.; Liu, X. 1999. A re-examination of text categorization methods. SIGIR ’99: Proceedings of the 22nd annual international ACM SIGIR conference on research and development in information retrieval. New York and Berkeley, CA: Association for Computing Machinery: 42–49.

Zammit, O.; Descombes, S.; Zerubia, J. 2006. Burnt area mapping using support vector machines. Forest Ecology and Management. 234(1): S240.

Zhang, R.; Ma, J. 2008. An improved SVM method P-SVM for classification of remotely sensed data. International Journal of Remote Sensing. 29(20): 6029–6036.

Zhou, G.; Li, C.; Cheng, P. 2005. Unmanned aerial vehicle (UAV) real-time video registration for forest fire monitoring. Geosci. Remote Sens. Symp. 2005 IGARSS05 Proc. 2005 IEEE Int., vol. 3, 2005.

Impacts of Six Different, Complex Fire Regimes in a Longleaf Pine Ecosystem: Results Over 25 Years

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Abstract—Studies on frequent fire return intervals often span a few years and historically it has been presumed that this is sufficient to assess fire effects in different seasons and/or frequencies. However, long-term data increasingly challenges this assumption. Our research targets an ecosystem dominated by the fire-dependent longleaf pine (*Pinus palustris*). Longleaf pine forests once dominated Southeastern United States uplands and it is well-accepted that the ecosystem was maintained by frequent fire. Nevertheless, important questions remain, including how frequent is frequent enough and how critical is season of burn. Results were evaluated in seven sampling periods spanning 25 years on the Escambia Experimental Forest (Forest Service, U.S. Department of Agriculture) in south-central Alabama. Treatments were six different complex fire regimes: fire every 2, 3, or 5 years in winter or late spring plus a no-burn treatment in each of 3 blocks. Data were collected on longleaf plus hardwood stems > 2.5 cm at breast height. By Year 25 there was little difference in longleaf growth or survivorship, but there were significant treatment-dependent differences in number and size of hardwood stems. Fire return intervals of 2-3 years were important but frequent growing-season burns appear to be critical for managing encroaching native hardwoods and maintaining habitat structure over long time periods.

Keywords: fire regime, season of burn, fire frequency, longleaf pine, hardwood stems

INTRODUCTION

Worldwide there is an increasing need to develop a better understanding of complex fire regimes in many different ecosystems over long time periods and this may be especially true in North America (e.g., Freeman et al 2017). Our paper describes results of long-term research initiated in 1984 and designed to evaluate effects of complex fire regimes on longleaf pine (*Pinus palustris*) and its habitat. The data evaluated cover 25 years and six different fire regimes plus an unburned treatment.

Six decades earlier, Aldo Leopold (1924) noted that fire should be considered as a natural component of the landscape. Since then, there have been many long-term studies established to consider ecological effects of disturbances. However, when fire is considered, often it is in the context of ecosystems with extended fire return intervals and associated research usually documents succession over time (e.g. Rogers 1996).

Currently there is growing interest and need in determining what constituted natural disturbance regimes (e.g., Turner et al. 2003). In the United States, there has been a focus on understanding habitat conditions related to fire prior to European settlement (e.g., Frost 1998, 2006). Using witness tree data and environmental variables, Predmore et al. (2007) determined that prior to European settlement, fire-dependent longleaf communities dominated southern

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

areas and Stambaugh et al. (2011) assessed cross-sections of 19 remnant old pines in southern Louisiana and found that the mean fire return interval for the period 1650-1905 was 2.2 years. Recently developed models suggest that large areas of the United States once burned multiple times a decade (Guyette et al. 2012), with some sites igniting more frequently than previously suggested. While these efforts provide better understanding fire return intervals, there have not been many efforts to consider this major component of a burn regime (frequency) while also including seasonality as a potential critical fire regime component.

There have been groundbreaking studies that targeted rapid fire-return intervals with burn treatments applied every one or two years (e.g., Glitzenstein et al. 1995). However, such efforts were rare and, like many other efforts, were often based on data collected over a decade or less. Although past research has provided important information, it is not clear whether frequent burn regimes studied over short time periods reveal ultimate fire effects. What may appear as slight differences among treatments over short time periods may not reveal fire effects based on small shifts over longer time periods. Also, many past fire regime studies often assess only effects on pines. However, in recent years there is a growing interest in fire effects on hardwood species, especially shrubs (Drewa et al. 2006; Kush et al. 1999; Thaxton and Platt 2006). If burning is ineffective over the long-term, hardwood species are likely to increase in dominance, slowly decrease light at the ground level, and so degrade native habitat structure. Appropriate habitat structure maintained by fire effects on hardwood species may be critical for maintaining the high diversity of ground cover plants (e.g., Kush et al. 1999) and vertebrates (e.g., Hermann et al. 2007). Both groups, herbaceous plants and vertebrates, have multiple species of conservation concern in longleaf pine habitat.

Long-term studies of fire regimes that include both frequency and season are needed to better understand effects that might appear to be minor or subtle over the short term. We report on results spanning 25 years, based on a fire effects study initiated in 1984. Results are based on prescribed fire regimes with three different, short-term frequencies (2, 3, or 5 years) plus no fire. In addition, inclusion of two seasons (winter and late spring) permits a comparison of complex regimes that has not commonly been available.

STUDY SITE

The study was conducted on the Escambia Experimental Forest (EEF) in Escambia County near Brewton, Alabama. The property is owned by T.R. Miller Mill Company; the Forest Service, in cooperation with the company, has maintained the site for research purposes since 1947. EEF is located on the Gulf Coastal Plain and encompasses approximately 1,200 ha. The predominant soil series is Troup, defined by low fertility and low organic matter content. The uplands are dominated by naturally occurring longleaf pine, with some small areas still supporting old individual trees. Much of the acreage of the site supports native ground cover with no indication of past agriculture activities. Additional information on EEF is found in Boyer (1987, 1995, 1999), Kush et al. (1999, 2000), and Barlow et al. (2010).

Over many years, a wide-range of long-term study plots, including the ones described in the current work, have been established on EEF using a shelterwood management system to study a variety of young longleaf pine stands (e.g., Croker 1956). Boyer (1984) describes establishment of the research plots and indicates that the parent, overstory trees in the plots used for the current project were removed in the winter of 1976. The juvenile “grass-stage” longleaf pine trees that remained were assumed to have established during the 1973 mast year.

METHODS

Study Design and Experimental Treatments

Seven treatments were replicated in each of three blocks, six burn treatments, and one unburned. The burn treatments were defined by two seasons and three fire return intervals (burn frequencies). Seasons were winter (mid-January through February) and late spring (mid-April through May); burn frequencies were every 2, 3, or 5 years. Each combination of treatments (season x burn frequency) was applied to one plot in each block. This resulted in treatment codes: Winter 2 (W2), Winter 3 (W3), Winter 5 (W5), Spring 2 (S2), Spring 3 (S3), and Spring 5 (S5). In addition, there was a plot in each block that remained unburned since 1979, 5 years prior to initiation of the first sampling efforts. Plots containing the No Burn treatment were coded as UB.

Areas sampled in each treatment plot are 20.1 x 20.1 m (0.04 ha). Prior to initiation of study treatments, research areas were thinned leaving 40 permanently marked study trees in each measurement plot. In Year 0, dominant longleaf trees averaged 3 to 4.3 m in height (Boyer 1984). All study areas, including those later assigned to a no fire treatment, were burned in the spring of 1979 to create an initial standardized time-since-last fire. Justification for the project and additional information on establishment of plots is found in Boyer (1984) and Barlow (2010).

Barlow et al. (2010) describes some aspects of conditions during the experimental fires, including ignition pattern (generally flank or strip head fires) and day-of-burn weather. Day-of-burn weather usually included fine fuel moisture of 7-10 percent, 35-55 percent relative humidity, and generally steady wind of 4.8-8.0 km/hr (3-5 mi/hr). Experimental burns usually followed rain and were executed in ways that were expected to minimize crown scorch of the pines.

Measurements

Beginning in 1984 and subsequently every 3 to 5 years, all measurement plots, including unburned ones, were assessed. Data were collected in late fall and early winter, after woody species had generally ceased growth but before any upcoming fire treatments. During each assessment year, all 40 longleaf pine individuals were tallied as alive or dead. Diameter at breast height (d.b.h.) was measured for all live trees and this value was used to calculate basal area (BA). Also, during each assessment year, all hardwood stems at least ~2.5 cm (1.0 in) in diameter at ~1.4 m (4.5 ft) height were counted and d.b.h. measured. Unlike longleaf pine trees, individual hardwood stems were not marked, and so individual stems could not be tracked over time. Also, unlike longleaf pines, the number of hardwood stems was not standardized at the initiation of treatments (see below). Although hardwood stems were identified to species during each sampling period, in the current paper we have pooled species and targeted the overall treatment effects on habitat structure.

Data were first collected in 1984 (Year 0) and the first experimental burn treatments were applied in 1985 (Year 1). Results spanning the first 25 years are reported below.

Statistical Analyses

Plots were evaluated for longleaf pine (1) tree survivorship and (2) mean BA of individual trees surviving until Year 25 and these assessments required multiple statistical approaches. A chi-square analysis was applied to assess survivorship of individual trees and repeated measure (ANOVA) using GLM Proc was used to assess mean BA. UB plots were not included in analyses because, although replicated among plots, this treatment is not based on two factors (season and frequency). However, as a basis for comparison we present results for the UB treatment in all graphs.

For hardwood stem data, ANOVA was also used to evaluate potential differences among sample years. Comparisons were made among treatments for (1) number of hardwood stems and (2) total BA of all hardwood stems within treatment type over 25 years.

RESULTS

Longleaf Pine Trees

Longleaf pine mortality was generally low; however, there was some loss of individuals over time. Over the entire sample period, there was a statistical difference related to year (chi-sq < 0.001; fig. 1). However, there was no significant difference based on longleaf pine mortality among the two seasons of burn (chi-sq = 0.9322) or three frequencies (chi-sq = 0.9751). Visual comparison between UB and all other treatments (fig. 1) suggests that mortality of trees in UB plots is similar to that experienced in burn treatments. Although treatments over time do not appear to have significantly influenced tree survivorship, data collected in Year 25 revealed differences in survivorship compared to earlier assessments. There was a substantial decline in number of live trees independent of treatment (fig. 1). Future observations will be required to better understand this result.

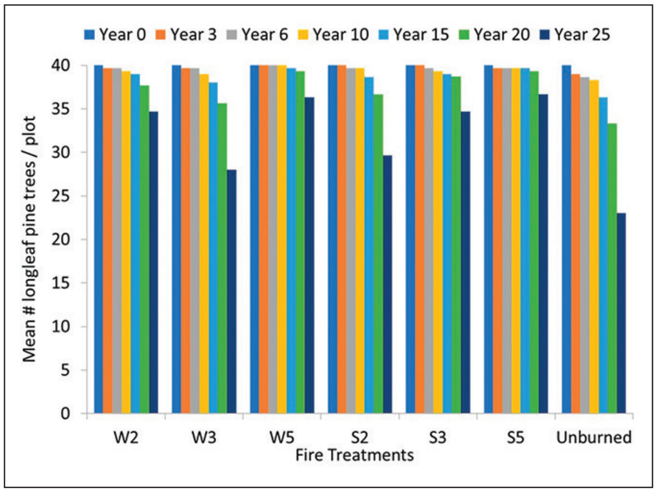

Figure 1—Mean number of longleaf pines per plot alive during each of seven sampling events spanning 25 years. Trees were 11 years old at Year 0.

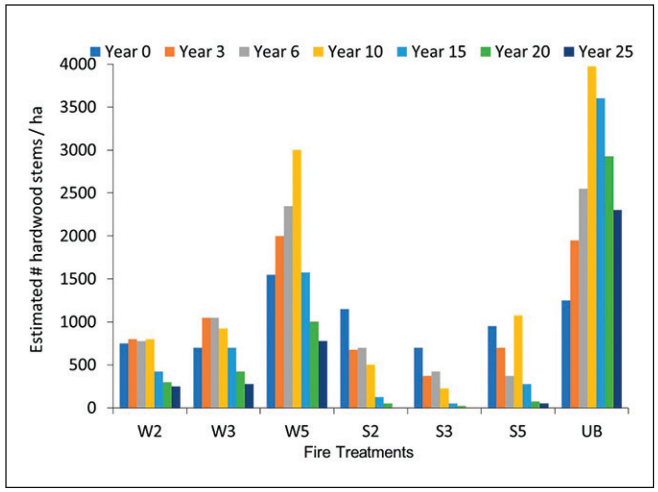

Figure 3—Estimated number of hardwood stems per hectare pooled over size classes. Hardwood stems below breast height (1.4 m) were not considered.

BA of longleaf pine trees alive in Year 25 did not differ significantly throughout the study, among season of burn ($p = 0.26$), fire frequency ($p = 0.80$), or season x frequency ($p = 0.13$) (fig. 2). In Year 25, the range of the average BA per tree, over all treatments and unburned plots, varied between 310 cm^2 to 344 cm^2.

Hardwood Stems

Density of all hardwood stems ≥ 2.5 cm d.b.h. (fig. 3) was significantly influenced by ($p = 0.02$) season of burn; however, there was no significant ($p = 0.07$) association with fire frequency. In addition, there was no significant difference related to the interaction of season x fire frequency ($p = 0.17$). Although UB plots could not be included in the analysis, observations indicated a common pattern in relationship of density of hardwood stems (pooled overall size classes) and change over time. Visual examination of figure 3 reveals that, beginning in Year 15, there were consistent declines in number of hardwood stems over all treatments. It is visually apparent that the magnitude of change differs among treatments (fig. 3) and appears to be especially true for all spring burn treatments. By Year 25, there are well-defined defined differences in treatment effect on number of hardwood stems, ranging from a mean of ~2,300 hardwood stems per hectare in UB plots to no hardwood stems observed in any of the S2 plots (fig. 3).

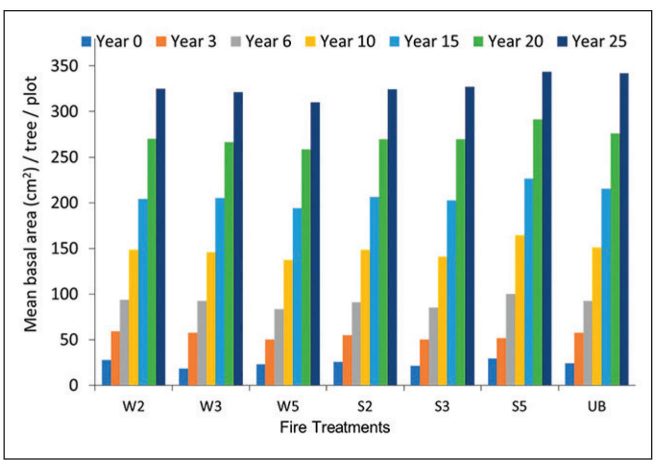

Figure 2—Mean basal area of individual longleaf pines per plot, alive in Year 25 of the study. Trees were 36 years old in Year 25.

When hardwood basal area was pooled over all stems, statistical comparison among fire treatments indicates a significant difference in hardwood stem BA associated with season of burn (fig. 4, $p = 0.02$). A visual comparison across all treatments reveals, after Year 15, there were consistent declines of BA in spring burn plots. Winter burn plots show less consistent patterns although all three fire return intervals supported higher BA in Year 25 compared to Year 0 (fig. 4). In addition, the mean BA of hardwood stems in UB plots steadily increased over all years (fig. 4).

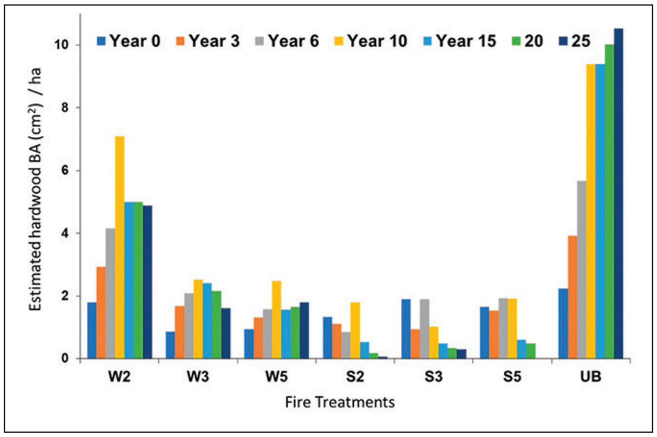

Figure 4—Estimated total basal area per hectare of all hardwood stems. Note that hardwood stems below breast height (1.4 m) were not included.

SUMMARY

In the current paper, we summarized results of a long-term research project on Escambia Experimental Forest. The data spans 25 years and is part of an ongoing, replicated project that compares six complex treatments based on two seasons (winter and late spring) and three different fire frequencies (every 2, 3, or 5 years). A seventh treatment remains unburned and serves as a comparison to burned plot treatments. The treatments were designed to cover some of the common categories of prescribed fire applied to this habitat type.

Summary of Longleaf Pine Results

An unexpected result was that during most of the 25-year study period, there was almost no effect of any treatment, including unburned, on survivorship or growth of longleaf pines. This was especially evident early in the research. Longleaf individuals were 11 years old at Year 0 of the project and this may have contributed to the high degree of early survivorship over all treatments. However, assessment of data collected in Year 25 revealed a potential shift in that pattern. Up until that time, all treatments averaged a total of 3 percent loss or less of trees. Although in Year 25, longleaf trees in plots that experienced any of the burn treatments during that time were more likely to survive compared to those in the UB plots. In addition, within the burn treatments during this last sample period, the Year 5 plots (regardless of season of burn) experienced less mortality compared to trees in Year 2 and Year 3 plots. However, there may be a confounding factor: During Year 25, plots assigned to Year 2 and Year 3 treatments were burned, but Year 5 plots were not scheduled for fire during that same period. Additional years of burn treatments and data collection will be required to fully understand this result and to determine if the pattern continues.

Summary of Hardwood Stem Results

Results of effects of different fire regimes on hardwood stem dominance provide information with significance for conservation concerns. Season of burn (winter versus late spring) may play a more significant role than the frequency of burn (2, 3, or 5 year) when hardwood control is considered. As suggested by Barlow et al (2015), frequency of growing season fire appears to be important but may play a smaller role compared to season of burn, at least during the 25-year period.

Although the assessments are complex, they reveal that both regime factors (season and frequency) may play important roles in managing for hardwood control. For example, by Year 25, spring fires demonstrated significantly better control of the number of hardwood stems compared to winter burns. This was also the case for managing total BA of hardwood stems. Not only did it appear as if spring fires were more effective in controlling hardwoods, burns every 2 or 3 years were more likely to reduce BA compared to burns every 5 years. Over the 25 years of the study, controlling midstory hardwood stem numbers to meet conservation goals appears most likely to have benefit from frequent burns in the growing season compared to other fire regimes and fires every 2 or 3 years appear to be the most productive. Because burns every 5 years may result in highly ineffective control of hardwood stems, especially those stems above breast height, we suggest caution against management plans that rely not only on burns based on that frequency but also that plan to apply fire every 4 years. However, management needs may be met with longer fire return intervals if there are little or no conservation interests of concern or if the site undergoes periodic herbicide treatment fires every 4-5 years.

Final Thoughts

Our results appear to support estimations of historical fire return intervals suggested by Frost (1998, 2006) and models developed by Guyette et al. (2012). Frost (1998, 2006) places the location of the Escambia Experimental Forest study site as being on the border between areas that burned, on average, every 1-3 years and 4-6 years. Work by Guyette et al. (2012) indicates that the site averaged fires every 2-4 years.

Unfortunately, neither body of research (Frost 1998, 2006; Guyette et al. 2012) addresses the fire regime component of seasonality, nor is there a large body of literature that addresses that topic. However, it is generally assumed that most lightning strikes in the Southeast United States often occurred in the middle of the summer (e.g., Komarek 1964, 1974), with some burns happening during that period, but with fires ignited as early as late spring and not ceasing until early fall (e.g., Duncan et al. 2010). Long-term research on this topic is generally lacking.

Over much of the 25-year study period, all burn treatments supported hardwood stems at densities that apparently did not exist historically in longleaf pine ecosystems in south Alabama. Bartram (1791) described what are now understood to be longleaf pine ecosystems as open, park-like grassland. Over two centuries later, many researchers working on patches of what are thought to be healthy longleaf ecosystems describe similar habitat (c.f. Hanberry et al. 2018). Once hardwoods are widely established, it requires significant effort to effectively prescribe fire to eliminate them from the system. The size and number of hardwood stems in the spring 5-year treatment could not support natural regeneration of longleaf pine; competition is too severe to allow establishment of seedlings. If plots in the spring 2- and 3-year treatments were to go another year of two without fire, it would be difficult to effectively manage for longleaf pine, native ground cover, and other aspects of conservation concern. Historically longleaf pine ecosystems supported a minor hardwood component on the upland sandy sites that are prevalent on Escambia Experimental Forest. Lack of frequent growing season fire allows high densities of hardwood stems to establish in the understory of longleaf ecosystems. This outcome is a major factor contributing to the high number of threatened and endangered species in the Southeast. Proactive use of prescribed fire is needed to effectively limit hardwoods in longleaf pine forests. Difficulty and expense of removing hardwoods from these systems is time-consuming and costly, and often dangerous the longer fire is not applied or is done so ineffectively.

ACKNOWLEDGMENTS

This paper is in memory of Dr. William Boyer who envisioned the research project over 40 years ago: he understood, when few others did, the importance of fire to the management of longleaf pine ecosystems. He was promoting the use of frequent fire in the growing season when most were content to burn every 3 years in the dormant season. He was studying what was happening when most were just looking.

REFERENCES

Barlow, R.J.; Kush, J.S.; Gilbert, J.C.; Hermann, S.M. 2015. Prescribed fire effects in a longleaf pine ecosystem: Are winter fires working? In: Proceedings of the 17th Biennial Southern Silvicultural Research Conference. e–Gen. Tech. Rep. SRS–203. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 551 p.

Barlow, R.J.; Kush, J.S.; Hermann, S.M.; Boyer, W.D. 2010. Impacts of fire on longleaf pine stand dynamics with different seasonal and fire return intervals. In: Robertson, K.M.; Galley, K.E.M.; Masters, R.E., eds. Proceedings of the 24th Tall Timbers Fire Ecology Conference. The Future of Prescribed Fire: Public Awareness, Health, and Safety. Tallahassee, FL: Tall Timbers Research Station. 127–132.

Bartram, W. 1791. Travel through North and South Carolina, Georgia, and East and West Florida. New York: Dover Publishers. 414 p.

Boyer, W.D. 1984. Timing of prescribed fire for optimum hardwood control with minimum impact on hardwood growth. A Study Plan for the Southern Forest Experiment Station, USDA Forest Service. (4110 FS-SO-1116-2.25).

Boyer, W.D. 1987. Volume growth loss: a hidden cost of periodic burning in longleaf pine? Southern Journal of Applied Forestry. 11: 154–157.

Boyer, W.D. 1995. Responses of groundcover under longleaf pine to biennial seasonal burning and hardwood control. Edwards, M.B., comp. Proceedings of the eighth biennial southern silviculture research conference. General Technical Report SRS-1. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. 512–516.

Boyer, W.D. 1999. Longleaf Pine: Natural Regeneration and Management. Alabama's Treasured Forests, Fall 1999. 7–9.

Croker, T.C. 1956. Can the shelterwood method successfully regenerate longleaf pine? Journal of Forestry. 54: 258–260.

Drewa, P.B.; Thaxton, J.M.; Platt, W.J. 2006. Responses of root-crown bearing shrubs to differences in fire regimes in *Pinus palustris* (longleaf pine) savannas: exploring old-growth questions in second-growth systems. Applied Vegetation Science. 9(1): 27–36.

Duncan, B.W.; Adrian, F.W.; Stolen, E.D. 2010. Isolating the lightning ignition regime from a contemporary background fire regime in east-central Florida, USA. Canadian Journal of Forest Research. 40: 286–297.

Freeman, J.; Kobziar, L.; White Rose, E.; Cropper, W. 2017. A critique of the historical-fire-regime concept in conservation. Conservation Biology. 31(5): 976–985.

Frost, C.C. 1998. Presettlement fire frequency regimes of the United States: a first approximation. In: Pruden, T.; Brennon, L., eds. Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers Fire Ecology Conference Proceedings. No. 20. Tallahassee, FL: Tall Timbers Research Station.

Frost, C.C. 2006. History and future of the longleaf pine ecosystem. In: Jose, S.; Jokela, E.; Miller, D., eds. Longleaf pine ecosystems: ecology, management, and restoration. New York: Spring-Verlag. 438 p.

Glitzenstein, J.; Platt, W.J.; Streng, D. 1995. Effects of fire regime and habitat on tree dynamics in North Florida longleaf pine savannas. Ecological Monographs. 65(4): 441–476.

Guyette, R.P.; Stambaugh, M.C.; Dey, D.C.; Muzika, R. 2012. Predicting fire frequency with chemistry and climate. Ecosystems. 15: 322–335.

Hanberry, B.B.; Coursey, K.; Kush, J.S. 2018. Structure and composition of historical longleaf pine ecosystems in Mississippi, USA. Human Ecology. 46(2): 241–248.

Hermann, S.M.; Kush, J.S.; Gjerstad, D.H. 2007. Emerging issues in forest health and their significance for rare species of the Southeast United States. In: HydroGeoLogic, eds. Proceedings from the Southeast Region threatened, endangered, and at-risk species workshop, Cocoa Beach, FL.

Komarek, E.V., Sr. 1964. The natural history of lightning. Proceedings of the Third Annual Tall Timbers Fire Ecology Conference. Tallahassee, FL: Tall Timbers Research Station. 139–183.

Komarek, E.V. 1974. Effects of fire on temperate forests and related ecosystems: Southeastern United States. In: Ahlgren, C.E.; Kozlowski, T.T., eds. Fire and ecosystems. New York: Academic Press.

Kush, J.S.; Meldahl, R.S.; Boyer, W.D. 1999. Understory plant community response after 23 years of hardwood control treatments in natural longleaf pine (*Pinus palustris*) forests. Canadian Journal of Forest Research. 29: 1047–1054.

Kush, J.S.; Meldahl, R.S.; Boyer, W.D. 2000. Understory plant community response to season of burn in natural longleaf pine forests. Tall Timbers Fire Ecology Conference Proceedings. Tallahassee, FL: Tall Timbers Research Station. 21: 32–39.

Leopold, A. 1924. Grass, brush, timber, and fire in southern Arizona. Journal of Forestry. 22: 1–10.

Predmore, S.A.; McDaniel, J.; Kush, J.S. 2007. Presettlement forests and fire in southern Alabama. Canadian Journal of Forest Research. 37(9): 1723–1736.

Rogers, P. 1996. Disturbance ecology and forest management: a review of the literature. General Technical Report INT-GTR-336. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Stambaugh, M.C.; Guyette, R.P.; Marschall. J.M. 2011. Longleaf pine (*Pinus palustris* Mill.) fire scars reveal new details of a frequent fire regime. Journal of Vegetation Science. 22(6): 1094–1104.

Thaxton, J.M.; Platt, W.J. 2006. Small-scale fuel variation alters fire intensity and shrub abundance in a pine savanna. Ecology. 87(5): 1331–1337.

Turner, M.G.; Collins, S.L.; Lugo, A.L.; Magnuson, J.J.; Rupp, T.S.; Swanson, F.J. 2003. Disturbance dynamics and ecological responses: the contribution of long-term ecological research. BioScience. 53(1): 46–56.

Assessing Wildfire Risk in Real Time on the 2017 Frye Fire

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Abstract—The Frye Fire started June 7, 2017, in the Pinaleño Mountains of southeast Arizona. The Pinaleños are host to important resources and assets including Mount Graham International Observatory, recreation residences, a church camp, Forest Service infrastructure, spiritual significance to tribes, and 11 endemic fish and wildlife species. This assessment was stimulated by the need to make sense of the numerous resources and assets within the planning area of the Frye Fire in order to enable quality dialog between the Coronado National Forest and the Incident Management Team. The assessment was created to help guide the management of the fire to best meet the desires of the local unit and stakeholders. Highly valued resources and assets (HVRAs) in the fire's planning area were identified and prioritized. The response function to fire for each individual HVRA was identified as positive, neutral, or negative by flame-length class by local staff. The net value change was then calculated to discern the probable effects to an area if it were to burn and isolate which HVRA was driving that response. This assessment allowed us to verify the incident strategies, develop tactics, prioritize actions on the ground, and align the strategy and tactics by providing pertinent information to ground resources.

Keywords: risk assessment, fire management, Frye Fire, incident strategies, incident tactics, intent-based planning

INTRODUCTION

The Frye Fire started June 7, 2017, in the Pinaleño Mountains of southeastern Arizona on the Coronado National Forest (CNF). Since it was a lightning-caused fire, the Forest Plan is flexible on management options but encourages managing lightning-caused fires to promote diverse and resilient ecosystems. Given the direction provided in the Forest Plan, how do you restore or maintain fire as a natural process while protecting the things we care about? As is often the case with any fire, the values and assets identified as important by the CNF and stakeholders created a blurry picture of how to manage the fire as there were often multiple values and assets present in any particular area. Which value or asset is of the highest importance? In addition, if it is likely that the fire will burn into an area that has important values and assets, how do you provide substantive information to guide the desired fire effects? In essence, how do you want the area to look if there is the option?

This assessment was stimulated by the need to make sense of the numerous values and assets within the planning area of the Frye Fire to enable quality dialog between the CNF and the Incident Management Team (IMT). As is often the case within a fire area, there were many competing values and assets that respond differently to fire. The intent of the exploratory analyses was to (1) identify the values and assets within the planning area and then prioritize those values and assets, (2) calculate the net value change to inform fire strategy, and (3) better align strategy and tactics by applying risk assessment methods to an incident.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

METHODS

This assessment draws upon similar methods used by the Forest Service, U.S. Department of Agriculture, in a regional wildfire risk assessment prepared for the Southwestern Region (Southwestern Region Fire and Aviation Management 2017) and described in multiple publications (Finney 2005; Scott et al. 2013). There are three components included in assessing wildfire risk: susceptibility, intensity, and likelihood. The value in this approach is that the process and methods have been defined and the necessary inputs are readily available.

Project Area

The Pinaleño Mountains are an island mountain range with vast ecological diversity including desert shrub and grassland vegetation near the base of the mountain range, forest woodland ecosystems at mid elevation, and cold forest at the upper reaches of Mount Graham. Elevation ranges from 3,000 to 10,700 ft. Approximately 29,000 ac of the project area burned in 2004 in the Nuttall Complex in addition to multiple smaller fires. The Frye Fire had already burned approximately 38,500 acres in 3 weeks when this assessment was completed.

The Pinaleño Mountains provide habitat for the endangered Mount Graham red squirrel, threatened Gila trout, and threatened Mexican spotted owl. In the vicinity of Mount Graham are the Columbine Administrative Site and recreation residences, a Bible camp, and the Mount Graham International Observatory that includes three research telescopes. Situated mid-slope southeast of Heliograph Peak are a couple hundred recreation residences in Turkey Flat.

Susceptibility

What are the effects to the HVRAs at different fire intensity levels? This component takes into account the potential effect of fire on the HVRAs identified by the administrative agency and additional stakeholders. The IMT had numerous discussions with the CNF and stakeholders to identify and map critical values and assets. The initial list was modified to exclude values and assets within the current fire perimeter and those assets that listed a tactical mitigation, such as obtaining approval for ground-disturbing activities. The HVRAs were categorized into three groups and the groups were prioritized by CNF agency representatives. Each group included sub-HVRAs, essentially the individual assets and values that were identified. For each sub-HVRA, resource staff identified the response function to different fire intensity levels (in this case, three flame-length classes including 0-4 ft, 4-8 ft, and > 8 ft) as being positive, neutral, or negative.

Intensity

What are the predicted fire intensities based on the current fuel conditions? Late June is typically the height of the Southwest's fire season as the fuels are dry and available to burn prior to the arrival of adequate monsoonal moisture. A Basic fire behavior simulation was conducted in FlamMap (Finney 2006), which provides a predicted flame length for every pixel within the planning area based on weather and wind inputs. Since approximately 2 weeks remained until the predicted arrival of monsoonal moisture, inputs were representative of conditions in late June 2017. Live herbaceous moisture of 30 percent and live woody fuel moisture of 90 percent were used, representing fully cured and two-thirds cured conditions, respectively. Dead fuel moistures of 3 percent, 3 percent, and 5 percent were used for 1-hr, 10-hr, and 100-hr fuels, respectively. The Scott and Reinhardt (2001) crown fire method was used. Gridded winds were initialized at 270° using WindNinja (Wagenbrenner et al. 2016) in FlamMap, producing wind speeds of 8 to 15 mph with ridgetop winds of approximately 30 mph based on wind speed ranges observed in the fire area the previous week.

Likelihood

How likely is it that any given area will burn? This component includes the likelihood, or probability, for the HVRAs to be affected within a specified timeframe. In this case, a 14-day Fire Spread Probability (FSPro, Noonan-Wright et al. 2011) analysis was used. FSPro simulates thousands of potential fire perimeters using different weather scenarios informed by current conditions and the historical record of the selected Remote Automated Weather Station (RAWS) to produce ensemble burn probabilities. Noon Creek RAWS at an elevation of 4,925 ft was used for weather data as it represented lower elevations within the fire area. Columbine RAWS at an elevation of 9,521 ft was used for wind data as it represented wind speed and direction based on field observations and direction of fire growth. A total of 3,000 fires were simulated in FSPro.

Net Value Change

Net value change is the net change in value of an HVRA when it burns. For the Frye Fire, we explored conditional net value change (cNVC) and expected net value change (eNVC). The cNVC includes susceptibility and intensity; eNVC is the product of cNVC and likelihood. Once the HVRA groups were identified, the relative importance for each HVRA and sub-HVRA were identified. Relative importance scores provide quantitative weights to distinguish the importance of HVRAs and sub-HVRAs in the net value change products and are a key step when there are multiple overlapping values and assets. Both cNVC and eNVC were calculated in ArcGIS using Python scripts.

RESULTS

Susceptibility

The HVRAs were categorized into three prioritized groups, including (1) built assets, (2) natural and cultural resources, and (3) ecosystem function. Built assets included structures, improvements, infrastructure, and private lands (fig. 1). Natural and cultural resources included critical terrestrial and aquatic habitat, range allotment infrastructure, and archaeological sites (fig. 2). Ecosystem function includes 12 fire groups created by combining ecological response units with similar historical fire regimes (fig. 3) and are consistent with the fire groups used in the Regional Wildfire Risk Assessment.

The response functions (table 1) were provided by CNF staff representing wildlife, fisheries, range, and fire in addition to agency representatives. Some of the values for response functions, notably Residentially Developed Populated Areas (RDPA), transmission lines, communication sites, and the fire groups used for ecosystem function were derived from the Regional Wildfire Risk Assessment.

Intensity

The area predicted to burn with flame lengths greater than 8 ft ranges from the mid to higher elevations in forests in rugged terrain (fig. 4). Predicted flame lengths decrease substantially in the foothills and nonforested ecosystems. The remainder of the analysis area was either nonburnable (rock) or had already burned in the preceding weeks.

Likelihood

Average fire size for the 3,000 simulations was 23,800 ac over the 2-week analysis period, not including suppression actions or growth from burnouts, potential rollout, or spotting due to outflow winds (fig. 5).

Conditional Net Value Change (cNVC)

The cNVC includes susceptibility (table 1) and flame lengths (fig. 4). The cNVC is the average net value change for any pixel within the planning area should it burn during the course of the Frye Fire (fig. 6); the sub-HVRAs that are responsible for creating a negative response under conditions analyzed are identified. This product fostered continued dialog between the CNF and the IMT and directed incident tactics aimed at keeping flame lengths less than 4 ft.

Expected Net Value Change (eNVC)

The expected net value change is the product of the cNVC (fig. 6) and burn probabilities (fig. 5) and displays the net value change if a pixel were to burn (fig. 7). The value of the eNVC is that it allows you to focus on the probability footprint for the specified time period rather than the cNVC for the entire analysis area. The eNVC was used to ensure the incident strategies were aligned with potential losses indicated by negative value change and potential benefits captured by positive value change.

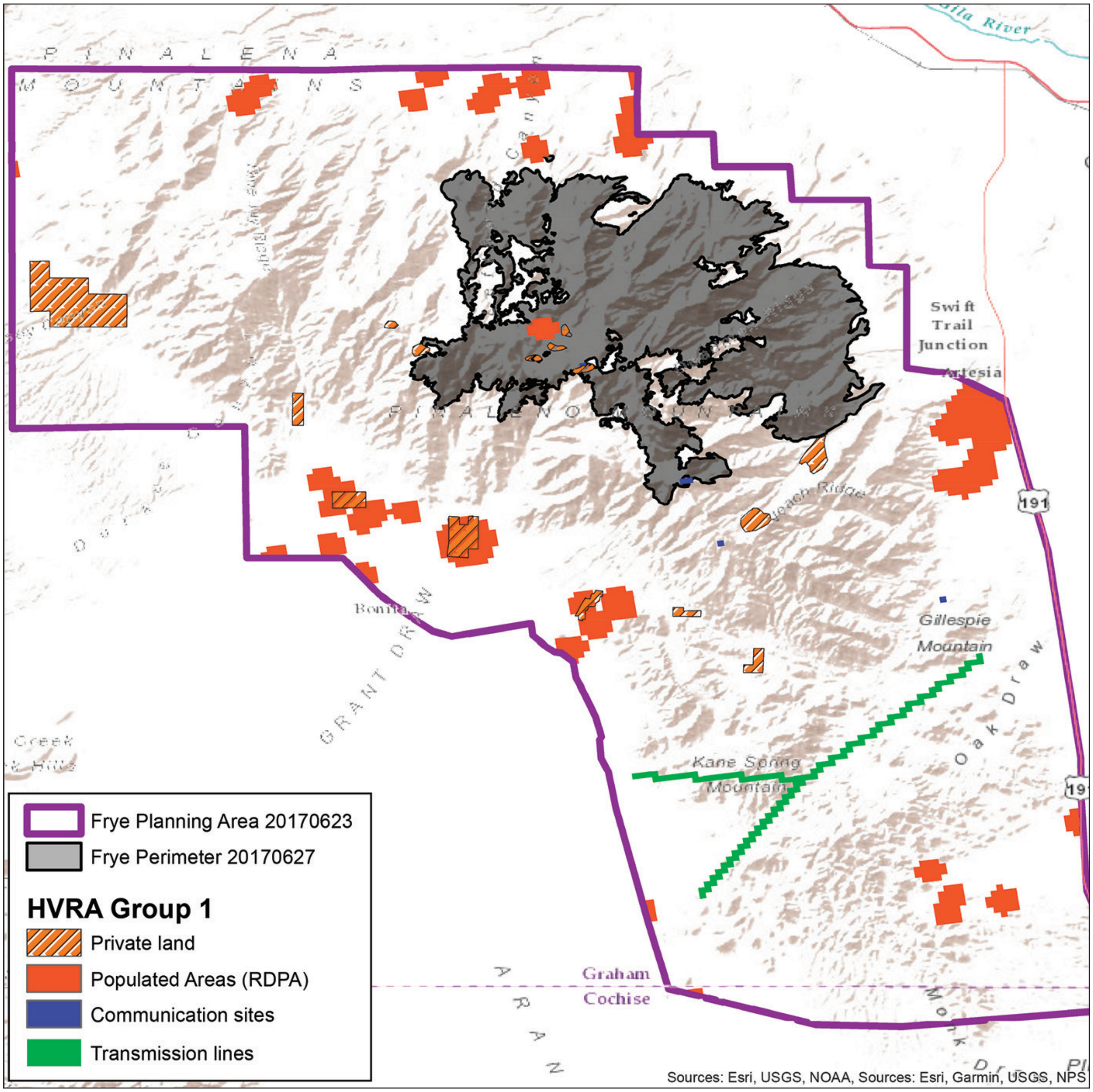

Figure 1—Locations of sub-HVRAs in HVRA Group 1 representing built assets.

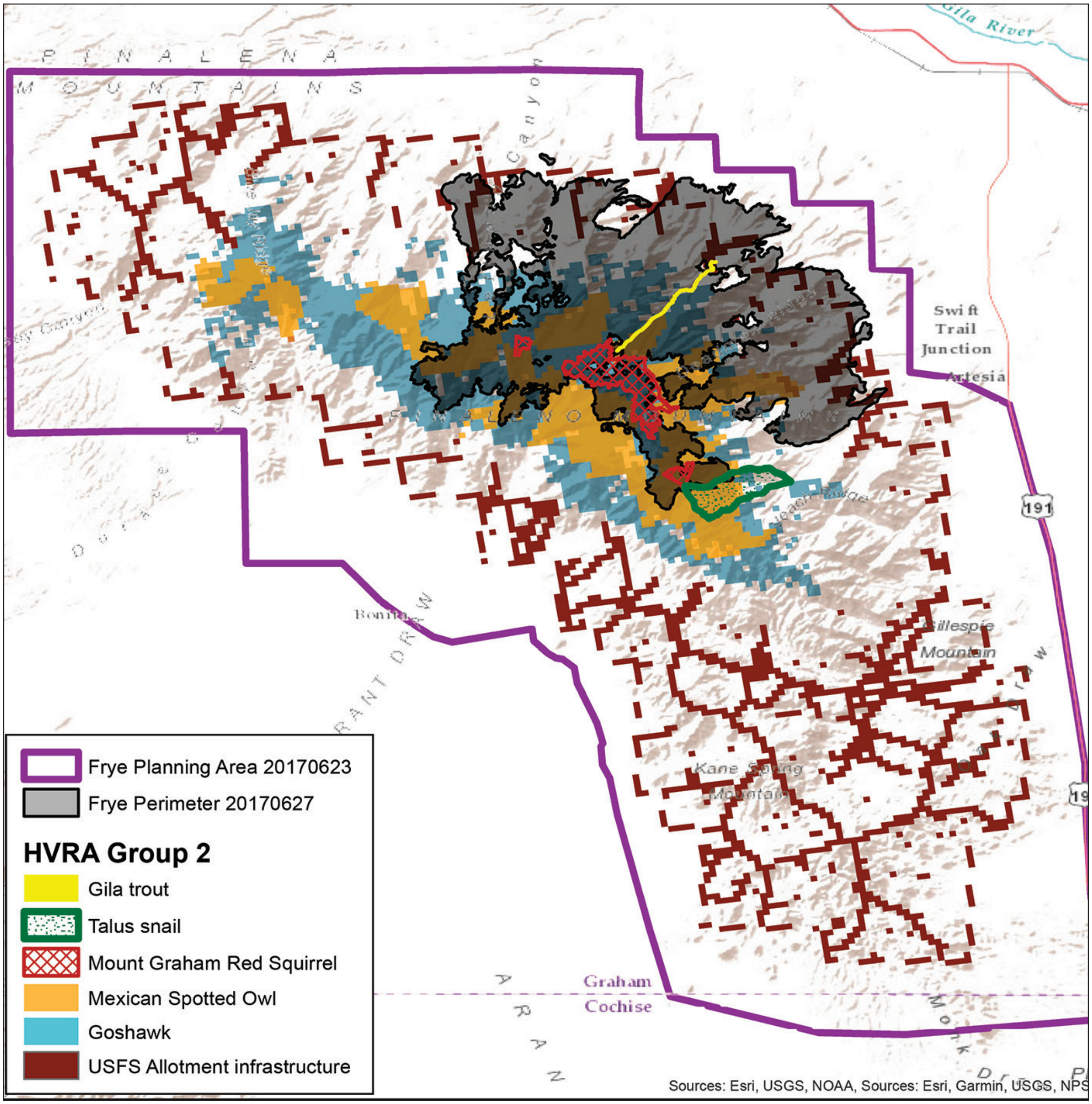

Figure 2—Locations of sub-HVRAs in HVRA Group 2 representing natural and cultural resources. Archaeological sites are not displayed.

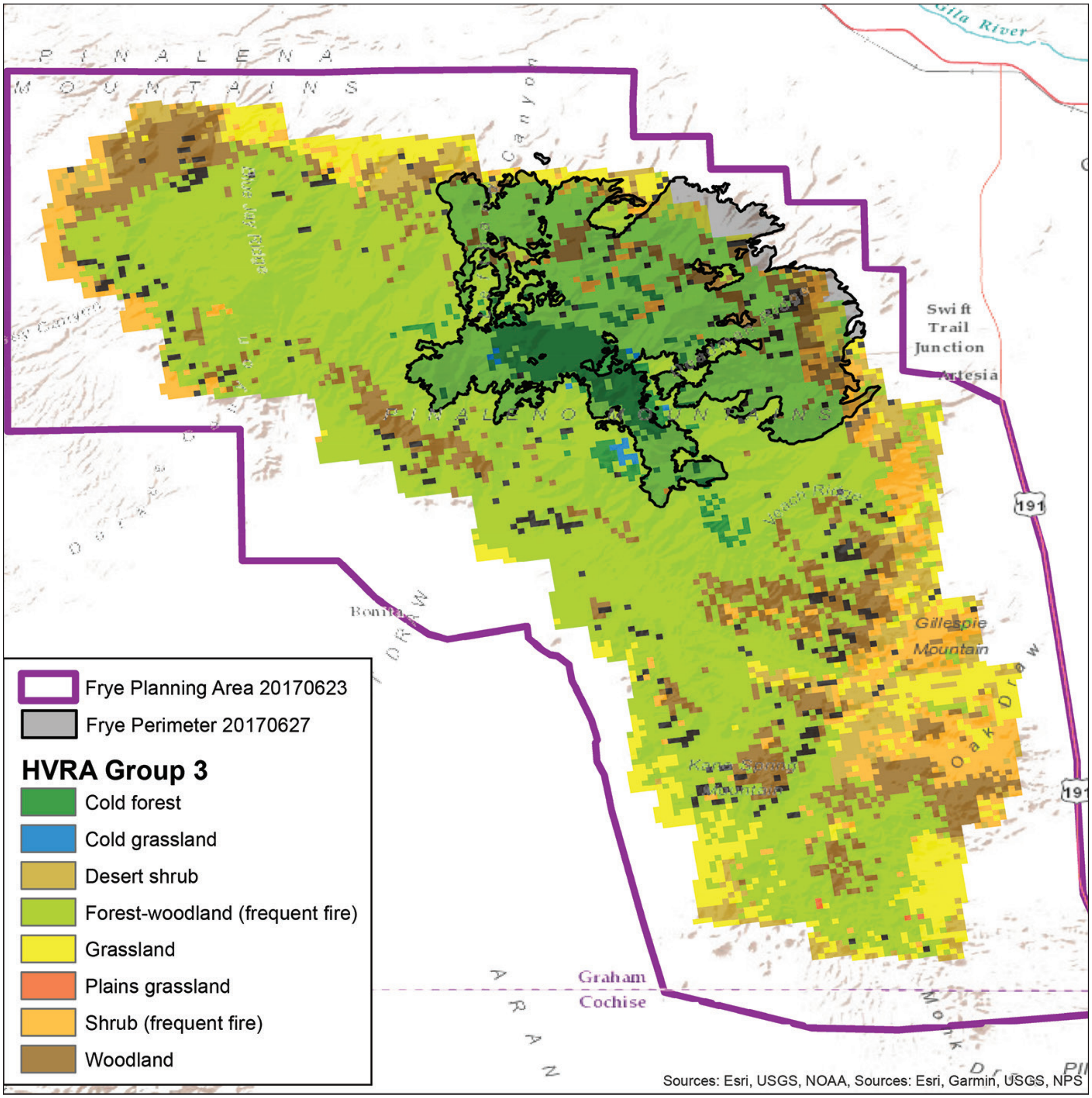

Figure 3—Locations of sub-HVRAs in HVRA Group 3 representing ecosystem function.

Table 1—Response functions of each sub–HVRA to different fire intensities (flame lengths). Negative response functions range from −0.1 (slightly negative) to −1 (fully negative). Neutral response functions are 0. Positive response functions range from 0.1 (slightly positive) to 1 (fully positive).

Group priority	HVRA	Sub–HVRA	Flame length class 1 (0–4 ft)	Flame length class 2 (4–8 ft)	Flame length class 3 (> 8 ft)
1	Built assets	Residentially Developed Populated Areas (RDPA)	−0.4	−1	−1
		Private land and inholdings	−0.4	−1	−1
		Transmission lines	0	−0.4	−1
		Communication sites	0	−0.4	−1
2	Natural and cultural resources	Mexican spotted owl	0.7	−0.2	−1
		Northern goshawk	0.7	−0.2	−1
		Mount Graham red squirrel	0.7	−0.2	−1
		Talus snail	0.6	−0.2	−1
		Gila trout	0.6	−0.2	−1
		USFS allotment infrastructure	0	−0.7	−1
		Archaeological sites	−0.1	−0.2	−1
3	Ecosystem function	Cold forests	1	1	0.8
		Forest-woodland (frequent fire)	1	0.3	−0.6
		Woodlands	1	0.8	0.6
		Grasslands	1	1	1
		Cold grasslands	1	1	1
		Alpine	−1	−1	−1
		Desert shrub	−0.5	−0.7	−0.9
		Salt scrub	−0.5	−0.7	−0.9
		Shrub	1	0.5	−0.4
		Shrub (frequent fire)	0.5	1	1
		Plains shrubland	1	0.8	0.7
		Plains grassland	1	1	1

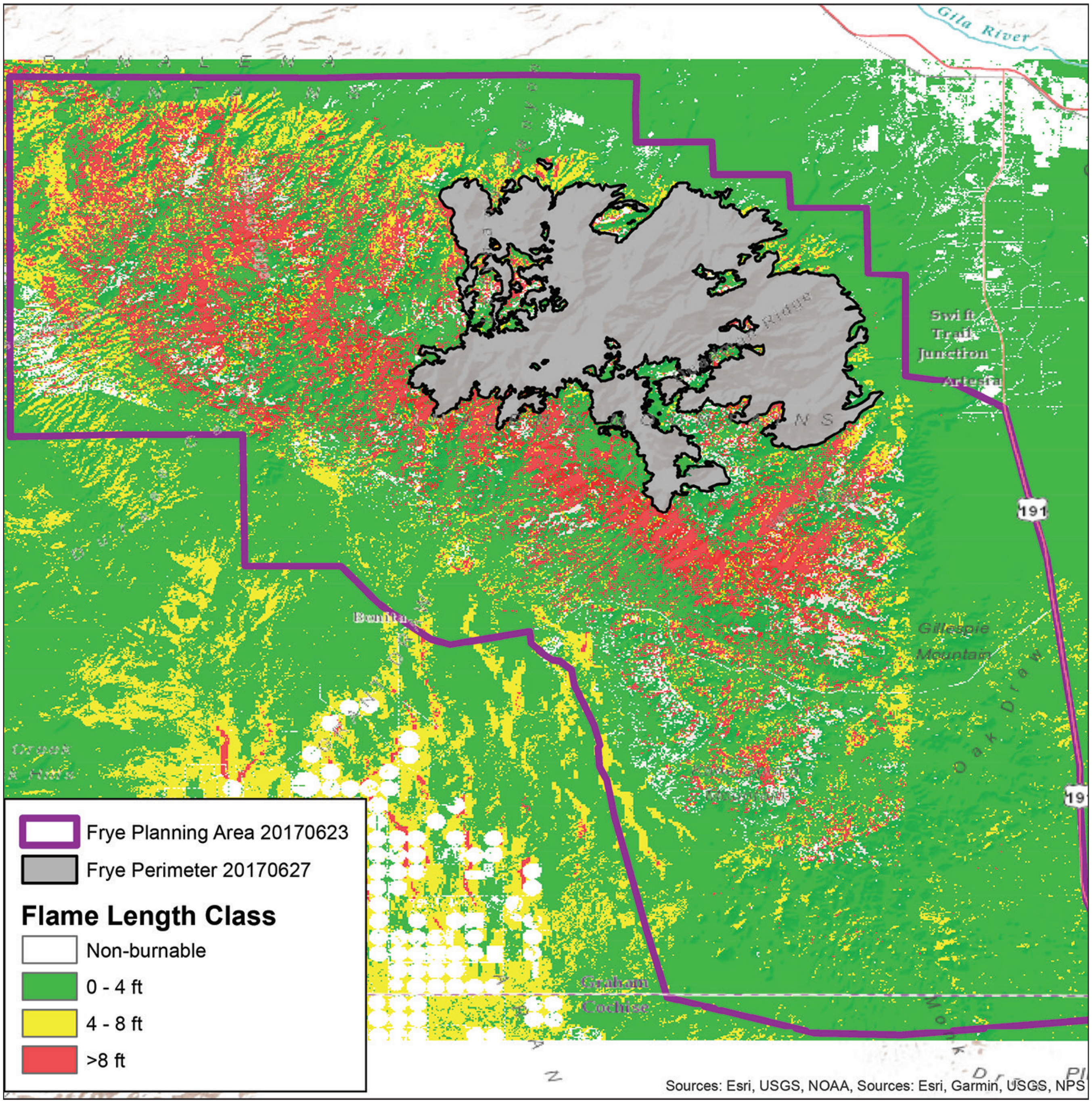

Figure 4—Predicted flame lengths for the Frye Fire for the period representing conditions during the end of June to early July 2017.

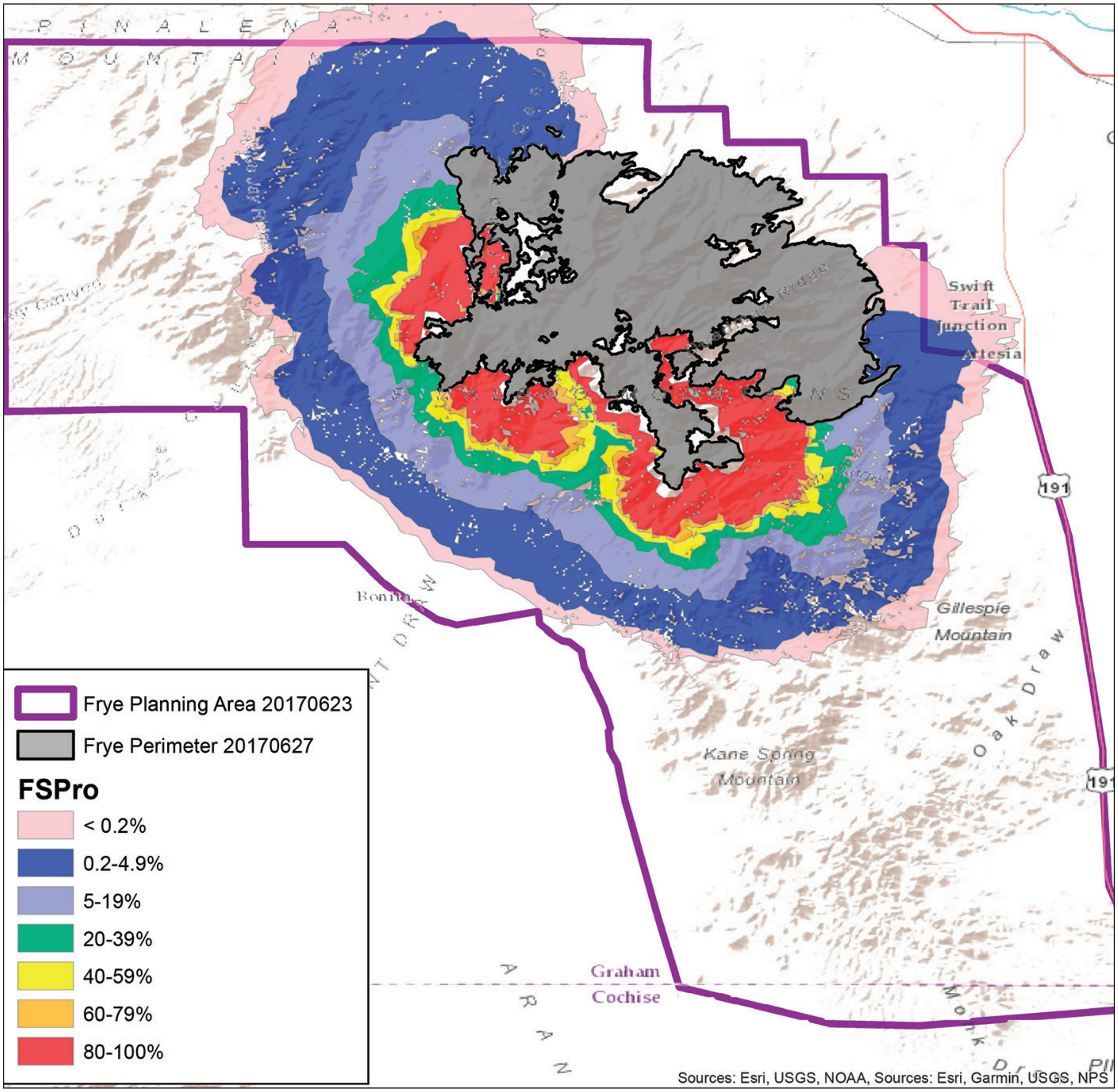

Figure 5—FSPro simulation for the Frye Fire for the period from June 29 until July 12, 2017, displaying burn probabilities for an ensemble of 3,000 individual fires.

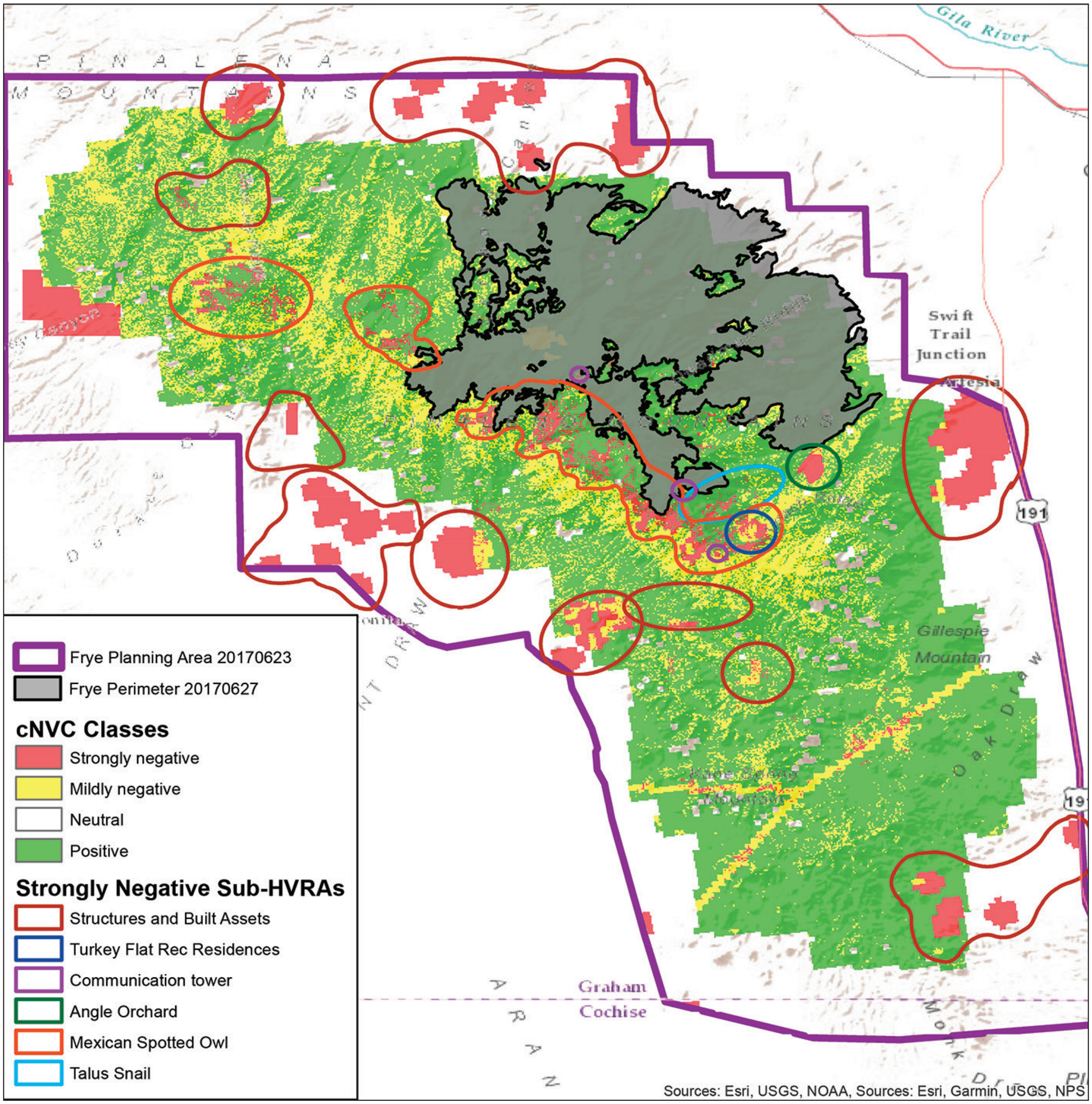

Figure 6—Conditional net value change (cNVC) for the Frye Fire, which combines susceptibility with flame lengths. The sub-HVRAs that showed a strong negative response were identified to provide guidance for incident personnel.

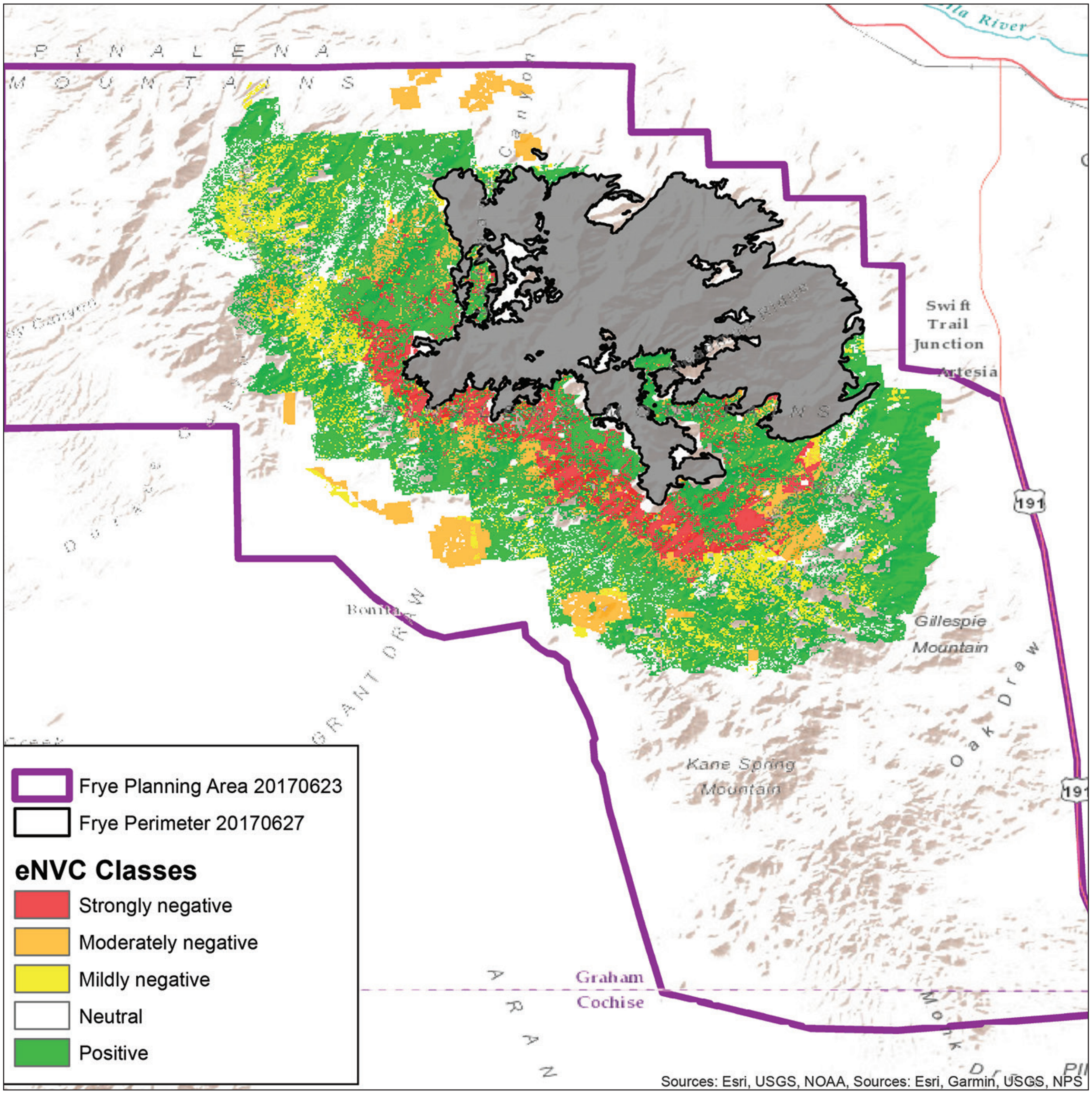

Figure 7—Expected net value change (eNVC) for the Frye Fire. The eNVC combines cNVC with burn probabilities from FSPro.

DISCUSSION

While risk is commonly analyzed during wildfires, the authors are not aware of any other attempts to apply and tailor the wildfire risk assessment methods to an ongoing incident. The Frye Fire cNVC data were compared with the cNVC data from the Southwestern Region Wildfire Risk Assessment (fig. 8). There are some notable differences between the two risk assessments: the Frye Fire used a pixel size of 60 m while the regional assessment used 180 m; the HVRA groups and sub-HVRAs were different as the values and assets for the Frye Fire were locally identified by the CNF and other stakeholders; and the response functions were created by local staff for three flame-

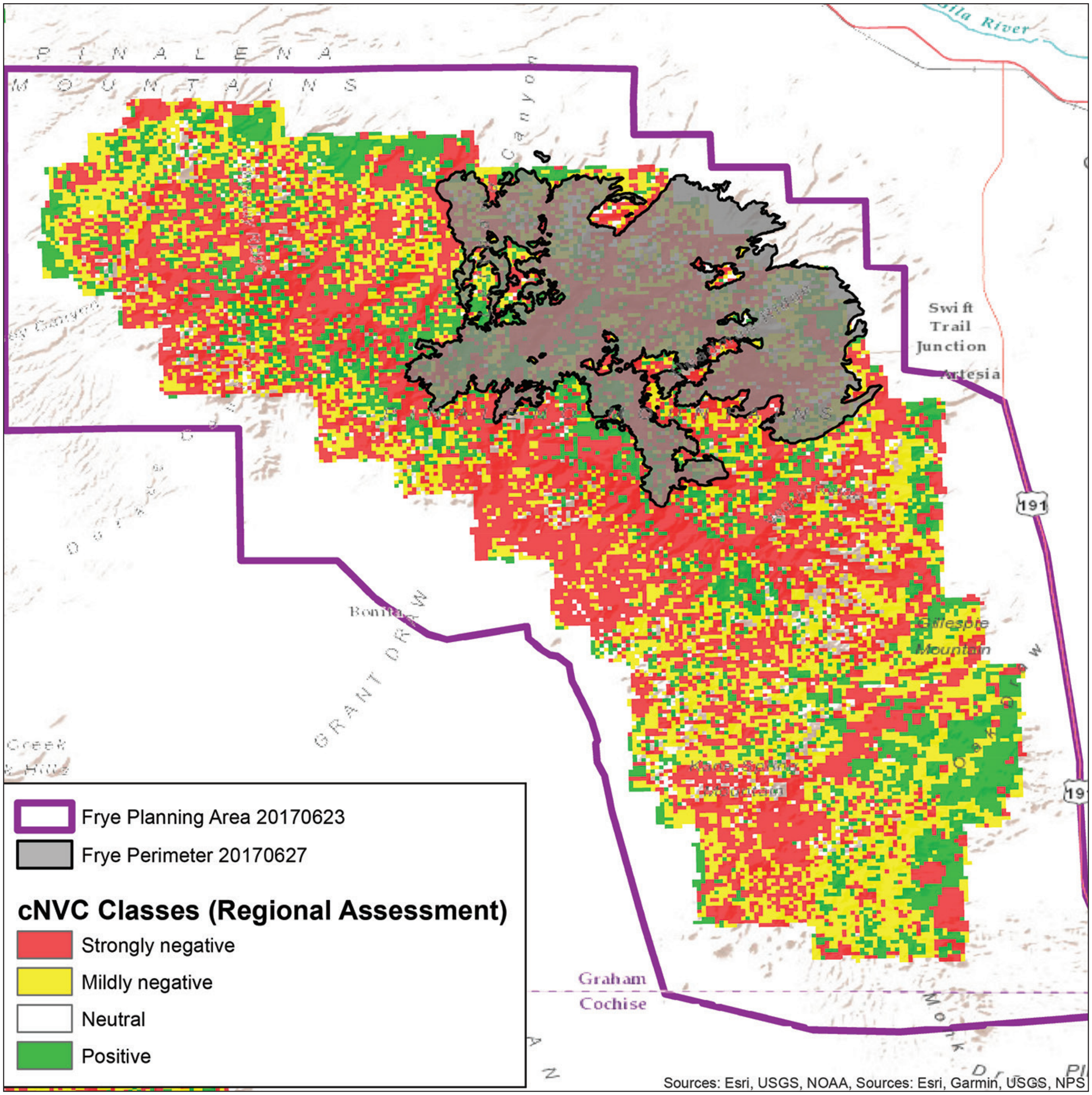

Figure 8—Conditional net value change for the Pinaleño Mountains from the Southwestern Regional Wildfire Risk Assessment (Southwestern Region Fire and Aviation Management 2017).

length classes whereas the regional assessment used conditional flame lengths from the large fire simulator system known as FSim (Finney et al. 2011). The driving reasons to complete this assessment were to guide the management of the fire using incident-specific products rather than the range of weather conditions and regional values and assets used in the regional assessment.

CONCLUSION

What makes an incident a good candidate for an incident-specific cNVC or eNVC? The simplest answer is any incident that has a large number of nested values and assets. Some have made the case that this type of information is most useful for fires that have an incident strategy other than full suppression; however, these products may be applied to a fire with a full suppression strategy that may further guide priorities for operational resources, desired fire effects, and dialog regarding firefighter exposure.

How can this assessment be recreated for another incident? First and foremost, you must find a GIS analyst who has experience using scripts, as that is currently the only way to calculate the products. The GIS analyst could work remotely, but this will create an additional workload for the person at the incident meeting with the local unit and stakeholders and gathering data.

REFERENCES

Finney, M.A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management. 211: 97–108.

Finney, M.A. 2006. An overview of FlamMap fire modeling capabilities. In: Andrews, P.L.; Butler, B.W., eds. Proceedings, fuels management—how to measure success. 2006 March 28-30, Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 213–220.

Finney, M.A.; McHugh, C.W.; Grenfell, I.C.; Riley, K.L.; Short, K.C. 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment. 25(7): 973-1000.

Noonan-Wright, E.K.; Opperman, T.S.; Finney, M.A.; [et al.]. 2011. Developing the U.S. wildland fire decision support system. Journal of Combustion. 2011: 168473. doi:10.1155/2011/168473.

Scott, J.H.; Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Scott, J.H.; Thompson, M.P; Calkin, D.E. 2013. A wildfire risk assessment framework for land and resource management. Gen. Tech. Rep. RMRS-GTR-315. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p.

Southwestern Region Fire and Aviation Management. 2017. Southwestern wildfire risk assessment: 2017 regional wildfire risk assessment results. Unpublished report on file with: U.S. Department of Agriculture, Forest Service, Fire and Aviation Management, Fuels and Fire Ecology, Albuquerque, NM. 41 p.

Wagenbrenner, N.S.; Forthofer, J.M.; Lamb, B.K.; Shannon, K.S.; Butler, B.W. 2016. Downscaling surface wind predictions from numerical weather prediction models in complex terrain with WindNinja. Atmospheric Chemistry and Physics. 16: 5229–5241.

Why Do We Continually Do the Things We Do? Help Wanted in Changing a Mindset About Prescribed Fire in the South

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Abstract—Prescribed fire is a commonly used land management tool in the southeastern United States. Despite its use, there are several issues that are making land management difficult for private forest landowners. We focus on three of the issues. The first is the increased planting of longleaf pine when prescribed fire is withheld from these plantations for too long, allowing stands to fill in with other species. A second major issue is landowners with upland hardwood stands dominated by oaks. They want oaks but refuse to use fire that would aid in oak regeneration. The third issue is the use of fire in the dormant season in pine stands, allowing for the development of a heavy woody component. Private landowners need help to change these practices. How do we in the science world get information to landowners to help change their perspective?

Keywords: prescribed fire, fire return interval, longleaf pine, season of burn, oak management, private landowners, southern United States

INTRODUCTION

Prescribed fire has been a part of land management across most of the South for probably as long as people have been living here. Fire historian Stephen Pyne (1982) noted:

> The South has long dominated national fire statistics, leading in both frequency and acreage burned (page 143)… The fire history of the South is in good part a history of its fuels. … It is the forest understory—the rough, with its tall grass, hardwood saplings, reproduction and vines…—that is the typical fire hazard (page 145)… The regular firing of the woods prevented the fuel buildups that encouraged episodic fires elsewhere, and the fire history of the South is remarkable for the absence of conflagrations until the advent of industrial forestry in the 1930s (page 146).

Industrial forestry changed the use of prescribed fire in the southeastern United States. The tool was removed from the toolbox because fire was viewed as destructive. Today, university people doing forestry extension work face a variety of concerns from landowners when discussing prescribed fire. This paper presents an Alabama landowner's perspective about forest management and the use of prescribed

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

fire. This is important because 67 percent of Alabama is forested and 94 percent of the forests are privately owned (Alabama Forestry Commission 2017).

A major goal is extension work is to help landowners with management issues. The Auburn University School of Forestry and Wildlife Sciences has a demonstration forest to aid landowners in making management decisions. The Mary Olive Thomas Demonstration Forest (MOT) is a 162-ha (400-acre) tract of land just 8 km (5 miles) from the Auburn University main campus. It was bequeathed to the Alabama Cooperative Extension System in 1977 with the stipulation that it be used for the purpose of forest demonstration. Management has been delegated to the School of Forestry and Wildlife Sciences. The overall management objective for MOT is to develop and maintain the property to meet the needs of extension, teaching, and research so as to maximize the benefit to Auburn University and the people of the State of Alabama. There are several ongoing demonstrations on MOT and we focus on three: lack of fire in young longleaf pine (*Pinus palustris* Mill.) plantations; the fear of damaging hardwoods with the use of prescribed fire; and the effects of dormant-season fire on the hardwoods underneath a pine overstory.

PRIVATE LANDOWNER ISSUES

Mr. Franklin Randle is a native-born Southerner. He has been exposed to and has been aware of prescribed fire and its effects, both positive and negative, for most of his life. He has been intrigued by the use of fire to manage a property, but for whatever reason thought that large acreages were needed to employ this powerful tool. He thought one had to a have a pine plantation to utilize prescribed fire. Since he had neither large acreage, nor a pine plantation, he thought prescribed fire had no place on his farm.

Mr. Randle's first experience with prescribed fire issues began with the decision to plant longleaf pine on a highly eroded site after several failed attempts to establish improved pasture. He realized fire was integral to the establishment and maintenance of longleaf pine and associated species. A site prep burn was conducted in late fall, followed by planting. He quickly saw that fire was a valuable tool for reducing fuel loads and putting control pressure on undesirable species. However, a limited knowledge of technique and a couple of inadequacies in preparations nearly resulted in a couple of fire escapes. This left him vexed and, as a result, he did not follow up with prescribed fire for several years. Subsequently, he saw how much more quickly an area could grow up in undesirable species after only one fire.

He decided he needed to learn all he could to most effectively employ fire as a management tool on his farm. Extensive reading on the role of fire in forest/grassland ecology led him to realize that not only should he be regularly burning his longleaf stand to maintain and proliferate its grass/herbaceous groundcover, but that also his mesic hardwood timberland, hitherto unutilized, should have a fire regime reintroduced to promote a similar ground cover. As a grazer of sheep, Mr. Randle found the prospect of periodically grazing the flock through the wooded acreage of the farm appealing.

In reading various historical accounts of the region, it became apparent that the landscape upon which his farm lies consisted of wooded grasslands with a fire return interval of 1-5 years. This challenged his preconceived notion that the hardwood area was natural or healthy or how it should be. From his reading, it certainly seemed that it would not have the structure it now has—one of an almost completely closed canopy allowing almost no sunlight through thus eliminating the possibility of a grass-based ground cover to develop or thrive. Additionally, we determined that for the desired oak species (white, southern red, northern red, post), as well as hickories and yellow poplar to proliferate themselves for future generations, regeneration would be necessary. Upon walking through the stand, we observed that the only desirable hardwood regeneration taking place was also where remnant ground cover existed. These areas coincided with openings in the canopy allowing adequate sunlight to reach the ground to support this expression.

The first hurdle in achieving his management goals was to convince family members to allow the use of fire on the farm. In general, they had three major concerns. First, they did not want to use fire in the hardwood stand. The belief that fire does not belong in hardwoods, as it will kill the trees, is common in this region of Alabama. However, with a couple of walks through the stand Mr. Randle was able to show the lack of regeneration of the preferred species, as well as bring awareness to the substantial increase in highly undesirable species such as Chinese privet, autumn olive, kudzu, sweetgum, and red maple.

Mr. Randle has realized the importance of prescribed fire for what he wants to accomplish with his property through reading and through observation. His issues and concerns are those we have dealt with for years from an education, research, and extension perspective in a university setting. The following information from three demonstrations at MOT helped Mr. Randle in making management decisions.

LACK OF FIRE IN YOUNG LONGLEAF PINE PLANTATIONS

At the turn of the 20th century, longleaf pine forests dominated the southeastern United States, covering an estimated 24-36 million ha (59-89 million acres) (Frost 1993). These forests were very open, the result of frequent fires due to lightning strikes (Chapman 1932) and possibly aided by Native Americans. By the 1990s, around 1.2 million ha (4 million acres) remained (Outcalt and Sheffield 1996). Longleaf pine has been reduced to 3 percent of its former range and has been labeled as one of the most endangered ecosystems in the country (Noss et al. 1995). Several causes have been noted for the demise, including over-logging, fire suppression, industrial forestry, and urbanization (Frost 1993; Ware et al. 1993). The decline in longleaf pine acreage and a policy of fire suppression have put hundreds of plants and animal species in peril, with over 30 species listed as federally endangered or threatened (Van Lear et al. 2005).

Since the late 1990s, there has been a renewed interest in longleaf pine management, conservation, and restoration. One of the major efforts is “America’s Longleaf Initiative,” a collaborative effort of public and private-sector partners. Launched in 2009, this Initiative has a 15-year goal to increase the longleaf acreage from 1.4 to 3.2 million ha (3.4 to 7.7 million acres) by 2024 (Regional Working Group for America’s Longleaf 2009). This is a worthy goal, but the important question for longleaf pine is its future management. Planting longleaf pine seedlings is not enough for successful restoration; active management is key.

In 1995, Hurricane Opal passed to the west of Auburn, resulting in the loss of mature loblolly pine (*Pinus taeda*) across 50 ha (123.6 acres) of MOT. As part of a reforestation effort, the decision was made to replant a 7.7-ha (19-acre) area in longleaf pine at a density of 1,648 seedlings ha^{-1} (680 seedlings acre^{-1}). To prepare the site, the area was site-prepped and herbicide applied to control competing vegetation. The cost in 1996 of this restoration was \$776 ha^{-1} (\$320 acre^{-1}). First-year survival was less than 50 percent. The following year more longleaf was planted in areas where there had been mortality. Unfortunately, prescribed fire was not used as a management tool and the stand began to seed in with loblolly pine, water oak (*Quercus nigra*), and sweetgum from adjacent stands.

As part of two School of Forestry classes, field laboratory exercises were conducted to estimate the density and basal area of overstory trees, defined as trees whose crowns were getting light from above and some from the side, and density of shrub species. The density and basal area of longleaf pine averaged 180 trees ha^{-1} (436 trees acre^{-1}) and 2.3 m^2 ha^{-1} (10 ft^2 acre^{-1}), respectively. For loblolly pine, the density and basal area averaged 1,310 trees ha^{-1} (3,170 trees acre^{-1}) and 16.5 m^2 ha^{-1} (69.3 ft^2 acre^{-1}), respectively. Hardwood stems, dominated by water oak and sweetgum, averaged 1,295 stems ha^{-1} (3,134 trees acre^{-1}) and 13.3 m^2 ha^{-1} (55.9 ft^2 acre^{-1}). Despite planting, longleaf pine was not a dominant component of the forest vegetation.

The ecology of longleaf pine indicates it evolved with a frequent fire return interval (FRI). Over most of its range, this interval may have been every 1-5 years (Chapman 1932). In the early 1900s, it was realized that fire was a necessary management technique for regeneration of longleaf pine. One of the major reasons for the decline in longleaf pine in the early 1900s was fire suppression. Fire is critical in the early stages of longleaf pine’s life (Chapman 1932). Gifford Pinchot (1899) wrote in a National Geographic article that longleaf pine was the rare exception among trees in that it could survive fire when it was less than

10 years old because of its grass-stage. Failing to burn young longleaf stands goes against its nature. Heyward (1939) studied several stands across the South and provided information on the composition of burned and unburned longleaf forests. His research showed that hardwoods were a problem in longleaf pine stands that had experienced 10 or more years of fire suppression, especially if the hardwoods were larger than 5 cm (2 inch) d.b.h.

As the data gathered by the two courses showed, planting by itself does not lead to the successful establishment of longleaf pine. The situation where a longleaf pine plantation seeds in with other species is not unique; it is happening all across the southeastern United States where longleaf is being planted. Longleaf pine stands need to be burned early in their life and often, approximately every 1-3 years. If young plantations of longleaf pine are not burned early, then the longleaf pine will be few and far between.

FEAR OF USING FIRE IN UPLAND HARDWOOD MANAGEMENT

The second issue we often hear from landowners is that "we want oaks but we do want to use fire in these stands." Successful oak regeneration and management has two main requirements: the presence of competitive oak regeneration and timely release of this oak regeneration (Loftis 2004). In xeric forests, regeneration of oak is dependent on the accumulation of advance reproduction and the creation and maintenance of the conditions that favor such accumulation (Smith and Miller 1993). Another issue is the poor retention and growth of oak seedlings already present (Lorimer et al. 1994). Many landowners are not aware of the need for proper conditions to facilitate oak regeneration through natural means. To achieve the conditions needed, prescribed fire can be the most important and cost-effective tool to use. However, this is the last thing that comes to mind when landowners think about hardwood management.

An extensive review of the literature determined that larger diameter oaks and yellow poplar should not be adversely impacted by properly conducted prescribed fires. Frequent, low-intensity fires are a natural part of upland southern hardwood systems. Oak seedlings are naturally adapted to fire. They develop strong root bases before they begin growing upwards, which initially is quite slow. As a result, fire will only topkill oak seedlings, and the powerful oak root base will resprout growing stronger each time so that it is eventually able to outcompete other faster-growing species. With lack of fire, upland oaks are often outcompeted by faster-growing species and will eventually die due to lack of sunlight. The proper use of fire will kill and reduce oak competition, allowing them to develop.

In 2014, we initiated a project at MOT to demonstrate how prescribed fire can be used in southern upland hardwood management. Approximately 4 ha (10 acre) on MOT was selected because of its high proportion of oaks and hickories in the overstory. No management activities had been conducted in over 30 years other than a firewood salvage in 1996 after Hurricane Opal caused many overstory trees to topple.

The results of this inventory showed that the stand averaged 33 trees ha^{-1} (138 trees acre^{-1}) and 22.9 m^2 ha^{-1} (96 ft^2 acre^{-1}). Basal area/acre per species group were 5.3 (22.3), 4.2 (17.5), 4.1 (17.3), and 5.0 (21.2) m^2 ha^{-1} (ft^2 acre^{-1}) for white oaks (*Quercus* spp.), red oaks (*Quercus* spp.), yellow-poplars, and hickories respectively. Notable species found in the overstory consist of white oak, northern red oak, post oak, yellow poplar, pignut hickory (*Carya glabra*), and American beech (*Fagus grandifolia*). The midstory is comprised mostly of American beech of both small and large diameters. American beech accounted for 1.9 m^2 ha^{-1} (8 ft^2 acre^{-1}). The understory is relatively open, lacking much in the way of advance regeneration of desirable species and had a developed leaf litter layer.

In mid-March 2015, we conducted a prescribed fire in the hardwood stand. We had four people run lines, each about 36 m (120 ft) apart, to avoid a large flaming front. The winds were less than forecasted and, in some areas, there was little fire movement. It was estimated that about 65 percent of the stand burned, removing about the same percentage of leaf litter. During the following summer and fall, we did visual checks of trees to assess basal stem damage to overstory trees. Oaks, yellow poplar, and hickories sustained no damage. However, there was some damage to smaller stems of American beech but no mortality was seen.

Since we did not get the coverage we had hoped from the 2015 fire, we burned the stand again in March 2016. We followed the same procedure but this time picked a day with lower humidity, 40-45 percent, and higher winds, 5-8 kph (3-5 mph). This time we got 100 percent coverage of the stand and complete leaf litter layer removal using the same ignition techniques as the 2015 fire. This fire did have an impact on the American beech, causing mortality in the smaller diameter classes, less than 15 cm (6 inch) d.b.h., and basal damage to some of the larger beech trees. We also noticed considerable die-back in the tops of many of the beech trees. The oaks, yellow-poplars, and hickories continued to show no signs of basal stem damage. With this burn, we saw a slight increase in oak regeneration, particularly white oak regeneration for a few months after the fire. By the end of the 2016 growing season, there was no surviving oak regeneration. We cannot say if the mortality was due to the dense shade created by the overstory or the drought experienced by the State—probably a combination of both factors.

A similar approach to burning the stand was followed in 2017. The stand was burned in early March, 2 days after a 2.5 cm (1 inch) rain and again we had complete consumption of the forest floor. There has been no sign of visual damage to the base of the oaks, hickories, and yellow-poplars. However, we are seeing more mortality in the smaller diameter beech trees.

Our take-home message was that you can burn in upland hardwood stands and you will need to if you are interested in getting advanced oak regeneration before any removal of overstory trees happens. You do have to pay attention to conditions on-site and what the day of burn conditions are. We have worked hard at burning on days when there is rapid movement of fire through the stand and not allowing for a longer residence time around the bases of the hardwoods.

USE OF WINTER (DORMANT-SEASON) PRESCRIBED FIRE

The third issue is that most landowners who use prescribed fire in pine plantations conduct burns during the winter (dormant season). Their hope is the fire will bring about a grassy understory to benefit wildlife. Instead, what they often get is an understory dominated by stems of sweetgum and water oak.

Recently developed models suggest that prior to the 1800s, large areas of the United States burned multiple times a decade (Guyette et al. 2012). The southeastern United States experienced the most frequent FRI, possibly as short as every 1.5 to 4.0 years (Frost 2006; Guyette et al. 2012). An important result of these very short FRIs was to create and maintain an open tree canopy with a diverse herbaceous ground layer (Van Lear et al. 2005).

The landscape that early settlers in the southeastern United States encountered was largely the result of frequent, low-intensity, nonlethal fires that swept through presettlement forests every 2 to 10 years (Chapman 1932; Mattoon 1922). These fires were ignited by a combination of lightning strikes (Komarek 1974) and aboriginal burning (Robbins and Myers 1992).

However, across much of the modern landscape, this natural process of frequent fire has functionally been eliminated. In the absence of fire, forested stands develop a thick undergrowth of broad-leaved species and the diversity of herbaceous vegetation declines due to decreased light and increased litter depth (Peet and Allard 1993).

In 1996, a demonstration was established on MOT to assess the impacts of different FRI with fires conducted during the winter (dormant) season. The plots were set up in a loblolly pine stand planted in 1979. There are three replicates: (1) 1-year FRI, (2) 2-year FRI, (3) three-year FRI; and a (4) no-burn treatment. For the most part, these fires have been happening from mid-January to mid-March.

What do the dormant-season fires do? It is all a matter of perspective. Figure 1 was taken during December 2017, just before the area was to be burned, and this 1-year FRI stand has the appearance of being dominated by grasses and herbaceous plants. However, if you look at the area from your knees down (see the dark line in fig. 1), you will see sweetgum stems making up a good portion of the understory. Data have never been collected on the density of these stems but there are easily several hundred to the acre. With the increase in the time between fires, i.e., a longer FRI, there is an associated increase in the number of hardwood stems, especially sweetgum. Figure 2 illustrates a 3-year FRI with the photograph taken

Figure 1—One-year FRI taken in December, 9 months after burning on the Mary Olive Thomas Demonstration Forest near Auburn, Alabama. (Photo by John Kush.)

Figure 2—Three-year FRI taken in April, 33 months after burning on the Mary Olive Thomas Demonstration Forest near Auburn, Alabama. (Photo by John Kush.)

in April 2018 over 2 years since the last burn. There are several thousand sweetgum stems to the acre, a majority of them 1.2-2.1 m (4-7 ft) tall. There are several hundred sweetgum stems that are 7.6 cm (3 inch) d.b.h. and bigger.

Despite sweetgum being a species very sensitive to fire, the winter burns at MOT are not eliminating the stems. In fact, the 2-year and 3-year FRI appear to be increasing the density of sweetgum stems. The fire top-kills the stem and this results in 2-4 stems sprouting from the base of the top-killed sweetgum.

CONCLUDING COMMENTS

Through university classes and extension programs, we try to make future land managers and current landowners aware of the need for prescribed fire in young longleaf pine plantations, its need in the management of upland hardwoods, and its need for use during the growing season if landowners do not want off-site hardwood stems in their pine stands. We have shown that demonstrations exist of what not to do; we are in need of more examples of what to do and we need to figure out a better way to get that message across. The fuels are changing in the South and they are not changing for the better. This is our call to the science world to get information to landowners to help change their perspective on the use of prescribed fire in the South.

REFERENCES

Alabama Forestry Commission. 2017. Forest resource report: 2017. https://www.forestry.alabama.gov/PDFs/AlabamaForestResourceReport.pdf.

Chapman, H.H. 1932. Is the longleaf type a climax? Ecology. 13(4): 328-334.

Frost, C.C. 1993. Four centuries of changing landscape patterns in the longleaf pine ecosystem. In: Hermann, S.M., ed. Proceedings of the 18th Tall Timbers Fire Ecology Conference. Tallahassee, FL: Tall Timbers Research Station.

Frost, C.C. 2006. History and future of the longleaf pine ecosystem. In: Jose, S.; Jokela, E.; and Miller, D., eds. Longleaf Pine Ecosystems: Ecology, Management, and Restoration. New York: Springer-Verlag: 9-42.

Guyette, R.P., Stambaugh, M.; Dey, D.C.; Muzika, R. 2012. Predicting fire frequency with chemistry and climate. Ecosystems. 15: 322–335.

Heyward, F. 1939. The relation of fire to stand composition of longleaf pine forests. Ecology. 20(2): 287–304.

Komarek, E.V. 1974. Effects of fire on temperate forests and related ecosystems: Southeastern United States. In: Ahlgren, C.E.; Kozlowski, T.T., eds. Fire and ecosystems. New York: Academic Press.

Loftis, D.L. 2004. Upland oak regeneration and management. In: Upland oak ecology symposium: history, current conditions, and sustainability. Spetich, M.A., ed. Gen. Tech. Rep. SRS–73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 311 p.

Lorimer, C.G.; Chapman, J.W.; Lambert, W.D. 1994. Tall understory vegetation as a factor in the poor development of oak seedlings beneath mature stands. Journal of Ecology. 82(2): 227–237.

Mattoon, W.R. 1922. Longleaf pine. U.S. Department of Agriculture Bulletin, 1061.

Noss, R.F.; LaRoe, E.T.; Scott, J.M. 1995. Endangered ecosystems of the United States: a preliminary assessment of loss and degradation. USDI National Biological Service, Biological Report 28. 58 p.

Outcalt, K.W.; Sheffield, R.M. 1996. The longleaf pine forest: trends and current conditions. Res. Bull. SRS-9. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Peet, R.K; Allard, D.J. 1993. Longleaf pine vegetation of the southern Atlantic and eastern Gulf Coast regions: a preliminary classification. In: Hermann, S.M., ed. Proceedings of the 18th Tall Timbers Fire Ecology Conference: the longleaf pine ecosystem: ecology, restoration, and management. Tallahassee, FL: Tall Timbers Research Station.

Pinchot, G. 1899. The relations of forests and forest fires. National Geographic Magazine. 393-403.

Pyne, S.J. 1982. Our pappies burned the woods: a fire history of the South. In: Fire in America: A cultural history of wildland and rural fire. Princeton, NJ: Princeton University Press.

Regional Working Group for America's Longleaf. 2009. Range-wide conservation plan for longleaf pine. http://www.americaslongleaf.org/media/86/conservation_plan.pdf.

Robbins, L.E.; Myers, R.L. 1992. Seasonal effects of prescribed burning in Florida: a review. Miscellaneous Publication No. 8. Tallahassee, FL: Tall Timbers Research Station.

Smith, H.C.; Miller. G.W. 1987.Managing Appalachian hardwood stands using four regeneration practices—34-year results. Northern Journal of Applied Forestry. 4(4): 180-185.

Van Lear, D.H.; Carroll, W.D.; Kapeluck, P.R.; Johnson, R. 2005. History and restoration of the longleaf pine-grassland ecosystem: implications for species at risk. Forest Ecology and Management. 211: 150-165.

Ware, S.; Frost, C.C.; Doerr, P.D. 1993. Southern mixed hardwood forest: the former longleaf pine forest. In: Martin, W.H.; Boyce, S.G.; Echternacht, A.C., eds. Biodiversity of the Southeastern United States: lowland terrestrial communities. New York, NY: John Wiley & Sons.

Fire History (1889–2017) in the South Fork Flathead River Watershed within the Bob Marshall Wilderness (Montana), Including Effects of Single and Repeat Wildfires on Forest Structure and Fuels

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Abstract—Wilderness areas offer value to society as a source of scientific information. We used fire perimeter records from the upper South Fork Flathead River watershed (Montana) to characterize the area burned one or more times during three periods: the pre-fire exclusion period (1889–1934), the fire exclusion period (1935–1980), and the fire management period (1981–2017). We also quantified the effects of a recent reburn on forest structure and fuels using a before-after-control-impact study design. Total area burned and area burned multiple times depended strongly on time period. The active fire regime during the fire management period mirrored total area burned and area reburned in the pre-exclusion period. At once-burned sites, fuel loads for most fuel types increased or were stable from 2011 to 2015, reflecting ongoing deposition of fire-killed branches and trees. In contrast, the second fire either reduced or maintained surface fuels in 2015 relative to 2011 levels. Seedlings decreased significantly in the twice-burned plots while there was no change in once-burned plots; live overstory tree densities were stable over time in both once- and twice-burned plots. Managers can use the results presented here to inform the design and monitoring of forest landscape restoration prescriptions.

Keywords: fire effects; fire management; reburns; wilderness management; wildland fire use

INTRODUCTION

Wilderness areas offer value to society as a source of scientific information. Large wilderness areas provide unparalleled opportunities to develop and test scientific theories about the causes and consequences of natural disturbances (Miller and Aplet 2016). For example, they have been critical for testing theory about self-limiting wildfire severity and spread (Collins et al. 2007; Parks et al. 2015b), river channel dynamics and forest-stream interactions (Hauer et al. 1999; Montgomery and Abbe 2006), and couplings between upland wildfires and fluvial habitat dynamics through the delivery of sediment and large wood to the channel network by debris flows (Benda and Bigelow 2014). Much of the scientific value of large wilderness areas is derived from the untrammeled character of disturbance-driven landscape systems, for example, active fire regimes in which lightning-ignited wildfires are allowed to burn, and large alluvial rivers with unimpeded flow and channel migration (fig. 1). Intensively managed lands in which fires are suppressed, hillsides are logged, rivers are dammed,

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Figure 1—Aerial oblique view (looking south) showing the 2013 Damnation Creek fire reburning an area of old-growth western larch/mixed-conifer forest previously burned by the 2000 Helen Creek fire alongside the South Fork Flathead River, Bob Marshall Wilderness, Montana, USA. Much of the scientific value of large wilderness areas is derived from the untrammeled character of disturbance-driven landscape systems; for example, active fire regimes in which lightning-ignited wildfires are allowed to burn, and large alluvial rivers with unimpeded flow regimes and channel migration (photo: J. Flint, USFS).

and geomorphic processes are altered by road building do not provide the same scientific opportunities as large wilderness areas for understanding natural disturbance processes.

The use of wilderness areas as scientific observatories is consistent with the purpose and intent of the Wilderness Act of 1964. Yet wilderness areas have long been underutilized for scientific purposes (Franklin 1987), even as their potential scientific value to society grows due to land conversion, increasing human population, and anthropogenic climate change. For example, wilderness areas provide control areas with which to compare active management strategies for climate change adaptation (Belote et al. 2015a, 2017). Research in wilderness also contributes to the design and improvement of sustainable forest management practices used outside wilderness areas, including silvicultural treatments that produce commercial timber (Hopkins et al. 2014).

Since the early 1980s (fig. 2), managers have allowed many lightning-ignited fires to burn with minimal interference in forests of the Bob Marshall Wilderness (BMW) in northwestern Montana (Smith 1986). This accumulated mosaic of fires affords important opportunities to investigate wildfire effects on forest structure, postfire tree regeneration, and fuel loads in forest ecosystems.

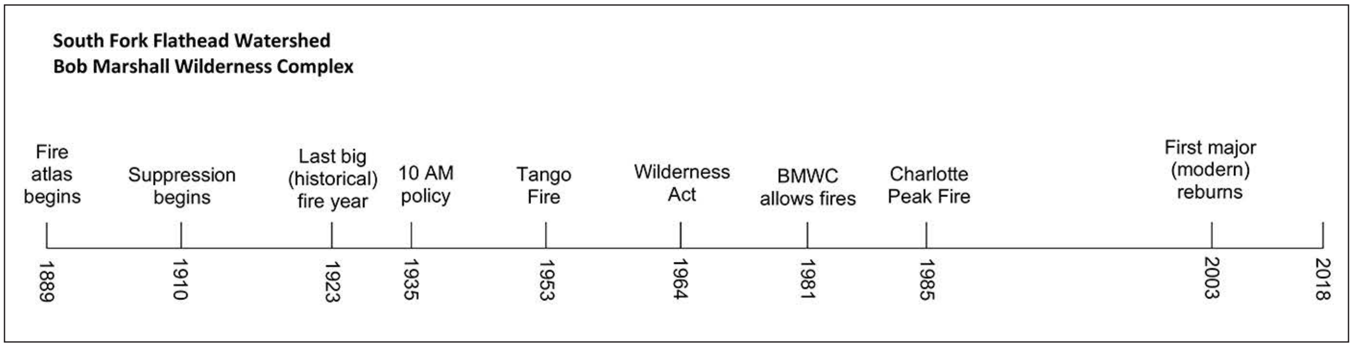

Figure 2—Timeline of fire and fire management activity in the upper South Fork Flathead River watershed within the Bob Marshall Wilderness, Montana, USA. Key management changes include implementation of the 10 AM policy in 1935, and the decision to allow for fire management within the Bob Marshall Wilderness in 1981.

Of particular scientific interest are the comparative effects of single and repeat wildfires (also called reburns) on forest vegetation and fuels. Short-interval reburns (less than about 25 years between fires in western conifer forests) can have strong effects on fuels (Stevens-Rumman and Morgan 2016; Ward et al. 2017), vegetation composition and structure (Coop et al. 2016; Coppelatta et al. 2016), and postfire successional trajectory (Larson et al. 2013). One challenge to studying reburn effects is the inability to impose experimental control over wildfire events. Consequently, most reburn studies have been retrospective, with no experimental control or prefire measurements. This is particularly true in wilderness areas, where regulations prohibit experimental manipulations.

The subject of this study is the fire history since 1889 in the upper South Fork (SF) Flathead River watershed within the BMW, including effects of single and repeat wildfires on tree regeneration, forest structure, and fuels. Our first objective was to characterize the area burned one or more times in each of three management periods: the pre-fire exclusion period (1889–1934), the fire exclusion period (1935–1980), and the fire management period (1981–2017). Our second objective was to investigate the effects of a recent reburn event on tree regeneration, forest structure, and fuels using a before-after-control-impact (BACI) (Green 1979) study design in old-growth western larch (*Larix occidentalis*)/mixed-conifer forest.

METHODS

Study Area

The study area comprises the portion of the upper SF Flathead River watershed (above Bunker Creek) within the BMW, Montana, an area of 222,243 ha. Elevation along the main stem of the SF Flathead River within this area ranges from 1,183 to 1,436 m; maximum elevation within the watershed is 2,834 m. Forest composition within the valley is dominated by lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*), western larch, Engelmann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*), with minor amounts of ponderosa pine (*Pinus ponderosa*) (Arno et al. 2000; Belote et al. 2015b; Keane et al. 2006; Larson et al. 2013). High elevation sites support whitebark pine (*Pinus albicaulis*) and alpine larch (*Larix lyallii*), and fires in the BMW burn to the alpine treeline (Cansler et al. 2016), where they influence structural complexity of the alpine treeline ecotone (Cansler et al. 2018). Native Americans used the area more or less continuously from at least 1665 to 1938 based on tree ring dating of bark peeling scars on old ponderosa pine trees (Östlund et al. 2005).

Fire History

We divided the fire management history for the study area into three time periods: pre-exclusion, exclusion, and fire management. We defined the pre-exclusion period as all years before 1935. Although the creation of the Forest Service, Department of Agriculture in 1905 meant that some backcountry fire suppression activity did occur between 1905 and 1934, it was largely ineffective due to lack of personnel and technology (Koch 1935; Pyne 1982). Instead, climate largely drove fire activity prior to 1935 (Heyerdahl et al. 2008; Morgan et al. 2008).

The exclusion era began in 1935 (fig. 2) with the initiation of the 10 AM policy at the national level, which stated that all fires should be attacked with the purpose of suppression before 10 o'clock the following morning (Silcox 1935). The increase in firefighting crews and equipment during this period, combined with a climatic shift to generally cooler springs and wetter summers, made backcountry fire suppression more effective (Morgan et al. 2008; Pyne 1982). However, following the passage of the Wilderness Act in 1964 and the subsequent success of the White Cap wilderness fire management program in the Selway-Bitterroot Wilderness (Idaho and Montana), the 10 AM policy was abandoned in 1978 (Smith 2014; van Wagtendonk 2007; Wilderness Act 1964). By 1981, managers began allowing some lightning-ignited fires within the BMW to burn in the Danaher Creek drainage, thus beginning the fire management period in our study area (fig. 2). A fire plan for the entire BMW was put in place in 1983 (Flathead National Forest 1983a,b).

We compiled preexisting fire atlases for the northern Rocky Mountains (Gibson et al. 2014; Parks et al. 2015a). The Gibson atlas provided fire perimeters for 1889 through 1978 for the study area, whereas the Parks atlas covered 1979 through 2012. We then updated the fire perimeter data to include fires through 2017 using BMW fire perimeters obtained from Spotted Bear Ranger District fire management staff. All fire perimeters were clipped to the upper SF Flathead River watershed boundary (upstream of Bunker Creek), then clipped again to the BMW boundary, and divided by management period for analysis. This allowed us to determine the spatial and temporal differences in area burned one or more times during different management periods.

Field Methods

All fuels and forest structure measurements were made in n = 20 plots, half of which were located in the vicinity of Little Salmon Park on the west side of the SF Flathead River (once-burned plots), and the other half of which were located in the area around the confluence of Damnation Creek and the SF Flathead River on the east side of the river (twice-burned plots). Plot locations were randomly distributed along an approximately 3 km reach of the main valley, centered on the coordinates of 47.66165°N, -113.34091°W and ranging in elevation from 1,340 m to 1,600 m. In the area sampled by our field plots, the west side of SF Flathead River burned in the 2003 Little Salmon Complex Fire. The east side of the river burned in the 2000 Helen Creek Fire, and again in the 2013 Damnation Fire (fig. 1). The area west of the river did not burn a second time. All three fires were ignited by lightning. Multiple cohorts of 200- to over 700-year-old western larch dominated the overstory of these mixed-conifer forests, with lodgepole pine, Douglas-fir, subalpine fir, and Engelmann spruce making up the rest of the tree community. These study areas were selected in an earlier study of postfire tree mortality in old-growth western larch/mixed-conifer forests (Belote et al. 2015b).

We used spatial partitioning of fire events and repeated measurements of plots to establish our BACI design. In 2011, 10 plots were established and sampled on each side of the river to characterize the severity and effects of the 2000 and 2003 fires (Belote et al. 2015b). Half of these plots reburned in the 2013 fire (fig. 1). In 2015, all plots were relocated using global positioning system coordinates and remeasured to compare the twice-burned area on the east side of the corridor to the once-burned area on the west side of the corridor. We used the before reburn (2011) and after reburn (2015) measurements as our before and after with the once-burned plots as our control and the twice-burned plots as the impact.

We censused seedlings, saplings, and live and standing dead trees for all tree species within each plot. For seedlings (<1.37 m tall), we recorded the height class (0–40 cm, 40–80 cm, or 80–137 cm) and species of stems within four 1-m-radius subplots which were centered 6 m north, east, south, and west of plot center, as well as within a 1-m-radius subplot at plot center. To inventory saplings (>1.37 m tall and <20 cm diameter at breast height [d.b.h.]), we recorded the diameter class (0–5 cm, 5–10 cm, or 10–20 cm), status (alive or dead), and species of all saplings within 17.84

m of plot center. For overstory trees (stems ≥20 cm d.b.h.), we recorded the species, diameter, tree type (live standing tree, dead standing tree, or uprooted or snapped (or both) below d.b.h. but inferred to have been standing at time of fire) within 17.84 m of plot center. Additionally, we recorded trees with a d.b.h. greater than 80 cm within 43.7 m of plot center.

To inventory fine wood debris (FWD), we recorded fuels transects based on the planar intersect technique of Brown and Van Wagner (Brown 1974; Van Wagner 1968, 1982). Each plot had four transects which ran north, east, south, and west from plot center. Along each transect, we counted the number of intersections of 1 hour (0–0.64 cm) and 10 hour (0.65–2.54 cm) fuel particles from 3 m to 6 m from plot center. Likewise, we counted the number of intersections of 100 hour fuels (2.55–7.62 cm) from 3 m to 9 m from plot center. We also measured litter (undecomposed organic material) and duff (partially decomposed organic material) depths at 3 m and 9 m from plot center along each transect.

To inventory coarse woody debris (CWD; >7.6 cm diameter), we measured the large-end diameter, small-end diameter, and length of all woody debris particles within the perimeter of a 6-m-radius subplot with its origin located at plot center. If a piece of woody debris tapered to a diameter less than 7.6 cm, the small-end diameter and length were measured only up to the point at which the debris still had a diameter equal to or greater than 7.6 cm. If a piece of woody debris extended beyond the boundary of the 6-m-radius subplot, we recorded only the length within the boundaries of the subplot. We recorded species (if identifiable) and decay class (1–5, with 1 indicating a sound log with no decay and 5 indicating a very decayed log).

Field Data Analysis

We summarized fine fuel (1–100 hour) loads for each plot using Brown's (1974) equations for mixed-species fuels. We classified all CWD as 1,000 hour fuels. To estimate 1,000 hour fuel loads, we approximated the volume of logs as a conical frustum, and estimated wood densities by decay class using values for conifer wood from Liu et al. (2006). Because Liu et al. (2006) used four decay classes, we used the density value from their fourth decay class for our classes 4 and 5.

We tested for significant differences in four BACI contrasts using permutation tests where we randomly shuffled before reburn/after reburn and once-burned/twice-burned labels among plots 10,000 times (Roff 2006). Our contrasts were differences in means (n = 10 plots) of response variables between twice-burned after reburn and twice-burned before reburn (Impact After – Impact Before; IA – IB), once-burned after reburn and once-burned before reburn (Control After – Control Before; CA – CB), before reburn twice-burned and before reburn once-burned (Before Impact – Before Control; BI - BC), and after reburn twice-burned and after reburn once-burned (After Impact – After Control; AI – AC). We calculated two-tailed P-values as the ratio of the number of values at least as large in magnitude (absolute values) as observed values to the number of simulations (10,000). We repeated these analyses for seedling, sapling, and tree (live and dead) densities, fuel loads in each fuel size class (1–1,000 hour), and litter and duff depths. All analyses were performed in the R environment (R Core Team 2018).

RESULTS

Fire History

Our assessment of area burned from the fire history maps revealed that 127,327 ha (314,632 acres) burned from 1889 through 1934 (pre-exclusion), only 585 ha (1,446 ac) burned during the exclusion period, and 117,489 ha (290,321 ac) have burned since the beginning of the fire management period (fig. 3). Our analysis identified 1889, 1910, 2003, and 2017 as major fire years for this study area, or years when the area burned exceeded the 90th percentile of annual area burned from 1889 through 2017 (fig. 4). During these 4 years, 150,709 ha (372,410 ac) burned, which constitutes approximately 61 percent of all area burned over the course of the study period.

The total area and annual rate of area that reburned in the fire management period (9.3 percent cumulatively) were similar to the amounts in the pre-exclusion period (7.6 percent), although there was less area burned three or four times during the fire management period than in the pre-exclusion period (table 1). In contrast, only 0.3 percent of the total area burned, with no reburns, during the exclusion period (fig. 5, table 1). Fire rotation was 79 years, 17,096 years, and

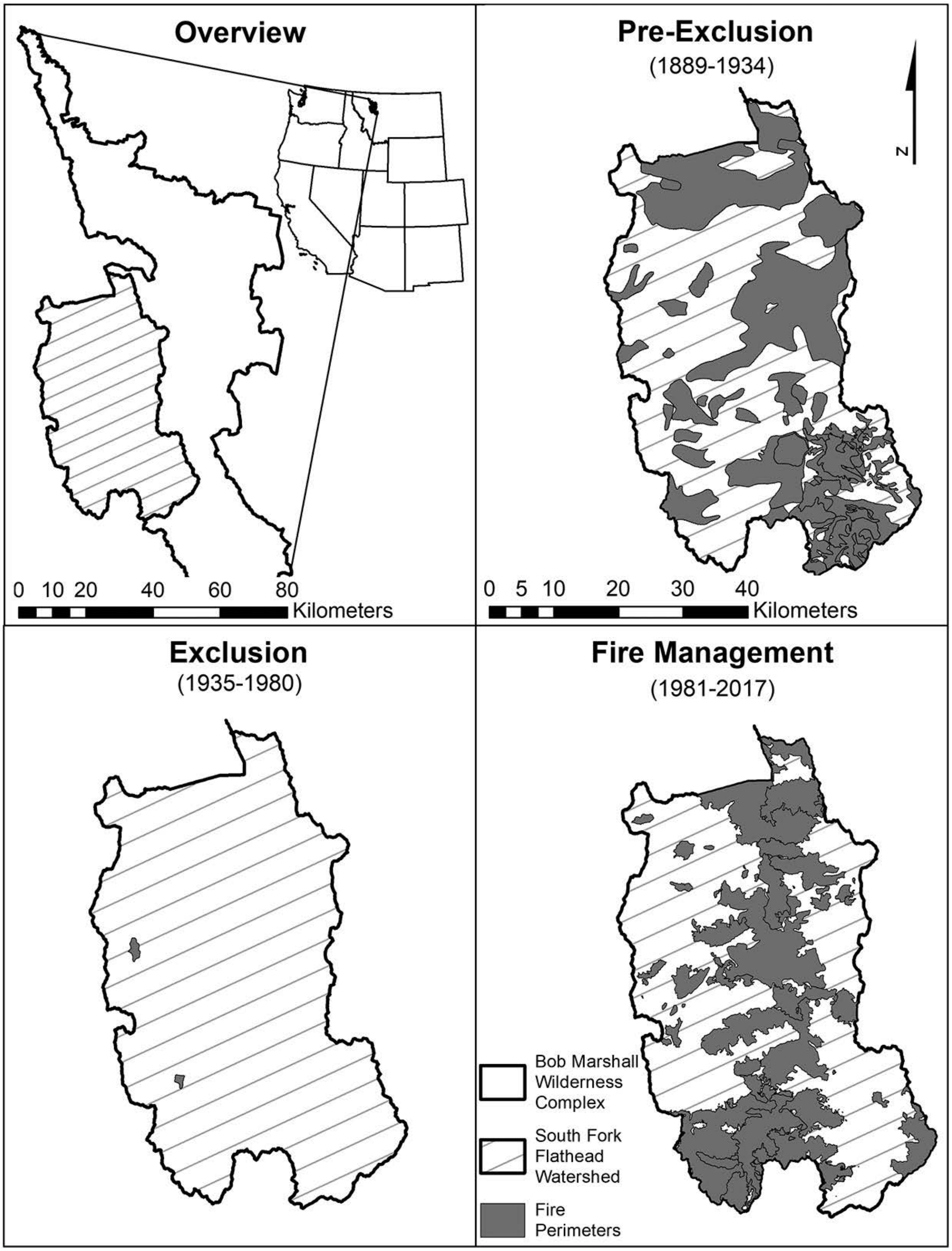

Figure 3—Maps of area burned within the upper South Fork Flathead River watershed of the Bob Marshall Wilderness, Montana, USA during the three contiguous management periods: pre-exclusion (1889-1934), exclusion (1935-1980), and fire management (1981-2017). Fire extent is greatly reduced during the fire exclusion period due to a combination of climatic shifts and increased backcountry suppression activity.

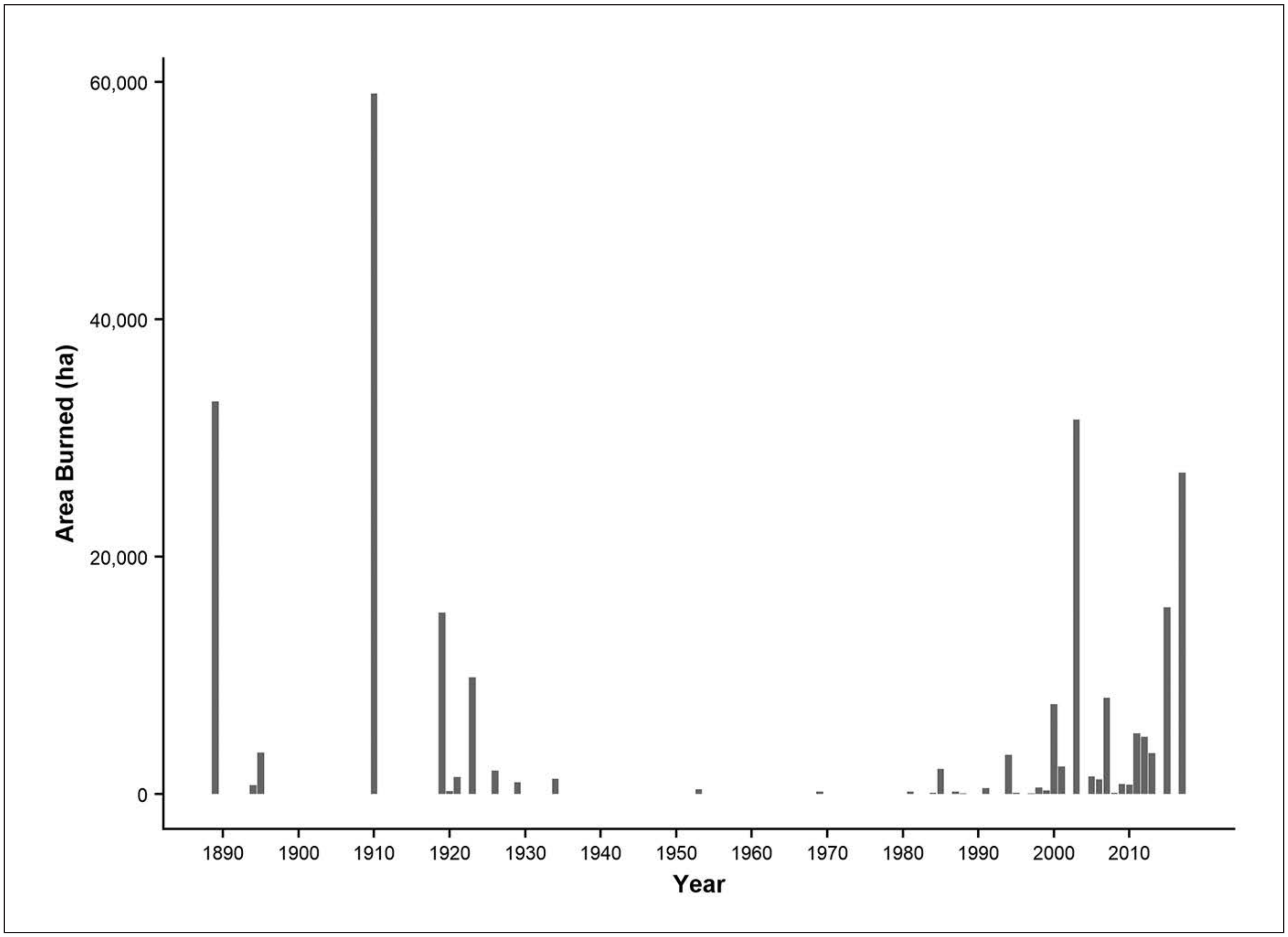

Figure 4—Area burned by year over the course of the fire atlas period. A few years (1889, 1910, 2003, 2017) account for a large percentage of total area burned, consistent with Morgan et al.'s (2008) concept of regional fire years.

Table 1—Results from spatial analyses of area that burned multiple times in the South Fork Flathead River valley (Montana) during three periods.

	Unburned	Burned 1x	Burned 2x	Burned 3x	Burned 4x
Pre-exclusion (1889–1934)					
Total area (ha)	118,386	87,147	10,375	5,701	582
% of area	53.3	39.2	4.7	2.6	0.3
Burn rate (ha yr^{-1})	-	1,936.6	230.6	126.7	12.9
Fire exclusion (1935–1980)					
Total area (ha)	221,606	585	0	0	0
% of area	99.7	0.3	0	0	0
Burn rate (ha yr^{-1})	-	13.0	0	0	0
Fire management (1981–2017)					
Total area (ha)	128,373	73,027	17,968	2,760	63
% of area	57.8	32.9	8.1	1.2	0.03
Burn rate (ha yr^{-1})	-	2,028.5	499.1	76.7	1.7

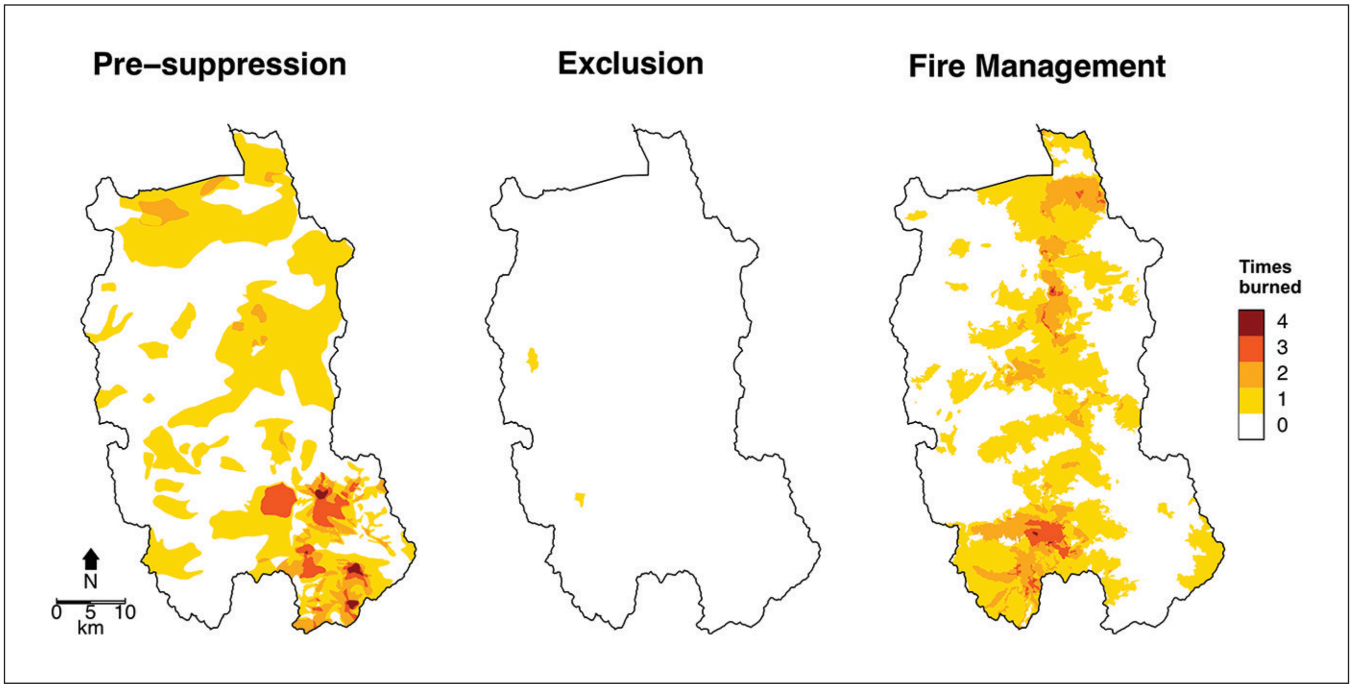

Figure 5—Areas within upper South Fork Flathead River watershed within the Bob Marshall Wilderness, Montana, USA that burned multiple times during three contiguous periods: pre-exclusion from 1889-1934 (45 years), exclusion from 1935-1980 (45 years), and fire-management from 1981-2017 (36 years).

68 years during the pre-exclusion, exclusion, and fire management periods, respectively.

Reburn Effects on Tree Regeneration, Forest Structure, and Fuels

Seedling density decreased significantly in the twice-burned plots while there was no significant decrease in once-burned plots (fig. 6, table 2). Seedling densities were not different between once-burned and twice-burned plots in either before or after periods. Sapling density significantly increased in the once-burned plots but was stable in the twice-burned plots (fig. 6, table 2). Live tree densities were stable over time in both once- and twice-burned plots. There was a marginally significant decrease in standing dead tree density in the once-burned plots, while the twice-burned plots were stable (fig. 6, table 2).

Fine fuels in the 1 hour size class declined in twice-burned plots, with no significant decrease in the once-burned plots (fig. 7, table 3). Accumulation of 10 hour fuels was significant in the once-burned plots, while there was no change in the twice-burned plots. Hundred- hour fuels also accumulated significantly in the once-burned plots and were stable in the twice-burned plots. The large (1,000 hour) fuels were stable over time in both once- and twice-burned (fig. 7, table 3). Litter and duff depths increased significantly without fire in the once-burned plots, with no changes detected in the twice-burned plots (fig. 8, table 3).

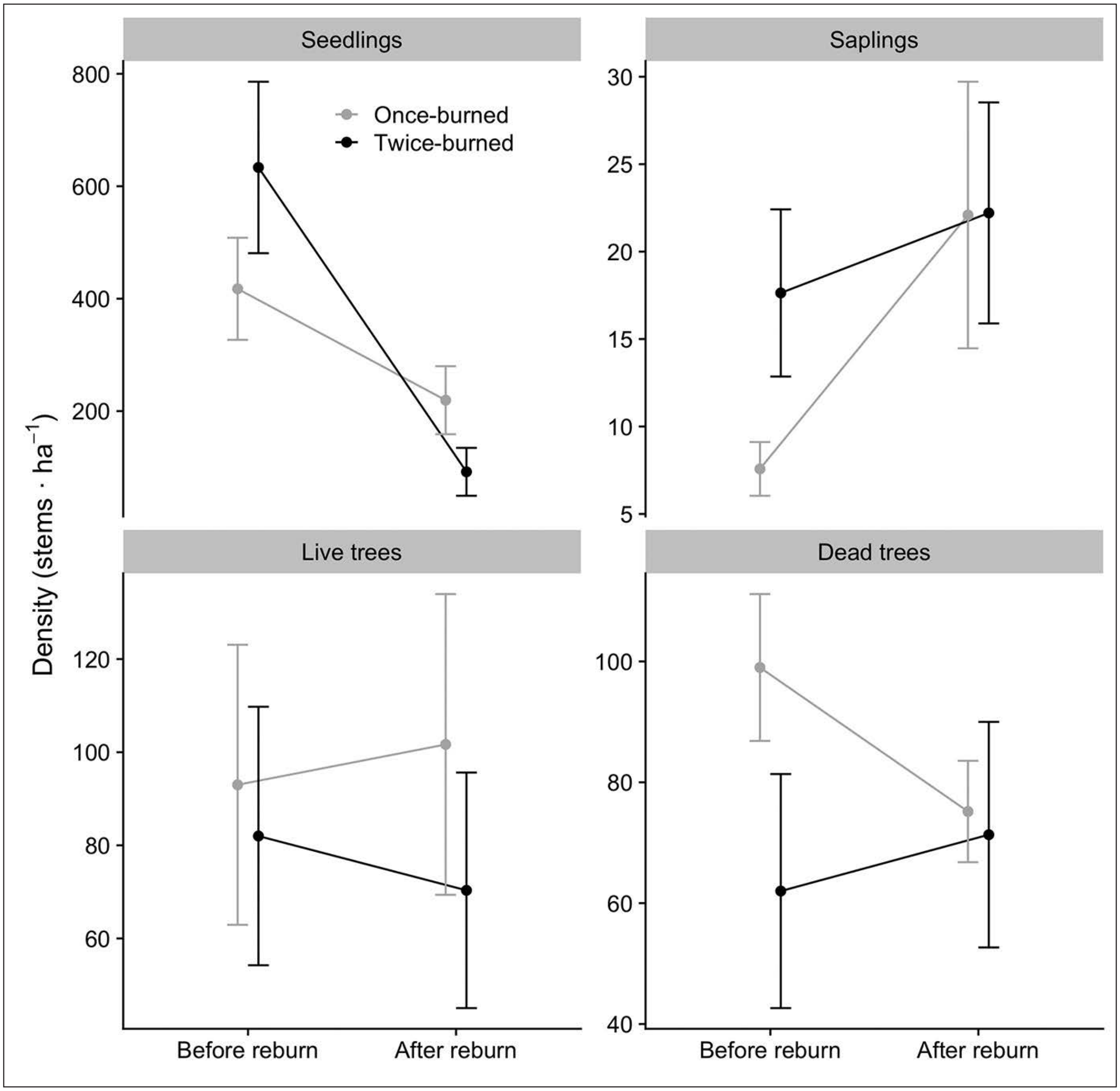

Figure 6—Effects of single and repeat fires on density of seedlings, saplings, and trees. Contrasts are between once-burned plots (2000 or 2003 fire; *n* =10) and twice-burned plots (2013 fire; *n* = 10) and between two sampling times: before reburn (2011) and after reburn (2015). Seedlings are individuals <1.37 m tall, saplings are >1.37 m tall and <20 cm in DBH. Trees are stems ≥20 cm DBH. Values are means with vertical bars representing ±1 standard error.

Table 2—Results from permutation tests on mean differences in seedling, sapling, live tree, and dead tree densities for four before-after-control-impact contrasts in burned area in the South Fork Flathead River valley (Montana). Contrasts are differences between twice-burned after reburn and twice-burned before reburn (Impact After – Impact Before; IA – IB), once-burned after reburn and once-burned before reburn (Control After – Control Before; CA – CB), before reburn twice-burned and before reburn once-burned (Before Impact – Before Control; BI – BC), and after reburn twice-burned and after reburn once-burned (After Impact – After Control; AI – AC). Significant results are indicated in bold with an asterisk. Marginally significant results are indicated in bold only.

	Contrast	Difference in density (stems ha^{-1})	P-value
Seedlings	IA – IB	**-541**	**0.003***
	CA – CB	-198	0.297
	BI – BC	216	0.25
	AI – AC	-127	0.504
Saplings	IA – IB	5	0.538
	CA – CB	**15**	**0.044***
	BI – BC	10	0.169
	AI – AC	0	0.985
Live trees	IA – IB	-12	0.776
	CA – CB	-8	0.833
	BI – BC	-11	0.778
	AI – AC	-14	0.714
Dead trees	IA – IB	9	672
	CA – CB	-24	0.287
	BI – BC	**-37**	**0.092**
	AI – AC	-4	0.866

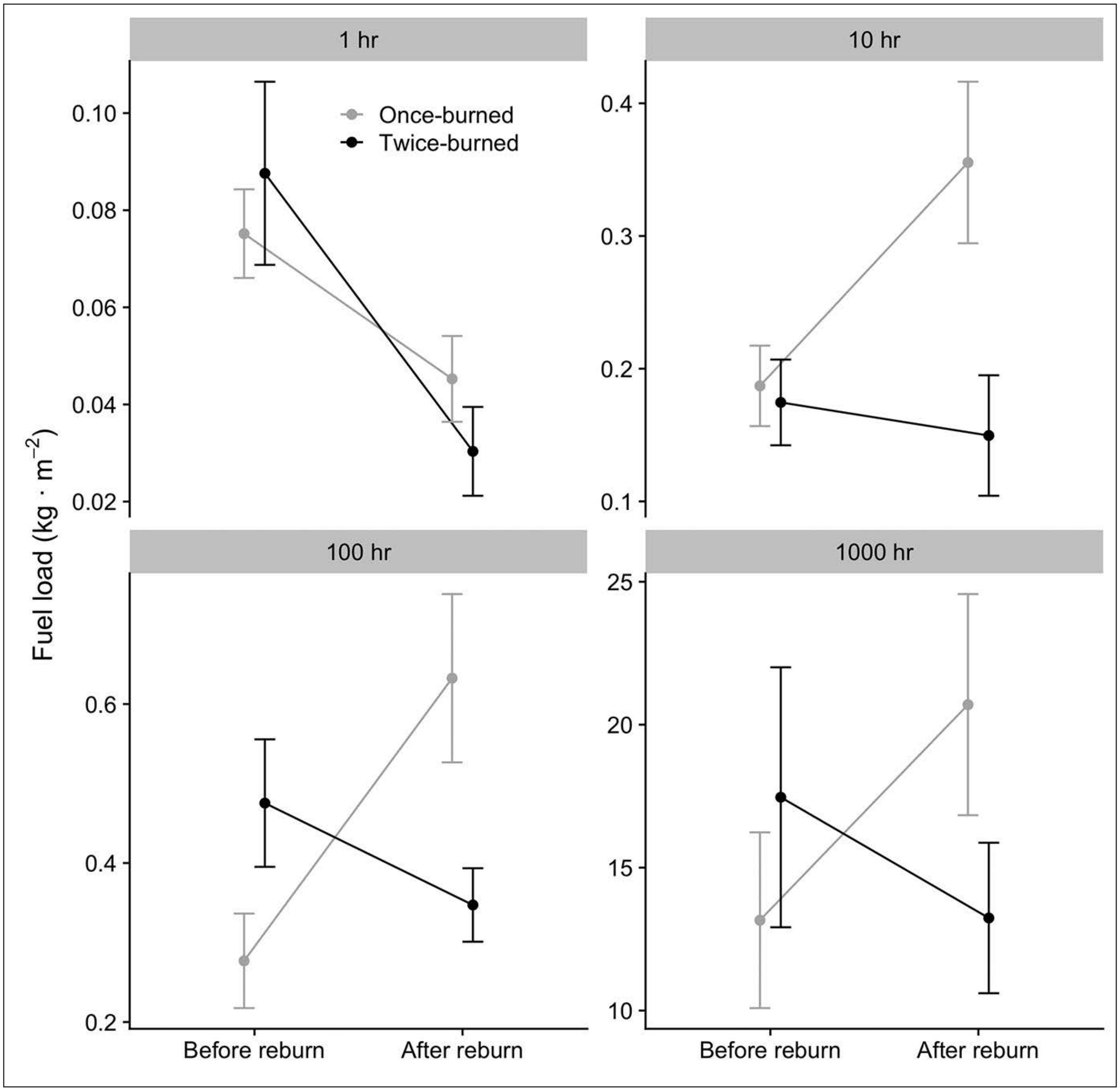

Figure 7—Effects of single and repeat fires on 1-1000 hr fuel loads. Contrasts are identical to those described in figure 6. Fine fuel (1-100 hr) loads were measured and estimated using Brown's (1974) methods. 1 hr fuels are woody debris 0-0.64 cm in diameter, 10 hr are 0.65 - 2.54 cm, 100 hr are 2.55 - 7.62 cm, and 1000 hr are >7.6 cm. Values are means with vertical bars representing ±1 standard error.

Table 3—Results from permutation tests on mean differences in 1 hour, 10 hour, 100 hour, 1,000 hour, litter, and duff fuel amounts for four before-after-control-impact contrasts in burned area in the South Fork Flathead River valley (Montana). Litter and duff are expressed as depth (cm); 1–1,000 hour fuels as load (kg m^{-2}). Contrasts are the same as in table 1. Significant results are indicated in bold with an asterisk. Marginally significant results are indicated in bold only.

	Contrast	Difference in fuel load (kg m^{-2} or cm)	P-value
1 hour fuels	IA – IB	**-0.06**	**0.002***
	CA – CB	-0.03	0.141
	BI – BC	0.01	0.54
	AI – AC	-0.02	0.466
10 hour fuels	IA – IB	-0.03	0.726
	CA – CB	**0.17**	**0.015***
	BI – BC	-0.01	0.869
	AI – AC	**-0.21**	**0.003***
100 hour fuels	IA – IB	-0.13	0.298
	CA – CB	**0.36**	**0.003***
	BI – BC	0.20	0.101
	AI – AC	**-0.29**	**0.017***
1,000 hour fuels	IA – IB	-4.22	0.42
	CA – CB	7.54	0.148
	BI – BC	4.31	0.415
	AI – AC	-7.46	0.155
Litter depth	IA – IB	-0.38	0.507
	CA – CB	**1.04**	**0.053**
	BI – BC	-0.29	0.612
	AI – AC	**-1.71**	**0.001***
Duff depth	IA – IB	-0.01	0.988
	CA – CB	1.21	0.153
	BI – BC	-0.57	0.517
	AI – AC	**-1.79**	**0.033***

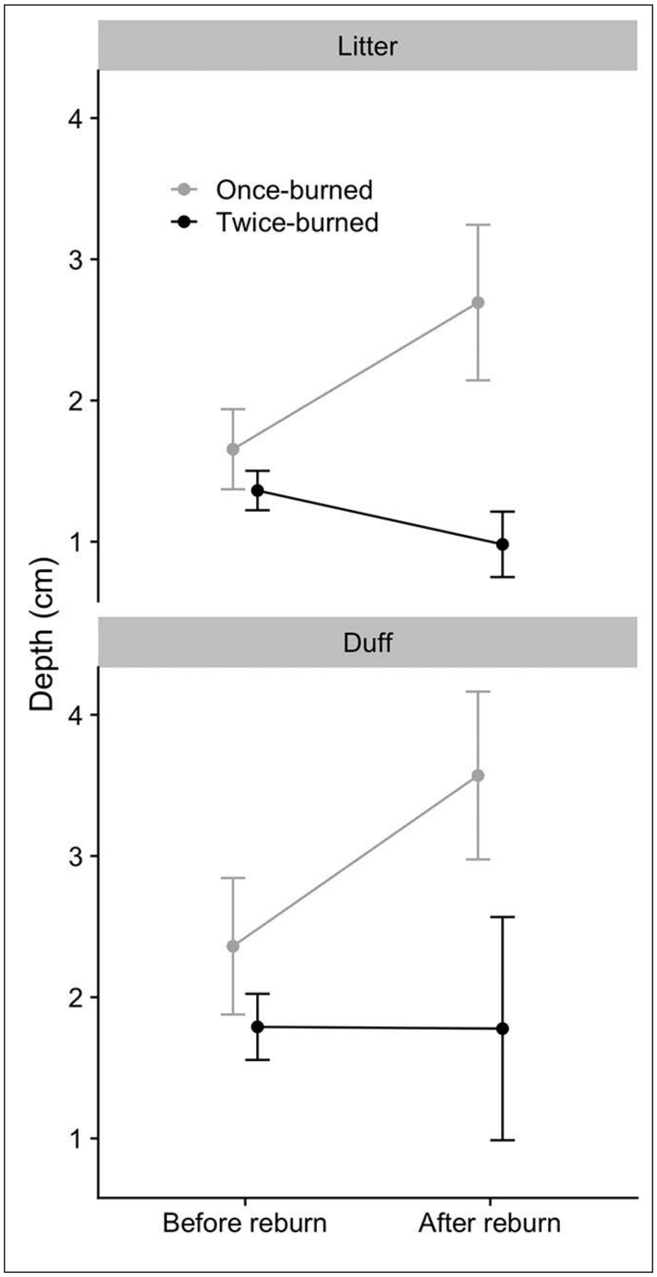

Figure 8—Effects of single and repeat fires on litter and duff fuel depths. Contrasts are identical to those described in figure 6. Litter is organic material that is finer than 1 hr fuels, but is undecomposed. Duff is partially decomposed organic material. Values are means with vertical bars representing ±1 standard error.

DISCUSSION

Fire History

Our analysis of 128 years of fire history data demonstrates that modern reburns have recent precedent: They were a conspicuous component of the historical fire regime in the BMW. Modern reburns are neither anomalous nor unprecedented; they are a key element of the natural fire regime in the western BMW, creating structurally and functionally distinct habitat compared to once-burned sites (Larson et al. 2013; Ward et al. 2017). The current regime of active fire since 1981 mirrors total area burned (figs. 3 and 4) and area reburned in the pre-exclusion period (fig. 5, table 1). A tree ring-based fire history in the southeastern portion of our study area also documented a regime of frequent, widespread fires, including large reburns, since 1749 (Gabriel 1976), corroborating our results and extending the temporal depth of the record with a second line of evidence.

The striking differences in total area burned and area reburned across the three time periods (table 1, fig. 5) are due to the interaction of climatic variability and fire management policy. Annual and decadal variation of climate is the primary driver of fire area burned in the northern U.S. Rocky Mountains, including the western BMW (Heyerdahl et al. 2008; Higuera et al. 2015; Morgan et al. 2008). The success of fire suppression efforts during the exclusion period (Steele 1960) was very likely conditioned upon the lower frequency of hot, dry springs and summers during the mid-20th century relative to the pre-exclusion and fire management periods, during which all regional fire years occurred in the northern U.S. Rockies (Morgan et al. 2008).

Reburn Effects on Tree Regeneration, Forest Structure, and Fuels

Reburn effects on the tree community were primarily concentrated in the smaller tree size classes: seedlings and saplings (fig. 6). Seedlings that established after the initial 2000 fire had not yet grown large enough by the second fire in 2013 to develop fire resistance traits (e.g., thick bark), and consequently suffered high mortality. Climate change may make postfire tree regeneration less successful following future fires on environmentally stressful sites (Stevens-Rumman and Morgan 2016). However, we observed abundant tree regeneration establishing after both single and repeat wildfires at our sites, which were situated on the valley bottom on gentle topography. We interpret the net stability of the sapling community in the twice-burned sites as the combined effect of ingrowth of seedlings into the sapling size class balanced by fire-caused sapling mortality in the reburn event.

The overstory tree community was highly resistant to change over time in both the once-burned and twice-burned plots. The initial fires (in 2000 and 2003) preferentially removed the least fire-resistant trees through direct fire-related mortality and postfire bark beetle (family Scolytidae) attack (Belote et al. 2015b; Hood and Bentz 2007). Thus, we interpret the stability of the overstory tree population in the once-burned plots as the result of the return to low background rates of tree mortality by the time of our sampling, 8 and 12 years post-fire (Keane et al. 2006; Leirfallom and Keane 2011; Van Mantgem et al. 2011). In the twice-burned plots, the relative stability of the overstory was likely due to the high fire-resistance of the trees that survived the initial fire (Belote et al. 2015b; Harrington 2013; Larson et al. 2013), combined with modest recruitment from the sapling size class into the overstory tree size class, offsetting mortality caused by the second burn.

Single and repeat fires had sharply contrasting effects on surface fuels (figs. 7 and 8). In once-burned plots, most fuel types increased or were stable from 2011 to 2015. This reflects the ongoing deposition of bark, branches, and boles from fire-killed trees, adding to the surface fuel load (Dunn and Bailey 2012, 2015). In contrast, the second fire either reduced or maintained surface fuels in 2015 relative to 2011 levels (figs. 7 and 8). Fuel consumption in the second fire offset new deposition, leading to significant differences between once-burned and twice-burned sites in 2015 for multiple fuel classes. Based on these results, it is not appropriate to characterize single fires following a long fire-free period as "fuel reduction treatments." Rather, single fires lead to steady accumulation of new surface fuels as fire-killed trees and branches fall to the forest floor (Dunn and Bailey 2012, 2015). In contrast, reburns do function as fuel reduction treatments, maintaining or reducing surface fuels through time (Donato et al. 2016; Stevens-Rumman et al. 2016; Ward et al. 2017).

The scope of inference for these analyses of single and repeat wildfire effects on tree regeneration, forest structure, and surface fuels is old-growth western larch/mixed-conifer forest. The presence of large-diameter, fire-resistant western larch trees is an important factor to consider when interpreting and generalizing our results (Harrington 2013). In particular, overstory stability in reburns might be diminished at sites with lesser proportions of fire-resistant species (Belote et al. 2015b). We acknowledge that this case study, while providing strong inference due to the BACI design, does not sample the full range of possible reburn effects (Coppelatta et al. 2016; Stevens-Rumman et al. 2016).

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Our analyses have implications for wilderness fire management, as well as for design of forest restoration and ecological forestry treatments outside of wilderness areas. The most important finding from our analysis of 128 years of fire history data is the similarity between the current active fire regime (1981–2017) and the pre-exclusion historical period (1889–1934), in terms of both annual area burned and amount of area burned two to four times. These results demonstrate that the modern fire regime has a recent historical precedent, and that reburns are a component of the natural fire regime of the western Bob Marshall Wilderness. Our analyses of reburn effects on tree regeneration, forest structure, and fuel loads suggest that a broader range of posttreatment conditions than described by Hopkins et al. (2014) is appropriate for combined thinning and prescribed fire treatments that seek to restore effects of past harvest and fire exclusion in western larch/mixed-conifer forests. Repeat fires result in simpler forest stand structure, lower fuel loads, and less tree regeneration than do single fires (fig. 9). The similar relative abundance of unburned, once-burned, and reburned area we observed in the pre-exclusion and fire management periods (table 1) should be informative to managers seeking to use thinning, prescribed fire, and managed wildfires to restore fire-prone forest landscapes outside wilderness areas (Hessburg et al. 2015).

Figure 9—(A) Example conditions in once-burned (in 2003) old-growth western larch/mixed-conifer forest characterized by heavy surface fuels and abundant tree regeneration (photo: AJ Larson, University of Montana). (B) Example conditions in twice-burned (in 2000 and 2013) old-growth western larch/mixed-conifer forests with reduced surface fuels and tree regeneration, and abundant charring (Ward et al. 2017) on residual coarse woody debris (photo: AJ Larson, University of Montana).

Wilderness provides value to society as a source of scientific information that enhances our ability to sustainably manage nonwilderness lands. The Wilderness Act of 1964 identifies scientific and educational uses as two of the purposes of wilderness areas. Scientists and educators are thus wilderness stakeholders who have a role in delivering to society the information value derived from wilderness areas. Managers can use the results presented here to inform the design and monitoring of forest landscape restoration prescriptions for large planning areas (sensu Hessburg et al. 2015), as well as for stand-level restoration (Hopkins et al. 2014) and ecological forestry (Crotteau et al. 2018) treatments that produce commercial products.

ACKNOWLEDGMENTS

We thank Sarah Bisbing, Alina Cansler, Cory Davis, Matt Dietz, Hugh Irwin, Miles LeFevre, Signe Leirfallom, Eryn Schneider, and the many other field crew members who assisted with field data collection. Funding was provided by Joint Fire Science Program Award 14-1-02-9, USDA NIFA Award 233302, USDA Forest Service Agreement 17-JV-11221639-092, and The Wilderness Society. We are grateful to Deb Mucklow, Seth Carbonari, Jim Flint, and Tad Wehunt for permitting our research, and for their responsible stewardship of our study area. We thank Joe Muretta for pack stock support, and for sharing his insights about landscape change in the Bob Marshall Wilderness, including short- and long-term effects of wildfires on travel, stock use, outfitting, and the wilderness experience. Reviews by Alina Cansler and Sean Jeronimo improved this paper.

REFERENCES

Arno, Stephen F.; Parsons, David J.; Keane, Robert E. 2000. Mixed-severity fire regimes in the northern Rocky Mountains: Consequences of fire exclusion and options for the future. In: Cole, David N.; McCool, Stephen F.; Borrie, William T.; O'Loughlin, Jennifer, comps. Proceedings, 5th Wilderness science in a time of change conference; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 225–232.

Belote, R. Travis; Dietz, Matthew S.; Aplet, Gregory H. 2015a. Allocating untreated "controls" in the National Wilderness Preservation System as a climate adaptation strategy: A case study from the Flathead National Forest, Montana. Northwest Sci. 89: 239–254.

Belote, R. Travis; Dietz, Matthew S.; McKinley, Peter S.; [et al.]. 2017. Mapping conservation strategies under a changing climate. Bioscience. 67: 494–497.

Belote, R. Travis; Larson, Andrew J.; Dietz, Matthew S. 2015b. Tree survival scales to community level effects following mixed-severity fire in a mixed-conifer forest. Forest Ecology and Management. 353: 221–231.

Benda, Lee; Bigelow, Paul. 2014. On the patterns and processes of wood in northern California streams. Geomorphology. 209: 79–97.

Brown, James K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-GTR-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 25 p.

Cansler, C. Alina; McKenzie, Donald; Halpern, Charles B. 2016. Area burned in alpine treeline ecotones reflects region-wide trends. International Journal of Wildland Fire. 25: 1209–1220.

Cansler, C. Alina; McKenzie, Donald; Halpern, Charles B. 2018. Fire enhances the complexity of forest structure at in alpine treeline ecotones. Ecosphere 9(2): e02091.

Collins, Brandon M.; Kelly, Maggi; Van Wagtendonk, Jan W.; Stephens, Scott L. 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecology. 22: 545–557.

Coop, Jonathan David; Parks, Sean Aaron; McClernan, Sarah R.; Holsinger, Lisa M. 2016. Influences of prior wildfires on vegetation response to subsequent fire in a reburned southwestern landscape. Ecological Applications. 26: 346−354.

Coppelatta, Michelle; Merriam, Kyle E.; Collins, Brandon M. 2016. Post-fire vegetation and fuel development influences fire severity patterns in reburns. Ecological Applications. https://doi.org/10.1890/15-0225. [Accessed 2018 June 29].

Crotteau, Justin S.; Keyes, Christopher R.; Hood, Sharon M.; [et al.]. 2018. Stand dynamics 11 years after retention harvest in a lodgepole pine forest. Forest Ecology and Management. 427: 169–181.

Donato, Daniel C.; Fontaine, Joseph B.; Campbell, John L. 2016. Burning the legacy? Influence of wildfire reburn on dead wood dynamics in a temperate conifer forest. Ecosphere. 7: 1–13.

Dunn, Christopher J.; Bailey, John D. 2012. Temporal dynamics and decay of coarse wood in early seral habitats of dry-mixed conifer forests in Oregon's Eastern Cascades. Forest Ecology and Management. 276: 71–81.

Dunn, Christopher J.; Bailey, John D. 2015. Temporal fuel dynamics following high-severity fire in dry mixed conifer forests of the eastern Cascades, Oregon, USA. International Journal of Wildland Fire. 24: 470.

Flathead National Forest. 1983a. Analysis of the fire management situation. U.S. Department of Agriculture, Forest Service.

Flathead National Forest. 1983b. Bob Marshall Wilderness–Great Bear proposed fire management plan. U.S. Department of Agriculture, Forest Service.

Franklin, Jerry F. 1987. Scientific use of wilderness. In: Lucas, Robert C., ed. Proceedings, National Wilderness Research Conference: Issues, state-of-knowledge, future directions; 1985 July 23–26; Fort Collins, CO. Gen. Tech. Rep. GTR-INT-220. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 42–46.

Gabriel, Herman W. 1976. Wilderness ecology: The Danaher Creek Drainage, Bob Marshall Wilderness, Montana. Missoula, MT: University of Montana. Thesis. 224 p.

Gibson, Carly E.; Morgan, Penelope; Wilson, Aaron M. 2014. Atlas of digital polygon fire extents for Idaho and western Montana. 2nd ed. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2009-0006-2. [Accessed 2018 March 20].

Green, Roger H. 1979. Sampling design and statistical methods for environmental biologists. New York: Wiley Interscience. 272 p.

Harrington, Michael G. 2013. Duff mound consumption and cambium injury for centuries-old western larch from prescribed burning in western Montana. International Journal of Wildland Fire. 22: 359–367.

Hauer, F. Richard; Poole, Geoffrey C.; Gangemi, John T.; Baxter, Colden T. 1999. Large woody debris in bull trout (*Salvelinus confluentus*) spawning streams of logged and wilderness watershed in northwest Montana. Canadian Journal of Fisheries and Aquatic Sciences. 56: 915–924.

Hessburg, Paul F.; Churchill, Derek J.; Larson, Andrew J.; [et al.]. 2015. Restoring fire-prone Inland Pacific landscapes: Seven core principles. Landscape Ecology. 30: 1805–1835.

Heyerdahl, Emily K.; Morgan, Penelope; Riser, James P., II. 2008. Multi-season climate synchronized historical fires in dry forests (1650–1900), northern Rockies, USA. Ecology. 89(3): 705–716.

Higuera, Philip E.; Abatzoglou; John T.; Littell, Jeremy S.; Morgan, Penelope. 2015. The changing strength and nature of fire-climate relationships in the northern Rocky Mountains, USA, 1902–2008. PLOS One. E0127563.

Hood, Sharon; Bentz, Barbara. 2007. Predicting postfire Douglas-fir beetle attacks and tree mortality in the northern Rocky Mountains. Canadian Journal of Forest Research. 37: 1058–1069.

Hopkins, Taylor; Larson, Andrew J.; Belote, R. Travis. 2014. Contrasting effects of wildfire and ecological restoration in old-growth western larch forests. Forest Science. 60: 1005–1013.

Keane, Robert E.; Arno, Stephen; Dickinson; Laura J. 2006. The complexity of managing fire-dependent ecosystems in the wilderness: Relict ponderosa pine in the Bob Marshall Wilderness. Ecological Restoration. 24: 71–78.

Koch, Elers. 1935. The passing of the Lolo Trail. Journal of Forestry. 33: 98–104.

Larson, Andrew J.; Belote, R. Travis; Cansler, C. Alina; [et al.]. 2013. Latent resilience in ponderosa pine forest: effects of resumed frequent fire. Ecological Applications. 23(6): 1243–1249.

Leirfallom, Signe B.; Keane, Robert E. 2011. Six-year post-fire mortality and health of relict ponderosa pine in the Bob Marshall Wilderness Area, Montana. Res. Note RMRS-RN-42. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 5 p.

Liu, Wendy H.; Bryant, David M.; Hutyra, Lucy R.; [et al.]. 2006. Woody debris contribution to the carbon budget of selectively logged and maturing mid-latitude forests. Oecologia. 148: 108–117.

Miller, Carol; Aplet, Gregory H. 2016. Progress in wilderness fire science: Embracing complexity. Journal of Forestry. 114: 373–383.

Montgomery, David R.; Abbe, Tim B. 2006. Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. Quaternary Research. 65: 147–155.

Morgan, Penelope; Heyerdahl, Emily K.; Gibson; Carly E. 2008. Multi-season climate synchronized forest fires throughout the 20th century, Northern Rockies, USA. Ecology. 89(3): 717–728.

Östlund, Lars; Keane, Bob; Arno, Stephen; Andersson, Rikard. 2005. Culturally scarred trees in the Bob Marshall Wilderness, Montana, USA – Interpreting Native American historical fire use in a wilderness area. Natural Areas Journal. 25(4): 315–325.

Parks, Sean A.; Holsinger, Lisa M.; Miller, Carol; Nelson, Cara R. 2015a. Fire atlas for the Crown of the Continent Ecosystem (Glacier National Park, Great Bear Wilderness, Bob Marshall Wilderness, and Scapegoat Wilderness). Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2015-0022. [Accessed 2018 March 20].

Parks, Sean A.; Holsinger, Lisa M.; Miller, Carol; Nelson, Cara R. 2015b. Wildland fire as a self-regulating mechanism: The role of previous burns and weather in limiting fire progression. Ecological Applications. 25(6): 1478–1492.

Pyne, Stephen J. 1982. Fire in America. [Paperback ed.]. Princeton, NJ: Princeton University Press. 654 p.

R Core Team. 2018. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at http://www.r-project.org/.

Roff, Derek A. 2006. Introduction to computer-intensive methods of data analysis in biology. Cambridge, UK; New York, NY: Cambridge University Press. 368 p.

Silcox, Ferdinand A. 1935. Policy memo to regional foresters (all regions). May 25. Located at: University of Idaho Library, Moscow, ID. 7 p.

Smith, Diane. 2014. From research to policy: The White Cap wilderness fire study. Fire History Today. Spring/Fall: 4–12.

Smith, Jeffrey J. 1986. When let-burn fires get ready to roll, campers hit the trail. Smithsonian. 17: 42–55.

Steele, Rob W. 1960. The role of forest fire in the Bob Marshall Wilderness Area. Missoula, MT: University of Montana. 32 p.

Stevens-Rumman, Camille; Morgan, Penelope. 2016. Repeated wildfires alter forest recovery of mixed-conifer ecosystems. Ecological Applications. 26: 1842−1853.

Van Mantgem, Phillip; Stephenson, Nathan L.; Knapp, Eric; [et al.]. 2011. Long-term effects of prescribed fire on mixed conifer forest structure in the Sierra Nevada, California. Forest Ecology and Management. 261: 989–994.

Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. Forest Science. 14: 20–26.

Van Wagner, C.E. 1982. Practical aspects of the line intersect method. Information Report PI-X-12. Chalk River, Ontario, Canada: Canadian Forestry Service, Petawawa National Forestry Institute. 10 p.

van Wagtendonk, Jan W. 2007. The history and evolution of wildland fire use. Fire Ecology. 3(2): 3-17.

Ward, Aspen; Cansler, C. Alina; Larson, Andrew J. 2017. Black carbon on coarse woody debris in once- and twice- burned mixed conifer forest. Fire Ecology. 13: 143–147.

The Wilderness Act of 1964. Pub. L. 88-577. 16 U.S.C. 1131-1136. (September 3, 1964). https://www.wilderness.net/nwps/legisact. [Accessed 2018 June 14].

Using Prescribed Burn Fire Severity Assessments to Estimate Postburn Hydrologic Risk

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Abstract—Research conducted via the Australian Bushfire Cooperative Research Centre (BCRC) developed methods for assessing postfire hydrologic risk to human life, infrastructure, and water quality. End users of BCRC products identified the project for utilization, and a small team of practitioners and researchers was established. The utilization team developed a three-phase plan. Phase one was an Australia-wide assessment of postfire hydrologic risk and the development of national guidelines based on general principles. Phase two was the application of the national risk guidelines to the water catchments of the Australian Capital Territory. The tools developed included risk algorithms based on geographic information systems, combined with an Australian adaptation of the FIREMON fire severity mapping system. Phase three is aimed at parameterizing the postfire hydrologic models for specific catchments to deliver quantitative information. The project has generated some lessons about the research utilization process: 1) End users must be clear about what they need and have a sound technical understanding of the research, 2) all parties need to have a common picture of what is to be developed and how it is to be used, and 3) researchers should be prepared to synthesize their work such that the complexity of processes does not impede the development of practical tools.

Keywords: burn, fire, hydrologic, quality, risk erosion, sedimentation, water

INTRODUCTION

Heavy rain in areas burned by bushfire can mobilize enormous volumes of sediments and nutrients into rivers and water reservoirs, threatening the quality and supply of water to Australian cities and damaging freshwater ecosystems (Nyman et al. 2011; Sheridan et al. 2009). This is primarily because burned headwater catchments contain large amounts of ash sediment and debris that are readily flushed into rivers and water supply reservoirs by surface runoff. High sediment loads from debris flows cause high turbidity and water contamination due to increased nutrients and metals from pollutants in the runoff (Langhans et al. 2017; Nyman et al. 2015).

This type of contamination occurred in mountainous regions of south-eastern Australia on three occasions in the past 15 years. Postfire debris flows after the Canberra fires in 2003 resulted in water restrictions

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

in the Australian Capital Territory (ACT) (White et al. 2006) until a new water treatment plant was constructed. Similar contamination occurred in the Ovens River after the Eastern Victorian alpine bushfires in 2003 and in Lake Glenmaggie after the 2007 bushfires in Victoria. Serious postfire water quality issues have also been documented in the Nattai Catchments near Sydney in New South Wales and the Lofty Ranges near Adelaide in South Australia. These scenarios from various landscapes across south- eastern Australia highlight the importance of considering water quality issues when managing fire in high value water-supply catchments (Nyman and Sheridan 2014).

RESEARCH

The problem that fires pose to water quality was recognized by fire and land management agencies represented on the former Bushfire Cooperative Research Centre (BCRC). In response, the BCRC commissioned the forest hydrology research group of the University of Melbourne to investigate the effects of forest fire on catchment processes. The project was part of the Fire in the Environment theme, which ran from 2010 through 2014 (Bell et al. 2014). Research investigated how fire severity and rainfall intensity in steep hilly landscapes contribute to sedimentation and pollution in forested water supply catchments in south-eastern Australia (Jones et al. 2014). The aim was to deliver findings that could help inform and guide development of tools and resources for land and fire managers to assess and address risks to critical water assets in forested catchments. The work built on many years of research conducted by the forest hydrology research group in collaboration with Melbourne Water and Victorian Department of Environment, Land, Water and Planning (e.g., Sheridan et al. 2009, 2011).

Research Methods

The research addressed two key questions: 1) What are the real risks to uninterrupted water supply if catchments are burned by bushfires? and 2) Can the risk be reduced with prescribed fire? The scientific methods included reviews of the international research literature, surveys of extreme erosion events, and field experiments to quantify the relationships between fire severity, aridity, and postfire erosion (Nyman et al. 2011). The field studies encompassed a wide range of forest environments in Victoria burned during the 2009 Black Saturday bushfires.

Research Outputs

The research showed that at the study site water quality risk was primarily associated with slope, fire severity, and aridity. Risk increased on steeper slopes, at higher fire severities, and in drier landscapes. The relationships between the factors were characterized in a series of models and published in international journals (Langhans et al. 2017; Noske et al. 2016; Nyman et al. 2013a,b, 2015; Sheridan et al. 2016).

Another key outcome from the research was that the results showed the risks to water quality are largely associated with large-magnitude events that are threshold driven. Thus, during most erosion events the risks to water quality are relatively small. But in a few cases the combination of rainfall intensity, fire severity, and slope result in extreme events such as debris flows, and these are the ones most likely to have consequences for water supply and infrastructure. The focus of model development is therefore to represent the conditions when thresholds of extreme events are exceeded.

SCIENCE TO ACTION

Utilization of the research commenced with a meeting between the lead end users, researchers, and the Australasian Fire Authorities Council (AFAC). A key issue going into the meeting was: To what extent can novel research outputs from a Victorian catchment be applied to the landscapes of AFAC members, which span Australia and New Zealand? The challenge was to make practical sense of the science and translate it so that the value was maximized for all AFAC members (AFAC 2017).

The solution was found in recognizing that the validity of the detailed knowledge obtained from the study site decreased as the domain over which it was applied increased. This was represented in a matrix that aligned management objectives against the state of knowledge and data availability (fig. 1). Quantitative predictions about the amount of sediment that was likely to be produced following fire were valid for the study site. Qualitative predictions about hydrologic

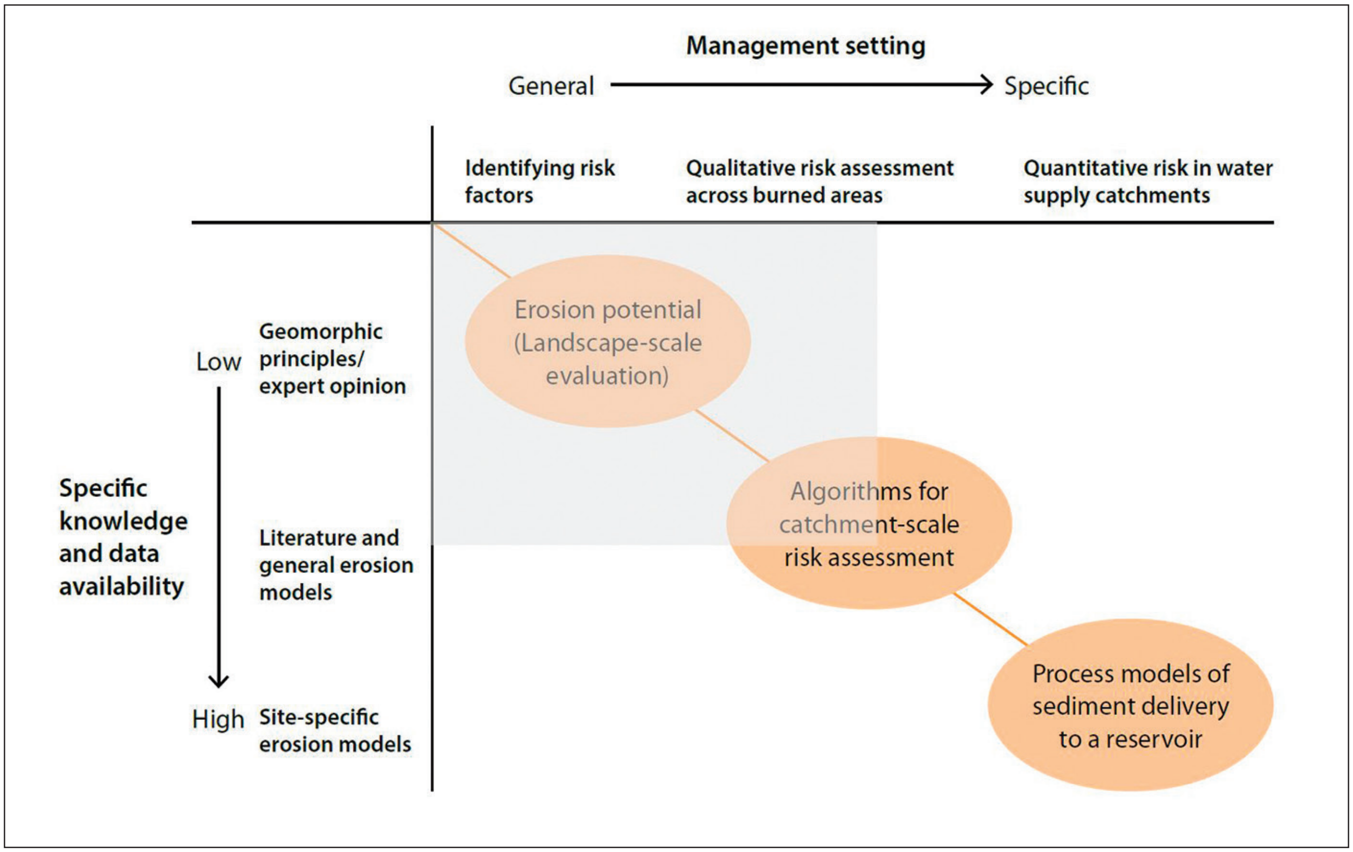

Figure 1—Diagram illustrating how science gained from one specific site could be translated generally for application in different contexts. The types of models for risk assessments vary depending on the management setting (top axis) and the scientific knowledge (left axis) of the underlying hydrogeologic processes. The shaded area represents the region of the science-management space that was targeted in the first phase of utilization.

risk were valid for similar landforms with the same hydrogeomorphic properties. In light of this matrix it was also established that the broad assessment of risk associated with bushfire could be carried out at a landscape scale across Australia and New Zealand using existing data and models. The resulting research utilization plan had three phases reflecting the stages identified in the matrix.

Phase One: National Guidelines

The first utilization product, funded by AFAC, was an Australia- and New Zealand-wide assessment of erosion risk associated with wildfire (Nyman and Sheridan 2014). The work assessed the postfire erosion potential in water catchments in every Australian State and Territory and New Zealand and was accompanied by generic guidelines for evaluating risk to water quality. Spatial data generated during the project were distributed to each jurisdiction, and the report was made available to AFAC members from the AFAC website.

Phase Two: Risk Assessment Tools for the Australian Capital Territory

The second utilization product, funded by ACT Parks and Conservation Service, was a suite of geographic information system tools that generate postfire risk assessments of erosion, flooding, and water quality for the ACT. The tools were developed by combining the results of the BCRC research with other work funded by the Victorian Department of Environment, Land, Water and Planning for use by the bushfire rapid risk assessment teams in Victoria. The tools were tested successfully during the 2015–2016 bushfire season and are in use in the ACT.

Phase Three: Quantitative Predictions

Implementation of the third phase of utilization in the ACT requires the calibration of models to deliver quantitative predictions. Data for this purpose are being collected in conjunction with the burning program. Rainfall gauges, turbidity monitors, streamflow monitors, and sediment traps (fig. 2) are installed in suitable locations as soon as possible after burns to gather these data. Controls are installed in permanent watercourses above and below burns and in representative gully lines adjacent to areas planned to be burned.

OPERATIONS

The Australian Capital Territory Parks and Conservation Service uses the postfire hydrologic risk tools for two purposes: 1) to plan prescribed burning operations and 2) to target drainage and infrastructure works in identified risk-prone areas with significant water assets and important ecosystems.

Conducting a Fuel Reduction Burn

The workflow for incorporating water quality risk into a prescribed burn has four stages, illustrated using the Wombat Creek fuel reduction burn conducted by ACT Parks and Conservation Service in April 2017: 1) assessment of the proposed burn for erosion sources (fig. 3); 2) completion of the burn plan, taking account of water quality risk (fig. 4); 3) assessment of fire severity (Key and Benson 2006; Leavesley et al. 2015) (fig. 5); and 4) assessment of the postfire hydrologic risk using the tools (fig. 6).

Identifying Risk-Prone Areas After a Wildfire

The identification of areas prone to hydrologic risk following a fire is a two-stage process requiring an assessment of fire severity (figs. 7 and 8) and an assessment of the postfire hydrologic risk (figs. 9–11).

Figure 2—A sediment trap and a V-notch weir installed in a burned gully.

Figure 3—Potential sources of debris flow within the Wombat Creek (Australian Capital Territory) burn; erosion source areas are indicated by brown shading.

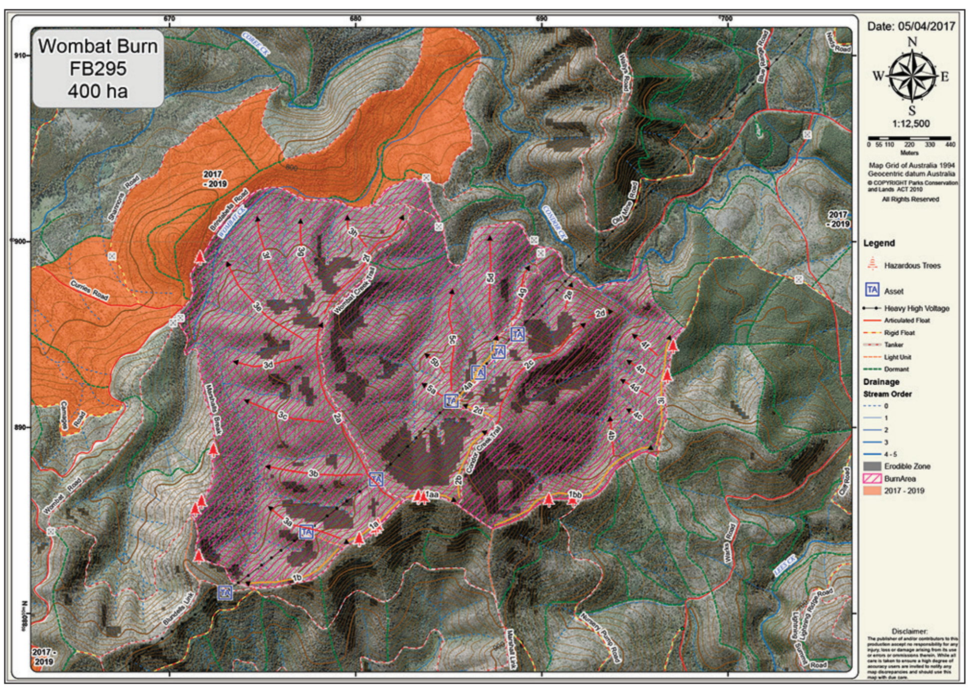

Figure 4—Operational burn map for the Wombat Creek burn (Australian Capital Territory). Pink cross-hatching indicates the fireground, brown shading indicates potential sources of erosion, and red arrows indicate the ignition plan. The ignition pattern was designed to minimize burning over the potential erosion source areas on southeastern aspects of the burn.

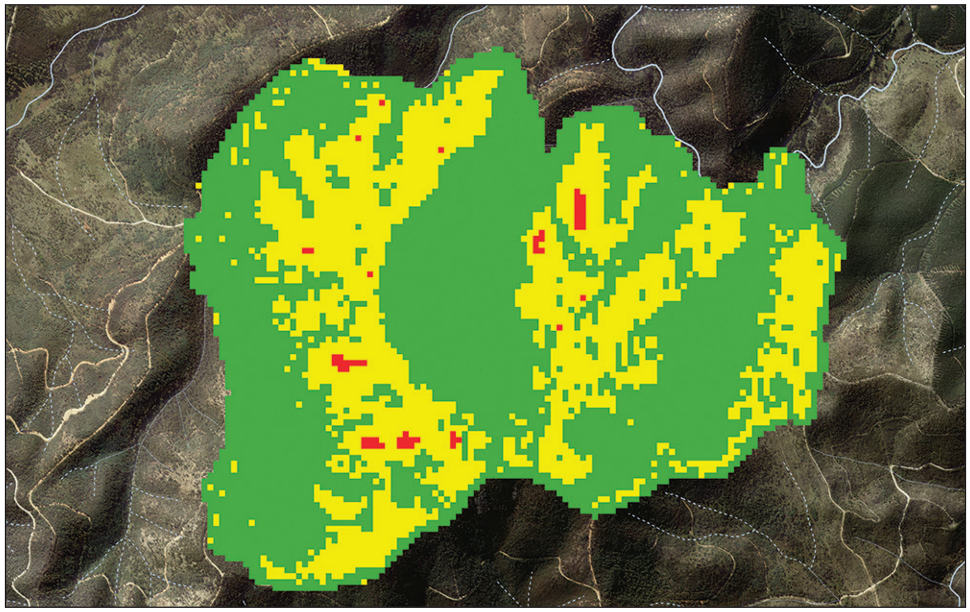

Figure 5—Fire severity assessment of the Wombat Creek burn (Australian Capital Territory; ACT) using the FIREMON method developed by the Forest Service, U.S. Department of Agriculture and adapted for the ACT. Green indicates unburned area; yellow indicates minimal burn effects to the canopy, and red indicates substantial canopy scorch or consumption. The objective of minimizing burning within potential erosion source areas was achieved.

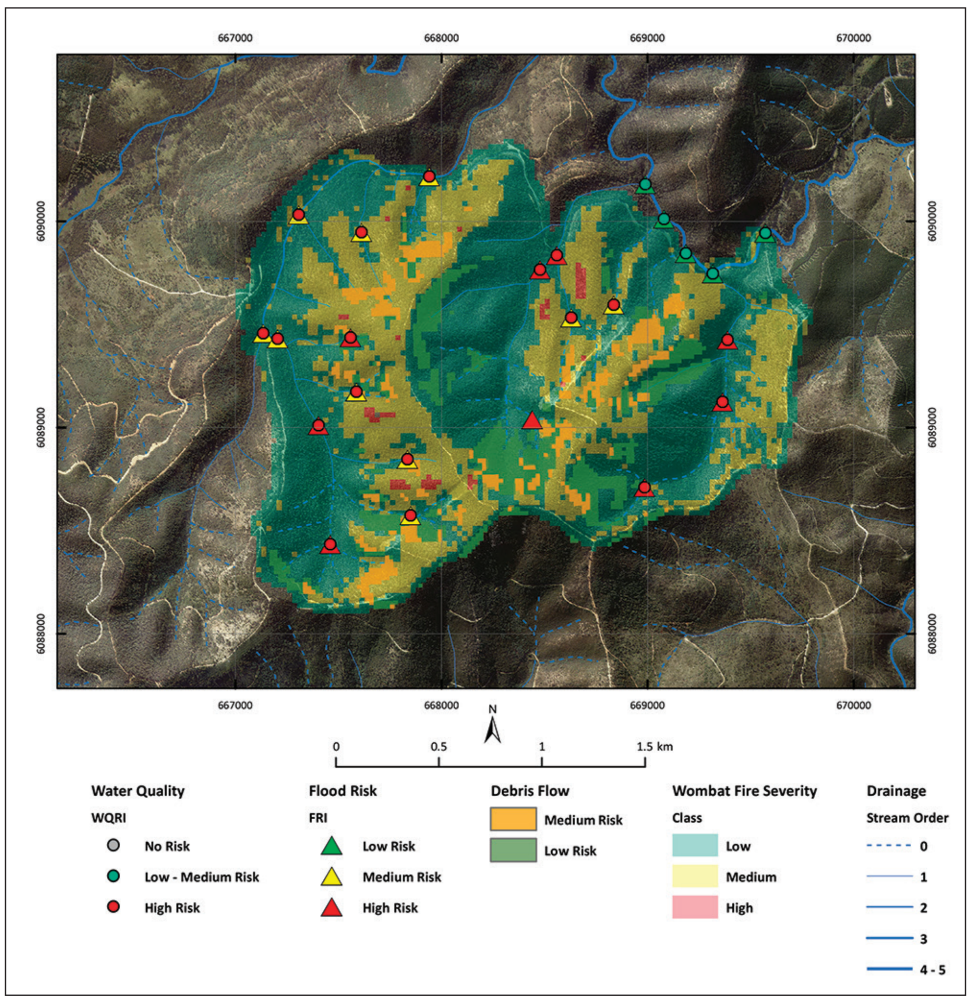

Figure 6—Postfire hydrologic assessment of the Wombat Creek burn (Australian Capital Territory). The burn was conducted in steep terrain with relatively high risk of postburn hydrologic effects. The burn increased the erosion risks, but the effects were limited to the burn area so that the effect at the nearest main stream, Condor Creek, was low.

Figure 7—Aftermath of the Brandy Flat burn (Australian Capital Territory), which escaped containment across a creek and burned at high intensity, causing full canopy consumption or scorch over a wide area.

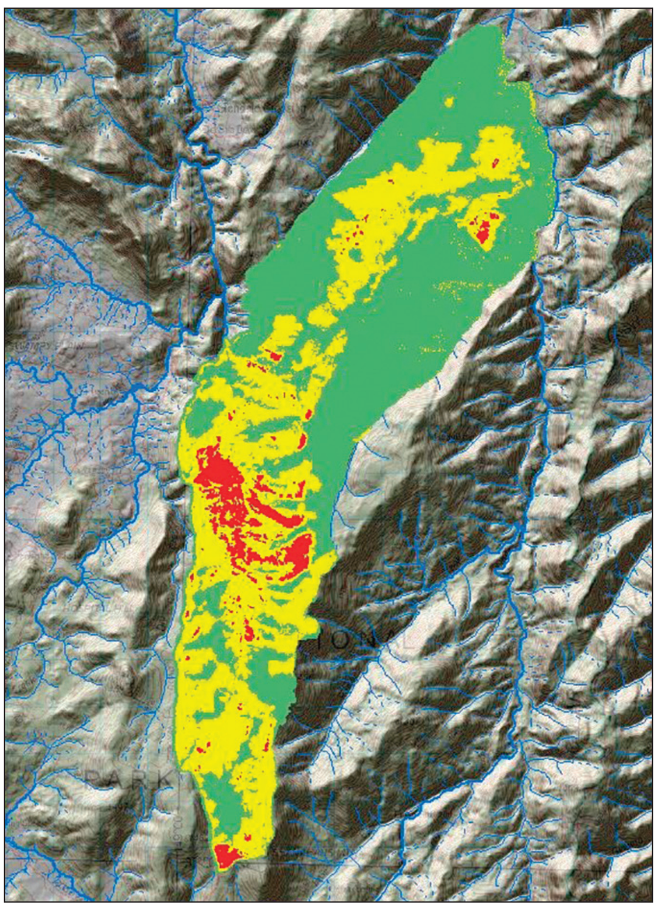

Figure 8—Fire severity assessment of the Brandy Flat burn (Australian Capital Territory; ACT) using the FIREMON method adapted for the ACT. The burn was conducted in April 2016 and escaped containment across a creek. The fire then burned at high intensity. Green indicates unburned area, yellow indicates minimal burn effects to the canopy, and red indicates substantial canopy scorch or consumption.

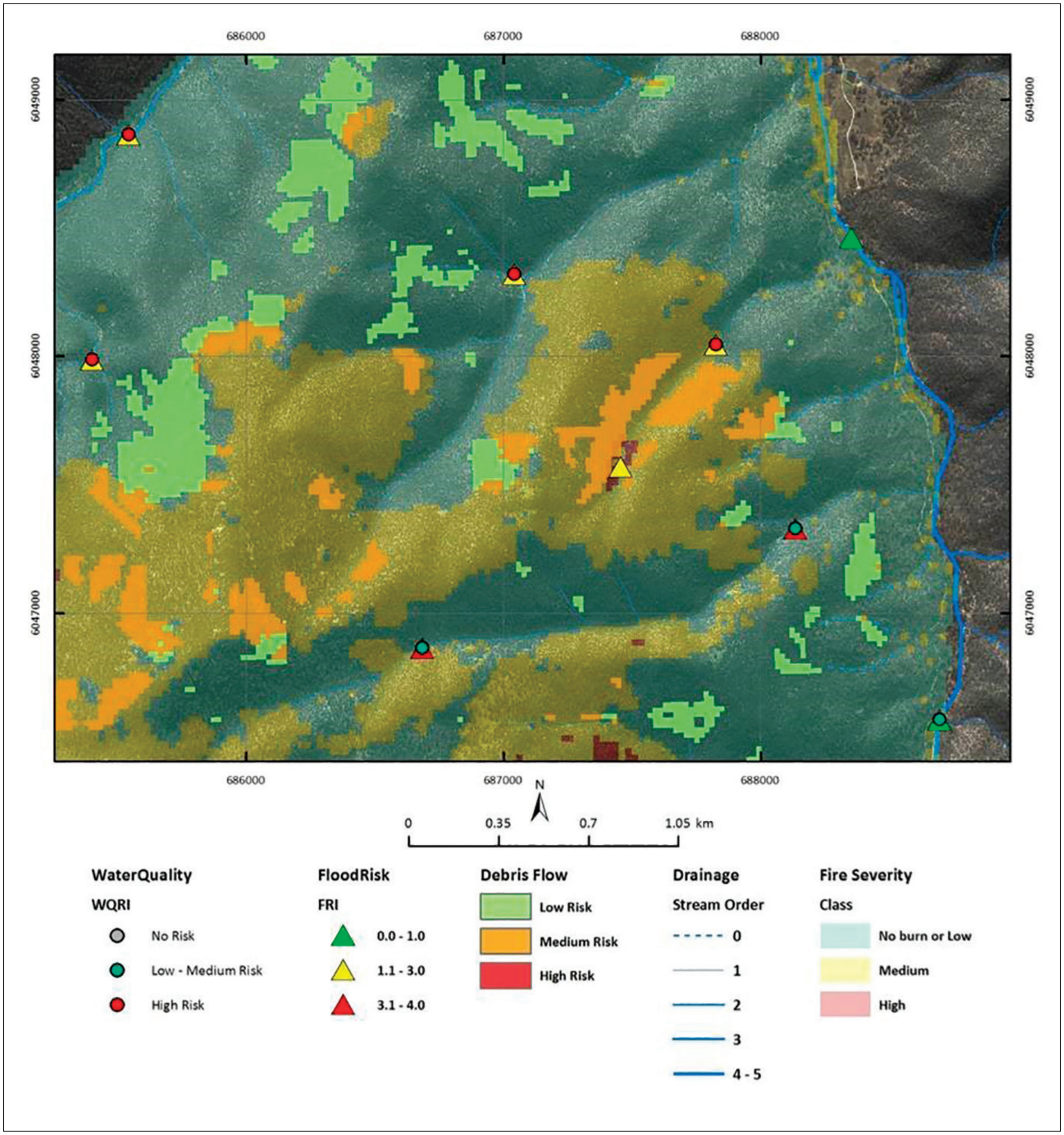

Figure 9—Postfire hydrologic assessment of the northern end of the Brandy Flat burn (Australian Capital Territory). The burned gully in the center of the picture (grid square: 687 047) was subject to erosion during intense rainfall 2 weeks after the burn. The assessment shows increased hydrologic risk in the gully but only low risk in the Naas River (east of easting 688) into which it flows.

Figure 10—A burned hillside that was the source of erosion following the Brandy Flat burn (Australian Capital Territory) in 2016.

Figure 11—Sedimentation in the Naas River (Australian Capital Territory) in 2016 after the Brandy Flat burn. The boulders in the background of the photo at left are from a previous and much larger event, possibly associated with the Canberra bushfires in 2003. Eroded material consists of ash, organics (right top), and mineral soil (right bottom).

UTILIZATION: CRITICAL SUCCESS FACTORS

The critical factors in improving the management of postfire hydrologic risk were the creation of a strong researcher-end user partnership, appreciation of the science and research methods, and a shared commitment to collaborative discovery in the utilization phase (AFAC 2017).

There are three key lessons from this research utilization process.

1) Members of the ACT Parks and Conservation Service staff undertook the lead end-user role during the BCRC research phase of the project and were motivated to do so because a high proportion of the ACT is water catchment. This meant that there was end user involvement early in the project, ensuring that researchers were aware at the outset of the context in which the bushfire sector would need to use the information.
2) Continuous engagement in the partnership made end users comfortable with supporting the project as it traveled the path of investigative discovery. This was important because the results of research are by definition uncertain, so it is not usually clear where a project will lead or what might be delivered at the end.
3) The shared commitment to collaborative discovery in the utilization phase allowed the complexity of the research models to be simplified for operational use in a way that maintained the quality of the information. This type of work can be particularly challenging for researchers, whose research work typically involves a focus on details and a concomitant expansion of complexity.

ACKNOWLEDGMENTS

Ryan Lawrey, Mick Ivill, and Matt O'Brien assisted in helitruthing the fire severity assessments of the Wombat Creek and Brandy Flat burns. John Lee conducted the FIREMON fire severity analyses, and Heike Apps conducted the postfire hydrologic assessments. Brian Levine planned the Wombat Creek burn and produced the burn map. Tony Scherl managed the water quality monitoring, and Brenda Leahy wrote an AFAC research utilization case study for this project. Christian Bihlmaier and Brian Levine reviewed an earlier draft of the manuscript.

REFERENCES

Australasian Fire and Emergency Service Authorities Council (AFAC). 2017. Science-backed tools enhance water catchment management. AFAC Case Study. Melbourne, Victoria, Australia.

Bell, Tina; Nyman, Petter; Possell, Malcolm; [et al.]. 2014. Fire in the landscape: Final project report. Melbourne, Victoria, Australia: Bushfire Cooperative Research Centre. 64 p.

Jones, Owen; Nyman, Petter; Sheridan, Gary J. 2014. Modelling the effects of fire and rainfall regimes on extreme erosion events in forested landscapes. Stochastic Environmental Research and Risk Assessment. 28: 2015–2025.

Key, Carl H.; Benson, Nathan C. 2006. Landscape assessment (LA): Sampling and assessment methods. In: Lutes, Duncan C.; Keane, Robert E.; Caratti, John F.; [et al.]. FIREMON: Fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: LA-1 through LA-51. [CD included].

Langhans, Christophe; Nyman, Petter; Noske, Philip J.; [et al.]. 2017. Post-fire hillslope debris flows: Evidence of a distinct erosion process. Geomorphology. 295: 55–75.

Leavesley, Adam J.; Siqueira, A.; Lee, J.W.; [et al.]. 2015 Assessing planned burn severity in forest and woodland using Landsat 8 Operational Land Imager (OLI). Poster presented at Bushfire and Natural Hazards CRC & AFAC conference; 2015 September 1–3; Adelaide, Australia.

Noske, Philip J.; Nyman, Petter; Lane, Patrick N.J.; Sheridan, Gary J. 2016. Effects of aridity in controlling the magnitude of runoff and erosion after wildfire, Water Resources Research. 52: 4338–4357.

Nyman, Petter; Sheridan, Gary. 2014. Erosion in burned catchments of Australia: Regional synthesis and guidelines for evaluating risk. AFAC; Bushfire CRC; University of Melbourne. https://www.afac.com.au/docs/default-source/ru/final-regional-synthesis-erosion-report.pdf.

Nyman, Petter; Sheridan, Gary J.; Jones, Owen D.; Lane, Patrick N.J. 2011. Erosion and risk to water resources in the context of fire and rainfall regimes. Paper presented at Bushfire CRC & AFAC Conference Science Day; 2010 November 29–December 3; Sydney, Australia.

Nyman, Petter; Sheridan, Gary J.; Lane, Patrick N.J. 2013a. Hydro-geomorphic response models for burned areas and their applications in land management. Progress in Physical Geography: Earth and Environment. 37: 787–812.

Nyman, Petter; Sheridan, Gary J.; Moody, John A.; [et al.]. 2013b. Sediment availability on burned hillslopes. Journal of Geophysical Research: Earth Surface. 118: 2451–2467.

Nyman, Petter; Smith, Hugh G.; Sherwin, Christopher B. [et al.]. 2015 Predicting sediment delivery from debris flows after wildfire. Geomorphology. 250: 173–186.

Sheridan, Gary; Lane, Patrick; Smith, Hugh; Nyman, Patrick. 2009. A rapid risk assessment procedure for post-fire hydrologic hazards: 2009/10 fire season. Report ISBN 9780734041470. Melbourne, Australia: Victorian Department of Sustainability and Environment.

Sheridan, Gary; Sherwin, Christopher B.; Feikema, Paul M.; [et al.]. 2011. Post-fire hydrologic risk algorithms: GIS code and instructions for the 2010/11 fire season. Melbourne, Australia: University of Melbourne, Department of Forest and Ecosystem Science.

Sheridan, Gary; Nyman, Petter; Langhans, Christophe; [et al.]. 2016. Is aridity a high-order control on the hydro-geomorphic response of burned landscapes? International Journal of Wildland Fire. 25: 262–267.

White, Ian; Wade, Alan; Worthy, Martin; [et al.]. 2006. The vulnerability of water supply catchments to bushfires: Impacts of the January 2003 wildfires on the Australian Capital Territory. Australian Journal of Water Resources. 10: 179–194.

Prescribed Burn Decision Support Tool (PB DST): An Essential Process to Support Your Decisionmaking

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Abstract—Prescribed burning is an essential tool for the management of fire. Burns can be complex and involve many variables that pose high levels of risk. Fire planners develop detailed plans to minimize risk, but risk will never be completely eliminated. Burn escapes and shrinking burn windows due to climate change have highlighted the need for a standardized tool to deal with the risks associated with prescribed burning. The Prescribed Burn Decision Support Tool (PB DST) is a risk assessment tool that assists practitioners in recognizing and documenting the risks associated with a prescribed burn and in identifying appropriate controls in a consistent, transparent, repeatable, and quantifiable manner. Based on the International Organisation for Standardization 31000: 2009, Risk Management – Principles and Guidelines, the PB DST facilitates fire planners in describing the burn context, identifying risks, and then determining the likelihood and consequence of potential escape and impacts from smoke. The tool, which has been validated in Australia, also provides fire managers with risk mitigation advice and assists agencies with succession planning by nurturing robust decisionmaking practices among developing staff. The strength of the PB DST has been the demonstrated ability to consistently document decisionmaking based on the best available information.

Keywords: prescribed fire, smoke management, risk management, fuel reduction, incident management

INTRODUCTION

In the review of the Margaret River Bushfire Inquiry (Ferguson 2010; Keelty 2012), the following point was made:

> Fire managers are being held more accountable. Greater accountability that brings with it higher expectations of fire manager performance and lower thresholds for failure. Bushfire management is often high profile, high risk and high consequence.

It is acknowledged that prescribed burning is an essential tool for the management of fire in the Australian landscape. Burns can be complex and involve many variables that pose high levels of risk, thus making it one of the more difficult activities conducted by fire managers. Fire planners write detailed plans to minimize risk, but risk can never be completely eliminated. Shrinking burn windows and high profile escaped prescribed burns such as Margaret River, Washington, in 2011 and Lancefield,

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Victoria, in 2015 (Independent Lancefield-Cobaw Fire Investigation Team, 2016), as well as numerous other escaped burns, have highlighted the need for a documented decision support tool that uses the ISO 31000: 2009 risk assessment process.

Various agencies in Australia and around the world have developed risk assessment tools and complexity analysis for prescribed burns. However, these have mainly been developed as planning tools and do not provide guidance or advice for operations while underway. In the United States, simplified matrices have been developed that advise incident commanders (ICs) on staffing requirements for mop-up and patrol procedures post ignition.

Often, ICs or divisional commanders (DCs) are questioned on their decisionmaking: Was it a suitable time to implement a prescribed burn? Why did implementation continue? Why did you leave a burn unattended? What are sufficient mop-up distances? How often should we patrol? Will the smoke have an adverse impact on the community?

Fire managers routinely work together to make these decisions, largely based on their past training and experiences. In Australia, these decisions, while documented in some internal fashion, are typically not done in a consistent, robust, or transparent manner. Additionally, as agencies work on succession planning, our industry lacks tools which nurture robust decisionmaking practices for trainee command staff.

What Is the Prescribed Burn Decision Support Tool (PB DST)?

The PB DST is a consistent, transparent, and semi-quantitative risk assessment tool that assists managers in recognizing and documenting the risks of escapes and impacts of smoke while identifying appropriate controls. The foundation utilizes ISO 31000: 2009, Risk Management – Principles and Guidelines and the tool links directly to the Australian Digital Forecast Database (ADFD) and Australian fire behavior models. The PB DST assists managers in identifying the burn context and determining the likelihood and consequence of potential escape and impacts from smoke, prior to lighting and while underway.

How Does the PB DST Work?

PB DST is applied to burn implementation in a complementary role to the burn plan. The tool is designed to be used in the days and hours prior to ignition, and to assess the relative risk of proceeding based on current and predicted weather. The tool can be re-run for each subsequent day of ignition and patrol. The tool includes automated 7-day ADFD grids and predicted fire behavior to support decisionmaking.

The PB DST is a six-step process. Step 1, identifying the burn context, allows the assessor to capture the context of the burn based on the current environment. Context can include all those factors that are not quantifiable but play a critical role in whether it is appropriate to implement the burn or not. An example is the political context.

At the “core” of the PB DST is a series of matrices (Steps 2 through 4) used by the assessor to determine the likelihood and consequence of the risk of escape as well as the potential impacts of smoke from the prescribed burn (fig. 1). In order to preserve the concept of a simple and effective tool, the factors chosen for each of the matrices represent the minimum levels that may contribute to an escape burn or adverse impact of smoke.

Steps 2 and Step 3 address the risk associated with prescribed burn escape; Step 2 assesses the likelihood and step 3 assess the consequence. The factors for determining likelihood have been grouped into five broad categories: burn day conditions, long-term conditions, fuels, control, and forecast conditions. The weather factors are the only factors that need to be updated for each day of subsequent ignition. The factors for consequence have been grouped into two broad categories: built and natural assets (external to burn area).

Step 4, smoke management, is a new module (released March 2018), which was added to support fire managers with dealing with one of the biggest challenges while implementing prescribed burns. Step 4 was designed to assist in quantifying the risk of smoke impacts and identifies mitigation actions for fire managers to consider prior to and during

		Factors	Low (1)	Mod (2)	High (3)	Very High (4)	Score
Weather factors (#4 & #5) to be completed prior to ignition and for each subsequent day of ignition.							
4	Burn Day Conditions	Max Wind	0-5km/h	6-10km/h	11-15km/h	>16km/h	4
		Min RH	>60%	59-41%	40-30%	≤29%	3
		Max FDI	0-3	4-9	10-15	≥16	2
5	Forecast Conditions from commencement	Max Wind (12hrs-24hrs)	≤9	10-15	16-20	>21	2
		Min RH (12hrs-24hrs)	>60%	50-59%	30-49%	≤29%	1
		Max FDI (12hrs-24hrs)	<12	13-20	21-25	>26	1
		Max Wind (24hrs-36hrs)	≤9km/h	10-15km/h	16-20km/h	>21km/h	4
		Min RH (24hrs-36hrs)	>60%	50-59%	30-49%	≤29%	3
		Max FDI (24hrs-36hrs)	<12	13-20	21-25	>26	2
		Max Wind (36hrs-72hrs)	≤9km/h	10-15km/h	16-20km/h	>21km/h	4
		Min RH (36hrs-72hrs)	>60%	50-59%	30-49%	≤29%	3
		Max FDI (36hrs-72hrs)	<12	13 to 20	21-25	>26	2

Figure 1—An example of the "core": Steps 2-4 of the PB DST. Each of the matrices consist of a list of factors divided into four categories that the assessor selects based on the prescribed burn assessed. The example above is the weather section of the likelihood (Step 2).

the implementation. Similar to the previous steps, a number of key factors that affect the amount and dispersal of smoke have been identified and grouped into different categories: weather, fuels, and topography. The consequence of smoke management consists of two factors within asset vulnerability: the proximity of smoke-vulnerable assets and the density of population and/or sensitivity to smoke.

The likelihood and consequence of weighted scores of both risk of escape and impact of smoke are then prepopulated into Step 5, risk matrix, to determine overall risk. Risk mitigation advice is then applied to the risk score. The final step, Step 6, is the approval form for the assessor and IC to document the preburn and post ignition decisionmaking process.

Multiple agencies in Victoria, Tasmania, NSW, South Australia and the Australian Capital Territory (ACT) have been trialing the PB DST, resulting in thousands of assessments over the last 3 years. The tool has been endorsed by Forest Fire Management Group and ideally the goal is to reach consensus on a consistent product for the Prescribed Burn National Toolbox. In the ACT, the value of the PB DST was evident following an escape on the Brandy Flat burn in 2016 where the ability to present a detailed summary of the decisionmaking prior to, during, and after the burn was invaluable when subject to political review.

CASE STUDIES: BRANDY FLAT AND POTTER'S HILL BURNS

Brandy Flat: The Context

In late autumn of 2016, The ACT commenced its annual burn program with five urban burns implemented over a 3-day period. The PB DST was completed for each burn to determine its suitability to implement. The late start to autumn burning was due to unseasonably warm conditions followed by frequent, small rain events. An extended period of burning appeared unlikely due to recent rain and the climatic outlook.

The rural burn program, which typically consists of larger, multi-day burns in remote and rugged country, commenced on 30 March. The ignition of two burns was planned over several days. On 1 April, these burns were nearing completion and implementation began on an additional two burns planned over a 2-3 day period. On 2 April, operations continued; objectives were being met, predominantly low-intensity backing fires with isolated patches of moderate intensity. Consumption of fuels was within acceptable ranges, which included removal of surface, near-surface, and elevated fuels while maintaining the mid- and over-story canopy. South and east facing slopes would not carry fire.

Following the completion of the PB DSTs on 2 April, it was determined that implementation would occur on a further four urban ecological burns and one new rural burn (Brandy Flat burn) on 3 April. The implementation of these burns was well within resource capabilities as the remaining burns were primarily aerial ignition requiring minimal resources. The Brandy Flat burn, a 3,000 ha ridgetop burn, consisted of a 9 km long ridgeline running north-south. The distance to the road on the western slope from the ridgeline was nearly 2 km in places. Based on the current and predicted fire behavior, it was determined that it would take a number of days to reach the road.

Likelihood and Consequence of the Brandy Flat Burn

The Brandy Flat burn rated as a moderate risk in the PB DST. There were no assets (built, natural, or cultural) inside or adjacent to the burn area and it was located outside the ACT's drinking water catchment. Benign fire weather was predicted, but the PB DST did highlight that Fire Danger Index (FDI) was predicted to increase to 12 and the relative humidity would decrease to the mid-20s on 6 April, 4 days out from the assessment. Both of these indices were within prescription.

To confirm the risk profile, the PB DST was updated each morning for all burns that had planned active ignition. On 3 April, there was no major change in the predicted weather for the Brandy Flat burn. The risk of escape remained moderate and, based on the current and predicted fire behavior, the IC approved implementation. Consideration was given to the increase in predicted fire weather for 6 April, but the burn would be backing down slope and into the predicted and predominant wind pattern. There was doubt as to whether the burn would back down far enough to reach the road.

The PB DST for the Brandy Flat burn on 4 April displayed only a slight increase in fire danger and operations continued as planned. However, the afternoon weather grids predicted a notable increase in the predicted fire weather for 6 April. The FDI was now approaching very high fire danger; minimum relative humidities were now forecasted to drop to 16 percent from 24 percent and the predicted winds had increased to 33 km/hr, up from 25 km/hr. The use of the PB DST focused the identification of pressure points for each burn, which then resulted in adjustments to strategies on 5 April. Aerial ignition was utilized to increase the area burned, thus strengthening those areas of concern. Additionally, another helicopter was ordered, other burns were consolidated, and crews were prepared for the predicted changes in weather. The PB DST allowed for the documentation of these decisions in a standardized, consistent, and repeatable-manner as the burn progressed.

For the Brandy Flat burn, the southwest corner of the burn was a pressure point. The control line was an ephemeral drainage that would be susceptible to pressure due to the predominant wind pattern (northwest). To mitigate this issue and strengthen the control line, prior to implementation, fuels were reduced and a hoselay was inserted that tied the road to the dry creek. When the PB DST was updated on the morning of 6 April, a further increase in the predicted fire danger was identified. The predicted FDIs were now approaching 28, with winds 35-40 km/hr.

The PB DST focused the Incident Management Team and a strong plan was outlined in the Incident Action Plan for 6 April. Resources were allocated in the right locations, which included moving crews out of potentially dangerous areas of the fire line and helicopters focused on areas of concerns. As the day progressed, the weather was tracking as predicted, but by early afternoon the winds started to exceed the predictions. Then, without warning the burn area began to experience local wind channeling with winds 50-70 km/hr. Fire behavior intensified significantly and helicopters were working to decrease fire intensity. A spot-over occurred adjacent to the ephemeral drainage along the southwest control line and made an uphill run.

The spot-over was eventually incorporated into our contingency plan, which met our future fuel reduction commitments in the area. No assets or damage occurred as a result of the escape due to the remote nature of the burn. In terms of weather, there was a stark difference between the information received on 3 April when the decision was made to commence lighting, compared to the actual day (fig. 2). The actual FDI recorded was over double the original forecast, 06/04/2016 Wednesday

Date	Time	Temp	RH	Dir	Speed	FDI	FMC
6/Apr/2016	12:00 AM	14.5	60.6	NW	8.5	2.1	9.9
6/Apr/2016	1:00 AM	13.5	63.8	NW	8.7	1.8	10.4
6/Apr/2016	2:00 AM	13.1	65.1	WNW	8.7	1.7	15.2
6/Apr/2016	3:00 AM	12.7	66.4	WNW	8.7	1.6	15.8
6/Apr/2016	4:00 AM	12.2	67.7	WNW	8.5	1.5	16.1
6/Apr/2016	5:00 AM	11.6	69.4	WNW	8.9	1.4	16.3
6/Apr/2016	6:00 AM	11.6	69	WNW	9.3	1.5	16.6
6/Apr/2016	7:00 AM	12.6	65.6	WNW	9.8	1.7	17.0
6/Apr/2016	8:00 AM	15	58.2	NW	12	2.5	16.9
6/Apr/2016	9:00 AM	18.2	49.5	NNW	14.4	4.1	16.3
6/Apr/2016	10:00 AM	21.3	41.9	NNW	16.8	6.2	14.8
6/Apr/2016	11:00 AM	23.4	36.3	NNW	18.5	8.5	12.9
6/Apr/2016	12:00 PM	24.6	32.4	NW	20.4	10.5	11.2
6/Apr/2016	1:00 PM	25.3	29.7	NW	22	12.3	10.0
6/Apr/2016	2:00 PM	25.7	28.1	NW	19.3	12.4	6.1
6/Apr/2016	3:00 PM	25.4	27.9	WNW	16.7	11.6	5.2
6/Apr/2016	4:00 PM	24.2	30	W	14.1	9.7	5.0
6/Apr/2016	5:00 PM	22	34.8	WNW	13.3	7.5	5.5
6/Apr/2016	6:00 PM	19.4	42.3	NW	12.6	5.2	5.9
6/Apr/2016	7:00 PM	17.2	51.4	NW	11.9	3.5	6.8
6/Apr/2016	8:00 PM	16	59	NW	10.4	2.5	8.1
6/Apr/2016	9:00 PM	15.6	63.9	W	8.9	2.0	9.5
6/Apr/2016	10:00 PM	15.1	67.8	WSW	7.4	1.7	10.5
6/Apr/2016	11:00 PM	14.6	69.6	WSW	7.8	1.6	11.1

06/04/2016 Wednesday

Date	Time	Temp	RH	Dir	Speed	FDI	FMC
6/Apr/2016	12:00 AM						
6/Apr/2016	1:00 AM						
6/Apr/2016	2:00 AM						
6/Apr/2016	3:00 AM						
6/Apr/2016	4:00 AM	13.6	47	NW	21.3	4.3	
6/Apr/2016	5:00 AM	12.9	46.8	NW	29.5	5.1	
6/Apr/2016	6:00 AM	12.5	46	NW	36.7	6.1	13.9
6/Apr/2016	7:00 AM	13.2	41.6	NW	37.9	7.5	14.1
6/Apr/2016	8:00 AM	15.1	37.3	NW	33.4	8.5	14.1
6/Apr/2016	9:00 AM	18	31.7	NW	28.6	10.2	13.4
6/Apr/2016	10:00 AM	20.8	25.4	NW	28.9	14.2	12.4
6/Apr/2016	11:00 AM	23.1	20.1	NW	29.8	18.8	11.0
6/Apr/2016	12:00 PM	24.7	17.1	NW	37.2	26.2	5.0
6/Apr/2016	1:00 PM	25.7	15.7	NW	36.3	27.8	4.4
6/Apr/2016	2:00 PM	26.1	15.9	NW	34	26.5	4.1
6/Apr/2016	3:00 PM	25.9	16.8	WNW	33.3	25.1	4.0
6/Apr/2016	4:00 PM	24.8	23	WNW	30.8	18.4	4.0
6/Apr/2016	5:00 PM	22.9	26.2	WNW	22.7	12.8	4.1
6/Apr/2016	6:00 PM	20.6	30.8	WNW	14.3	8.3	4.6
6/Apr/2016	7:00 PM	18.5	39.6	W	9.7	5.1	5.0
6/Apr/2016	8:00 PM	17.2	46.1	W	10.2	4.0	6.6
6/Apr/2016	9:00 PM	16.4	48.8	W	10.9	3.6	8.0
6/Apr/2016	10:00 PM	15.9	50.7	W	11.3	3.3	8.9
6/Apr/2016	11:00 PM	15.3	55.6	WSW	12	2.8	9.3

Figure 2—Comparison of ADFD gridded weather forecasts for Brandy Flat burn that highlights the FDI; 03/04/16 at 05:15 hrs (left) and 06/04/16 at 04:47 hrs (right).

and the relative humidity was nearly 15 percent less. The day ended up being one of the warmest days in April recorded in the ACT for the past 30 years.

PB DST as a Documentation Tool

The first major escape from a prescribed burn within the ACT occurred in 2015. Afterward, fire managers received considerable questioning and some criticism from both inside and outside the organization about how the escape occurred. Following the escape from the Brandy Flat burn in 2016 (fig. 3), new questions and additional scrutiny were received about having lost two burns in recent years. The first being, surely "you" knew about the predicted fire weather for 6 April. This time around when the questioning occurred, fire managers were able to produce the daily PB DST assessments undertaken leading up to and during the period of lighting. Documents displayed the changes in predicted weather and how tactics were adjusted midway through the burn as the fire weather started to deteriorate. The Executive Management team was provided a clear and well documented picture that this situation was beyond our control and fire managers acted using best practices. What became quite clear is that a consistently applied risk-based decision support tool for prescribed burning is essential.

Figure 3—Spot-over from Brandy Flat burn as it made an uphill run. (Photo courtesy of Steve Forbes.)

Potter's Hill: Decisionmaking Based on the Best Available Information

The strength of the PB DST has been the ability to consistently document decisionmaking based on the best available information. In March 2018 the ACT was implementing a number of large, rural prescribed burns. A decision was to be made as to whether it was appropriate to implement another large burn as two other burns were winding toward completion. The Potter's Hill burn was chosen due to its solid control lines and relatively standard ignition patterns. The forecasted weather was very favorable (fig. 4) with the next 7 days all well within prescription. Additionally, the fuel moisture, which is sampled regularly, was also within acceptable range (10-hour fuels ranged between 10-16 percent). Based on the best available information, the PB DST was completed and there was a low risk of escape and moderate impact of smoke.

The decision was made to begin implementation on March 10, 2018. Over the course of the burn the weather fluctuated greatly, which resulted in limiting active ignition when the FDI was outside of prescription (fig. 5). The standardized forms allowed the IMT to capture their decisions. The PB DST proved invaluable again as this information changed almost daily, which then affected the decisionmaking of the IMT, all captured in the PB DST. Through the course of the burn, 18 March was highlighted by the PB DST as a "day of concern." The initial forecast for the 18th (made on March 12) predicted an FDI of 16, which is slightly out of prescription and not too much of a concern (fig. 4). The following day the prediction decreased and then it slowly started to increase as March 18 became closer. Strategic decisions were made by the IMT to strengthen the weaker control lines prior to March 18, but ignition options were limited by unfavorable weather on March 15.

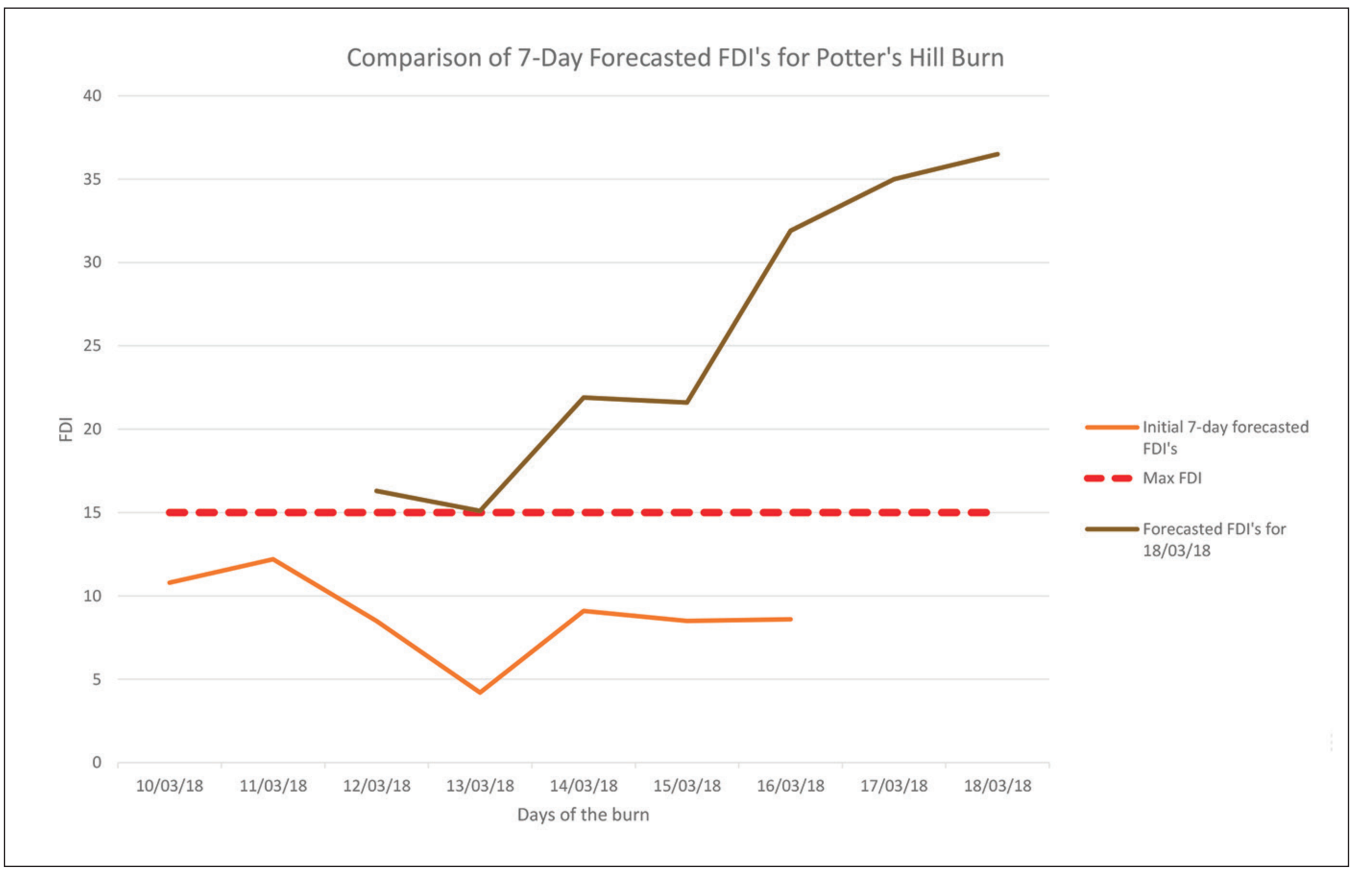

Figure 4—Forecasted FDI for the Potter's Hill burn: the initial 7-day forecasted FDI (orange) prior to implementation and the escalating forecasted FDI for March 18 (brown).

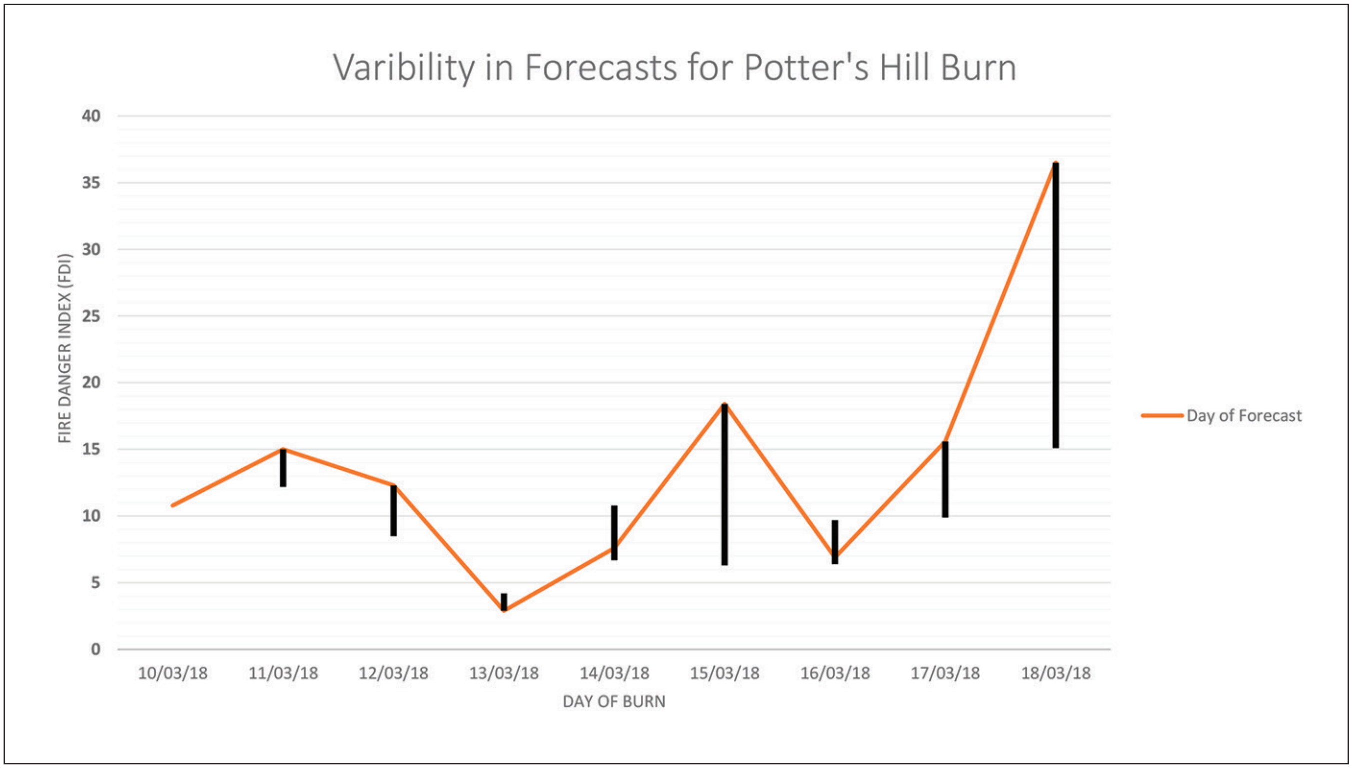

Figure 5—The range (black) of forecasted FDI for the Potter's Hill burn, highlighted by predicted forecast on each given day (orange).

On March 16, the predicted FDI had nearly doubled and it was clear that March 18 could be a problem day. March 18 was ultimately declared a Total Fire Ban for the ACT and a preemptive IMT was established at the State Control Centre. Regardless of the best attempts to shore up control lines, the observed weather was too difficult to overcome as all aircraft were shut down due to strong winds. A spot-over occurred and the fire made a run (fig. 6). Long-range spotting of 6-10 km occurred; however, with the quick work of crews and aircraft—when they were able to fly the fire—was held to 200 ha.

It is important for fire managers to utilize the best information that is available at the time of decisionmaking. This is done at all times but was highlighted on the Potter's Hill burn and documented on the PB DST. The weather and fuel moisture were well within prescription; crews were ready and available and the burn had strong containment lines. But ultimately after the decision was made, the information changed and an escape occurred. The "low" risk rating on the initial PB DST was attributed to the benign predicted fire weather and the lack of "high level" assets. The risk was deemed acceptable. This places fire managers in precarious situations, as in Australia where we implement 5-8 million hectares a year of prescribed burns. It is not in our best interest to begin second guessing the Bureau of Meteorology (BoM), for example, otherwise we will find ourselves with little or no burn windows. But with the advent of the PB DST we can now document in a clear and transparent way how we utilized the available information before and during implementation.

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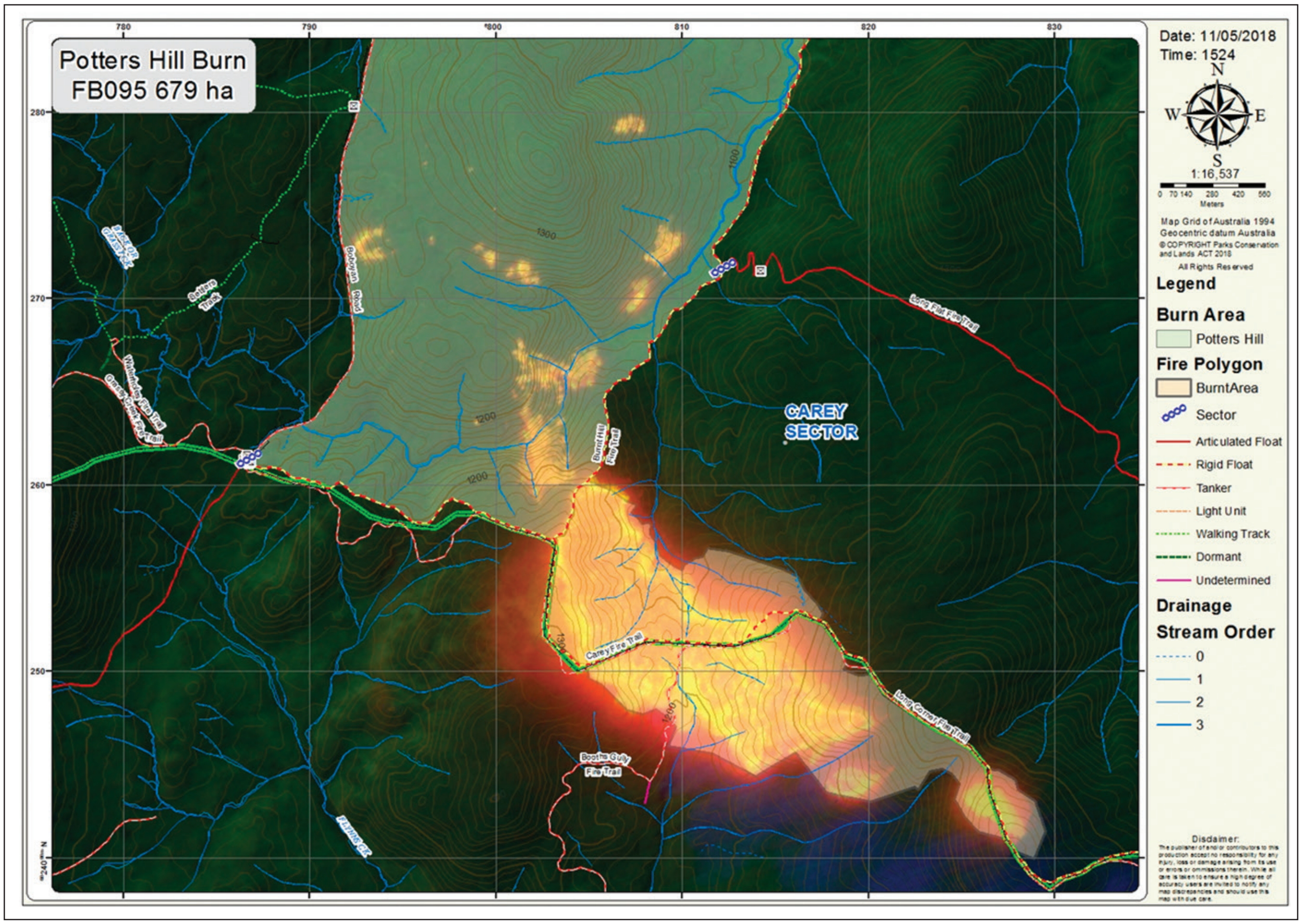

Figure 6—Map of the line scan for the Potter's Hill escaped burn.

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ADDRESSING THE CHALLENGE OF SMOKE MANAGEMENT

For decisionmakers and fire managers, the two most important questions regarding prescribed burns can be summarized as: Will the burn behave and will the smoke impact stakeholders? The latter question has a direct impact to communities and industry and is one of the biggest challenges for our industry. There are a number of factors that contribute to smoke management; despite recent developments, there has not been a consistent method to document and demonstrate how fire managers have considered this information and the decisions made as a result.

In Australia, steps have been taken to assist with predicting the effects of smoke and smoke forecasting. Three years ago, a smoke plume model was developed by the New South Wales Rural Fire Service that provides information on smoke dispersal from a single prescribed burn. More recently, a new experimental smoke forecasting system (AQFx), which takes a landscape approach to air quality, has been developed and hosted by the BoM. Prior to the PB DST smoke module, there had not been a consistent tool or process to document the information from these smoke forecasting tools.

Fire planners are now able to gather data from the smoke plume model or AQFx along with other factors that contribute to smoke and then consider the potential consequences in a transparent and systematic manner. This has facilitated the ability to determine whether it is suitable or not to proceed. Smoke management is complex and a range of variables can affect smoke dispersal on any given day.

A number of lessons have been learned since the inclusion of this module. Consistent feedback emphasized additional public engagement by the IMT, resulting in better communication and signage with the public. In the documentation of numerous assessments, it was determined that the impact of smoke would be minimal based on predicted wind direction; this seemed to give the IMT confidence to proceed with the best information available at the time. In some cases, the burn assessor documented that regardless of predicted winds there would be an impact to the community; however, the risk benefit outweighed the short-term impact to the public. This scenario is often debated: Is smoke from a prescribed burn better than from a bushfire? Lastly, there are occasions where the result of the assessment was determined to be a “Very High” risk of smoke. In these situations, context played a large role. This situation occurred on recent pile burns that were not in proximity to the public. The ventilation index was poor due to light winds, but the wind direction would disperse the smoke away from assets. Utilizing the PB DST, assessors were able to clearly document why they believed it was still suitable despite the risk rating.

CONCLUSION

Prescribed burns are becoming more difficult to implement due to a range of factors, including decreased opportunities, increased scrutiny, and increasing expectations resulting in higher accountability. These factors contributed to the development of the Prescribed Burn Decision Support Tool, a tool designed by fire managers to be utilized by fire managers. This tool supports fire managers by providing a consistent, transparent, repeatable, and robust system that documents the decisionmaking process before, during, and after the operation.

REFERENCES

Ferguson, E. 2010. A review of the ability of the Department of Environment and Conservation, Western Australia, to manage major fires. Perth, WA: Department of Environment and Conservation. 6 p.

Independent Lancefield-Cobaw Fire Investigation Team. 2016. Independent investigation of the Lancefield-Cobaw Fire, Department of Environment, Land, Water and Planning. Available at: https://www.ffm.vic.gov.au/__data/assets/pdf_file/0002/20000/Independent-investigation-into-Lancefield-Cobaw-fire.pdf.

Keelty, M.J. 2012. Appreciating the risk: report of the special inquiry into the November 2011 Margaret River bushfire. Perth, WA: Government of WA.

Wildland Firefighter Burnover Fatalities on Prescribed Fires and Wildfires in the United States, 1990 to 2017

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Abstract—In the 28-year period from 1990 to 2017, there were 41 incidents in the United States where firefighter burnover fatalities occurred on wildland fires. Ninety-six fatalities and 78 injuries were reported, with an average of 1.5 incidents and 3.4 fatalities per year. The great majority (76 percent) of fatalities occurred in mountainous terrain, where the most common situation was that fire personnel became trapped while working upslope or upcanyon from the fire when the fire made a sudden upslope run. The information for my report came primarily from serious accident investigations of individual incidents. The information presented in this paper will help managers and fire personnel better understand the environmental conditions and some of the human and organizational factors that are present during fatal burnovers.

Keywords: accident, burnover, fatalities, incident

INTRODUCTION

This report is a review and analysis of wildland firefighter burnover fatalities on prescribed fires and wildfires in the United States from 1990 through 2017. The National Wildfire Coordinating Group (NWCG) Glossary of Wildland Fire Terminology (2018) defines a burnover as "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." Information for my analysis was gleaned primarily from serious accident investigation (SAI) reports.

In the United States between 1990 and 2017, there were 41 incidents where firefighter burnover fatalities occurred on prescribed fires and wildfires, resulting in 96 fatalities and 78 injuries. During this period there was an annual average of 1.5 incidents and 3.4 fatalities. An NWCG report for the period of 1990 to 2006 indicated there were 64 total burnover fatalities with an average of 3.8 per year (Mangan 2007).

Burnover fatalities are a rare occurrence when we consider the large number of fires that are suppressed each year in the United States, but the results are catastrophic. Five incidents between 1990 and 2017 resulted in 44 fatalities: 6 in the Dude Fire (Arizona), 5 in the Esperanza Fire (California); 14 in the South Canyon Fire (Colorado), and 19 in the Yarnell Hill Fire (Arizona).

A better understanding of the commonalities during burnover entrapments is needed. Environmental conditions (e.g., fuels, weather, topography, climate), human and organizational factors, and other variables must be considered. Greater understanding of the conditions, situations, and commonalities under which entrapments occur can improve research, training, strategic and tactical decisionmaking, planning, and safety practices. All of these efforts can help reduce burnover injuries and fatalities.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

METHODS

Information for this report was obtained mainly from SAI reports, which were usually completed by agency or interagency teams, and the National Institute for Occupational Safety and Health (NIOSH). Other sources of information on historical incidents included:

- Wildland Fire Lessons Learned Center
- California Department of Forestry
- Texas State Fire Marshall
- NWCG (various reports)
- WLF Always Remember
- Information from various websites
- Historical Palmer Drought Severity Indices (PDSIs)

The SAI reports for the burnovers vary widely in scope and detail, with the document lengths running from 10 to 290 pages. There were nine incidents where no investigative report could be found; however, I was usually able to obtain some basic information.

In completing this report I used other tools, which included U.S. Geological Survey topographic maps, Google Earth, historical fire weather observation data, and FireFamily Plus software. A database was also established to gather, organize, sort, and analyze information.

FINDINGS

Locations of Burnovers

Burnover fatalities have occurred in 18 states: Arizona, California, Colorado, Idaho, Montana, New Mexico, Oregon, South Dakota, Utah, Washington, Georgia, Kentucky, Florida, Mississippi, Oklahoma, Tennessee, Texas, and Virginia.

Topography

Topography is a major factor in burnovers. Seventy-three fatalities occurred in mountainous terrain; upslope fire runs resulted in 67 fatal burnovers, and downhill fire runs resulted in 6 fatal burnovers. In addition, 59 percent of the SAI reports state that the fire was running up a canyon or chimney. Incidents in flat to rolling terrain resulted in 11 fatalities. There were 12 fatalities that occurred where not enough information was available to determine the type of typography.

Fuels

Burnovers generally occur during extreme fire behavior (EFB) events. Extreme fire behavior can occur on any scale, great or small, in any fuel type, and at any time of the day or night. There is no time or circumstance when fire managers can safely assume EFB will not occur (Werth et al. 2011). Other studies of burnovers have shown there is no significant trend when examining fuel types (Munson and Mangan 2000).

My analysis classified vegetation present at the incident scene into fuel types (grass, shrub, and timber). Table 1 displays the number of sites where one, two, or all fuel types were present at the location of the fatal burnover or incident.

Weather

In a review of weather information from the SAI reports, an incomplete picture of onsite weather observations and weather forecast information emerged. Evaluating observed weather values such as air temperature, wind speed, wind direction, and relative humidity was not practical due to the lack of weather observations in several of the SAI reports.

I determined that evaluating weather factors was best done by using information from National Fire Danger Rating System (NFDRS) weather stations and daily fire danger rating indices. The index that was chosen for this analysis was the Energy Release Component for NFDRS fuel model G (ERCg). Fuel model G represents dense conifer stands where there

Table 1—Number of burnover sites having a given number of fuel types.

One fuel type present	Two fuel types present	Three fuel types present	Unknown	Total number of incidents
7	17	10	7	41

is a heavy accumulation of litter and downed woody material. The NFDRS weather station closest to and most representative of the incident scene was selected, and weather observation data for the time period of the entrapment were downloaded; ERCg was calculated in the FireFamily Plus software. The results of this analysis showed that the great majority (78 percent) of fatalities occurred when conditions were much drier or more extreme than normal. Table 2 shows the number and percentage of fatalities by ERCg.

Climatic Factors

The PDSI was used as an indicator of climatic conditions that occurred during the fatal burnover incidents. Historical PDSI information was obtained for every incident. An analysis of this information indicated that 84 percent of the fatal burnovers occurred when the PDSI was at the moderate, high, or extreme level.

Temporal Factors

An analysis of the month and time of day when fatal burnovers occurred was completed.

The majority (68 percent) of fatalities occurred in June, July and August, with the peak month being June (30 percent). No fatalities occurred in January and February.

Time-of-day analysis indicated that 69 percent of the fatalities occurred between 3 and 5 p.m. No fatalities occurred between 11 p.m. and 6 a.m.

Human and Organizational Factors

There are many human and organizational factors that play into a fatal burnover. Generally, the SAI reports do not provide a great deal of information on this topic.

The most common occurrence in burnovers is that fire crews were trapped while working upslope or upcanyon from the fire when the fire made a sudden upslope or upcanyon run (71 percent of fatalities). This situation was also referenced in another study (Wilson and Sorenson 1978), in which one of the four main common denominators of fire behavior in tragedy (burnover) and near-miss fires is “when fire responds to topographic conditions and runs uphill.”

Table 2—Number and percentage of total fatalities by Energy Release Component (ERCg) values.

ERCg	Number of fatalities	Percentage of fatalities
97th percentile	19	20
90th percentile	40	42
80th percentile	15	16
Low/Moderate	14	15
Unknown	8	8

Other findings of my analysis include:

- The average age of individuals involved in burnovers was 33 years old.
- Regarding qualifications of individuals, 43 percent of total fatalities occurred with our most experienced and highest qualified fire personnel (e.g., overhead personnel, Type 1 crews, helitack, and smokejumpers) (table 3). The SAI reports do not provide detailed information on the qualifications and experience of people involved in entrapments.
- In my evaluation of safety standards that may have been compromised, as measured by the Standard Firefighting Orders (Fire Orders) and the 18 Situations that Shout Watch Out (Situations), this report found that 15 serious accident reports

Table 3—Percentage of fatalities by resource type.

Resource type	Percentage of fatalities
Type 1 resource: hand crew (e.g., hotshot, helitack, smokejumper)	39
Type 2 resource: hand crew (e.g., regular, inmate)	23
Engine crews	23
Dozers and tractor plows	8
Overhead (e.g., division supervisors, burn boss, incident commander)	4
Unknown	3

(37 percent of the total incidents) addressed this matter. On burnover incidents an average of eight Situations were present and seven Fire Orders were compromised.

- State employees were involved in the largest percentage (27 percent) of burnover incidents, followed closely by individuals from Federal agencies (24 percent) (table 4).

Trends

From 1990 through 2017, looking at 10-year averages, there has been a slight decrease in the number of fatalities during burnovers, from about 3.7 to 3.6 per year. The number of incidents from 1990 to 2017 has also slightly decreased from about 1.3 to 1.1 per year. Of particular note are the following:

- From 2007 to 2017 there were 5 separate years when no fatal burnovers occurred. This is very significant because in the previous 10-year period, 1997 to 2006, there was only 1 year when no fatal burnovers occurred.
- There have been no fatal burnovers of Type 2 hand crews since 2010.
- The trend in burnover fatalities for engine crews is sharply up. From 1990 to 2003 there were 6 fatalities and from 2004 to 2017 there were 16 fatalities.

CONCLUSIONS

Every fatal burnover is unique; however, there are many commonalities in burnover incidents across the United States. Fatal burnovers generally occur on wildland fires because of extreme fire behavior (fuels, weather, topography, and climate) and a wide variety of human and organizational failures. Answers to questions on human and organizational failures are not usually found in SAI reports.

The findings of my analysis show that there has been some improvement in the last 10 years in the total number of burnover fatalities and incidents. Of concern is the significant increase in entrapments of engine crews, which is probably related to the growing number of fires being fought in the wildland-urban interface.

Table 4—Affiliation of people involved in burnovers by percentage of incidents.

Affiliation of individuals involved in burnovers	Percentage of incidents
State	27
Federal	24
Volunteer department	22
Municipal department	10
Other	10
Unknown	7

There are multiple contributing factors in any incident and often complex coincidences that cause organizations to fail. Often on a wildland fire incident there are many participants, none of whom may have complete information.

The *Esperanza Fire Accident Investigation Factual Report, Riverside County, California October 26, 2006* gives a good example of how our culture can affect operations. The report states: “Contributing Factor 1. Organizational culture—The public (social and political) and firefighting communities expect and tolerate firefighters accepting a notably higher risk for structure protection on wildland fires, than when other resources/values are threatened by wildfire.”

It appears that burnovers result from a series of mistakes that may lead to a fatality or injury. An analysis of these incidents showed that an average of seven Fire Orders were not followed or were otherwise compromised. In these situations, Fire Orders seem to have been generally ignored or misunderstood.

The preponderance of burnovers in mountainous terrain is due to several factors. Weather and fire behavior can be hard to predict in the mountains, and steep slopes and narrow canyons have a major effect on fire intensities, fire spread rates, and spread direction. In addition, travel in mountainous terrain on foot can be very difficult and slow.

Extreme fire behavior can be eruptive in nature and surprise fire personnel, entrapping them. This report has shown that fatal burnovers occur during the hottest and driest time of the day and during the months of peak fire season, with exceptions. The National Fire Danger Rating System has been shown to be a good tool for helping to predict the potential for extreme fire behavior.

In 1957 the Forest Service, Department of Agriculture commissioned a task force to recommend further action needed in both administration and research to materially reduce the chances of men being killed by burning while fighting fire (Moore et al. 1957). This task force found that there are a large number of factors common to many tragedy fires (burnovers) and developed a list of the most significant ones. These factors marked the origin of the Fire Orders and Situations.

Commonalities on fatal burnovers cannot be narrowed down to a few factors that could define when an entrapment might happen. Fire personnel need to evaluate all environmental conditions on any given incident, including fuels, weather, topography, and climate and how they all relate and interact with each other. Weather forecasts and fire danger ratings need to be closely monitored. There are many complex and interrelated factors that lead to fatal burnovers. I have concluded that the current Fire Orders and Situations are still very relevant and if followed can help prevent burnover situations.

SUMMARY

This report has shown that fatal burnovers have decreased in the last 10 years, but only slightly. I recognize that missing information from several SAI reports and the lack of investigations or reviews on nine incidents may affect the conclusions in this report, and efforts need to be made to obtain missing information. It is my hope that having a better understanding of burnovers will help reduce the number of injuries and fatalities.

REFERENCES

Mangan, Richard. 2007. Wildland fire firefighter fatalities in the United States: 1990–2006. NWCG PMS 841. Boise, ID: National Wildfire Coordinating Group, Safety and Health Working Team, National Interagency Fire Center. 28 p. https://www.fs.fed.us/t-d/pubs/pdfpubs/pdf07512814/pdf07512814dpi72.pdf. [Accessed 2018 June 25].

Moore, W.R.; Parker, V.A.; Countryman, C.M.; [et al.]. 1957. Report of the task force to recommend action to reduce the chances of men being killed by burning while fighting fires. Washington, DC: U.S. Department of Agriculture, Forest Service. 30 p. plus appendixes. https://www.fireleadership.gov/toolbox/staffride/downloads/lsr2/lsr2_resource8.html. [Accessed 2018 June 25].

Munson, Steve; Mangan, Richard. 2000. Wildland firefighter entrapments 1976 to 1999. Missoula, MT: U.S. Department of Agriculture, Forest Service, Technology and Development Program. TE02P16-Technical Services, Fire & Aviation. https://www.fs.fed.us/t-d/pubs/htmlpubs/htm00512853/. [Accessed 2018 June 25].

Werth, Paul A.; Potter, Brian E.; Clements, Craig B.; [et al.]. 2011. Synthesis of knowledge of extreme fire behavior: Volume I for fire managers. Gen. Tech. Rep. PNW-GTR-854. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 144 p.

Wilson, Carl C.; Sorenson, James C. 1978. Some common denominators of fire behavior on tragedy and near miss forest fires. Broomall, PA: U.S. Department of Agriculture, Forest Service. 31 p.

Development of a New Open-Source Tool to Map Burned Area and Burn Severity

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Abstract—Accurate and complete geospatial fire occurrence records are important in determining postfire effects, emissions, hazards, and fuel loading inventories. Currently, the Monitoring Trends in Burn Severity (MTBS) project maps the fire perimeter and burn severity of all large fires on public lands. Although the MTBS project maps a large proportion of the fire acreage, it maps a smaller proportion of the actual number of fires in the United States, thereby creating a data gap. To fill this data gap, fire scientists at the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center (EROS; Sioux Falls, South Dakota) proposed creating an open-source Fire Mapping Tool (FMT; available at https://mtbs.gov/qgis-fire-mapping-tool) as part of a two-phase National Aeronautics and Space Administration (NASA) Applied Fire Science Program grant. Phase II developed the FMT to map burn perimeters and severity not included in the MTBS database. This paper will focus on Phase II and will explain the algorithms that enhance the FMT's functionality, demonstrate fire mapping procedures, and provide an example comparison between MTBS analyst fire products and those mapped using the FMT. The overall goal in the production of the FMT was to provide a freely available tool that can be used to map fires anywhere in the world.

Keywords: fire, Monitoring Trends in Burn Severity (MTBS), Normalized Burn Ratio (NBR), differenced NBR (dNBR), burn severity thresholding

INTRODUCTION

The Monitoring Trends in Burn Severity (MTBS) project was initially tasked to map the burned area and burn severity of fires ≥ 402 ha in the western and ≥ 202 ha of the eastern United States (Eidenshink et al. 2007). Although the MTBS project's acreage threshold accounts for the majority of burned areas in the United States, the project misses a large number of small burned areas (Howard et al. 2014). Multiple burned area products are available that include smaller fires (Leblon et al. 2016) that MTBS misses; however, they have varying levels of accuracy and may not provide an estimate of burn severity. New tools need to be developed that allow users to easily adjust potential fire perimeters from burned area products and map fire perimeters and estimate burn severity (Picotte et al. 2014).

Currently, the MTBS project uses Landsat 30-m data products to map fire perimeters and burn severity for the conterminous United States, Alaska, Hawai'i, and Puerto Rico. MTBS analysts carry out a labor-intensive burn mapping protocol: (1) the identification of a fire using the Fire Occurrence Database; (2) identification and retrieval of postfire (at the minimum) and potentially prefire Landsat imagery; (3) processing of Landsat imagery and production of Normalized Burn Ratio (NBR; Key and Benson 2006) derivatives; (4) creation of differenced Normalized

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Burn Ratio (dNBR; Key and Benson 2006) image if post- and prefire images are available; (5) creation of a fire perimeter shapefile by tracing the outline of the fire perimeter visible within Landsat imagery; (6) determination of a dNBR offset to characterize potential between-image changes other than fire (Key 2005); (7) production of Relativized dNBR (RdNBR; Miller and Thode 2007) maps; and (8) visual determination of low, moderate, and high burn severity thresholds (Eidenshink et al. 2007). Because MTBS maps the entirety of the outside of the fire perimeter and does not map unburned islands within the fire perimeter, MTBS fire perimeter data tend to have errors of commission (Kolden and Weisberg 2007; Kolden et al. 2012; Sparks et al. 2015). There are also potential concerns with using the MTBS burn severity products, because burn severity thresholds are not consistently applied between fires and do not necessarily relate to the total amount of vegetation damage (Kolden et al. 2015). However, potential spatial patterns of burn severity can be useful to managers, and thresholds could be modified by ground-collected data that assess ground-based fire effects (e.g., Composite Burn Index [CBI] data).

Filling the small fire data gap was part of Phase I of the NASA Applied Sciences Program "Utilization of Multi-Sensor Active Fire Detections to Map Fires in the United States" project (Howard et al. 2014). Although modeling procedures to map fires within the Grand Canyon and in northern Florida were developed (Howard et al. 2014), this development became redundant with the advent of the Burned Area Essential Climate Variable (BAECV; Hawbaker et al. 2017). BAECV is a burned area product that combines burn probability modeling with a region growing algorithm to map potential burned areas that are approximately 4 ha or larger in size (Hawbaker et al. 2017). Currently the 1984-2015 BAECV data are available for the conterminous United States. (https://www.sciencebase.gov/catalog/item/57867943e4b0e02680c14fec, accessed 3/13/2018). However, users should be aware of the BAECV product's varying level of regional accuracy that was best in the Arid West and Mountain West and worst in the Great Plains and Eastern United States. (Vanderhoof et al. 2017a; Vanderhoof et al. 2017b). Leveraging BAECV data will allow users to potentially obtain a fire perimeter for any fire event greater than 4 ha visible with Landsat imagery.

The second phase (i.e., Phase II) of the NASA Applied Sciences Program "Utilization of Multi-Sensor Active Fire Detections to Map Fires in the United States" project was to create a tool that would allow users to map fires in a similar fashion to MTBS (Howard et al. 2014). Tools were developed during the first phase of the project to follow the MTBS processing steps to create burn perimeters and severity imagery; however, additional work was needed to refine them and make them easily accessible to users. This paper will explain the refinements, including the incorporation of algorithms to calculate the dNBR offset and burn severity thresholds, and subsequent integration of this functionality into the open-source FMT (available at https://mtbs.gov/qgis-fire-mapping-tool) Quantum Geographic Information System (QGIS) package (QGIS Development Team 2013) to facilitate the burn severity mapping processes. Finally, an example of the FMT's use in the creation of fire perimeter and burn severity products compared with MTBS products will be presented.

METHODS

MTBS Historical Data

MTBS historical metadata (available at https://www.mtbs.gov; accessed on 03/18/2018) was compiled for 18,497 fires that occurred between 1984 and 2014 within the conterminous United States, Alaska, Hawai'i, and Puerto Rico. Fires may have been assessed using either a single scene (i.e., postfire only NBR) or dNBR assessment strategy depending on image availability. Each fire was subsequently classified by its assessment strategy. Overall, 11,998 and 6,599 fires were classified by dNBR and NBR assessment strategies, respectively. Additional information that was obtained from the metadata included the MTBS id, dNBR offset value if the dNBR assessment strategy was used, and low, moderate, and high burn severity thresholds when assessed. All postfire NBR, dNBR, and classified burn severity image products were also obtained for each fire. Metadata and imagery were then used in the development of the dNBR offset process, thresholding process, and assessment of each process.

dNBR Offset Process

Currently, MTBS analysts calculate the dNBR offset by manually selecting hundreds to thousands of unburned pixels within the dNBR image that are outside the fire perimeter but occur within a similar vegetation type. The mean of all selected pixels is then calculated. If the mean dNBR value (unitless) is between -50 and 50 and the standard deviation is < 50, the offset is considered acceptable. If the value of the offset violates either assumption, then this indicates that the pre- and postfire images may not be seasonally and temporally similar (Key 2005; Key and Benson 2006; Zhu et al. 2006), suggesting that the analyst should pick more similar pre- and postfire Landsat imagery if available.

The MTBS dNBR offset logic was adjusted and automated by examining all unburned pixels in the postfire dNBR image. The unburned range of dNBR pixels was set to between -100 and 100, as suggested by Key and Benson (2006). Instead of selecting pixels from a limited region outside the fire perimeter, all unburned pixels within the clipped dNBR image extent (fire extent + 3,000 m) were selected. The median offset was calculated in lieu of calculating the mean offset value according to MTBS protocols to remove the effect of outlying values. Additionally, the standard deviation of all unburned pixels was calculated. The dNBR offset and standard deviations were subsequently calculated for all dNBR-assessed MTBS fires. Unfortunately, the standard deviation of all unburned pixels was not calculated for the MTBS dNBR offset value, making a comparison between standard deviations between the two methodologies impossible.

Similarity between analyst and calculated dNBR offset values was assessed by calculating goodness of fit (i.e., R^2). To determine whether differences existed between MTBS analyst and calculated dNBR offsets, the percentage of both datasets that fell within the suggested ±50 range was assessed. The percentage of overlap between analyst and calculated dNBR offsets that ranked outside the ±50 range was also assessed. Only the calculated method was assessed for the percentage of fires with dNBR offset unburned pixel standard deviation values ≥ 50.

Burn Severity Threshold Process

MTBS analysts visually assess the unburned/low severity breakpoint (Eidenshink et al. 2007), which may not be consistently done for each fire and requires that analysts be trained in the thresholding process. To create a level of consistency and to create a starting point from which to map the low/unburned burn severity breakpoint, an algorithm was developed that examines all pixels within a range of values of NBR and dNBR and subsequently suggests an unburned/low severity breakpoint using the Otsu thresholding method (Otsu 1979). The Otsu method is a nonparametric thresholding technique that optimizes the threshold grayscale image classes (Otsu 1979). This methodology has been previously used to determine the burned/unburned threshold (Melgani et al. 2002).

The Otsu method was applied to a range of potential unburned pixel values starting at -100 and ranging to 269 for dNBR and > 300 for NBR images to the clipped NBR and dNBR images for all 1984-2014 MTBS mapped fires. Similar methodologies were applied for the low/moderate and moderate/high dNBR and NBR thresholds by varying the range of the data input. Low/moderate severity ranges for dNBR were specified as 270 to 439 and NBR were -65 to 300. High severity ranges were > 440 and < -65 for dNBR and NBR, respectively. These dNBR thresholds approximately encompass previous thresholds determined by comparing ground-collected CBI data with dNBR in multiple studies (Cocke et al. 2005; Epting et al. 2005; Hall et al. 2008; Key and Benson 2006; Picotte and Robertson 2011b). NBR breakpoints follow those from Picotte and Robertson (2011b).

To compare the low, moderate, and high severity thresholds, it was then determined how many times the calculated thresholds were within ±50 units of dNBR or NBR compared with the value of the analyst-derived thresholds for the MTBS data. This ±50 threshold is an adequate level of between-analyst accuracy by the MTBS program. Percent agreement was calculated for dNBR and NBR separately by each severity class, by summing the number of times burn severity thresholds were within ±50 of one another and dividing by the total number of samples per severity class.

FMT Development

At the end of Phase I of NASA Project, open-source tools had been developed to map fires and to view the fires and the imagery (Howard et al. 2014). This process included some of the MTBS processes such as ordering and processing Landsat imagery to Top of Atmosphere (TOA) reflectance, the creation of NBR imagery, modeling of fire perimeters, and the visualization of data within the MTBS QuickLook tool (Howard et al. 2014). To make it easier for users to examine imagery and map fires, all processes (excluding the modeling of fire perimeters) were redeveloped in the QGIS (QGIS Development Team 2013) environment as the FMT plugin (fig. 1).

The FMT provides users with every MTBS processing step outlined in the introduction section. Additional functionality has been incorporated into the FMT to allow users to query the Landsat archive to determine scene availability; examine Normalized Difference Vegetation Index curves for similarity between Landsat scenes; process all Landsat products downloaded from the USGS EROS Science Processing Architecture (Jenkerson 2013) website (https://espa.cr.usgs.gov/, accessed 4/6/2018); produce NBR images; create burn perimeter and mask shapefiles; generate dNBR imagery if pre- and postfire imagery is available; automatically determine the dNBR offset; produce RdNBR imagery if pre- and postfire imagery are available; suggest dNBR or NBR low, moderate,

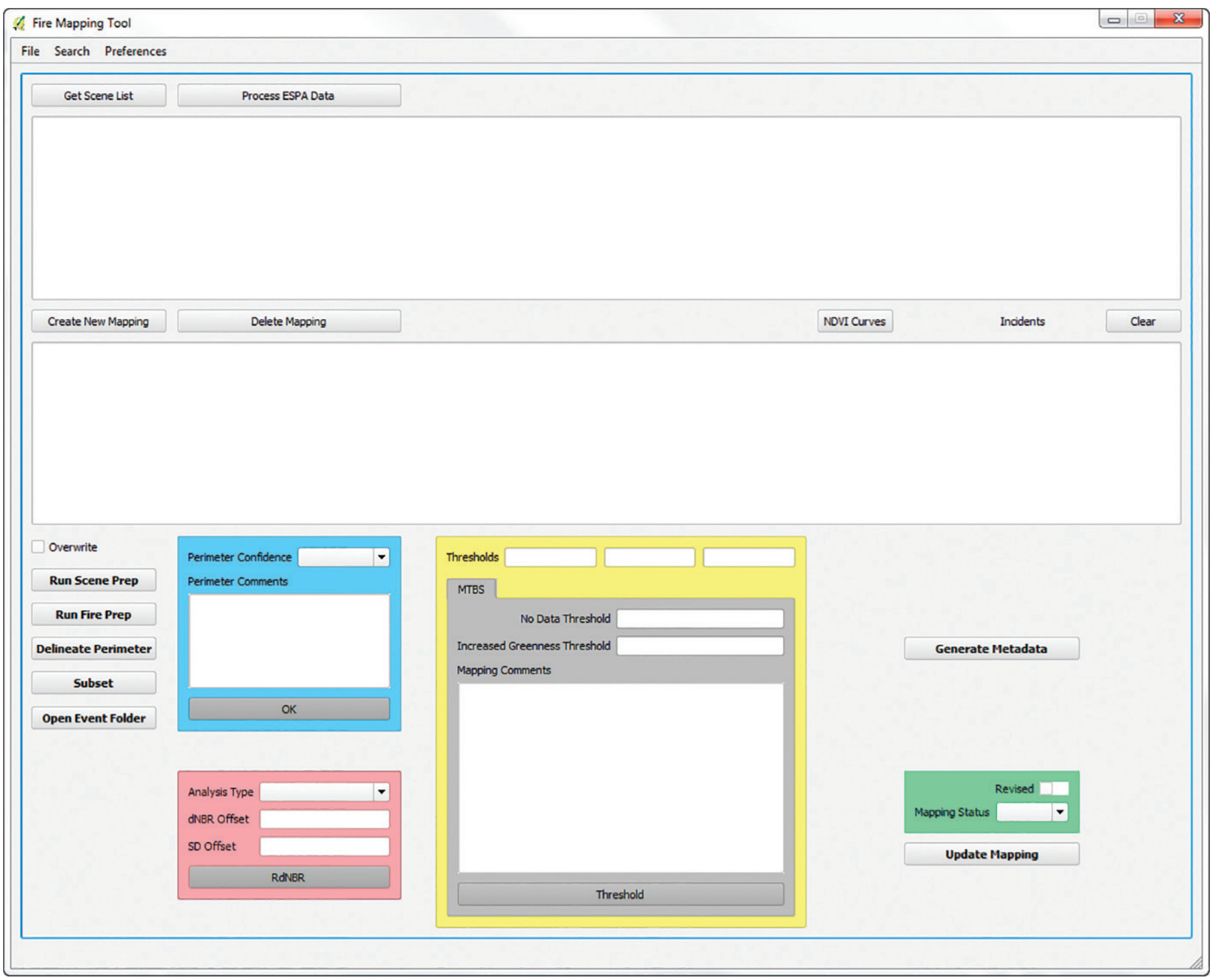

Figure 1—Fire Mapping Tool (FMT) interface.

and high burn thresholds; create the thresholded burn severity product; and produce metadata. The overall goal is to automate the MTBS image processing steps, while allowing users to visually examine the imagery within QGIS and manually edit shapefiles based on an examination of the imagery.

FMT Example

To demonstrate how the FMT can be used to map fires, the June 15, 2015, Paradise fire in the U.S. State of Washington was examined (fig. 2). The original MTBS-mapped products (https:\\www.mtbs.gov) for the Paradise fire were downloaded for comparison and to determine which pre- and postfire Landsat images were originally used by MTBS to map the fire. Prefire Landsat 8 Operational Land Imager (OLI) TOA reflectance corrected from July 29, 2014, and postfire August 8, 2016, Landsat 8 OLI TOA reflectance (fig. 2) imagery were ordered and downloaded from the ESPA Landsat data ordering and processing site. The FMT and the QGIS mapping interface were then utilized to map the burn perimeter and severity using the following steps (see https://mtbs.gov/qgis-fire-mapping-tool for additional documentation about the FMT tool):

1. Process all downloaded pre- and postfire Landsat TOA OLI imagery by extracting the reflectance image bands (2-7), stacking the Landsat image bands into one image, reprojecting the Landsat

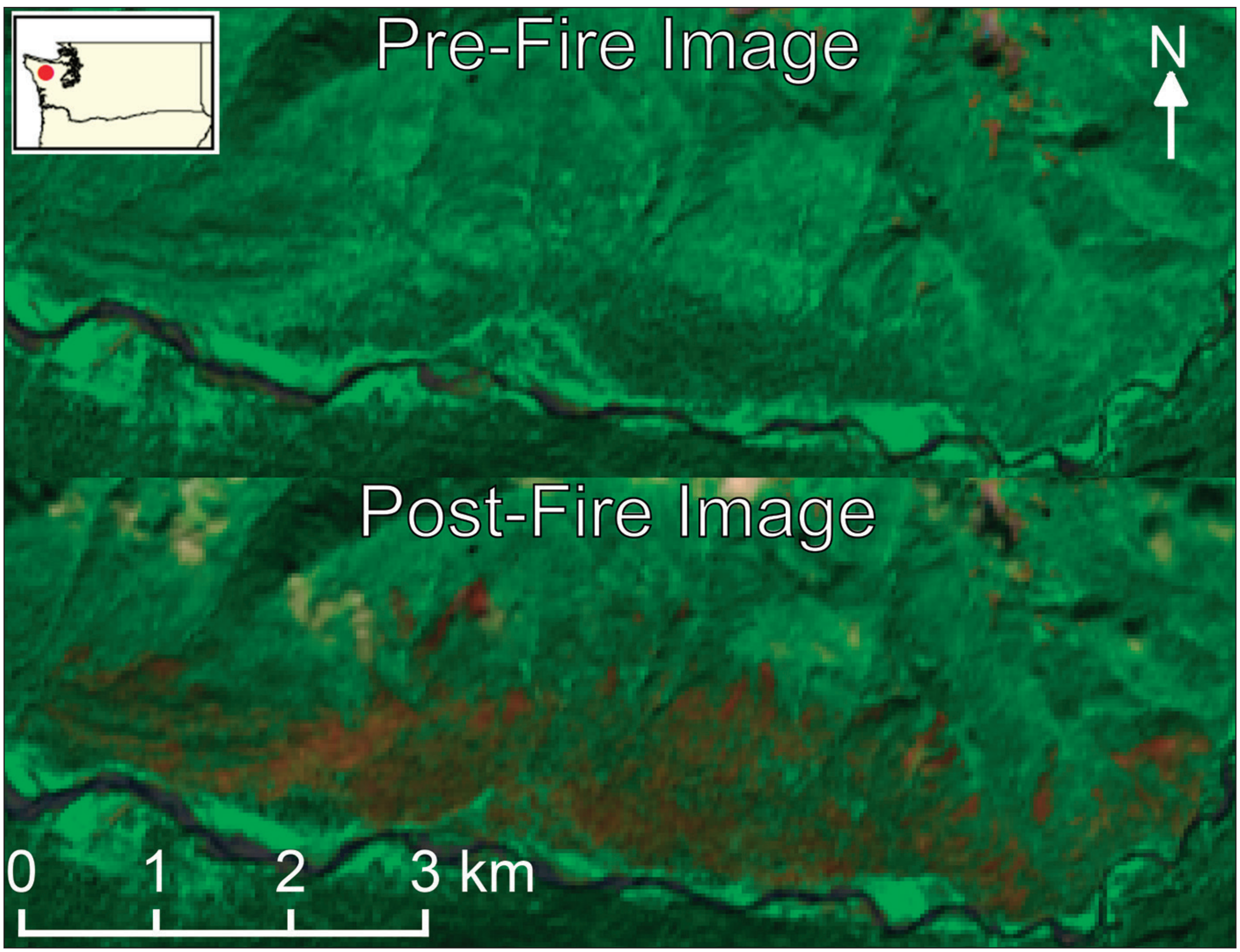

Figure 2—Prefire (July 29, 2014) and postfire (August 8, 2016) Landsat 8 Operational Land Imagery (OLI) images used in mapping the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map). Landsat images are shown using the shortwave infrared band combination 7, 5, and 4.

image to the Albers Equal Area CONUS projected coordinate system, and producing an NBR image ([band 5 – band 7]/[band 5 + band 7]).

2. Subtract NBR values from prefire NBR values to produce the dNBR image (fig. 3).
3. Automate production of empty fire perimeter and mask (for masking any image anomalies such as clouds, cloud shadows, or water) shapefiles.
4. Manually copy fire perimeter and mask perimeters from the MTBS shapefiles into the previously empty shapefiles within the QGIS mapping interface to allow for consistent comparison between the MTBS and FMT created products (fig. 4).
5. Automatically subset all reflectance, NBR, and dNBR images to the fire perimeter bounding box buffered by 3,000 meters.
6. Automatically calculate the dNBR offset and burn severity thresholds from the subset imagery.
7. Apply the burn severity thresholds to the dNBR imagery to create the burn severity image product.

No effort was made to change the calculated dNBR offset and burn severity thresholds to demonstrate how the automated process compared to the MTBS analyst-mapped version of the Paradise fire, although this can be done manually within the FMT.

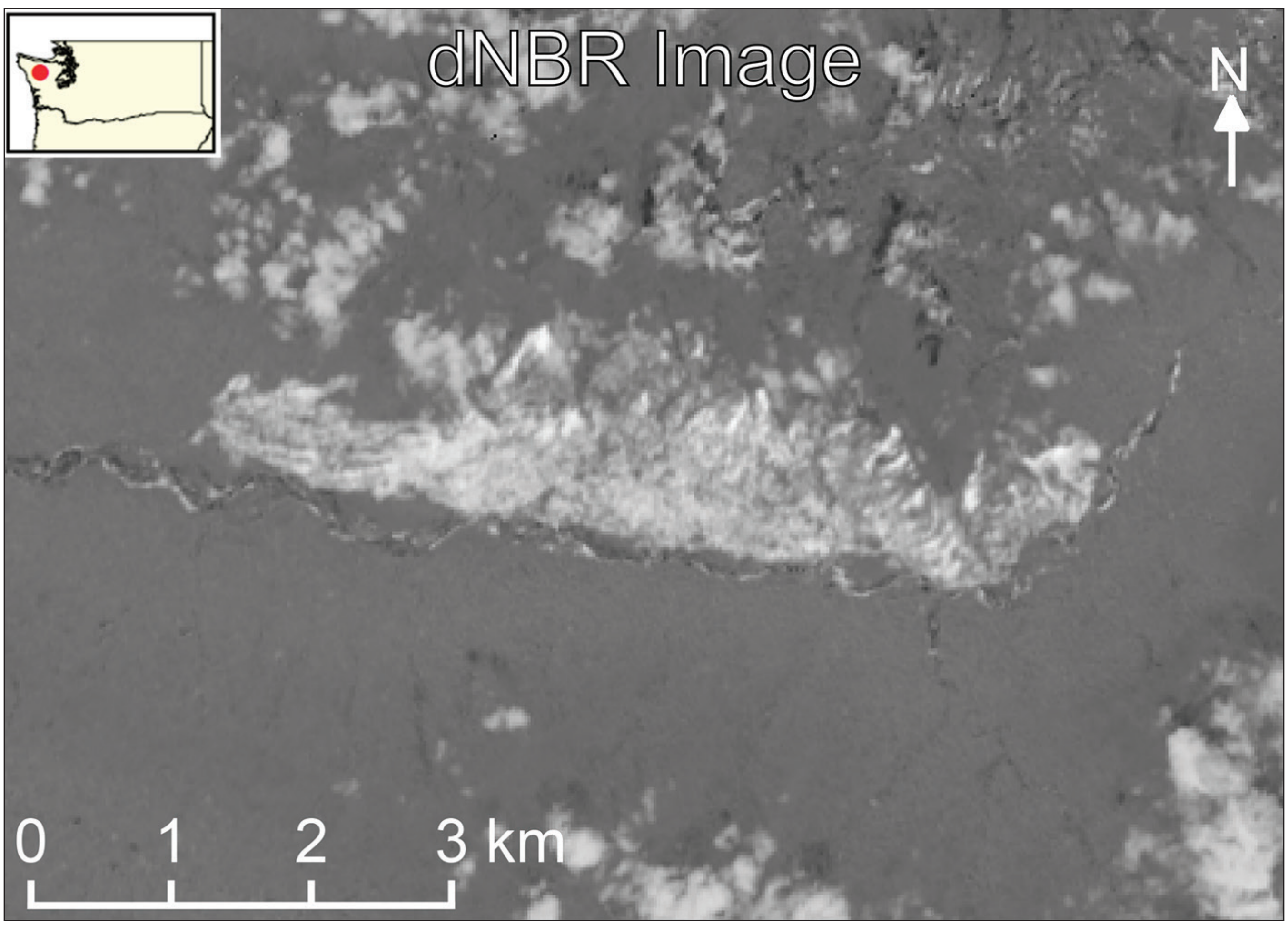

Figure 3—The differenced Normalized Burn Ratio (dNBR) image used for the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map). Higher dNBR values (lighter colors) indicate potential changes between pre- and post-fire NBR images, including those resulting from fire.

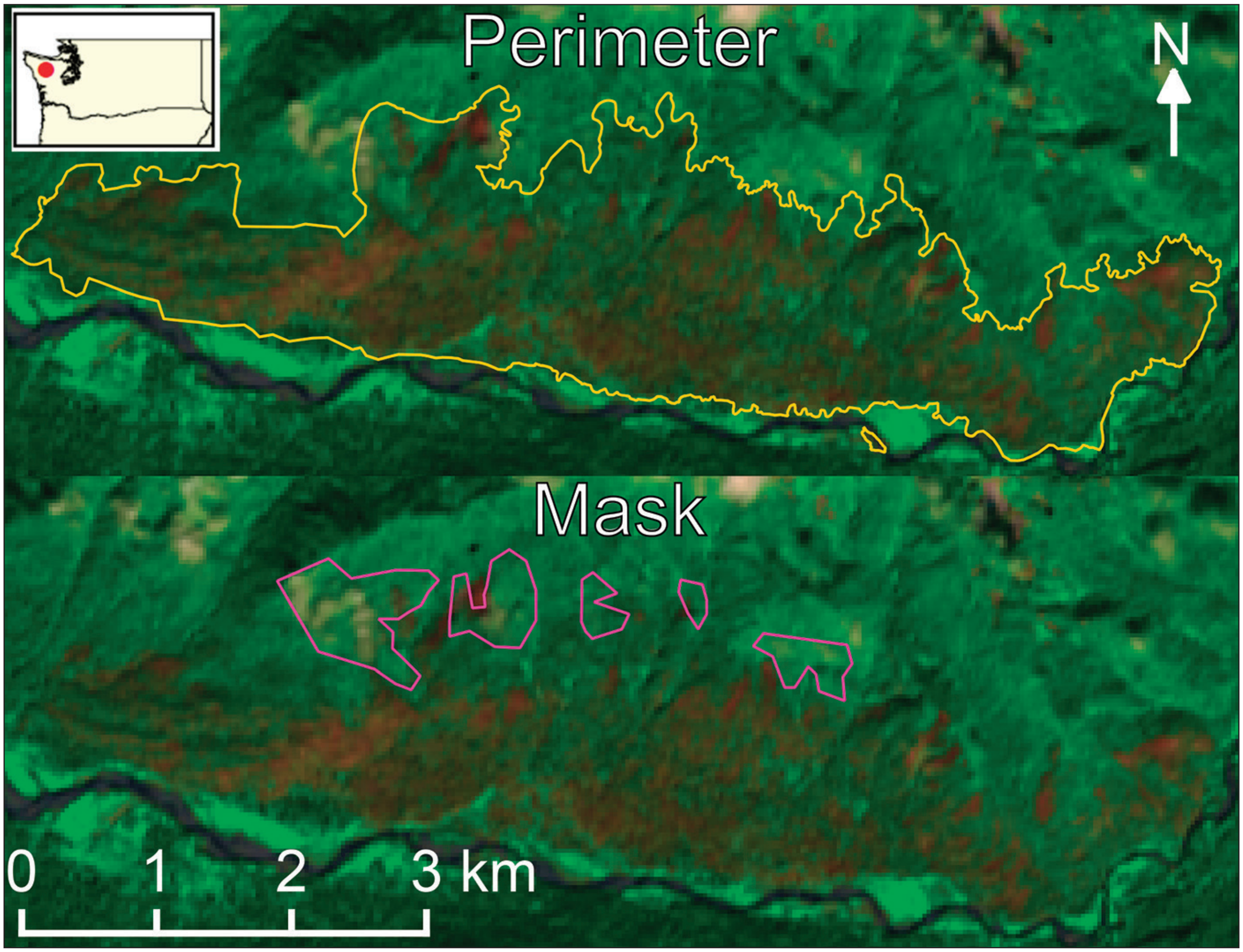

Figure 4—Fire perimeter (yellow) and masked clouds (pink) shapefiles obtained from the Monitoring Trends in Burn Severity (MTBS) project are overlain on Landsat imagery for the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map).

RESULTS

dNBR Offset Comparison

Overall, the calculated dNBR offsets were in agreement with those estimated by MTBS analysts (fig. 5). As values of the offset increased to 100 or decreased to -100, the strength of the relationship between analyst and calculated dNBR offsets was reduced. Calculated offsets had a narrower range (-84 to 83) than the analyst-derived offsets (-243 to 373). The median value of dNBR offsets were similar for the analyst (median = 5.0) and calculated (median = 4.0) estimates.

When dNBR offset values are evaluated by whether they are outside the ±50 range, 22 percent of analyst and 10 percent of calculated offsets violated this threshold. Thirty-five percent of analyst dNBR offset values that were outside the ±50 range were also estimated as outside the range by the calculated methodology. Seventy-nine percent of the calculated dNBR offset values that were outside the ±50 range were also estimated as outside the range by the MTBS analysts.

The median standard deviation of unburned pixels used in the calculation of the dNBR offset values was 42. Of these calculated standard deviation values, 13 percent were ≥50 and had a median value of 52. One percent of all calculated dNBR offset values had both ≥50 standard deviation and dNBR offset values outside the ±50 range.

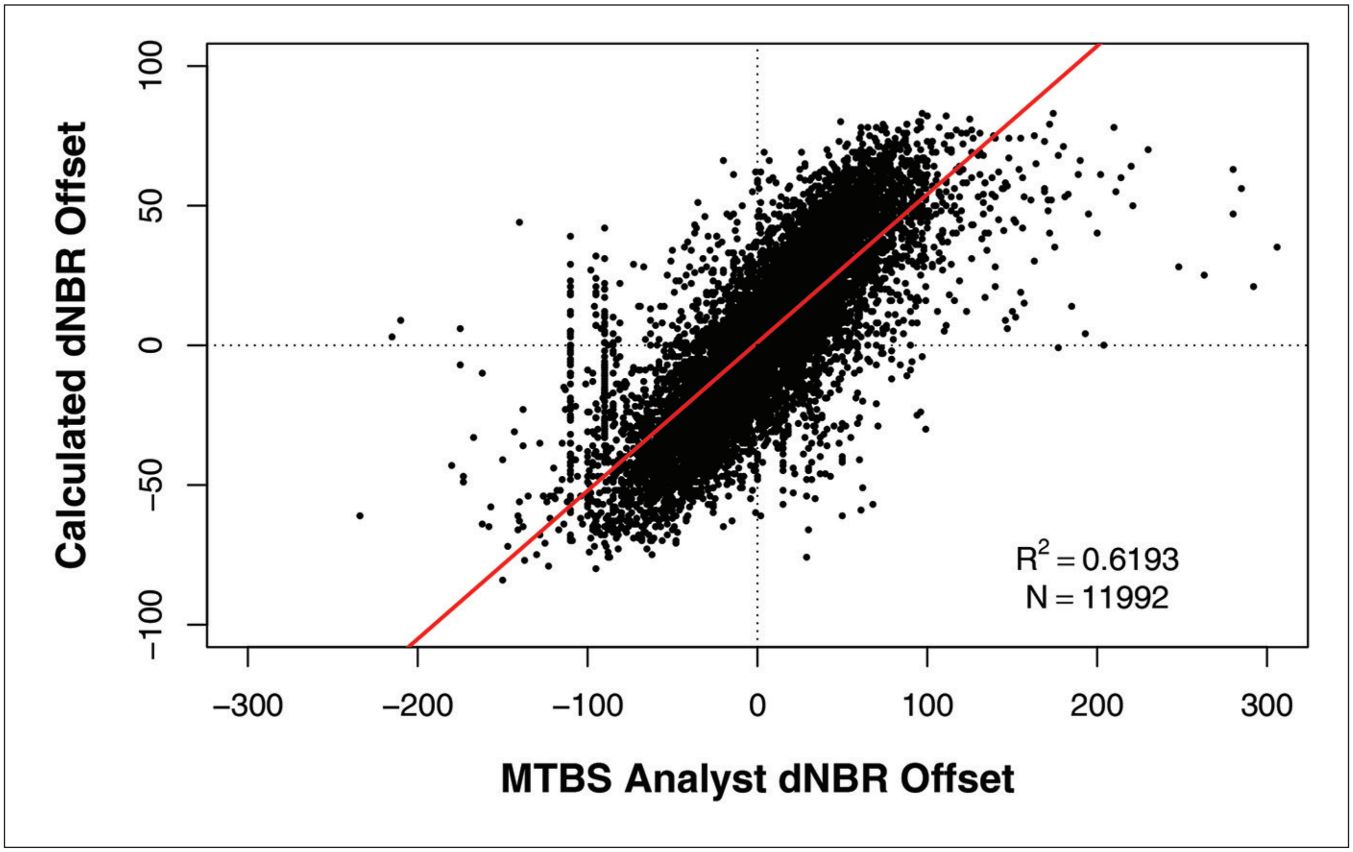

Figure 5—Linear regression between Monitoring Trends in Burn Severity (MTBS) analyst differenced Normalized Burn Ratio (dNBR) and calculated dNBR offset for 1984-2014 MTBS mapped fires.

Burn Severity Thresholding Comparison

Analyst and calculated low severity thresholds were similar for dNBR and exhibited a relatively high percent agreement (table 1). Moderate and high severity dNBR median thresholds exceeded the ±50 agreement threshold, although percent agreement for the moderate threshold was 41 percent. The percent agreement between analyst and calculated thresholds was always higher for dNBR (table 1) than for NBR (table 2) for all threshold groups.

The relationship between analyst and calculated NBR thresholds was poor, i.e., low percent agreement, for all severity threshold types (table 2). Calculated NBR burn severity thresholds were always much higher than the analyst-derived thresholds for all NBR threshold types. The difference between the analyst and calculated median NBR thresholds was only lower than the ±50 agreement threshold for high severity class.

Burn Mapping Example

The Paradise fire was mapped using the FMT in place of MTBS standard procedures. The main difference between these procedures for this example is that the dNBR offset and burn severity estimates were calculated using automated algorithms. Both the FMT calculated and MTBS analyst dNBR offset and offset standard deviation values were similar and < 50 (table 3). All dNBR burn severity thresholds were also similar (i.e., differed < 50) between the MTBS analyst and the FMT calculated values (table 3), which resulted in comparable burn severity classified images (fig. 6).

Table 1—Comparison between analyst and calculated dNBR burn severity threshold median values and standard deviations (StDev) for low, moderate, and high thresholds.

dNBR threshold	Analyst median	Analyst StDev	Calculated median	Calculated StDev	Sample size (N)	Agreement
Low	80	54.8	61	29.3	11,230	69%
Moderate	291	85.2	346	9.41	9,728	41%
High	510	123	590	78.6	7,395	28%

Table 2—Comparison between analyst and calculated NBR burn severity threshold median and standard deviations (StDev) values for low, moderate, and high thresholds.

NBR threshold	Analyst median	Analyst StDev	Calculated median	Calculated StDev	Sample size (N)	Agreement
Low	350	224.6	507	75.7	6089	22%
Moderate	-85	173	142	42.8	2245	10%
High	-200	152.3	-151	128.7	693	21%

Table 3—Comparison between MTBS analsyt and FMT calculated dNBR offset value, standard deviation (StDev), and burn severity breakpoints for low, moderate, and high thresholds for the June 15, 2015, Paradise fire.

	Low	Moderate	High	dNBR Offset Value	dNBR Offset StDev
MTBS analyst	100	321	588	15	27
FMT calculated	92	354	554	18	32

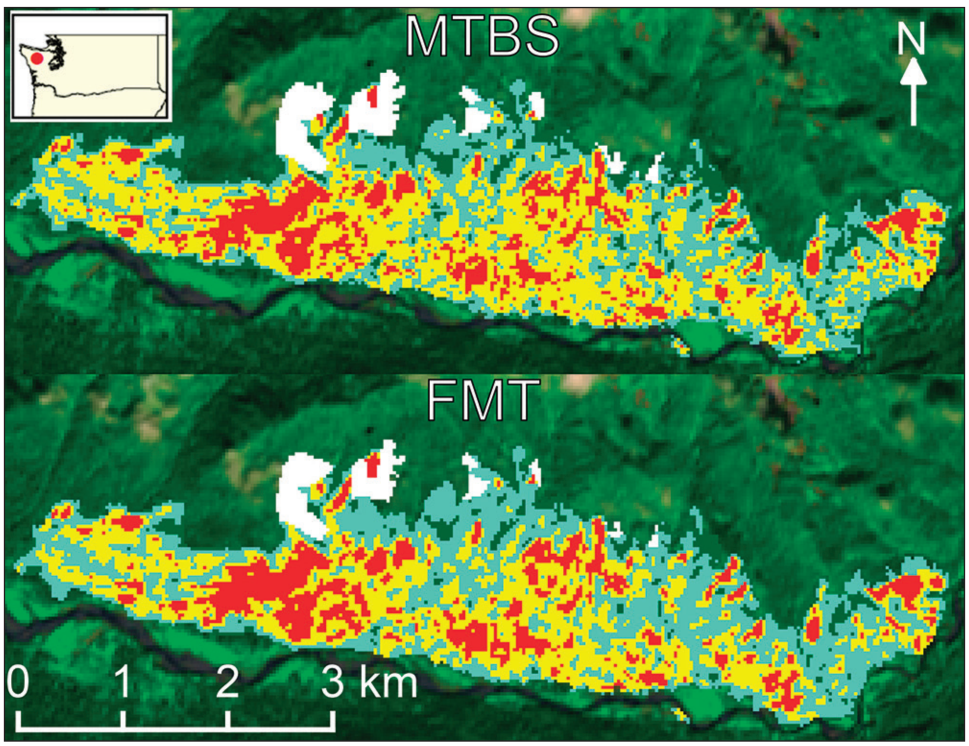

Figure 6—MTBS analyst and Fire Mapping Tool (FMT) burn severity images with unburned (dark green), low (mint green), moderate (yellow), and high (red) thresholds indicated for the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map).

DISCUSSION

The FMT was developed to automate the MTBS fire perimeter and burn severity mapping procedures. The tool is fully functional and has the added features of automatically calculating dNBR offsets and burn severity thresholds. Comparisons between the MTBS analyst and FMT-derived dNBR offsets and burn severity thresholds by utilizing the 1984-2014 MTBS archive suggest that the FMT's dNBR offsets are comparable. However, suggested burn severity values may be very different from those obtained by MTBS analysts.

The MTBS analyst and calculated dNBR offsets were remarkably similar, given that they were calculated using different methodologies. This suggests FMT's methodologies may be adequate for calculating the dNBR offset. FMT users should make sure that the dNBR offset value is within the ±50 range and find different pre- and postfire NBR image pairs if it exceeds this range. A significant percentage of the calculated offsets and standard deviations were outside the ±50 range, suggesting that there was some problem with the underlying imagery. Large differences between pre- and postfire NBR values, reflected in higher dNBR and subsequently offset values, may indicate variation in hydrology (Picotte and Robertson 2011a), phenology (Key 2006; Verbyla et al. 2008; Zhu et al. 2006), solar illumination (Veraverbeke et al. 2010; Zhu et al. 2006), topographical illumination (Veraverbeke et al. 2010), snow (Zhu et al. 2006), and vegetation change (Picotte and Robertson 2010; Zhu et al. 2006). Many of these problematic offsets were also validated by the comparison with MTBS analyst offsets, which also suggests that the tool is providing an adequate approximation of the offset.

Unlike an MTBS analyst, the FMT calculation does not assess whether the vegetation is similar between the areas within the burned and unburned areas. More dNBR imagery was identified by MTBS analysts as having a dNBR offset outside the ±50 range than those using the algorithm within the FMT, potentially because of the much larger sample size of pixels in different vegetation types that may not be representative of those within the burned area. Alternatively, by selecting a limited number of pixels within the unburned areas, MTBS analysts may overemphasize the values of some pixels that are not representative of the vegetation type.

The restricted range in unburned dNBR pixel values examined by the tool compared to MTBS analysts could also lead to an underestimation of the dNBR offset value. The FMT's median range of dNBR offset and standard deviation values was lower than that of MTBS, which potentially indicates that the tool's range of unburned pixels is too narrow. However, increasing the undisturbed pixel range below -100 would potentially introduce pixel values of postdisturbance regrowth, and increasing the value above 100 would potentially increase the number of postdisturbance pixels considered in the calculation of the dNBR offset value (Key and Benson 2006). This narrower range was therefore necessary to control for other potential disturbances or image anomalies (e.g., cloud shadows) that were not masked.

Although the current version of the FMT attempted to threshold low, moderate, and high burn severity breakpoints by utilizing the ranges developed by previous research with CBI, relationships between the assessed MTBS analyst breakpoints suggest that the calculated approach can yield much different values. This is potentially because 31 percent of the dNBR scene pairs exhibited issues in the image pairs, which was suggested by the ±50 dNBR offset or standard deviation values. Nonfire variation between pre- and postfire images can result in changes to the unburned/low threshold estimates (Key 2005; Picotte and Robertson 2011b). MTBS analysts examine the imagery to determine at what point the low severity threshold begins to include only pixels within the fire perimeter. If dNBR values are high or NBR values are low because of some nonfire change (e.g., phenology) within the postfire imagery, then the MTBS analyst may adjust the threshold value to account for this change. This analyst threshold adjustment may therefore be mostly due to the vegetation change in the imagery not resulting from fire.

Although the FMT was developed to automatically calculate burn severity thresholds based on past CBI thresholding efforts, there were limitations inherent in this approach. Burn severity estimated from dNBR/NBR and CBI has not been assessed in all burnable vegetation types, which may introduce error since severity thresholds can be directly related to vegetation type (Picotte and Robertson 2011b). The threshold ranges were developed from a limited number of studies and simplified to attempt to account for multiple vegetation communities. Another potential problem with the FMT's thresholding methodology is that time-since-fire is not considered when thresholding for burn severity. Time between fire and postfire image capture can directly influence the range of the burn severity breakpoints (Picotte and Robertson 2011b).

Comparisons between the calculated and MTBS methodology of determining low, moderate, and high severity breakpoints potentially suffers from the flaw that MTBS does not consistently map low, moderate, and high severity thresholds, although some effort was made for between-analyst cross calibration of burn severity thresholds (Eidenshink et al. 2007). Kolden et al. (2015) found that threshold breakpoints overlapped between severity classes, which indicates that MTBS thresholds can be subjective. This suggests that the non-overlap between the calculated and MTBS thresholds, especially for NBR thresholds, may not be problematic. The FMT's thresholding procedures have been developed to provide a more standardized and efficient framework for estimating burn severity.

CONCLUSIONS

Utilizing the FMT within the QGIS environment should allow users to quickly map postfire burn perimeters and severity using Landsat imagery. Most of the MTBS fire mapping capabilities have been automated within the FMT to assist users in producing MTBS-like products. The FMT has additional capabilities, including the dNBR offsetting and burn severity thresholding processes, which should provide a starting point for assessing the burn severity of fires.

More work needs to be done with the burn severity thresholding algorithms to tie remotely sensed estimates of burn severity with ground estimates, such as CBI. This would allow for a more direct comparison between mapped burn severity and actual on the ground metrics of burn severity, as suggested by Kolden et al. (2015) in their critique of MTBS data products. In the future, if more universal relationships between NBR or dNBR and CBI are developed via regression equations for specific vegetation types, it would be possible to integrate these equations into the FMT tool.

Although there has been extensive testing with the FMT, there are still potentially problems (i.e., bugs) that users will encounter. There are currently plans to keep the tool updated for the foreseeable future to deal with these potential problems. Additional capabilities to aid the user in mapping fires may also be added in the future, although no plans have been formulated for these tool improvements.

Because the FMT is open-source, freely available, and should work anywhere in the world, it is envisioned that this tool could help other countries develop an MTBS-like program. As previously mentioned, users should be careful especially when using the burn severity capabilities of the tool. The automated burn severity suggestions within the FMT may not work for vegetation communities outside the United States. If possible, users should use ground-collected data (e.g., CBI) to validate their burn severity thresholds.

ACKNOWLEDGMENTS

This project was supported by the NASA Applied Science Program grant NNH11ZDA001N, by the USGS Land Change Science Program, and by the MTBS project. ASRC Federal InuTeq contractor work was performed under USGS contract G13PC00028. The author would like to thank Steve Howard for leading Phase I and II of the NASA grant, Cheryl Holden and Karthik Vanumalai for their work in the tool's development, Casey Teske for testing earlier versions of the tool, and Kurtis Nelson, Ramesh Singh, and Tom Adamson for their helpful review comments. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

Cocke, A.E.; Fule, P.Z.; Crouse, J.E. 2005. Comparison of burn severity assessments using differenced normalized burn ratio and ground data. International Journal of Wildland Fire. 14: 189–198.

Eidenshink, J.; Schwind, B.; Brewer, K.; Zhu, Z.; Quayle, B.; Howard, S. 2007. A project for monitoring trends in burn severity. Fire Ecology. 3: 3–21.

Epting, J.; Verbyla, D.; Sorbel, B. 2005. Evaluation of remotely sensed indices for assessing burn severity in interior Alaska using Landsat TM and ETM+. Remote Sensing of Environment. 96: 328–339.

Hall, R.J.; Freeburn, J.T.; de Groot, W.J.; Pritchard, J.M.; Lynham, T.J.; Landry, R. 2008. Remote sensing of burn severity: experience from western Canada boreal fires. International Journal of Wildland Fire. 17: 476–489.

Hawbaker, T.J.; Vanderhoof, M.K.; Beal,Y.-J.; Takacs, J.D.; Schmidt, G.L.; [et al.]. 2017. Mapping burned areas using dense time-series of Landsat data. Remote Sensing of Environment. 198: 504-522.

Howard, S.; Picotte, J.; Coan, M. 2014. Utilizing multi-sensor fire detections to map fires in the United States. The International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences. 40: 161.

Jenkerson, C. 2013. User guide: earth resources observation and science (EROS) center science processing architecture (ESPA) on demand interface. Sioux Falls, SD: USGS Earth Resources Observation and Science Data Center. 32.

Key, C.H. 2005. Remote sensing sensitivity to fire severity and fire recovery. In: Proceedings of the 5th international workshop on remote sensing and GIS applications to forest fire management: fire effects assessment. De la Riva, J.; Perez-Cabello, F.; Chuvieco, E. Zaraoza, Spain: Universidad de Zaraoza.

Key, C.H. 2006. Ecological and sampling constraints on defining landscape fire severity. Fire Ecology. 2: 34–59.

Key, C.H.; Benson, N.C. 2006. Landscape assessment (LA): sampling and assessment methods. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Kolden, C.A.; Lutz, J.A.; Key, C.H.; Kane, J.T.; van Wagtendonk, J.W. 2012. Mapped versus actual burned area within wildfire perimeters: characterizing the unburned. Forest Ecology and Management. 286: 38–47.

Kolden, C.A.; Smith, A.M.; Abatzoglou, J.T. 2015. Limitations and utilisation of monitoring trends in burn severity products for assessing wildfire severity in the USA. International Journal of Wildland Fire. 24: 1023–1028.

Kolden, C.A.; Weisberg, P.J. 2007. Assessing accuracy of manually-mapped wildfire perimeters in topographically dissected areas. Fire Ecology. 3: 22-31.

Leblon, B.; San-Miguel-Ayanz, J.; Bourgeau-Chavez, L.; Kong, M. 2016. Remote Sensing of Wildfires. In: Land surface remote sensing. Baghdadi, Nicolas Zribi, Mehrez: Elsevier.

Melgani, F.; Moser, G.; Serpico, S.B. 2002. Unsupervised change-detection methods for remote-sensing images. Optical Engineering. 41: 3288-3298.

Miller, J.D.; Thode, A.E. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment. 109: 66–88.

Otsu, N. 1979. A threshold selection method from gray-level histograms. IEEE Transactions On Systems, Man, And Cybernetics. 9: 62-66.

Picotte, J.J.; Robertson, K.M. 2010. Accuracy of remote sensing wildland fire–burned area in southeastern U.S. Coastal Plain habitats. In: Robertson, K.M.; Galley, K.E.M.; Masters, R.E., eds. Proceedings of the 24th Tall Timbers Fire Ecology Conference: the future of prescribed fire: public awareness, health, and safety. Tallahassee, FL: Tall Timbers Research Station.

Picotte, J.J.; Coan, M.; Howard, S. 2014. Utilization of multi-sensor active fire detections to map fires in the U.S.: the future of monitoring trends in burn severity. In: Waldrop, T., ed. Proceedings, wildland fire in the Appalachians: discussions among managers and scientists. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Picotte, J.J.; Robertson, K. 2011a. Timing constraints on remote sensing of wildland fire burned area in the southeastern US. Remote Sensing. 3: 1680–1690.

Picotte, J.J.; Robertson, K.M. 2011b. Validation of remote sensing of burn severity in south-eastern US ecosystems. International Journal of Wildland Fire. 20: 453–464.

QGIS Develpment Team. 2013. QGIS Geographic Information System. Open Source Geospatial Foundation Project.

Sparks, A.M.; Boschetti, L.; Smith, A.M.; Tinkham, W.T.; [et al.]. 2015. An accuracy assessment of the MTBS burned area product for shrub–steppe fires in the northern Great Basin, United States. International Journal of Wildland Fire. 24: 70–78.

Vanderhoof, M.K.; Brunner, N.; Beal, Y.-J.G.; Hawbaker, T.J. 2017a. Evaluation of the US Geological Survey landsat burned area essential climate variable across the conterminous us using commercial high-resolution imagery. Remote Sensing. 9: 743.

Vanderhoof, M.K.; Fairaux, N.; Beal, Y.-J.G.; Hawbaker, T.J. 2017b. Validation of the USGS Landsat burned area essential climate variable (BAECV) across the conterminous United States. Remote Sensing of Environment. 198: 393-406.

Veraverbeke, S.; Verstraeten, W.W.; Lhermitte, S.; Goossens, R. 2010. Illumination effects on the differenced normalized burn ratio's optimality for assessing fire severity. International Journal of Applied Earth Observation and Geoinformation. 12: 60-70.

Verbyla, D.L.; Kasischke, E.S.; Hoy, E.E. 2008. Seasonal and topographic effects on estimating fire severity from Landsat TM/ETM+ data. International Journal of Wildland Fire. 17: 527–534.

Zhu, Z.; Key, C.H.; Ohlen, D.; Benson, N.C. 2006. Evaluate sensitivies of burn-severity mapping algorithms for different ecosystems and fire histories in the United States. U.S. Department of Interior Final Report to the Joint Fire Science Program: Project JFSP 01–1-4–12, Sioux Falls, SD.

A Deterministic Method for Generating Flame-Length Probabilities

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Abstract—Wildfire risk assessments rely on flame-length probabilities—the conditional probabilities that fire intensity will be within various flame-length classes. The factors affecting flame-length probability include the elements of the fire-behavior triangle—fuel, weather, and topography—plus the orientation of the flaming front relative to the heading direction. Current methods for determining flame-length probabilities include: (1) a single deterministic simulation of flame length at the head of the fire for one weather type (wind speed, wind direction, fuel moisture content); (2) multiple deterministic simulations of flame length at the head of the fire (for several weather types), which are then integrated; and (3) stochastic simulation of fire growth and flame length across a few to several dozen weather types. In this paper, we describe a deterministic process, called FLEP-Gen, that addresses shortcomings of the current methods. It improves upon the multiple-simulation approach by (1) incorporating fire intensity in non-heading spread directions and (2) weighting the weather types by their relative area burned rather than just their temporal relative frequencies. We present the mathematical basis for the process—based on the geometry of an ellipse—as well as spatial and nonspatial examples of its application to various fire management problems.

Keywords: wildfire hazard, fire intensity, flame length, effects analysis, elliptical dimensions

INTRODUCTION AND BACKGROUND

Fire intensity is a measure of the rate of heat release at the flaming front of a spreading wildland fire (Alexander 1982). Along with burn probability (the likelihood of fire burning a given point on the landscape), fire intensity is a primary component of wildfire hazard and is the main fire-behavior characteristic influencing the effects of wildfire on resources and assets (Scott et al. 2013; Thompson et al. 2013). Fire intensity is commonly measured by Byram's fireline intensity (kW/m) or by the length of flames generated (Scott 2012). There are two simple mathematical models in operational use in the United States that relate Byram's fireline intensity (FLI) to flame length (Byram 1959; Thomas 1963). In the suite of operational spatial models developed and supported by the Missoula Fire Sciences Laboratory (FARSITE, FlamMap, FSim, etc.; visit https://www.firelab.org/applications), the Byram model is applied to all surface fires, and the Thomas model is applied to passive and active crown fires.

For use in fire management planning systems, fire intensity has been classified into six Fire Intensity Levels (FILs). Although the FIL classification is nominally based on flame length (Roose et al. 2008), the *FLI* values that correspond to the flame-length class breaks for the two flame-length models can be determined (table 1).

An effects analysis relies on the conditional probability distribution across the FILs (Finney 2005; Scott et al. 2013). For an effects analysis, one must know the conditional probability—given that a fire occurs at a location—that fire intensity will be in each of the six FILs. Because FILs are indexed by flame length,

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Table 1—Six Fire Intensity Levels (FILs) as defined by flame length (ft) following Roose et al. (2008). The fireline intensity values corresponding to those flame-length values are shown as well. In operational spatial fire modeling systems developed by the Missoula Fire Sciences Laboratory, the Byram (1959) flame-length model is applied to surface fires and the Thomas (1963) model is applied to passive and active crown fires.

Fire intensity level (FIL)	Flame-length range (ft)	Flame-length range (m)	Surface fireline intensity (FLI) range (kW/m)	Crown fire fireline intensity (FLI) range (kW/m)
FIL1	< 2	< 0.6	< 88.6	< 108
FIL2	2–4	0.6–1.2	88.6–400	108–303
FIL3	4–6	1.2–1.8	400–965	303–554
FIL4	6–8	1.8–2.4	965–1803	554–851
FIL5	8–12	2.4–3.7	1803–4354	851–1559
FIL6	> 12	> 3.7	> 4354	> 1559

these are called conditional flame-length probabilities (*FLP*s). The sum of *FLP*s across all FILs equals 1.

Factors affecting fire intensity include the elements of the fire-behavior triangle—fuel, weather, and topography—plus a fourth factor, relative spread direction. Relative spread direction is the orientation of the flaming front relative to the heading direction—heading, flanking, and backing spread directions, and all directions between (Finney 1998; Scott 2007, 2012). Topography and some fuel characteristics, including fuel load and arrangement, are temporally constant within a fire season. Weather-related fire-environment variables, including wind speed, wind direction, and fuel moisture content, can vary considerably within a season, from day to day, and even from hour to hour (see Scott 2012).

Current methods for assessing fire intensity for use in a spatial wildfire hazard and risk assessment include:

- Single deterministic simulation of fire intensity at the head of the fire for one weather type (wind speed, wind direction, fuel moisture content). This results in a single fire intensity value for a pixel, and that fire intensity can be classified into an FIL.
- Multiple deterministic simulations of fire intensity at the head of the fire (for several weather types), which are then integrated into a single fire intensity value for the pixel; the simulations are typically weighted by the temporal relative frequency of the weather types.
- Stochastic simulation of fire growth across a few to several dozen weather types. Rather than producing a single fire intensity value for a pixel, a stochastic simulation produces a probability distribution of fire intensity across the FILs—the conditional *FLP*s—at each pixel.

These approaches have relative advantages and disadvantages. The single-simulation approach can be run at a fine pixel size (30 m) but fails to account for two important factors affecting fire intensity: the wide variety of weather types under which a pixel can burn, and non-heading spread directions, for which fire intensity is considerably lower than at the head of the fire.

The multiple-simulation approach accounts for some variability in weather types but still focuses on the head of the fire. Current methods of weighting the weather types (weighting by temporal relative frequency) do not account for any potential differences in area burned among the weather types. For example, even though strong winds occur rarely in time, the high spread rates associated with them mean that they should account for a larger proportion of overall area burned than the temporal relative frequency alone would suggest.

The stochastic simulation approach addresses several of the shortcomings of the deterministic simulation approaches by inherently weighting the weather types and spread directions by their actual influence on the landscape. But two disadvantages remain: the stochastic simulations cannot be accomplished across a large landscape at 30-m resolution, and limitations on computing time generally result in a small sample size from which to determine the distribution of flame lengths. For example, a typical pixel will burn just 10-100 times during a 10,000-iteration FSim run, and those 10-100 instances are classified into six flame-length probability bins. That is a small sample size to determine the relative frequency of flame length in those bins, but larger sample sizes are computationally unattainable.

In this paper a deterministic process, called FLEP-Gen, that addresses shortcomings of the current methods is described. It improves upon the multiple-simulation approach by (1) incorporating fire intensity in non-heading spread directions and (2) weighting the weather types by their relative area burned in combination with their temporal relative frequency rather than just their temporal relative frequencies.

NON-HEADING INTENSITY

By assuming that a wildfire grows as an ellipse with the ignition at the rear focus (Alexander 1985), the geometric properties of an ellipse can be used to find the relative fire-area burned at or above a given *FLI* based on just two factors—the *FLI* at the head of the fire and the length-to-breadth ratio (*LB*) of the ellipse (Alexander 1982; Catchpole et al. 1992). Following Finney (1998), *LB* can be estimated as

$$LB = 0.936e^{(0.1147U_m)} + 0.461e^{-.0692U_m} - 0.397$$

where U_m is the effective midflame wind speed (mi/h) after combining (vectoring) midflame wind speed, slope steepness, and wind direction (Finney 1998).

For surface fires, midflame wind speed is a function of fuelbed depth for unsheltered fuelbeds or a function of canopy cover and canopy height for fuelbeds sheltered by a forest canopy (Albini and Baughman 1979). For passive and active crown fires, midflame wind speed (for the purposes of estimating *LB*) is taken to be half of the 20-ft wind speed (Albini and Baughman 1979; Finney 1998). The backing ratio (*BR*), the ratio of backing spread rate to heading spread rate, can be calculated from *LB* as

$$BR = \frac{LB - \sqrt{LB^2 - 1}}{LB + \sqrt{LB^2 - 1}}$$

Certain elliptical dimensions (fig. 1) can be calculated from the headfire rate of spread (ROS_{head}), *LB*, and *BR* following equations taken directly or modified from Catchpole et al. (1992) and Finney (1998). The labeling of the elliptical dimensions *a* and *b* are reversed in Finney (1998) compared to Catchpole et al. (1992); this paper uses the labeling of Catchpole et al. (1992), for which the parameter *a* is the half-length of the ellipse length and *b* is the half-width:

$$a = \frac{ROS_{head}(1 + BR)}{2}$$

$$b = \frac{a}{LB}$$

$$c = a\sqrt{1 - LB^{-2}}$$

Following Catchpole et al. (1992), the proportional *FLI* (or *ROS*) can be determined for a given angle θ as a function of elliptical dimensions defined above:

$$PropFLI_{\emptyset} = \frac{\dfrac{b(a + c\cos\emptyset)}{\sqrt{a^2\sin^2\emptyset + b^2\cos^2\emptyset}}}{a + c}$$

where θ is the angle of the subtending circle of the ellipse (Catchpole et al. 1992). The proportional fire-area burned at or above that proportional *FLI* can be determined for the same angle θ as:

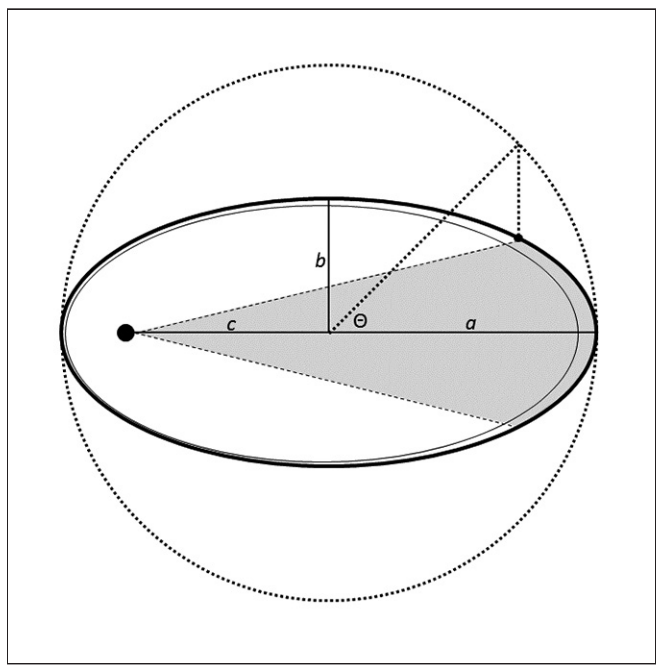

Figure 1—Elliptical dimensions *a*, *b*, and *c* as defined by Catchpole et al. (1992), where the angle Θ identifies a point on the ellipse based on the subtending circle, shown as the dotted circle. The shaded area represents the proportional fire-area burned at or above the proportional fireline intensity for a given Θ.

$$PropArea_{\emptyset} = \frac{(a\emptyset + c \sin \emptyset)}{\pi a}$$

The proportional area burned above any proportional intensity can then be plotted for a range of θ and for a range of *LB* values (fig. 2). This permits one to find the proportional fire-area burned at or above a given proportional fireline intensity value.

To use these equations operationally, the required proportional *FLI* is calculated as the ratio of threshold *FLI* for a given FIL class break (table 1) to the headfire *FLI*. Knowledge of the elliptical dimensions permits brute-force estimation (by iteration) of the subtending angle θ that produces the required proportional *FLI*; from θ, one can then calculate the proportional fire-area burned at or above the threshold *FLI*. This proportional fire-area burned is taken to be the probability of exceeding the threshold flame-length value, also called the flame-length exceedance probabilities (*FLEP*s) for the FIL class breaks. The *FLP*s are calculated from the *FLEP*s by subtraction. For example, the probability that flame length will be in FIL2 (flame lengths between 2 and 4 ft) is the probability of FL exceeding 2 ft minus the probability of FL exceeding 4 ft.

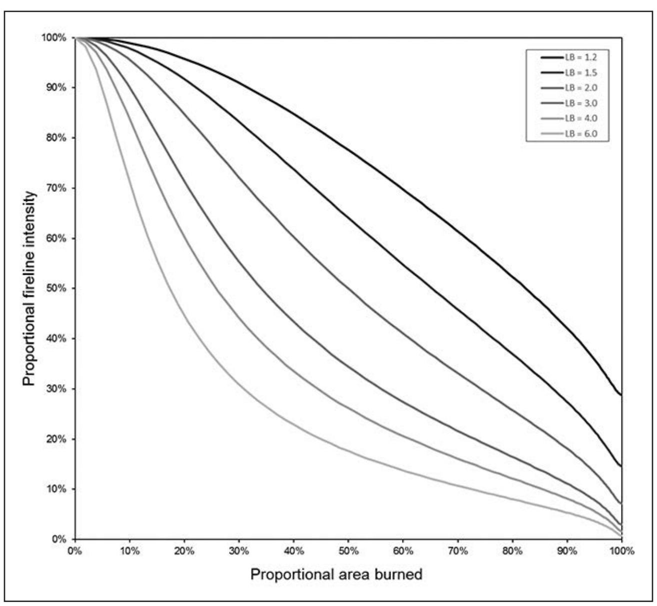

Figure 2—Plot of proportional fireline intensity against proportional fire-area burned for a range of length-to-breadth ratios. This figure is analogous to figure 4 of Catchpole et al. (1992).

The estimation of *FLP*s using this process can be illustrated for a simple fire environment of heavy shrub fuel (fuel model SH5; Scott and Burgan 2005) on flat ground under a 15 mi/h wind speed at the 6.1-m (20-ft) height. The example assumes dead fuel moisture contents of 4 percent for the 1-h timelag class, 5 percent for 10-h and 6 percent for 100-h, and 110 percent for the moisture content of live the woody component. Using Rothermel's (1972) surface fire-spread model as implemented in Nexus (Scott and Reinhardt 2001), the headfire intensity is 9,770 kW/m (*FL* = 17.4 ft). For that headfire intensity one can estimate the required proportional intensity values that correspond to the flame-length breakpoints, and then the proportional areas that correspond to those proportional intensities (table 2, fig. 3). These proportional areas represent the relative proportion of burned area exceeding the upper end of the flame-length range for each FIL. In this example, 49.87 percent of the elliptical fire area is burned at or above the 12-ft flame-length threshold (4,354 kW/m), 85.68 percent of the area is burned above an 8-ft flame-length threshold, 96.22 percent above a flame length of 6 ft, and 100 percent above 4 ft (table 2). The minimum fireline intensity, corresponding to the rear of the fire, is greater than the threshold for a 4-ft flame length, so 100 percent of the fire area would burn above this threshold. By subtraction, 0 percent of the fire area is burned in FIL1 and FIL2, 3.78 percent in FIL3, 10.54 percent in FIL4, 35.81 percent in FIL5, and 49.87 percent in FIL6. Note that the sum of these FLPs is 100 percent.

Table 2—Proportional intensity and proportional area burned for FIL class breaks, for a headfire fireline intensity = 9,770 kW/m and LB ratio = 2.275.

Fire intensity level	Proportional intensity	Proportional area (FLEP)
2' (FIL1/2)	0.00907	1.0000
4' (FIL2/3)	0.04091	1.0000
6' (FIL3/4)	0.09876	0.9622
8' (FIL4/5)	0.18459	0.8568
12' (FIL5/6)	0.44566	0.4987

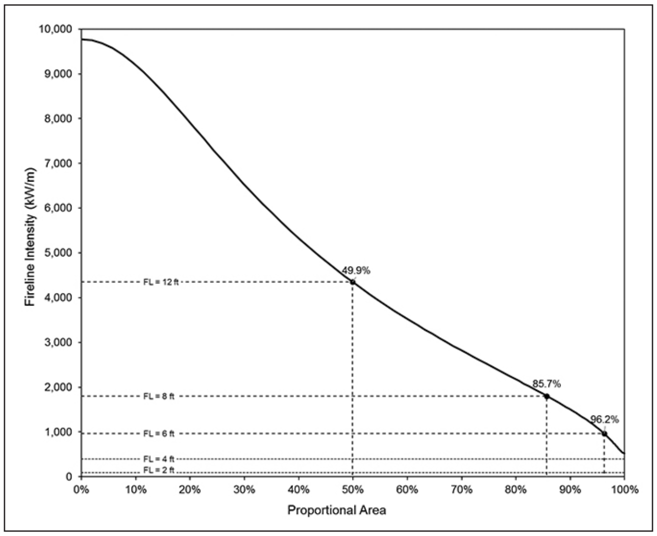

Figure 3—For a surface headfire intensity of 9,770 kW/m at a 20-ft wind speed of 15 mi/h (*LB* = 2.275), one can find the proportional fire-area burned at the fireline intensities that correspond to class breaks in the FIL classification. Those proportional areas determine the flame-length exceedance probability for each FIL. Flame-length probability for a class is found by subtraction. For example, the probability of FIL5 (flame lengths between 8 and 12 ft) is 35.8 percent (85.7 percent to 49.9 percent).

Table 3—Seven weather types defined only by 20-ft wind speed. Temporal relative frequency is a measure of how often these weather types occur. Relative burn-period length is a measure of the relative length of a daily burning period for each weather type.

Weather type (w)	20-ft wind speed (mi/h)	Temporal relative frequency % (TRF_w)	Relative burn-period length ($RBPL_w$)
1	0–1	6.2	1.0
2	1–5	20.2	1.2
3	5–10	58.9	1.4
4	10–15	13.1	1.6
5	15–20	1.0	1.8
6	20–25	0.5	2.0
7	25–30	0.1	2.2

WEIGHTING WEATHER TYPES

The above example illustrated that a given headfire intensity can be divided into the relative proportions of fire-area burned in predefined intensity classes for a single weather type—one wind speed, one wind direction, and one set of fuel moisture contents. Such weather types can be classified in a variety of ways but are typically organized by binning wind speed and wind direction, and by establishing one or more fuel moisture scenarios. Fire planning applications should ideally account for the full range of weather types that can occur, not just the most common or most extreme types.

To illustrate the weighting of multiple weather types, the single fuel moisture scenario described above will be extended to accommodate a full range of wind speeds. Wind direction is irrelevant in this example because flat ground was assumed, so there is no wind-slope alignment to consider. RAWS data for sustained 20-ft wind speed for the month of August (noon to 8 p.m. local time) were summarized to find the relative frequency distribution of wind speed as shown in table 3.

A time-weighted mean flame-length probability would be an improvement over using only a single weather condition to find flame-length probabilities, but it fails to account for drastically different potentials for burned area among the weather types. Lower fuel moisture and, especially, higher wind speeds, lead to greater spread rates. Higher spread rates in turn result in exponentially greater burned area. Daily burn-period length (hours of spread per day) may be longer for certain weather types (low moisture content and/or high wind, for example). If weather types had equal temporal probabilities of occurring, the higher wind speeds would account for a disproportionately large share of total area burned.

The solution presented here is to calculate a new area-based weighting factor that accounts for both the temporal relative frequency of a weather type and the relative contribution of that weather type to overall area burned, based on the rate of spread, relative burn-period length, and the dimensions of an ellipse. The basic area-weighted mean calculation is similar to that for time weighting but requires a new area-weighted relative frequency for each weather type (ARF_w). For example, the area-weighted conditional probability of fire in $FLP1$ is:

$$FLP1 = \sum FLP1_w * ARF_w$$

where $FLP1_w$ is the flame-length probability for weather type w and FIL1, and ARF_w is the area-weighted relative frequency of weather type w. ARF_w is calculated by combining TRF_w with an area-burned index (ABI_w):

$$ARF_w = \frac{TRF_w * ABI_w}{\sum(TRF_w * ABI_w)}$$

where TRF_w is the temporal relative frequency of weather type w. ABI_w is assumed to be proportional to the area of an ellipse:

$$ABI_w \propto \pi abt^2$$

where t is a variable representing the length of time of fire spread. Substituting a/LB for b, omitting the constant π, which does not affect the *ARF* weighting, and substituting for t a variable representing the relative burn-period length (minutes or hours per burn day; $RBPL_w$), *ABI* simplifies to:

$$ABI = \frac{a^2 * RBPL^2}{LB}$$

The *RBPL* factor will not play a role in the calculation unless it is allowed to vary among the different weather types. For example, drier and windier weather types may be associated with a longer daily burning period. ABI_w is therefore a function of the overall length of the ellipse and the *LB* ratio. The overall elliptical length can be estimated from the headfire *ROS*, *BR*, and *RBPL*. For this example, *RBPL* was assumed to increase with wind speed (table 3).

First, headfire *ROS* and *FLI* are calculated for the various weather types; from those results ABI_w and ARF_w are calculated using the equations above (table 4). Note that, compared to the *TRF* weighting factors, the *ARF* weighting factors give higher weight to the higher wind speed weather types and lower weight to the lower wind speed types. This is due to higher spread rates for higher wind speeds and the assumed longer *RBPL* for higher wind speeds, both of which increase *ABI*.

Next, the *FLP* calculations were done for each weather type independently, and the ARF_w factors from table 4 were used to calculate the overall weighted-mean *FLP*s (table 5). A graphical comparison of the *FLP*s resulting from the *TRF* and *ARF* weighting schemes illustrates the shift toward higher intensities when using the *ARF* weighting factors (fig. 4).

APPLICATIONS OF FLEP-GEN

FLEP-Gen is a process by which flame-length probabilities are deterministically generated for a given fuel complex (surface and canopy fuel characteristics) and set of weather conditions. The examples in this paper are inherently nonspatial—one point on the landscape. However, the FLEP-Gen process can be implemented spatially using custom applications of available fire-behavior modeling systems.

FLEP-Gen has many potential applications in wildfire incident and fuel management planning. Hazard and risk assessments are now being generated for individual wildfire incidents in order to better assess a wildfire's potential fire effects on resources and assets (Hollingsworth and Panunto 2017), enabling improved allocation of firefighting resources among competing wildfires. During a wildfire incident, the current and foreseeable weather conditions may be different than those used with a stochastic simulator based on long-term historical weather data covering entire fire seasons. Currently available deterministic methods can be based on incident-specific weather conditions (Hollingsworth and Panunto 2017) but still suffer from their focus on the head of a fire and a single weather condition, which can lead to overprediction of fire intensity and subsequent mischaracterization of fire effects. The FLEP-Gen process can be run with any set of weather types, including incident-specific conditions.

Assessing wildfire hazard consists of two components—wildfire likelihood and wildfire intensity given that a fire occurs. The wildfire intensity component is often estimated with a single flame-length value, usually for a given percentile weather condition, such as the 90th percentile. Flame length is typically estimated for the head of the fire for that weather condition. The FLEP-Gen process improves the estimation of wildfire intensity for a hazard assessment by incorporating non-heading spread directions, which produce lower intensities than at the head, and can incorporate a variety of wind speeds, wind directions, and moisture content scenarios.

Table 4—The temporal relative frequency, headfire behavior characteristics, area-burned index, and Area-based relative frequency for seven weather types (as defined by wind speed).

Weather type (w)	Temporal relative frequency (TRF_w) %	Headfire intensity (kW/m)	Headfire spread rate (m/min)	Headfire flame length (ft)	Area burned index (ABI_w)	Area-based relative frequency (ARF_w) %
1	6.2	590	1.89	4.8	2.068	0.1
2	20.2	2,798	8.95	9.8	34.93	5.1
3	58.9	6,113	19.6	14.0	137.4	58.6
4	13.1	9,770	31.3	17.4	305.0	28.9
5	1.0	13,668	43.7	20.3	522.7	3.8
6	0.5	17,757	56.8	22.9	768.9	2.8
7	0.1	22,004	70.4	25.3	1,019.5	0.7

Table 5—Flame-length probabilities for the six standard fire intensity levels (FILs), along with the time-weighted mean and area-weighted mean flame-length probabilities. FIL1 = 0–2 ft flame length; FIL2 = 2–4 ft; FIL3 = 4–6 ft; FIL4 = 6–8 ft; FIL5 = 8–12 ft; and FIL6 = 12+ ft.

Weather type	FIL1 %	FIL2 %	FIL3 %	FIL4 %	FIL5 %	FIL6 %
1	0.0	0.0	100.0	00.0	00.0	00.0
2	0.0	0.0	15.2	31.7	53.1	00.0
3	0.0	0.0	00.6	09.7	33.6	56.1
4	0.0	0.0	03.8	10.5	35.8	49.9
5	0.0	0.0	03.2	09.9	33.8	52.9
6	0.0	0.2	03.3	10.9	34.0	51.4
7	0.0	0.2	04.1	13.0	34.8	47.6
Weighted mean	**0.0**	**0.0**	**02.6**	**11.1**	**35.3**	**51.1**

Wildfire hazard, as defined above, is the foundation of an effects analysis. An effects analysis represents the full implementation of the wildfire risk assessment framework (Scott et al. 2013). An effects analysis relies heavily on an estimate of *FLP*s across the landscape. Presently, the estimate of *FLP*s for an effects analysis is limited by one or more factors:

- spatial resolution (cell size) of the stochastic simulation used to generate the *FLP*s;
- small sample size per grid cell from a stochastic simulator;
- limited weather conditions for a deterministic simulation; and
- headfire-only for a deterministic simulation.

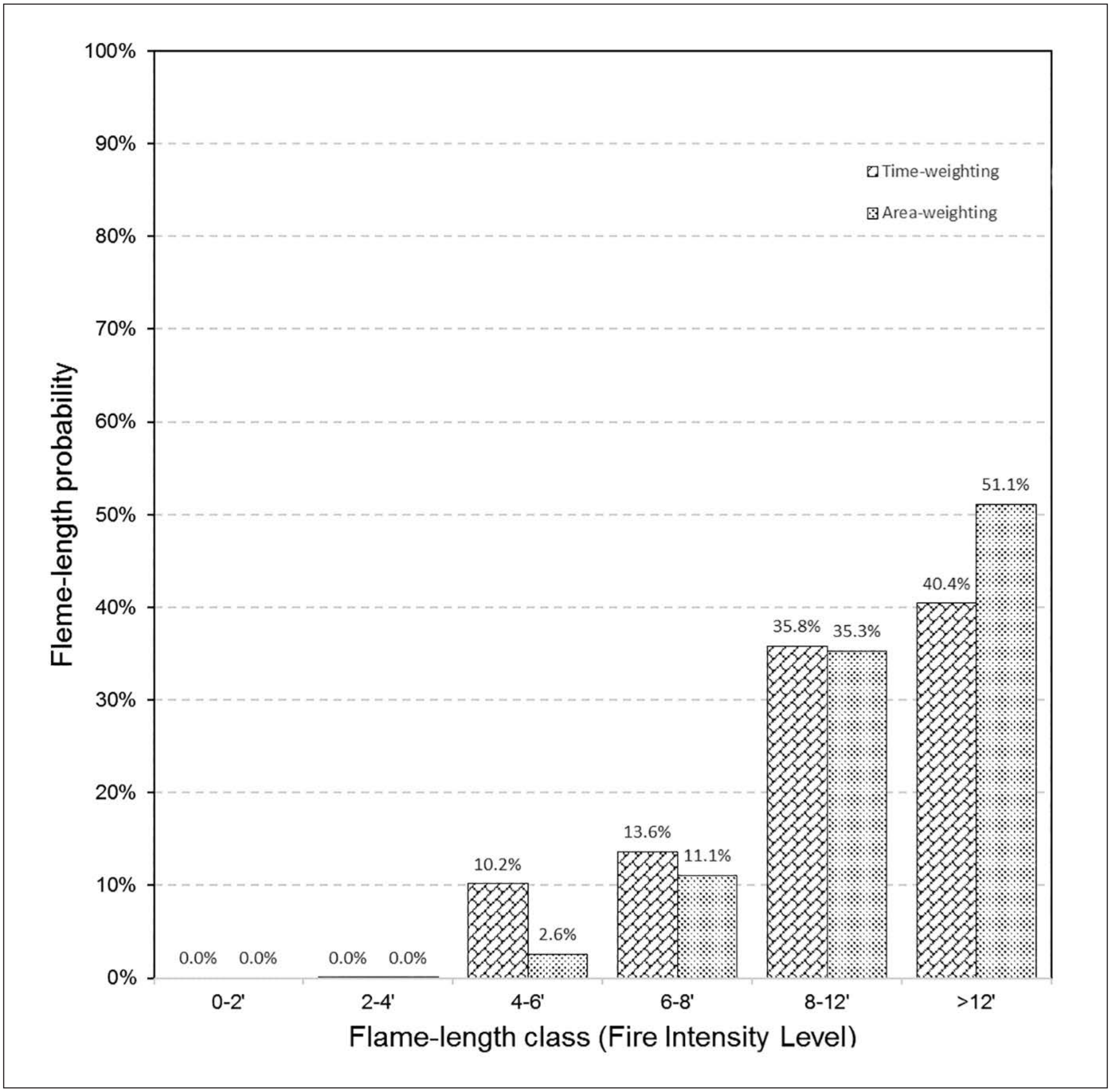

Figure 4—Comparison of integrated flame-length probabilities resulting from simple time-weighting (slanted bricks) of multiple wind speeds and area weighting (fine dots). If no consideration were given to non-heading intensity or to weighting multiple weather scenarios, fire intensity would be in the > 12-ft FIL with 74 percent probability (time weighting) or 95 percent (area weighting), because the headfire flame length exceeds 12 ft for all but the mildest weather types.

The FLEP-Gen process may be able to generate flame-length probability rasters suitable for an effects analysis at finer resolutions than is possible with a stochastic simulator and does not suffer from a problem of small sample size where BP is low. Instead, the FLEP-Gen process integrates flame-length probabilities for all possible weather scenarios, not only those that burned a given pixel, which may be biased toward extreme conditions in areas of lower burn probability. The process improves upon prior uses of deterministic simulations in an effects analysis by correctly weighting weather types and by incorporating fire intensity in non-heading spread directions.

The deterministic nature of the FLEP-Gen process makes it well suited to fuel management planning applications. It is relatively straightforward to generate an "ideal" fuelscape as a companion to the current-condition fuelscape. The ideal fuelscape represents the ideal treated fuel condition, without specific consideration to exactly how the ideal condition is attained (some combination of mechanical treatment and prescribed fire is assumed). For the ideal fuelscape, one can generate another set of *FLP*s, then compare those *FLP*s with the current condition to see how intensities are affected by the treatment.

Even better, the current the current condition and ideal fuelscapes can be used in the effects analysis to generate two *cNVC* rasters. This will show not only where the flame length is reduced, but it also emphasizes that it is much more desirable to reduce flame lengths in some parts of the landscape than others. The difference in *cNVC* rasters is an indication of the effects of the treatment on reducing wildfire risk to resources and assets.

The risk-reduction potential can then be summarized for any number of summary zones—by stand, hydrologic unit, admin unit (Region/Forest/District), political unit (city/county/State), fire district, etc. The summaries can then be used to support fuel management funding decisions and prioritization.

Finally, the FLEP-Gen process can be used in a measure of fuel management program performance. The FLEP-Gen process can be conducted for the current condition and for the proposed or actual posttreatment fuel condition. After running through an effects analysis, the total amount of risk-reduction accomplished by the treatment can be estimated and used to measure performance.

DISCUSSION

The FLEP-Gen process produces a set of *FLP* rasters comparable to those produced by a stochastic simulator. FLEP-Gen improves upon currently available deterministic methods by accounting for non-heading spread and integrating multiple weather scenarios. Though the example used the six-bin fireline intensity classification employed by FSim, the process can be adapted to fit with any desired fireline intensity classification.

FLEP-Gen is not computationally limited, as with stochastic simulators like FSim, to a coarser resolution for larger landscapes. It can be run at a 30-m pixel size consistent with native LANDFIRE data. Additionally, the FLEP-Gen results cover all possible weather scenarios input to the calculations and are not subject to the problem of small sample sizes associated with stochastic modeling, whereby pixels burn as few as 10 times in a 10,000-season simulation.

For this paper, results were based on a single set of fuel moisture inputs representing the 97th percentile weather and flat ground (which obviates wind direction). The process allows wind speed, wind direction, and fuel moisture to co-vary according to their distributions in the historical weather record. Further, an analyst can enable fuel moisture conditioning in FlamMap to allow fuel moistures to vary according to the environmental and topographic characteristics associated with each pixel. This feature is available in the current set of deterministic models but most commonly used in conjunction with a single wind speed and direction and heading intensities. This feature is not presently available in stochastic simulation models. Finally, an analyst can enable WindNinja (Forthofer et al. 2009) to downscale and vary wind patterns spatially across the landscape and integrate those results with the non-heading spread and multiple wind speeds used by the FLEP-Gen.

FLEP-Gen results and the associated cNVC grid(s) can be combined with burn probability grids produced by another tool such as FSim, RANDIG, or FSPro to generate an expected net value change raster (eNVC).

This information could be used in fuel treatment prioritization to evaluate where fuel treatments can simultaneously produce the greatest reduction in risk to highly valued resources and assets, and where treatments are most likely to interact with fire on the landscape based on higher burn probability values. Using the perimeter event set, produced by the above stochastic models, to overlay with cNVC results from FLEP-Gen and calculate exceedance probability curves is likely to be of interest in incident-level risk assessment and for fire management decisionmaking across many ongoing incidents.

There are two main limitations of the FLEP-Gen process compared to stochastic simulation of *FLP*s. First, FLEP-Gen does not capture any effects of landscape or fire-weather heterogeneity (and resulting fire-spread topology) on fire intensity. For example, assuming there is a strong directional component to the wind, lee sides of nonburnable or slow-burning features can produce lower fire intensities in a stochastic simulator, because fires must flank or back through the area rather than spread as a headfire. Similarly, a wildfire on which the wind direction shifts drastically can result in a different proportion of heading behavior than would be estimated for a point-source fire. The FLEP-Gen process does not capture these phenomena.

Second, FLEP-Gen does not capture any effect of progressive fireline containment on overall fireline intensity. In FSim, if the perimeter-trimming function is enabled, fire perimeter is extinguished on the lowest-intensity portions of the perimeter first. Again, FLEP-Gen does not capture that phenomenon. However, initial testing of both factors shows them to be relatively small. Further testing of FLEP-Gen is underway.

ACKNOWLEDGMENTS

I am grateful to Dr. Elizabeth Reinhardt, Assistant Director, Fire and Aviation Management, Forest Service, U.S. Department of Agriculture (retired), for funding the initial development of this process; and to Rick Stratton, National Fire Analyst for Planning and Budget, Fire, and Aviation Management, for its ongoing development. The spatial wildfire analysts at Pyrologix (Julie Gilbertson-Day, Kevin C. Vogler, and April M. Brough) developed the spatial implementation of this process. I wish to thank Dr. Mark Finney (Research Forester, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory) and Dr. Matthew Thompson (Research Forester, Forest Service, Rocky Mountain Research Station, Human Dimensions Project) for their helpful reviews of this paper.

REFERENCES

Albini, F.A.; Baughman, R.G. 1979. Estimating windspeeds for predicting wildland fire behavior. Res. Pap. INT-221. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Canadian Journal of Botany. 60(4): 349–357.

Alexander, M.E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Proc. 8th Conf. Fire and Forest Meteorology: 287–304.

Byram, G.M. 1959. Combustion of forest fuels. In: Forest fire: Control and use, 2nd edition. New York, NY: McGraw-Hill.

Catchpole, E.A.; Alexander, M.E.; Gill, A.M. 1992. Elliptical-fire perimeter-and area-intensity distributions. Canadian Journal of Forest Research. 22(7): 968–972.

Finney, M.A. 1998. FARSITE: Fire Area Simulator—model development and evaluation. Res. Pap. RMRS-RP-4. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Finney, M.A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management. 211(1): 97–108.

Forthofer, J.; Shannon, K.; Butler, B. 2009. Simulating diurnally driven slope winds with WindNinja. In: Proceedings of 8th Symposium on Fire and Forest Meteorological Society. Kalispell, MT: American Meteorological Society.

Hollingsworth, L.; Panunto, M. 2017. Wildfire risk assessment for the Frye Fire. Unpublished Report to the Coronado National Forest.

Roose, H.; Ballard, L.; Manley, J.; Saleen, N.; Harbert, S. 2008. Fire program analysis system—preparedness module. In: González-Cabán, A., tech. ed. Proceedings of the second international symposium on fire economics, planning, and policy: a global view. Gen. Tech. Rep. PSW-GTR-208. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 377–384.

Scott, J.H. 2007. Nomographs for estimating surface fire behavior characteristics without a computer. Gen. Tech. Rep. RMRS-GTR-192. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 119 p.

Scott, J.H. 2012. Introduction to wildfire behavior modeling. National Interagency Fuels, Fire, & Vegetation Technology Transfer. Available: http://pyrologix.com/wp-content/uploads/2014/04/Scott_20121.pdf.

Scott, J.H.; Thompson, M.P.; Calkin, D.E. 2013. A wildfire risk assessment framework for land and resource management. In: Gen. Tech. Rep. RMRS-GTR-315. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Thomas, P.H. 1963. The size of flames from natural fires. Proceedings of the Ninth International Symposium on Combustion. New York: Academic Press.

Thompson, M.P., Scott, J.; Helmbrecht, D.; Calkin, D.E. 2013. Integrated wildfire risk assessment: framework development and application on the Lewis and Clark National Forest in Montana. Integrated Environmental Assessment and Management. 9(2): 329–342.

Socioeconomic Impacts of the NASA RECOVER Decision Support System for Wildfire Emergency Response Planning

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Abstract—Today's extended fire seasons and large fire footprints have prompted State and Federal land management agencies to devote increasingly larger portions of their budgets to wildfire management. As fire costs continue to rise, timely and comprehensive fire information becomes increasingly critical to response and rehabilitation efforts. The National Aeronautics and Space Administration's Rehabilitation Capability Convergence for Ecosystem Recovery (RECOVER) postfire decision support system is a server-based application designed to rapidly provide land managers with the information needed to develop a comprehensive rehabilitation plan. This study evaluated the efficacy of RECOVER through structured interviews with land managers (n = 20) who used RECOVER and were responsible for postfire rehabilitation efforts on over 715,000 ha of fire-affected lands. Although the benefit of better-informed decisions is difficult to quantify, the results of this study illustrate that RECOVER's decision support capabilities provided information to land managers that either validated or altered their decisions on postfire treatments. Savings from streamlining data collection were estimated at over US $1.2 million and nearly 800 hours of staff time, and communication within an agency and with local stakeholders and partnering agencies was improved.

Keywords: GIS, land management, postfire recovery, uncertainty, value of information, wildfire policy

INTRODUCTION

The total cost of wildfire for the economies of the western United States is often far greater than what is reported by the media and strains the already limited resources of land management agencies. The millions of dollars used to suppress wildfires are typically reported as the actual cost of the fire, but this estimate usually does not account for the rehabilitation, direct costs, and indirect costs that persist well after a fire has been extinguished. For instance, costs related to watershed damage, debris flow, flooding, soil erosion, and an increase in invasive species, which may not be fully realized until years after a fire, can easily surpass the suppression expenses of a significant fire event (Western Forestry Leadership Coalition 2009). Additionally, some of the societal impacts of wildfires—such as effects on health, recreation, air and water quality, employment, infrastructure closures, wildlife habitat loss, and damage to cultural heritage sites— have also been underreported. Yet they too should be considered in the total cost of any fire event in order to gain a more accurate portrayal of the social

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

and economic impacts of wildfire. As Richardson et al. (2012) pointed out, concerns are growing among the public, wildfire researchers, and policymakers that the reported cost represents only a partial measure of the actual socioeconomic impact of damage from wildfire, limiting the effectiveness of the decisionmaking and policymaking process. In an effort to address these concerns, some land management agencies have adopted geospatial tools to assist in the collection and deployment of crucial information to support their prevention, suppression, and rehabilitation objectives. As wildfires in the western United States continue to increase in size and frequency, without a concomitant increase in the number of people managing wildfires, fire managers are likely to grow progressively more reliant on geospatial data and satellite imagery to develop rehabilitation plans.

After a fire is contained, and if deemed necessary, a burned area emergency response (BAER) team is assigned to rapidly assess the postfire conditions and develop a preliminary stabilization and rehabilitation plan. These BAER teams face strict time constraints, so data assembly, analysis, and decisionmaking must happen quickly in order to meet the statutory requirements (Robichaud et al. 2009). Currently, the postfire planning process requires substantial human resources and the information gathered depends on the availability of staff, time, funds, and data for a particular region (Dombeck et al. 2003; Schnase et al. 2014). Consequently, there are significant knowledge gaps in the postfire environment related to the lack of data and information that could significantly impact the planning effort (Venn and Calkin 2008). Given the importance of postfire stabilization and restoration for ecosystem recovery, especially in cases of severe fire events where the affected soil becomes hydrophobic or cannot return to prefire conditions, rapidly acquiring necessary data such as fire severity or debris-flow probability products becomes essential for the decisionmaking process (Robichaud 2009; Schnase et al. 2014; Venn and Calkin 2008). However, despite a wide variety of information services available to the wildfire community, none address the specific needs of postfire stabilization and restoration planning (Calkin et al. 2011; Schnase et al. 2014). Reducing uncertainty in the postfire planning environment will not only allow for better-informed decisions, but may also potentially reduce the direct and indirect costs associated with making decisions based on poor quality or untimely information (Kangas et al. 2010).

Thompson and Calkin (2011) stated that the uncertainty in wildland fire management, beyond the unpredictability of wildfire behavior, largely stems from inaccurate or missing data and that improved decision support technology could significantly reduce uncertainty in the postfire planning environment. The best geospatial tools used for postfire planning and decisionmaking, therefore, attempt to address knowledge gaps by presenting land managers with complete and reliable actionable information that allows decisionmakers to make better-informed decisions (Lentile et al. 2006). The value of information stems from the ability to make better decisions if new information is available (Kangas et al. 2010). The value of information can be negated, however, if the decisionmaker cannot take action—i.e., lack of timely access—regardless of the quality and accuracy of the data (MacCauly 2006; McCaffrey and Kumagai 2007). Thus, the timeliness of data accessed by the decisionmaker is a critical component to making the information valuable and actionable. Through the rapid collection and deployment of data crucial to submitting a comprehensive rehabilitation plan, lead land management agencies have the potential to meaningfully reduce costs and time associated with the postfire land management process. Further, these better-informed decisions are beneficial not only to the individual or agency tasked with postfire rehabilitation but also to the local community and the ecosystem as a whole.

To help illustrate the significant societal value of geospatial tools and Earth-observing satellite imagery, this research used the National Aeronautics and Space Administration's (NASA's) Rehabilitation Capability Convergence for Ecosystem Recovery (RECOVER) postfire decision support system as a case study to assess the socioeconomic impact of geospatial data for emergency response planning and to aid in the development of objective and defensible science. RECOVER is a highly automated, site-specific, decision support system that assembles nearly 30 fire-specific geospatial data layers and reports in an easy-to-use web map in as little as 5 minutes (Schnase et al. 2014). These data are available to the land manager in a near real-time environment to support their rehabilitation planning efforts.

Through structured stakeholder interviews with users of RECOVER and other geospatial tools, this project sought to identify the actual impact of rapid assembly and deployment of geospatial data in wildfire emergency response planning in order to assess the value of information derived from RECOVER's web maps and how these data influence and improve postfire decisionmaking. An analysis of the value of information derived from RECOVER provided a rich contextual comparison to those decisions made in the absence of geospatial tools, as well as assisted in determining a monetary value for the immediate outcomes of land managers' better-informed decisions enabled by RECOVER-based data. In addition, these interviews highlighted the significant time savings and cost savings for decisionmakers and support staff who used RECOVER, which are expressed later as approximate dollars saved. Finally, although more difficult to quantify, the ultimate social benefits of better-informed decisions—i.e., impacts on the ecosystem, recreation, and land use—are also considered in the final estimation of RECOVER's overall socioeconomic impact in the postfire emergency response planning process.

BACKGROUND

Changes in Land Use and Area Burned

Since 1985, both Federal and State land management agencies have reported significant increases in overall fire-related costs, with the Federal government shouldering the bulk of the expenses (Brunsentsev and Vroman 2016; Center for Western Priorities 2014; NIFC 2017). Some of the increased costs are attributable to inflation (e.g., real suppression cost per hectare increased by 17 percent from 1985–1989 to 2009–2013 while nominal costs increased by over 400 percent [Brusentsev and Vroman 2016]), but a significant increase in costs is the result of larger wildfires, an expansion of the wildland-urban interface (WUI), a better understanding of the role of fire in ecological processes, and policy changes requiring an assessment of all of the damages associated with wildfires (Brunsentsev and Vroman 2016; Vilsack 2015; Wigtil et al. 2016). The two primary fire management agencies, the Forest Service, U.S. Department of Agriculture, and the Department of the Interior, report that over a 54-year time period, despite no upward trend in the number of annual fires, the total area burned and length of the fire season more than doubled (Brusentsev and Vroman 2016). Given the generally xeric conditions found across the western United States, many of the large fires occur in this region (figs. 1 and 2).

Arguably, one of the most costly changes in land use has been the increased number of homes close to wildlands, which now account for one-third of all homes in the United States (Martinuzzi et al. 2015; Theobald and Romme 2007). The WUI, where undeveloped wildland and human development meet, has made fire management increasingly more costly. Fires in the WUI represent one of the most difficult

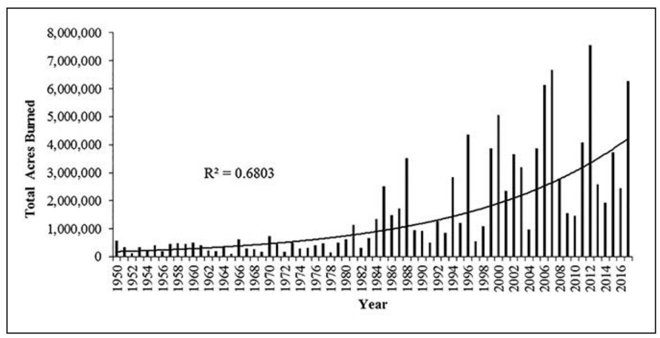

Figure 1—Acres burned per year across the western United States, 1950 through 2017. The line of best fit follows an exponential growth curve (Source: Idaho State University n.d.).

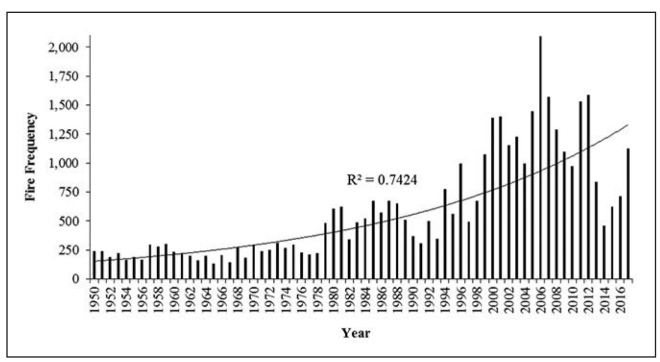

Figure 2—Fire frequency per year across the western United States, 1950 through 2017. The line of best fit follows an exponential growth curve (Source: Idaho State University n.d).

problems that agencies must manage because of the potential for loss of life, livelihoods, health, and property (Curth et al. 2012). Moreover, as social factors largely influence where and how people are affected by wildfires, better understanding wildfire potential, vulnerability, and management will help address persistent economic, structural, and human life losses from WUI fires as well as rising suppression costs (Wigtil et al. 2016). When the total costs associated with wildfires are determined, the impact of increased development along the WUI is significant.

True Costs of Wildfires

In addition to the agencies' balancing act in determining how to allocate their resources, incorporating the true costs of wildfire is a daunting task. Historically, the Forest Service has included only suppression-related expenses when reporting costs associated with wildfires. The media, while frequently including the costs of destroyed homes and other structures, also tend to underestimate the true costs associated with wildfires (USDA FS 2014). Estimating a comprehensive cost of wildfires can be a difficult undertaking given the far-reaching impacts of wildfire across multiple spectrums of the affected ecosystem and regional economy. Attempting to quantify some of these categories—e.g., a decline in air and water quality, loss of recreational or cultural heritage sites, and increased probability of debris flow—is challenging as they represent indirect costs that might not be realized for several years. However, inclusion of these costs, while significantly increasing the estimates, provides a more accurate assessment of the opportunity costs associated with wildfires.

Contemporary research that attempts to assess the comprehensive costs and impacts of wildland fire has categorized wildfire-related costs into direct, rehabilitation, indirect, and additional classes (Western Forestry Leadership Coalition 2009). These studies, without exception, find that the direct costs of suppression are only a small percentage of the expenditures associated with wildfires. In the research summarized by the Western Forestry Leadership Coalition (2009), suppression costs ranged from 3 to 53 percent of total cost, with the variation largely attributable to the characteristics of the terrain, the severity of the fire, and the proximity to a population base. Dunn et al. (2005) estimated the costs associated with the 2003 Old, Grand Prix, and Padua wildfires of southern California at almost $1.3 billion (all amounts reported in U.S. dollars) without including the value of lost income due to road and rail closures, lost recreational opportunities, or negative impacts on ecosystem and human health. Even without accounting for those additional losses, the costs associated with fire suppression accounted for only approximately 5 percent of the total estimated wildfire costs. Similarly, Rahn (2009) estimated the total economic impact of wildfires in San Diego County in 2003 at approximately $2.45 billion, with suppression costs representing less than 2 percent of the total. Although suppression expenses are a miniscule percentage of the total costs, these estimates are typically presented as the full and actual cost of wildfire.

Dynamic Component to Fire Management

Many of the indirect costs involved in fire management have a dynamic element. The value of these costs (or damages) is influenced by the passage of time and the choices made as time progresses. Efficiently using resources maximizes the net benefits associated with protecting assets threatened by wildfire. Choices based on accurate and more complete data regarding the characteristics of the land burned and the value that society places on rehabilitation increase the likelihood of making optimal decisions.

Studies analyzing the value of assets impacted by wildfires show the sensitivity of that assessment to the policies implemented and the time elapsed since the wildfire. Englin et al. (2001) found a statistically significant nonlinear effect of time since wildfire on nonmotorized recreation users with "an initial positive visitation response to recent fires, with decreasing visitation for the next 17 years, followed by an 8-year rebound in use." After estimating the costs of forest fires in Colorado, Lynch (2004) concluded that "damages to forest watershed values in the arid West may ultimately result in the most serious, long-term costs of large fires" and "[t]hat 'greening up' may well be a cover of noxious plants and another set of costs." Kobayashi et al. (2014) find that the productivity of western rangelands is being reduced by invasive grasses. The increase of invasive annual grasses has escalated the wildfire cycle (increasing the cost of wildfire suppression) and, where these grasses have irreversibly transitioned to a dominant status, decreased the capacity of the rangeland to provide forage and other ecosystem services. Mueller et al. (2009), using a hedonic approach, found that repeated forest fires in southern California caused housing prices to decrease in areas located near previous fires. In particular, they found that a second fire will reduce the value of a nearby house by a significantly larger amount (approximately 23 percent) than the first fire (about 10 percent). This result lends support for quick remediation of burned lands to prevent additional fires in the same region.

Practices that address the dynamic nature of fire management and help prevent future wildfires provide long-term benefits and ultimately reduce fire suppression needs. However, budget constraints of the primary Federal agencies frequently result in an emphasis on reactive rather than proactive practices. Scientists agree that the Hazardous Fuels Reduction program provides economic benefit and improves the quality of the land, but only 14 percent of the Forest Service-appropriated funds went to this component of preventive fire management (Western Forestry Leadership Coalition 2009). From O'Connor et al. 2016, active fire management "can reduce the severity of inevitable fire, improve recovery time, and contribute to ecosystem functioning before, during and after a blaze… Healthy ecosystems that experience a disturbance such as fire are more likely to recover without long-term or devastating negative effects." Further, the push toward long-term practices that support the development and maintenance of resilient fire-adapted lands "has potential to break out of the cycle of fire suppression, fuel accumulation, and continued exposure of human and natural systems to extreme fire conditions," (O'Connor et al. 2016).

The Role of Geographic Information System-Based Assessment and Planning

Using a fire management decision support system (FMDSS) to reduce uncertainty in order to make better-informed decisions helps alleviate some of the agencies' financial pressure and reduce the damage imposed on society by wildfire. With these concerns in mind, BAER teams, which identify and alleviate problems associated with land stability, water, invasive species, and habitat, frequently use Landsat data for postfire assessments. The use of Landsat data shortens their response time for both pressing situations and long-term planning. This imagery allows for examination of both prefire and postfire vegetation across a fire area and allows for improved remediation planning and the ability to assess the progress of remediation efforts over time. The annual cost savings from "operational efficiency improvements, avoided alternative replacement costs (assuming Landsat data were not available), and opportunity costs related to economic and environmental decision-support" are estimated at $28 million to $30 million (NGAC–LAC 2014).

RECOVER Decision Support System

The RECOVER decision support system is made up of a RECOVER server and a RECOVER client. The RECOVER server is a specialized Integrated Rule-Oriented Data System (iRODS) data grid server deployed in the Amazon Elastic Compute Cloud (EC2). The RECOVER client is a full-featured Adobe Flex Web Map geographic information systems (GIS) analysis environment. When provided a wildfire name and geospatial extent, the RECOVER server aggregates site-specific data from predesignated, geographically distributed data archives. It then does the necessary transformations and reprojections required for the data to be used by the RECOVER client. It exposes the tailored collection of site-specific data to the RECOVER client through web services residing on the server. RECOVER is transforming the information-intensive planning process by reducing from days to a matter of minutes the time required to assemble and deliver crucial wildfire-related data (Schnase et al. 2014).

Designed to provide postfire data to land managers across the western United States, RECOVER aids emergency rehabilitation teams by providing the critical and timely information needed for management decisions regarding stabilization and recovery strategies (Schnase et al. 2014). RECOVER is an automated, site-specific decision support system that rapidly brings together in a single analysis environment the information necessary for postfire rehabilitation decisionmaking and long-term ecosystem recovery monitoring. RECOVER uses rapid resource allocation capabilities to automatically collect Earth observational data, derived decision products, and historical biophysical data, which are then accessed by land managers to determine a sound rehabilitation plan. Utilizing this type of decision support tool has the potential to be useful to land managers, especially as the western United States typically experiences significant fire events annually, and the total cost of a single large wildfire can range from several million to over a billion dollars. Although only a small portion of the United States' multibillion dollar annual budget to support fire suppression activities actually goes toward postfire rehabilitation activities, the potential social and economic impact of a successful, or unsuccessful, rehabilitation strategy can be significant.

RECOVER's Purpose

According to agency partners—primarily the Idaho Department of Lands, Forest Service, and Bureau of Land Management (BLM), data assembly, pre-RECOVER, was the most significant bottleneck in wildfire-related decisionmaking (Schnase et al. 2014). After a major wildfire event, Federal land management agencies are required by law to develop and certify a comprehensive plan for public safety, burned area stabilization, resource protection, and site recovery within 21 days of fire containment. In some cases containment is delayed due to specific fire circumstances, giving land managers more time to assemble data and prepare plans. In these instances, RECOVER benefits the land manager by providing the manager with actionable information very quickly and providing him or her with additional postfire data describing the event (e.g., fire-affected vegetation [differenced Normalized Burn Ratio]). Initial rehabilitation plans, however, must be submitted within 1 week of when the fire was contained, which places a substantial burden on the agencies' resources, mainly staff time and availability, to collect and synthesize the necessary data for the decisionmaking process.

RECOVER was developed to provide site-specific, automatically deployable, and context-aware datasets on any given fire as quickly as possible to help land managers meet these statutory deadlines. RECOVER provides data that helps BAER teams assess the effects of wildfire, identify areas in need of reseeding or other postfire treatment, and monitor subsequent ecosystem recovery in response to prescribed treatments (Schnase et al. 2014). Given the potential of reseeding after a significant fire event—i.e., to stabilize hydrophobic soils in order to minimize the probability of a debris flow or to restore wildlife habitat and livestock rangeland to productive levels—RECOVER's features can significantly reduce the costs associated with assessment and planning phases as well as to better improve the land through rapid and accurate assessments of the effects of a fire event.

During the early phases of RECOVER's development, efforts were taken to develop system requirements that accounted for the actual decisionmaking process of the land manager in response to a fire event. According to agency partners, the time and resource commitment needed to gather and assess all of the information required to submit a comprehensive rehabilitation plan—especially after a few hundred thousand hectares burned—could be impractical. Thus, one of the objectives of RECOVER was to allow fire managers to shift their attention to more important and potentially impactful tasks of analysis, planning, and monitoring by significantly reducing the number of staff and amount of time needed to gather the information for the assessment reports (Schnase et al. 2014). Initial demonstrations by RECOVER yielded results that surpassed the contemporary data gathering methods, which relied heavily on field observations. Currently, RECOVER produces fire-specific web maps in less than 5 minutes, providing land managers with immediate actionable information.

Current Status of RECOVER

Since the 2013 fire season, RECOVER has been called upon to provide web maps for 60 wildland fires (fig. 3) and has supported and improved the work and decisionmaking of 9 different State and Federal agencies throughout the western United States.

While RECOVER has been used throughout the West, most users are located in Idaho. In addition to a summary of RECOVER users by State, figure 4 organizes the data by agency user. Land managers

Figure 3—Number of wildfire events that used the RECOVER decision support system across the western United States, 2013 through 2017.

now have almost instantaneous access to information and data that in the past took days or weeks to gather and assemble into a usable format. RECOVER saves agency costs for staff time and helps land managers accurately identify potential areas for rehabilitation and recovery efforts. This, in turn, benefits the ecosystem as well as primary users of the land such as hunters, ranchers, and recreationists.

METHODS

Interview Process

Twenty semistructured interviews were conducted with personnel from Federal and State agencies, representing a wide range of job functions and responsibilities, who had used RECOVER, or other geospatial data and satellite imagery, as part of their duties. These participants represent 78 percent (n = 47) of the fires in which RECOVER has provided web maps, an area covering over 715,000 ha. Fifteen interviews, representing about 555,000 ha, were with individuals who had personally used RECOVER to perform their job functions. Five interviews, representing an additional 160,000 ha, were with personnel who had requested fire data from RECOVER but did not use the tool to support

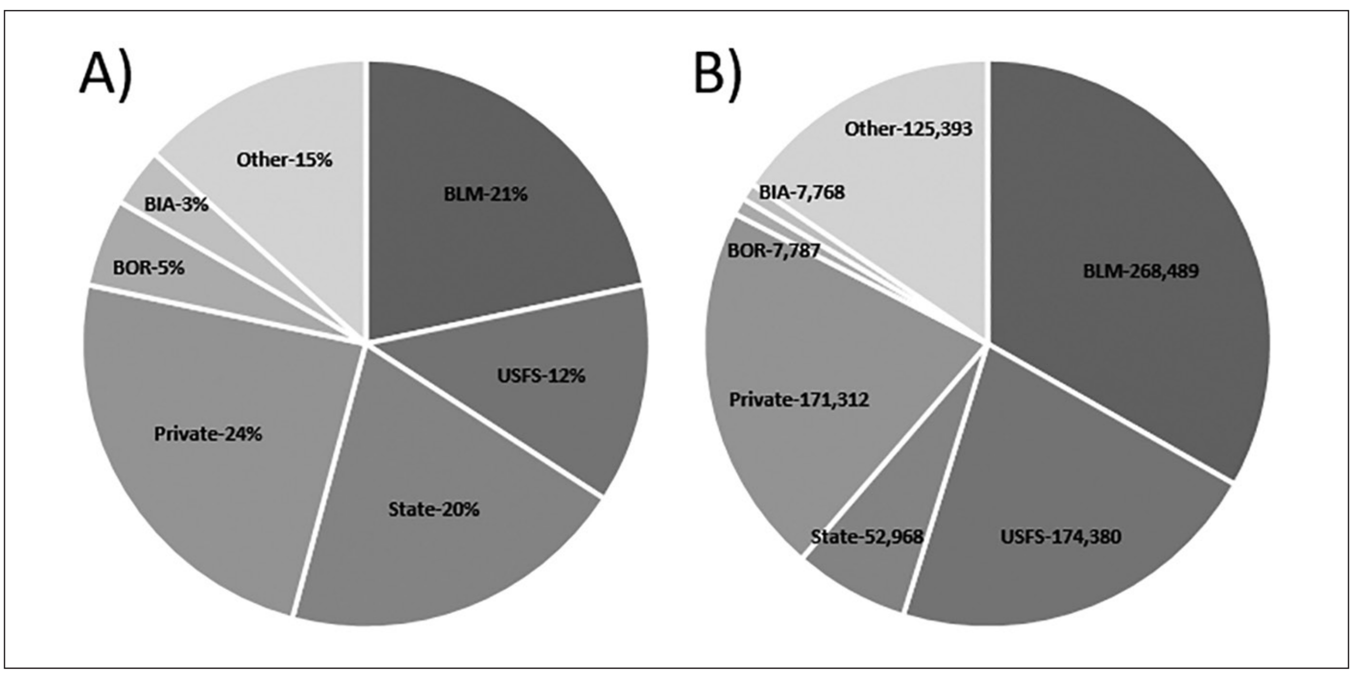

Figure 4—Percentage of fires (A) and hectares burned (B) by user agency. BIA: Bureau of Indian Affairs; BLM: Bureau of Land Management; BOR: Bureau of Reclamation; USFS: USDA Forest Service.

their postfire efforts. The responses and results of the actual users of RECOVER will be the focus of this paper. The participants were categorized into two subcategories, tier one and tier two users, based on their agency's role in the rehabilitation and recovery of lands directly affected by wildland fire. Personnel of entities that utilize geospatial data and satellite imagery (i.e., RECOVER) and assume primary responsibility for the rehabilitation and recovery efforts are considered tier one users (n = 15); participants whose agencies are concerned with other issues such as roads and transportation, water quality, and wildlife habitat fall into the tier two category (n = 5).

Through the semistructured interviews we sought to acquire insight into how RECOVER was being used, which features were thought to be most beneficial, and whether the individual or agency intended to adopt the tool. For the tier one participants, we wanted to understand how they perceived the relevance and usability of RECOVER's web map features for postfire decisionmaking. Specifically, we wanted to learn whether RECOVER's web maps reduced uncertainty in the decisionmaking environment by providing crucial and timely data to the user that aided in developing a rehabilitation plan, assessing burn severity, planning reseeding efforts, or helping circumvent postfire hazards such as debris flows. We also asked whether RECOVER had significantly reduced the amount of staff time that went into data collection for their Federally mandated rehabilitation report and whether RECOVER had improved communication within their agency, with partnering agencies, or with community stakeholders. Further, we requested the participants attempt to quantify the total staff time or dollars saved as well as to highlight specific instances where RECOVER data enabled the user to make a better-informed decision that either prevented or validated a potentially expensive rehabilitative treatment. Although attempting to quantify the indirect benefits of RECOVER proved a difficult task, several respondents provided data that could be aggregated and analyzed for trends, which helped assess the economic value of RECOVER's use.

Calculations

The participants' responses to questions about the value of information provided and whether staff time and related expenses were saved by using RECOVER were not easily quantifiable, because, to our knowledge, there are no universally acceptable approaches. We therefore developed our own approach to filling in these gaps. Where respondents gave ambiguous answers or rough estimates (i.e., "several days," "10 to 12 staff," and "a few hours"), we took the liberty of assigning values to these responses. "Several days" translated to a standard workweek of 5 days, "a few hours" became 3 hours, and "10 to 12 staff" became 11 staffmembers. Where public records were available, we used the actual hourly wage reported for the previous fiscal year (FY 2016–2017) of the participants who provided measurable data about the time or resources saved using RECOVER. We calculated the hourly rate of those respondents for whom public records were unavailable by using the 2016 U.S. general schedule (GS) pay rates for Federal employees with a standing equivalent to level 10, step 5 ($34.58 per hour) of the program. Additionally, the percentage used to account for fringe benefits was 21 percent, while 35 percent of that sum was chosen to assess the overhead rate and eventually arrive at the fully loaded hourly rate of $56.48 (table 1).

FINDINGS

Several recurring themes consistently emerged throughout the interviews that strongly indicated

Table 1—Calculation of fully encumbered hourly rate.

Expense	Amount (U.S. dollars)	Proportion of hourly wage
Hourly rate	$34.58	
Fringe benefits	$7.26	21%
Subtotal	$41.84	
Overhead rate	$14.64	35%
Fully loaded rate	**$56.48**	

the use of RECOVER played a critical role for land management personnel and agencies in their postfire rehabilitation efforts. All 20 respondents, regardless of actual level of use, initially sought to employ RECOVER for a variety of duties and objectives. For instance, attaining data and information on burn severity, debris-flow probability, and prefire vegetative cover were the most common responses (n = 14) with a majority coming from the tier one category (n = 11). The prevalence of tier one users finding these specific web maps to be of value is not surprising as land rehabilitation and recovery are their primary concern, and these web maps directly address the health and status of the affected ecosystem. Ninety percent (n = 18) of the total participants and about 93 percent (n = 14) of tier one users reported they plan to use RECOVER in future fire seasons, highlighting RECOVER's usability and effectiveness in reducing uncertainty in postfire decisionmaking.

Assistance in Reducing Uncertainty

As RECOVER was designed to support the development of BLM's Emergency Stabilization and Rehabilitation (ES&R) plans and Forest Service BAER plans, ascertaining whether its use actually reduced uncertainty in core areas such as assessing burn severity, planning reseeding efforts, mitigating postfire hazards, and developing a comprehensive rehabilitation plan was crucial. Of the 15 tier one RECOVER users, 40 percent (n = 6) reported they were able to circumvent some sort of postfire hazard, like a debris flow, by utilizing in a timely manner RECOVER's web maps. Quantifying the ultimate benefit of avoiding a postfire hazard like a debris flow is difficult because of the unique circumstances of each wildfire, but the occurrence of such an event can easily have catastrophic social and economic repercussions totaling in the millions of dollars (De Graff 2014). Still, over 45 percent (n = 7) of tier one users agreed that RECOVER assisted with the overall planning of reseeding efforts and 80 percent (n = 12) relied on RECOVER to help determine burn severity. Reducing uncertainty in these areas has the potential to save the agency costs and increase the effectiveness of its ecosystem recovery and sustainability efforts. Further, 40 percent (n = 6) of tier one users reported that RECOVER significantly improved their ability to develop a comprehensive rehabilitation plan. Without RECOVER, these land managers would very likely have needed to rely on field observations and invested significant agency resources over several days to acquire the data necessary to submit their plan.

Staff Time and Related Costs Saved

One of RECOVER's primary benefits is the rapid allocation and deployment of crucial geospatial data to support wildfire emergency response planning. Therefore, we wanted to gauge how much actual staff time was saved using RECOVER for various data collection duties. Twelve participants stated that RECOVER had saved their agencies a cumulative 800 hours of staff time, or roughly $43,000, of data collection expenses related to the rehabilitation plans. This also may benefit the public by allowing land managers more time to focus their attention on more important aspects of the rehabilitation and recovery process. Similarly, 60 percent (n = 12) of both tier one and tier two users reported that RECOVER improved overall communications by providing comprehensive and reliable maps automatically; 25 percent (n = 5) recorded improvements within the agency, and 50 percent (n = 10) with partnering agencies as well as with the public. Improved communication between partnering agencies is particularly important because wildfires typically expand into multiple jurisdictions (Federal, State, and private), where several different landowners may be affected (table 2). Cooperation and information sharing among the affected landowners will benefit the lead agency responsible for the rehabilitation planning as well as the users of the land. In total, participants determined approximately $2,000 and almost 60 hours of staff time were saved using RECOVER, instead of previous methods, for communications.

Better-Informed Decisions

Seventy-five percent (n = 15) of all RECOVER users and over 85 percent (n = 13) of tier one participants reported that the information RECOVER provided helped personnel make better-informed decisions that both directly and indirectly affected the roughly 715,000 ha of land they managed or monitored. Three tier one users attempted to place a monetary value on the benefits of RECOVER's use and value of

Table 2—Wildfires and management jurisdictions. BLM: Bureau of Land Management; BOR: Bureau of Reclamation; COE: U.S. Army Corps of Engineers; FS: USDA Forest Service.

Fire	Area burned (ha)	State	Land ownership (ha)
Powerhouse	13,619	California	BLM – 152; FS – 7,862; State – 100; Undetermined – 5,505
Charlotte	440	Idaho	BLM – 92; Private – 348
Gap	197	Idaho	BLM – 134; Private – 63
Henry’s Creek	21,422	Idaho	BLM – 2,075; BOR – 2,993; COE – 979; Private – 12,104; State – 3,271
Pioneer	76,278	Idaho	BOR – 1,890; FS – 73,985; Private – 329; State – 17; Undetermined – 57
Soda	93,253	Idaho	BLM – 72,834; BOR – 79; Private – 15,425; State – 4,915
Baker-ORPAC	136,179	Oregon	BLM – 45,600; BOR – 7; FS – 1,160; Private – 89,412
Juntura Complex	64,919	Oregon	BLM – 9,822; State – 30,986; Private – 24,111
Yale Road	2,573	Washington	State – 2,280; Private – 97

information by citing approximate staff time savings and immediate outcomes enabled by RECOVER. One participant reported that the agency had requested RECOVER’s debris-flow probability feature before making any decision about a $500,000 wood mulch aerial application. After analyzing RECOVER’s data and the results from the field observation assessment, the agency determined that the probability of a debris-flow event occurring was minimal and no longer justified the expense, thus saving $500,000. A second interviewee explained that the value of information provided by RECOVER would have taken several support staff working an entire week, or 280 hours, to gather all of the data RECOVER can deliver in a matter of minutes; we estimate the avoided expense at $15,814. A third participant discussed how RECOVER was used to validate a $700,000 wood mulch application treatment and confirm the accuracy of field observation assessments. In all, the actionable data and information that RECOVER provided had a minimum economic value of over $1.2 million to its users.

DISCUSSION

The sample of interviewees, although relatively small in number, represents a significant number of the larger fires that occurred in the targeted States. These participants were responsible for over 715,000 ha of fire-affected land, including the subsequent postfire planning and rehabilitation to ensure ecosystem recovery. Moreover, the interviewees represent 78 percent (n = 47) of fires for which RECOVER has produced decision support system web maps and aided postfire decisionmaking. The high percentage of RECOVER users interviewed, as well as the large area of land affected, illustrates the importance of their responses and the potential to extrapolate these results to similar postfire environments.

Participants frequently reported that RECOVER’s rapidly assembled and site-specific data provided key decisionmakers with the information needed to identify sites that had the greatest potential for negatively impacting the region, both socially and economically, and helped them determine appropriate treatment plans. RECOVER provided decisionmakers and their support staff with reliable data that often are otherwise difficult to obtain in a format that dramatically reduced the staff time needed to assemble such information. Due to the tight time constraint on reporting and the competition for funding that these agencies face, RECOVER’s ability to reduce data collection time by hundreds of hours per fire makes it a valuable and cost-effective tool for adoption by land management agencies.

The greatest potential benefit of RECOVER arises from the better-informed decisions that it enables. RECOVER allows land managers to effectively identify high-risk areas and determine more efficient treatments or management strategies that will restore or improve the land. By providing critical data quickly, land managers can complete thorough analyses before critical deadlines. Without this ability, land management agencies run the risk of recommending unnecessary and expensive treatment strategies, or forgoing a much needed rehabilitation technique.

These results illustrate the significant social and economic value for land management agencies, as well as for the land and land users, in using RECOVER and other geospatial data to assist in postfire rehabilitation planning. Although much of the added value is found in improved communication and decisionmaking by RECOVER users, a significant portion arises from staff time and cost savings from the reduction of data collection duties. In total, RECOVER saved 788.75 hours of staff time and had a positive economic impact of at least $1.2 million on land management agencies.

CONCLUSIONS

Projected increases in annual fire events and areas burned indicate the demand on agencies' resources related to fire planning, suppression, and postfire rehabilitation and recovery will only increase in the coming years. Wildland fires, especially those in the western United States, will continue to consume an increasingly large part of land management agencies' attention and budgets. The demands and constraints of the postfire environment—primarily the lack of time and access to reliable information and data—will continue to be a source of pressure for agencies and their personnel attempting to plan rehabilitation measures without universal adoption of geospatial tools. To reduce the negative impact that wildfires have on local economies, land management agencies must attempt to use all practicable resources and tools at their disposal to restore or improve public lands following a wildfire. As land management agencies continue to face budget cuts amid congressional and public pressure to streamline their operations and reduce runaway spending, utilizing proven geospatial tools and data to perform previously labor-intensive duties will go a long way toward making wildfire management more efficient.

ACKNOWLEDGMENTS

This study was made possible by a grant from the National Aeronautics and Space Administration Applied Sciences, A.35 Wildfires Program (NNX12AQ78G). This project was led by Keith T. Weber (PI), John L. Schnase (Co-PI), and Mark Carroll (Co-PI).

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES

Brusentsev, Vera; Vroman, Wayne. 2016. Wildfires in the United States: A primer. Washington, DC: Urban Institute. 22 p.

Calkin, David E.; Thompson, Matthew P.; Finney, Mark A.; Hyde, Kevin D. 2011. A real-time risk assessment tool supporting wildland fire decsionmaking. Journal of Forestry. 5: 274–280.

Carroll, Mark L.; Schnase, John L.; Weber, Keith T.; [et al.]. 2013. A new application to facilitate post-fire recovery and rehabilitation in savanna ecosystems. Institute of Electrical and Electronics Engineers, Oceanic Engineering Society: Earthzine. https://geospatial.inl.gov/bias/TessGardner/publications/A-New-Application-to-Facilitate-Post-Fire-Recovery-and-Rehabilitation-in-Savanna-Ecosystems/. [Accessed 2019 June 10].

Center for Western Priorities. 2014. The wildfire burden: Why public land seizure proposals would cost western states billions of dollars. Denver, CO. 9 p. http://westernpriorities.org/wp-content/uploads/2014/08/The-Wildfire-Burden1.pdf. [Accessed 2017 August 7].

Curth, Monica de Torres; Biscayart, Carolina; Ghermandi, Luciana; Pfister, Gabriela. 2012. Wildland-urban interface fires and socioeconomic conditions: A case study of a northwestern Patagonia city. Environmental Management. 49: 876–891.

De Graff, Jerome V. 2014. Improvement in quantifying debris flow risk for post-wildfire emergency response. Geoenvironmental Disasters. 1: 5–15.

Dombeck, Michael P.; Williams, Jack E.; Wood, Christopher A. 2003. Wildfire policy and public lands: Integrating scientific understanding with social concerns across landscapes. Conservation Biology. 18: 883–889.

Dunn, Alex E.; Gonzalez-Caban, Armando; Solari, Karen. 2005. The Old, Grand Prix, and Padua wildfires: How much did these fires really cost? A preliminary report on expenditures and discussion of economic costs resulting from the 2003 Old, Grand Prix and Padua Wildfire Complex. [U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station]. 17 p. https://www.fs.fed.us/psw/publications/adunn/2003_wildfires_report.pdf.

Englin, Jeffrey; Loomis, John; Gonzalez-Caban, Armando. 2001. The dynamic path of recreational values following a forest fire: A comparative analysis of states in the Intermountain West. Canadian Journal of Forest Research. 31: 1837–1844.

Idaho State University. n.d. ISU GIS TReC Historic Fires Database. http://giscenter.isu.edu/Research/Techpg/HFD/

Kangas, Annika S.; Horne, Paula; Leskinen, Peeka. 2010. Measuring the value of information in multicriteria decisionmaking. Forest Science. 56: 558–566.

Kobayashi, Mimako; Rollins, Kimberly; Taylor, Michael H. 2014. Optimal livestock management on sagebrush rangeland with ecological thresholds, wildfire, and invasive plants. Land Economics. 90: 623–648.

Lentile, Leigh B.; Holden, Zachary A.; Smith, Alistair M.S.; [et al.]. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire. 15: 319–345.

Lynch, Dennis L. 2004. What do forest fires really cost? Journal of Forestry. 102: 42–49.

Macauley, Molly K. 2006. The value of information: Measuring the contribution of space-derived earth science data to resource management. Space Policy. 22: 274–282.

Martinuzzi, Sebastiín; Stewart, Susan I.; Helmers, David P.; [et al.]. 2015. The 2010 wildland-urban interface of the conterminous United States. Res. Map. NRS-8. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 124 p. [includes pull-out map].

McCaffrey, Sarah; Kumagai, Yoshitaka. 2007. No need to reinvent the wheel: Applying existing social science theories to wildfire. In: Daniel, Terry C.; Carroll, Matthew S.; Moseley, Cassandra; Raish, Carol, eds. People, fire and forests: A synthesis of wildfire social science. Corvallis, OR: Oregon State University Press: 12–36.

Miller, H.M.; Richardson, L.; Koontz, S.R.; Loomis, J.; Koontz, L. 2013. Users, uses, and value of Landsat Satellite Imagery—Results from the 2012 Survey of Users. US Geological Survey, Open-file Report 2013-1269. (Washington, DC).

Mueller, Julie; Loomis, John; Gonzalez-Caban, Armando. 2009. Do repeated wildfires change homebuyers' demand for homes in high-risk areas? A hedonic analysis of the short and long-term effects of repeated wildfires on house prices in southern California. Journal of Real Estate Finance and Economics. 38: 155–172.

National Geospatial Advisory Committee–Landsat Advisory Group [NGAC–LAC]. 2014. The value proposition for Landsat applications—2014 update. Washington, DC. https://www.fgdc.gov/ngac/meetings/december-2014/ngac-landsat-economic-value-paper-2014-update.pdf. [Accessed 2017 August 7].

National Interagency Fire Center [NIFC]. 2017. Federal firefighting costs (suppression only). Boise, ID. Available at https://www.nifc.gov/fireInfo/fireInfo_statistics.html.

O'Connor, Christopher D.; Thompson, Matthew P.; Rodriguez y Silva, Francisco. 2016. Getting ahead of the wildfire problem: Quantifying and mapping management challenges and opportunities. Geosciences. 6: 35–53.

Rahn, Matt. 2009. Wildfire impact analysis. Fire Impact Analysis. 1: 1–15. http://www.wildfire-economics.org/Library/Rahn_2009.pdf. [Accessed 2017 August 7].

Richardson, Leslie A.; Champ, Patricia A.; Loomis, John B. 2012. The hidden cost of wildfires: Economic valuation of health effects of wildfire smoke exposure in Southern California. Journal of Forest Economics. 18: 14–35.

Robichaud, Peter R. 2009. Post-fire stabilization and rehabilitation. In: Cerdà, Artemi; Robichaud, Peter R., eds. Fire effects on soils and restoration strategies. Boca Raton, FL: CRC Press: 299–320.

Robichaud, Peter R.; Lewis, Sarah A.; Brown, Robert E.; Ashmun, Louise E. 2009. Emergency post-fire rehabilitation treatment effects on burned area ecology and long-term restoration. Fire Ecology. 5: 115–128.

Schnase J.L.; Carroll, M.L.; Weber, K.T.; [et al.]. 2014. RECOVER: An automated cloud-based decision support system for post-fire rehabilitation planning. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XL-1: 363–370.

Theobald, David M.; Romme, William H. 2007. Expansion of the US wildland-urban interface. Ecological Applications. 15: 799–805.

Thompson, Matthew P.; Calkin, Dave E. 2011. Uncertainty and risk in wildland fire management: A review. Journal of Environmental Management. 92: 1895–1909.

USDA Forest Service [USDA FS]. 2014. The rising cost of fire operations: Effects on the Forest Service's non-fire work. Washington, DC: U.S. Department of Agriculture, Forest Service. https://www.fs.fed.us/sites/default/files/2015-Fire-Budget-Report.pdf. 16 p. [Accessed 2017 August 7].

Venn, Tyrone J.; Calkin, David E. 2008. Challenges of socio-economically evaluating wildfire management on non-industrial private and public forestland in the western United States. Small-scale Forestry. 8: 43–61.

Vilsack, Tom. 2015. The cost of fighting wildfires is sapping Forest Service budget. The Seattle Times, Opinion. August 4. http://www.seattletimes.com/opinion/the-cost-of-fighting-wildfires-is-sapping-forest-service-budget/. [Accessed 2017 August 7].

Western Forestry Leadership Coalition. 2009. Conclusions and recommendations updated 2010. The true cost of wildfire in the western U.S. Lakewood, CO. 15 p. https://www.blm.gov/or/districts/roseburg/plans/collab_forestry/files/TrueCostOfWilfire.pdf. [Accessed 2017 August 7].

Wigtil, Gabriel; Hammer, Roger B.; Kline, Jeffrey D.; [et al.]. 2016. Places where wildfire potential and social vulnerability coincide in the coterminous United States. International Journal of Wildland Fire. 25: 896–908.

Forest Fire Prediction Modeling in the Terai Arc Landscape of the Lesser Himalayas Using the Maximum Entropy Method

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Abstract—The Terai Arc Landscape (TAL) is an ecologically important region of the Indian subcontinent, where anthropogenic habitat loss and forest fragmentation are major issues. The most prominent threat is forest fires because of their impacts on the microhabitat and macrohabitat characteristics and the resulting disruption of ecological processes. Moreover, wildfire aggravates conflicts between humans and wildlife in the forest fringe areas. The lack of a proper forest fire monitoring system in the TAL is a major management issue that needs attention for long-term forest viability. Hence, the present study was undertaken using maximum entropy modeling to predict the areas across the TAL at risk of wildfire and to identify key variables associated with fire occurrence. Spatiotemporally independent fire incidence locations along with other environmental variables were used to build the model. The accuracy of the model was assessed using the area under the curve. To evaluate the importance of each variable, a jackknife procedure was adopted. Areas in the projected map were categorized into high fire, marginal fire, and no fire areas. An adaptive forest management strategy can be implemented in the modeled high fire areas to mitigate forest fire and wildlife conflict in the TAL.

Keywords: forest fire, maximum entropy, Terai Arc Landscape, Tiger

INTRODUCTION

A forest fire, whether caused by natural forces or anthropogenic activities, could be an ecological and environmental disaster (Kandya et al. 1998; Saigal 1989). In India, fire affects about 2 to 3 percent of the forested area annually, and on average over 34,000 ha of forests burn each year (Kunwar 2003). Fire hazard is the likelihood of a physical event of a particular magnitude in a given area at a given time, which has the potential to disrupt the functionality of a society, its economy, and its environment (Boonchut 2005). Although fire serves an important function in maintaining the health of certain ecosystems, fires have become a threat to many forests and their biodiversity (Dennis and Meijaard 2001) because of changes in climate and in human use and misuse of fire.

The Terai Arc Landscape (TAL) is an ecologically important region of the Indian subcontinent and is facing the challenges of habitat loss and forest fragmentation due to a variety of threats from natural (catastrophic) and anthropogenic sources. The most prominent threat is human population pressure on natural resources and erratic land development activities in the region, resulting in the decline of forest cover and loss of biodiversity in the TAL (Semwal 2005). Parts of the TAL are reduced to tenuous linkages that connect relatively large

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

remaining wildernesses, and in some places these linkages are being lost and need restoration to halt further degradation of these natural habitats. Protect the TAL is imperative as the landscape is a mosaic of two of the most important tiger (*Panthera tigris*) reserves (Rajaji Tiger Reserve [RTR] and Corbett Tiger Reserve [CTR]), and contains the Sonanadi Wildlife Sanctuary. Several segments of forested areas are under different protection categories. The RTR-CTR Tiger Conservation Unit (TCU) is one of the 11 level I TCUs identified on the Indian subcontinent for the long-term conservation of tigers (Dinerstien et al. 1997). This TCU of about 7,500 km^2 stretches from the Yamuna River in the west to the Sharda River in the east. About 30 percent of this TCU is in the protected area (PA) network: 820 km^2 in Rajaji National Park (RNP); and 1,286 km^2 in the CTR, consisting of 521 km^2 in Corbett National Park (CNP), 302 km^2 in Sonanadi Wild Life Sanctuary (WLS), and a 463-km^2 buffer area carved out from the Kalagarh, Ramnagar, and Terai west Forest Divisions (FDs). The remainder makes up 12 Reserved Forests (RFs) from west to east. In contrast with the 521-km^2 core area of the CNP, which is free from human disturbance, the rest of the area is subjected to various types of pressures for fuel wood, fodder collection, and grazing, both from the Gujjar community living inside the forests and from the villages located at the periphery of the PAs (Johnsingh and Negi 2003). The Sonanadi WLS is one of the prime habitats for Asian elephants (*Elephas maximus*) in the landscape and has been designated a tiger nursery. This sensitive area is also not free from human disturbances. Though relocation is being proposed, about 184 Gujjar households were recorded as living inside the sanctuary. There is a dearth of scientific studies on these aspects of the FDs. Ninety percent of the 750 elephants in northwestern India reside in RNP, Sonanadi WLS, CNP, and adjoining areas in this Shivalik-Bhabar physiographic zone (Johnsingh and Joshua 1994). This is one of the five major elephant populations of the country.

Accurate mapping of fire hazard is important to help manage and protect critical tiger and elephant habitat in the TAL. Remote sensing has considerable advantages over a conventional method to map forest fire hazard, because of its continuity of coverage over large areas. Geographic information systems (GIS) are capable of combining different sources of information for modeling or mapping. For the optimal utilization of remote sensing and GIS to model forest fire hazard, however, factors affecting fire spread—fuel type, terrain, and human access—need to be studied. Yet this type of research is generally lacking in the tropical region compared to other regions (Darmawan et al. 2001).

Monitoring techniques based on multispectral satellite-acquired data have demonstrated potential as a means to detect, identify, and map fire danger in vegetation. Fire danger estimation demands frequent monitoring of vegetation stress. Vegetation moisture is a particularly difficult parameter to estimate as it accounts for little spectral variation with respect to other environmental factors (Cohen 1986).

In the present study maximum entropy (Maxent) (Phillips et al. 2006) was used due to its predictability and reliability. The objectives of this study were to generate fire prediction models to 1) predict potential fire occurrence areas using environmental variables in the TAL and 2) identify key environmental variables associated with fire occurrence and areas where fires are likely to occur.

MATERIALS AND METHODS

Study Area

The study was carried out in the Terai Arc Landscape of the Uttarakhand Himalayas (fig. 1) (28°43'29" to 30°30'18" North latitude and 77°34'54" to 80°19' 29" East longitude), located in north India, and covers an area of about 20,223 km^2. The area has an uneven topography, with elevation ranging from 103 m to 3,069 m. The Lansdowne, Ramnagar, Haldwani, Terai west, Terai central, and Terai east Reserved FDs are the important RFs in this portion of the study site.

The TAL has been identified as a priority landscape by the World Wildlife Fund (WWF) Tiger Action Plan 1 and the WWF AREAS programs. The "Terai-Duar Savannas and Grasslands" are also a Global 200 Ecoregion. The total area of the landscape is about 49,500 km^2, of which 30,000 km^2 lies in India. There are 13 PAs on the landscape, from the easternmost Parsa Wildlife Reserve in Nepal to Rajaji National Park to the west in India, which were established to

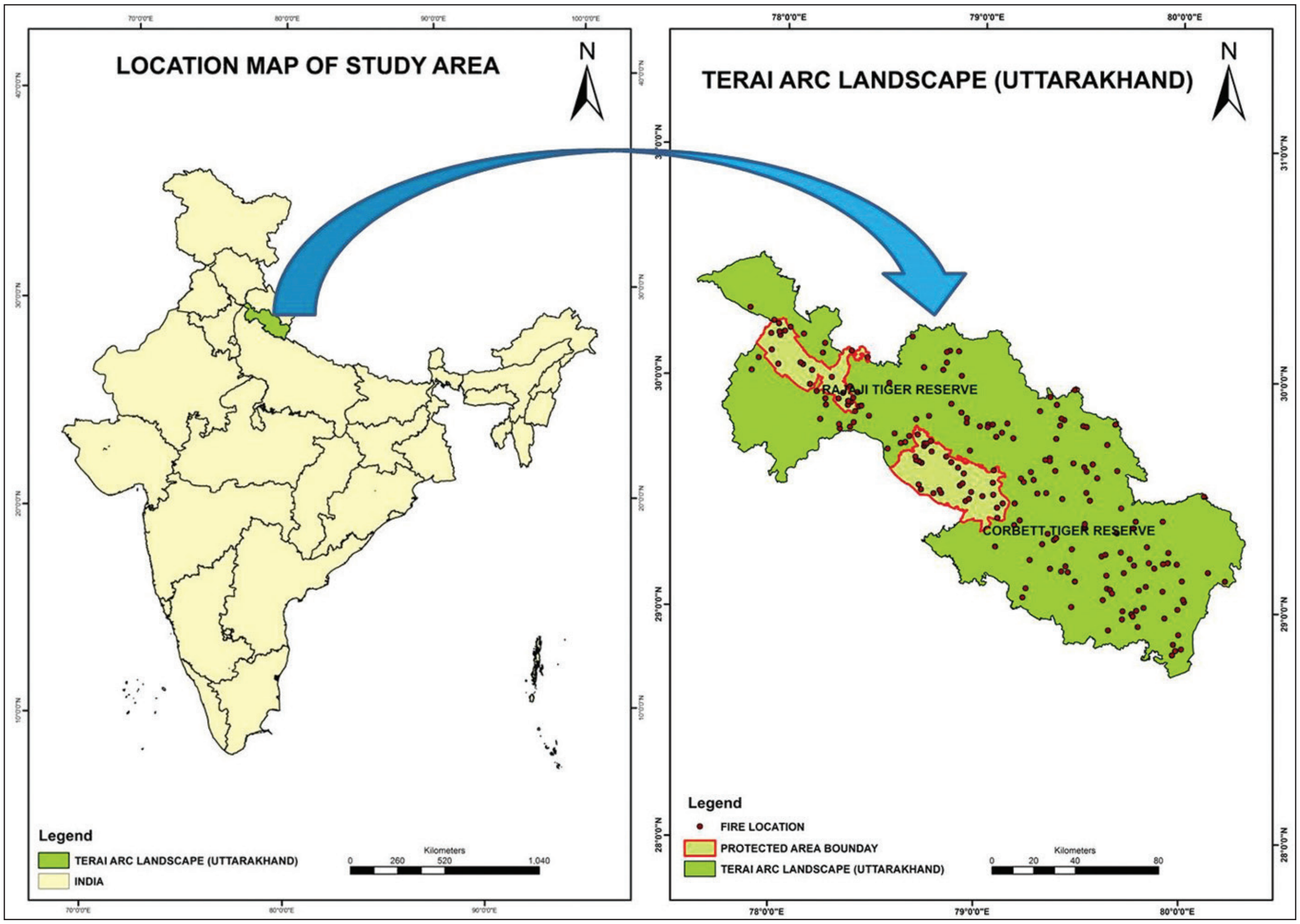

Figure 1—Location map of study area.

protect 3 of the 5 terrestrial flagship species identified by WWF: tiger, Asian elephant, and the greater one-horned rhinoceros (*Rhinoceros unicornis*). The TAL represents one of the densest populations of tigers in the world. The TAL is in the upper Gangetic Plain biogeographic zone 7, and vegetation is mainly of the tropical moist and dry deciduous type. The forests are made up of many economically important species such as *Shorea robusta*, *Dalbergia sissoo*, *Terminalia tomentosa*, and *Acacia catechu*. The Gangetic Plain is also characterized by tall grasses such as *Themeda*, *Saccharum*, *Phragmites*, and *Vetiveria* species. Both these elements (fauna and flora) of the TAL are of global ecological and local economic significance.

Datasets

The data used were Landsat 8 for November 21, 2013 (30-m spatial resolution), the Survey of India toposheet on a 1:50,000 scale with 20-m contour intervals, Cartosat digital elevation model (30-m resolution), and WorldClim bioclimatic data, ver. 1.4 (environmental variables; http://www.worldclim.org/bioclim.htm) (Hijmans et al. 2005). TRIMBLE® (Sunnyvale, California) JUNO® global positioning system was used for field purposes. Fire data for 2000 through 2014 were collected from the State forest department in the form of a point shape file. The digital boundary of the TAL was collected from IT Cell, Uttarakhand Forest Department, PA management plans, and work plans of divisions in the TAL.

Software Used

Erdas Imagine 2013 (DataONE, Albuquerque, NM) was used for digital image processing work and ArcGIS 10.1 (Esri®, Redlands, California) was used for map composition. For data analysis, we used Maxent and DIVA-GIS software, ver. 2 (Hijmans et al. 2002) for reducing spatial autocorrelation and ENMTools (Warren et al. 2010) for checking multicollinearity between predictor variables.

Environmental Fire Predictors

For inputting spatial data into GIS, we created resource maps using remote sensing, coupled with limited ground checks. The forest-type layer was generated by using a supervised classification approach in which 30 training sets were taken from Google Earth as ground control points. The forest cover map was generated using an unsupervised classification approach used for vegetation density mapping using Erdas Imagine 2013 software. The study area was classified into 50 spectral classes using an unsupervised image classification approach. Eventually the vegetation of the study area was stratified into four major types on the basis of density (table 1) as per the fundamental criteria of the Forest Survey of India (FSI 2013). Slope, aspect, and elevation maps were generated from the Cartosat 30-m digital elevation model using a boundary vector layer in ArcMap 10.1.

Table 1—Predictor variables tested for prediction modeling of fire in the Terai Arc Landscape.

Climate variable	Code	Source	Type
Bio 1 = Annual Mean Temperature	*Bio1*	Worldclim	continuous
Bio 2 = Mean Diurnal Range (Mean of monthly [maximum temperature – minimum temperature])	*Bio2*		
Bio 3 = Isothermality (P2/P7) × 100	*Bio3*		
Bio 4 = Temperature Seasonality (standard deviation × 100)	*Bio4*		
Bio 5 = Max Temperature of Warmest Month	*Bio5*		
Bio 6 = Min Temperature of Coldest Month	*Bio6*		
Bio 7 = Temperature Annual Range (P5–P6)	*Bio7*		
Bio 8 = Mean Temperature of Wettest Quarter	*Bio8*		
Bio 9 = Mean Temperature of Driest Quarter	*Bio9*		
Bio 10 = Mean Temperature of Warmest Quarter	*Bio10*		
Bio 11 = Mean Temperature of Coldest Quarter	*Bio11*		
Bio 12 = Annual Precipitation	*Bio12*		
Bio 13 = Precipitation of Wettest Month	*Bio13*		
Bio 14 = Precipitation of Driest Month	*Bio14*		
Bio 15 = Precipitation of Seasonality (Coefficient of Variation)	*Bio15*		
Bio 16 =Precipitation of Wettest Quarter	*Bio16*		
Bio 17 =Precipitation of Driest Quarter	*Bio17*		
Bio 18 =Precipitation of Warmest Quarter	*Bio18*		
Bio 19 =Precipitation of Coldest Quarter	*Bio19*		
Elevation (m)	*elevation*	Cartosat digital elevation model (DEM)	continuous
Slope (°) Aspect (°)	*Slope* *Aspect*	Calculated from Cartosat DEM	continuous
Distance to the nearest village/ tribal settlement (m)	*D2v*	Field data GPS location	continuous
Distance to the nearest water source (m)	*D2d*	Survey of India (SOI) toposheet	continuous
Distance to the nearest watch station (m)	*D2wt*	Field data GPS location	continuous
Distance to the nearest road (m)	*D2r*	SOI-toposheet	continuous
Actual evapotranspiration	*AET*	CGIR	continuous

(continued on next page)

Table 1 (continued)—Predictor variables tested for prediction modeling of fire in the Terai Arc Landscape.

Climate variable	Code	Source	Type
Aridity index	*AI Index*	CGIR	continuous
Population density	*Population density*	Diva GIS	continuous
Forest cover type 1 = Very Dense Forest 2 = Moderately Dense Forest 3 = Open Forest 4 = Scrub 5 = Water 6 = Nonforest	*fcm*	Satellite data	categorical
Forest type 1=Tropical Moist Deciduous 2=Dry Deciduous 3=Northern Subtropical Broadleaved 4=Himalayan Temperate Forest	*ftm*	Satellite data	categorical

Road network and drainage network layers were digitized from the Survey of India toposheet at 1:50,000 scale using ArcMap 10.1. The GPS location of the habitation and forest watch station was collected from field visits. Initially 19 bioclimatic variables from the WorldClim database were considered. A subset of Bioclim 30-m resolution of study area was clipped using the boundary vector layer in ArcMap 10.1.

Fire Occurrence Data

Fire incidence data from 2000 through 2014 were compiled by assessing the distribution of fire in the TAL as recorded by the forest department in Uttarakhand. Over the 15-year period, a total of 7,833 fires were reported in the TAL, of which 2,184 fires occurred in PAs (RNP and CTR). For the present study only 200 spatiotemporally independent fire locations were used for model building. The spatiotemporally autocorrelated fire locations were removed after testing using DIVA-GIS, ver. 2 (Hijmans et al. 2002). Only one location per 1-km grid cell was used if more than one observation was clustered in a grid (i.e., to avoid autocorrelation with a low sample size) (Pearson et al. 2007; Phillips et al. 2006).

Environmental Variables

A series of bioclimatic environmental variables obtained from the WorldClim database, ver. 1.4 (http://www.worldclim.org/bioclim.htm) (Hijmans et al. 2005) were selected. These metrics are derived from monthly temperature and rainfall data and represent biologically meaningful variables for characterizing a species' range. Thirty-one environmental variables were used. These included 11 variables for temperature and 8 for precipitation, expressing spatial variations in annual means, seasonality, extreme or limiting climatic factors, and elevation-interpolated climate surfaces at a resolution of 1 arc-second, or approximately 30 m × 30 m (derived from monthly temperature and rainfall records worldwide) (Hijmans and Graham 2006; Hijmans et al. 2005). Elevation data were used to generate the slope and aspect data layers. The forest density cover and forest type layer were generated from satellite data. All the spatial data layers were created at 30-m spatial resolution using the nearest neighbor resampling technique using Erdas 2013 and ArcGIS 10.1 software. ENMTools ver. 1.3 (Warren et al. 2010) was used to test multicollinearity between predictor variables. The ENMTools output matrix of Pearson Correlation Coefficients (r) was used, and variables with r greater than 0.7 were removed from the model building.

Fire Modeling

The Maxent software package, ver. 3.3.3.e (http://www.cs.princeton.edu/~schapire/maxent/) (Phillips et al. 2004) was used for fire prediction modeling. Maxent implements a maximum entropy algorithm, which generates a probability distribution map of similar conditions across the landscape considering the characteristics of the GPS-defined occurrence locations (Elith et al. 2011; Phillips et al. 2006). Maxent is a machine learning algorithm used to predict robust ecological niches of a species, based on presence records, even when only a few are available (Elith et al. 2006; Kumar and Stohlgren 2009; Papeş and Gaubert 2007; Phillips et al. 2006). This model has an advantage where presence and absence data are limited (Elith et al. 2006; Phillips and Dudík 2008).

Model Parameter Settings

The maximum number of background points was 5,000 and linear, quadratic, and hinge features were used (Phillips and Dudík 2008). One hundred replicates were run for model building (Flory et al. 2012) and the occurrence locations were partitioned randomly into two subsamples, using 75 percent of the locations as the training dataset and the remaining 25 percent for testing the resulting (partitioned) models. The accuracy of the model was evaluated using the area under the curve (AUC) of a receiver operating characteristic (ROC) plot (ranging from 0.5 = random to 1 = perfect discrimination). A jackknife procedure was adopted to assess the variables' importance (Yang et al. 2013). The average of 100 model predictions was used to produce a probability map of fire occurrence. The other settings for the default model parameters and values were used.

RESULTS

The Maxent model predicted hazard maps of fire based on available datasets with a mean training AUC value of 0.926 ± 0.016 and mean testing AUC value of 0.888 ± 0.013, indicating the model's high discrimination capacity. The model performed well, with a low omission rate at a 10-percent threshold ($p < 0.0002$). A fire probability map was generated from the model output where the values of fire probability range from 0 to 1 (fig. 2). The classified predicted occurrence map (fig. 3) shows good discrimination between high fire, marginal fire, and no fire areas. High and marginal fire areas covered 7.32 percent and 60.40 percent, respectively, of the total study area. Based on a 10-percent training presence logistic threshold, values below 0.2 were categorized as no fire areas. All values above 0.6 were categorized as high fire and those between 0.2 and 0.6 as marginal fire areas.

The classified predicted occurrence map showed that 23.06 percent of the CTR area was in the high fire category and 65.55 percent of the area was in the marginal fire category. Similarly, for RNP, 18.04 percent of the total area was in the high fire category and 79.0 percent of the area was in the marginal fire category.

Response curves showed how each environmental variable responded to predicted areas, both for each variable and its correlation with other variables. The results demonstrated that fires occur in dry deciduous forests (forest type 2) more than other forest types.

The Maxent program estimates the relative contribution of environmental variables in model development. Forest type, forest cover, precipitation in the wettest month, and distance to the closest village contributed the most, with 22.6 percent, 20.5 percent, 12.6 percent, and 8.2 percent, respectively. In terms of permutation importance, however, mean temperature of the coldest quarter, distance to settlement, precipitation in the wettest month, elevation, and precipitation in the driest quarter had the highest values: 14.4 percent, 11.1 percent, 8.7 percent, 8.3 percent, and 8.3 percent, respectively (fig. 4). The environmental variable with the highest gain when used in isolation is distance to settlement, which therefore appears to have the most useful information by itself (fig. 5). The environmental variable that has the largest effect when omitted is forest type, which therefore appears to have the most information that is not present in the other variables.

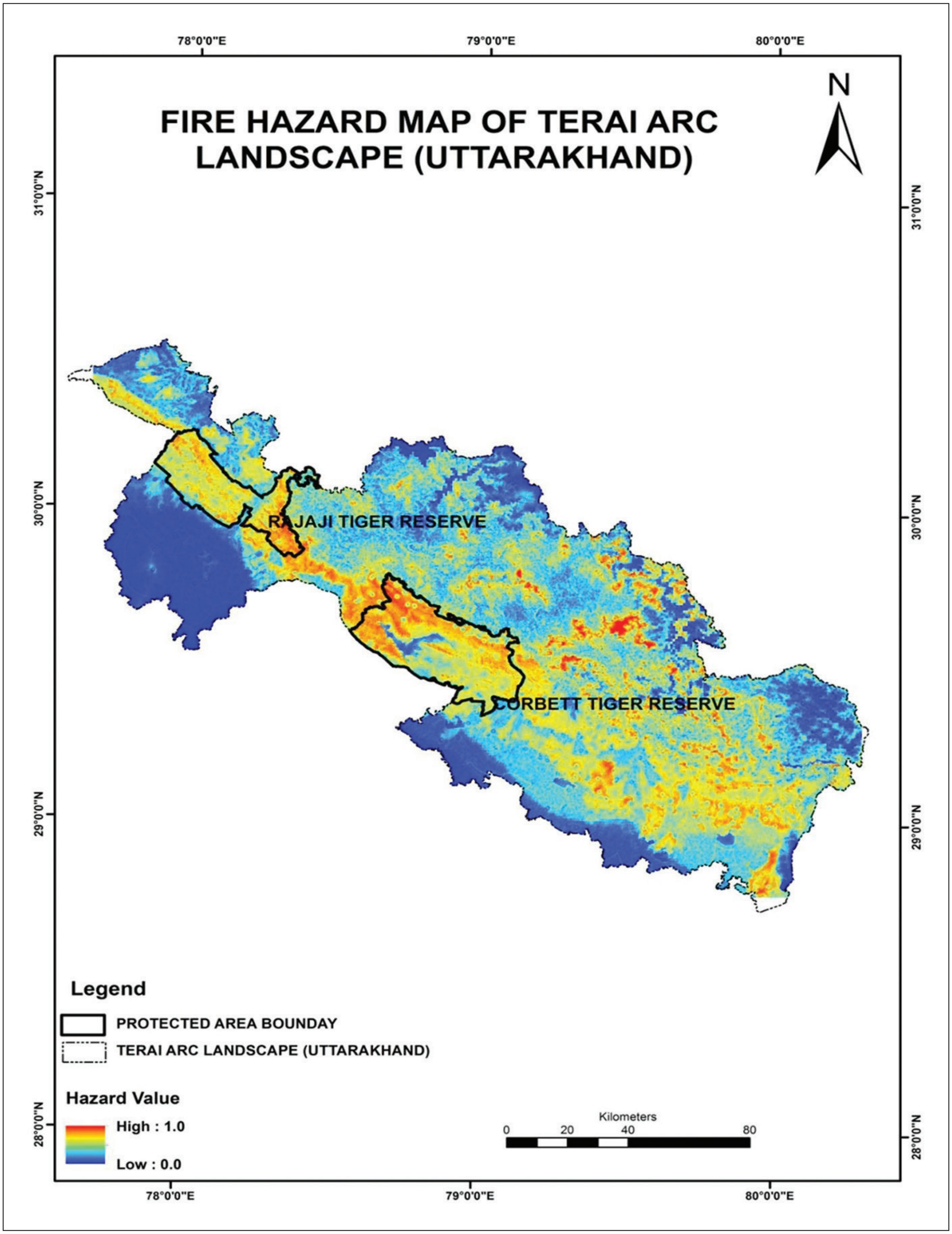

Figure 2—Predicted fire hazard map from low to high probability value.

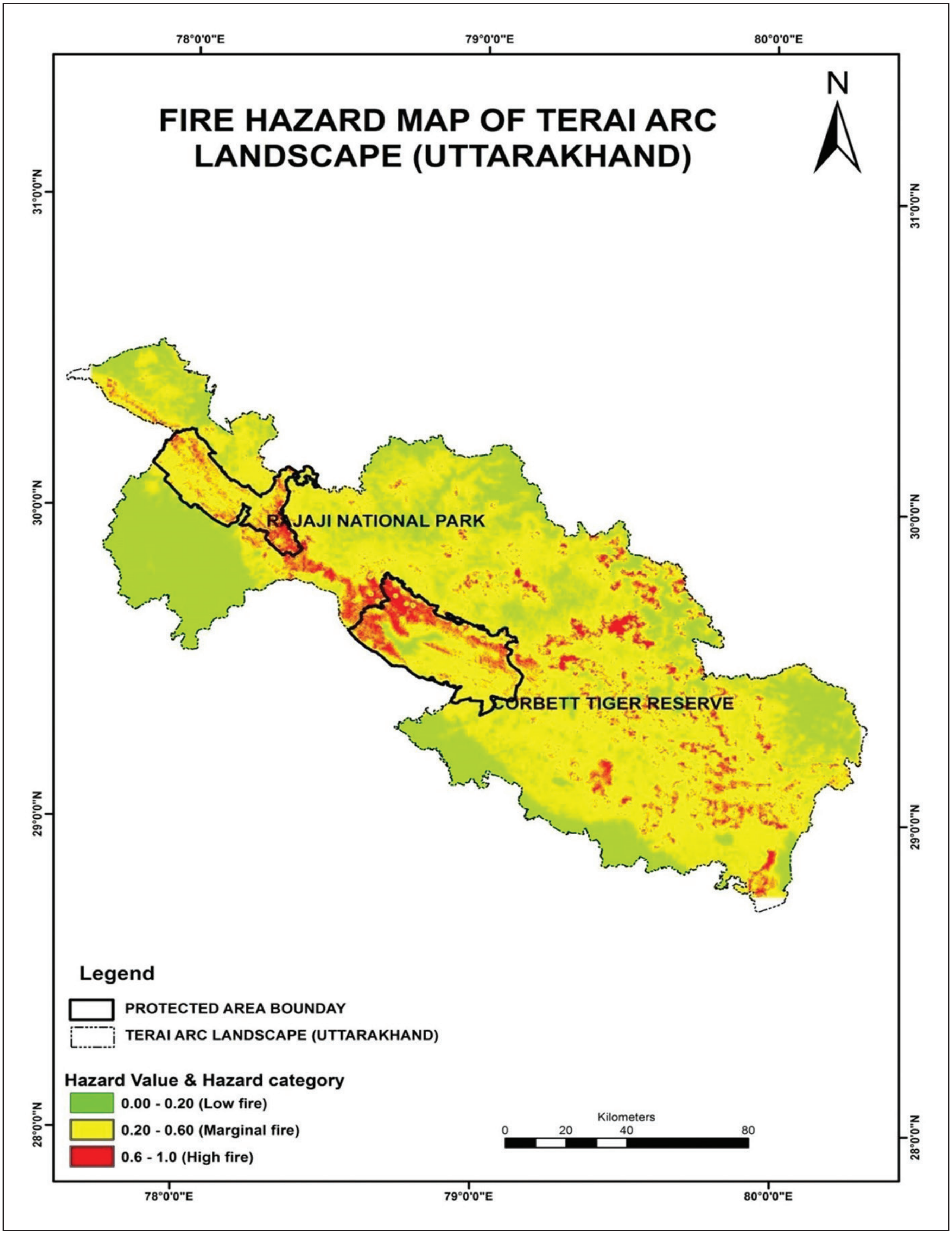

Figure 3—Classified predicted fire hazard map.

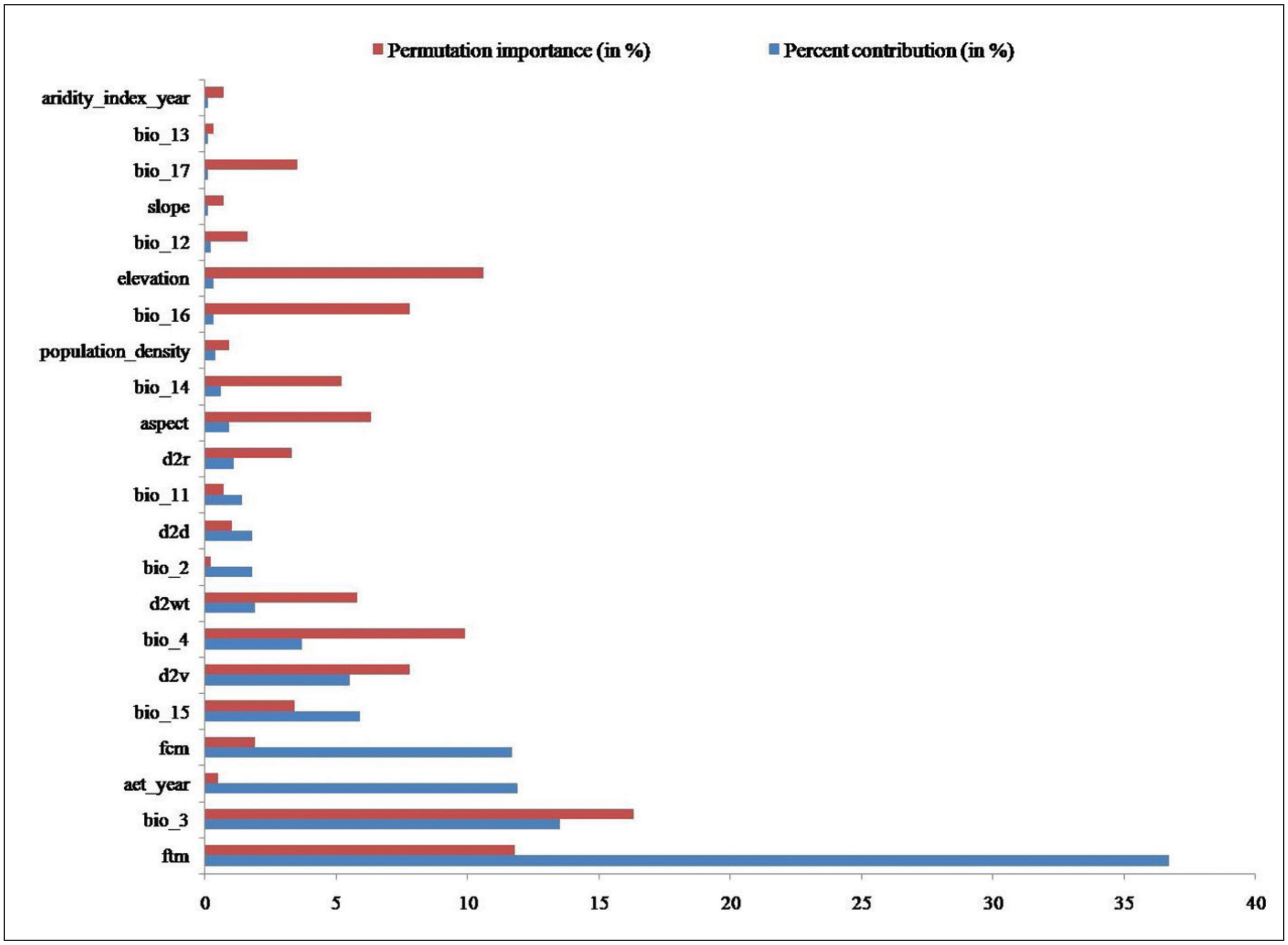

Figure 4—Percent contribution and permutation importance of predictor variables. See table 1 for explanations of codes for variables.

DISCUSSION

The study predicted the potential areas of fire occurrence in the TAL of the lesser Himalayas, India based on available presence records. The output of this model can be used to assist conservation planning and serve as a benchmark for future collection of presence and absence data on fire. Maxent models only identify regions with similar environmental conditions to occurrence localities across the species distribution range (Pearson et al. 2007). Forest type plays an important role in predicting the occurrence of fire, and the model output and previous field surveys revealed that the occurrence of fire in dry deciduous forest having canopy density between 40 and 70 percent and located near a village or other settlement is high compared to other areas. The variation of fire with elevation showed that the probability of fire was high up to an elevation of 2,000 m. Sizable anthropogenic disturbances in the study area were observed during the field visit, and the model also predicted high probability of fire in the forest areas near settlement locations.

The model predicted three categories of fire occurrence areas under high (1,481 km^2), marginal (12,218 km^2), and no fire (6,524 km^2) in the TAL. The model predicted that 10 percent of the total area with predicted potential fire was inside the protected area network.

The Maxent software is user-friendly and has a good ability to predict forest fires. The high fire areas predicted in our study should be used as a base map for management of fire. This study exemplifies the usefulness of prediction modeling of forest fire

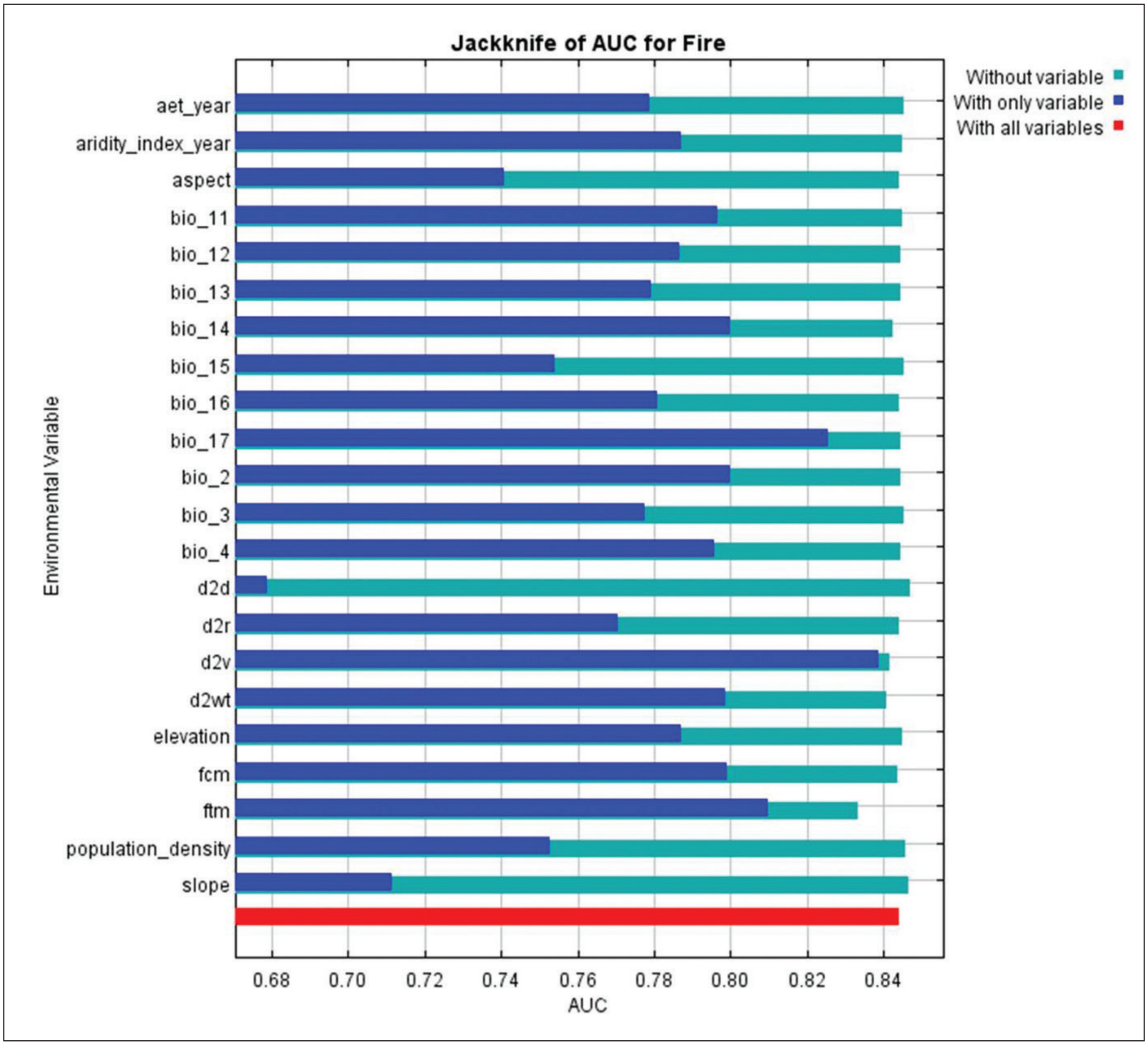

Figure 5—Jackknife of area under the curve (AUC) for fire. See table 1 for explanations of codes for variables.

and offers a more effective way for management of forest fire. The results of this study can be used for preparatory planning for mitigation and management of forest fires in the TAL. Overall, this study depicts a model for conservation of biodiversity, which is beneficial for both wildlife and human beings.

REFERENCES

Boonchut, Prat. 2005. Decision support for hazardous material routing. Enschede, the Netherlands: International Institute for GeoInformation Science and Earth Observation. Master of Science thesis. 121 p. https://systems.enpress-publisher.com/index.php/JGC/article/view/618.

Cohen, Jack D. 1986. Estimating fire behavior with FIRECAST: User's manual. Gen. Tech. Rep. PSW-GTR-90. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 11 p.

Darmawan, Mulyanto; Aniya, Masamu; Tsuyuki, Satoshi. 2001. Forest fire hazard model using remote sensing and geographic information systems: Toward understanding of land and forest degradation in lowland areas of East Kalimantan, Indonesia. Paper presented at the 22nd Asian Conference on Remote Sensing; 2001 November 5–9; Singapore. 2001 Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore; Singapore Institute of Surveyors and Valuers (SISV); Asian Association of Remote Sensing (AARS). https://crisp.nus.edu.sg/~acrs2001/pdf/234darmawan.pdf. [Accessed 2019 June 14].

Dennis, Rona; Meijaard, Erik. 2001. Impact of human-caused fires on biodiversity & ecosystem functioning, and their causes in tropical, temperate & boreal forest biomes. CBD Technical Series No.5. Montreal, QC: Convention on Biological Diversity. 21 p.

Dinerstien, Eric; Wikramanayake, Eric D.; Robinson, John; [et al.]. 1997. A framework for identifying high priority areas and actions for the conservation of tigers in the wild. Washington, DC: World Wildlife Fund/Wildlife Conservation Society. 72 p.

Elith, Jane; Phillips, Steven J.; Hastie, Trevor; [et al.]. 2011. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions. 17: 43–57.

Elith, Jane; Graham, Catherine H.; Anderson, Robert P.; [et al.]. 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography. 29: 129–151.

Flory, Abigail R.; Kumar, Sunil; Stohlgren, Thomas J.; Cryan, Paul M. 2012. Environmental conditions associated with bat white nose syndrome mortality in the north-eastern United States. Journal of Applied Ecology. 49: 680–689.

Forest Survey of India [FOI]. 2013. India state of forest report. Ministry of Environment & Forests, Government of India.

Hijmans, Robert J.; Cameron, Susan E.; Parra, Juan L.; [et al.]. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology. 25: 1965–1978.

Hijmans, R.J, Graham, Catherine H. 2006. The ability of climate envelope models to predict the effect of climate change on species distributions. Global Change Biology. 12: 2272–2281.

Hijmans, Robert J.; Guarino, Luigi; Bussink, Coen; Rojas, Edwin. 2002 DIVA-GIS Ver. 2. A geographic information system for the analysis of biodiversity data. Manual. Lima, Peru: International Potato Center.

Johnsingh, A.J.T.; Joshua, Justus. 1994. Conserving Rajaji and Corbett National Parks—The elephant as a flagship species. Oryx. 28: 135–140.

Johnsingh, A.J.T.; Negi, A.S. 2003. Status of tiger and leopard in Rajaji-Corbett Conservation Unit, northern India. Biological Conservation. 11: 385–393.

Kandya, A.K.; Kimothi, M.M.; Jadhav, R.N.; Agarwal, J.P. 1998. Application of GIS in identification of fire prone areas—A feasibility study in parts of Junagarh (Gujrat, India). Indian Forester. 7: 531–535.

Kumar, Sunil; Stohlgren, Thomas J. 2009. Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. Journal of Ecology and Natural Environment. 1: 94–98.

Kunwar, P.; Kachhawaha, T.S. 2003. Spatial distribution of area affected by forest fire in Uttaranchal using remote sensing and GIS techniques. Journal of the Indian Society of Remote Sensing. 31: 145–148.

Papes, M.; Gaubert, P. 2007. Modelling ecological niches from low numbers of occurrences: assessment of the conservation status of poorly known viverrids (Mammalia, Carnivora) across two continents. Diversity and Distributions. 13: 890–902.

Pearson, Richard G.; Raxworthy, Christopher J.; Nakamura, Miguel; Peterson, A. Townsend. 2007. Predicting species distributions from small numbers of occurrence records: A test case using cryptic geckos in Madagascar. Journal of Biogeography. 34: 102–117.

Phillips, Steven J.; Anderson, Robert P.; Schapire, Robert E. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modelling. 190: 231–259.

Phillips, Steven J.; Dudík, Miroslav. 2008. Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. Ecography. 31: 161–175.

Phillips, Steven J.; Dudík, Miroslav; Schapire, Robert E. 2004. Maxent software for modeling species niches and distributions. Available at http://rob.schapire.net. [Accessed 2019 June 14].

Saigal, P.M. 1989. A suggested classification of forest fires in India by types and causes. In: Proceedings of the National Seminar on Forest Fire Fighting; 1989 November 2–3; Kulamaru, Kerala, India.

Semwal, Rajeev L. 2005. The Terai Arc Landscape in India: Securing protected areas in the face of global change. New Delhi, India: World Wildlife Fund-India, New Delhi. 47 p.

Warren, Dan L.; Glor, Richard E.; Turelli, Michael. 2010. ENMTools: A toolbox for comparative studies of environmental niche models. Ecography. 33: 607–611.

Yang, Xue-Qing; Kushwaha, S.P.S.; Saran, S.; [et al.]. 2013. MaxEnt modeling for predicting the potential distribution of medicinal plant, *Justicia adhatoda* L. in Lesser Himalayan foothills. Ecological Engineering. 51: 83–87.

Extended Abstracts

FireWorks Educational Program: Hands-on Activities to Engage Students and the Public About Wildland Fire Science

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Wildland fire captures the public's attention every summer, but public understanding of fire is limited. The FireWorks Educational Program provides hands-on activities to increase public understanding of wildland fire. Although primarily designed for K-12 students, many of the activities are both suitable and fun for adults. FireWorks teaches students not only about wildland fire science, but also about how fire affects their local ecosystems.

The original FireWorks Curriculum was published in 2000 (Smith and McMurray 2000) and consisted of activities and associated trunks of materials featuring ecosystems in the Northern Rocky Mountains and northern Cascade Range. It was widely used by teachers and staff from Federal agencies, especially throughout the Northern Rocky Mountain region, but interest in the program was widespread. To address this interest, we expanded, revised, and modernized the program. Along with the update to the Northern Rocky Mountains and northern Cascade Range program, we partnered with the Plumas National Forest and the Plumas Unified School District to develop a program for the Sierra Nevada in California. Today, the FireWorks curricula for the two regions consist of new and updated activities that reflect recent advances in fire research and national educational standards. Separate curricula are available at the elementary, middle, and high school levels and are correlated to national education standards. Activities cover the physical science of wildland fire, the wildland fire environment, fire effects on the environment, fire ecology, fire history and succession, and people's relationships with fire.

Details about FireWorks curricula and associated hands-on materials, delivered in the "trunks" are available at: https://www.frames.gov/fireworks/fireworks-home/.

REFERENCE

Smith, Jane Kapler; McMurray, Nancy E. 2000. FireWorks curriculum featuring ponderosa, lodgepole, and whitebark pine forests. Gen. Tech. Rep. RMRS-GTR-65. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 270 p.

Keywords: conservation education, outreach, fire ecology, fire behavior, fire history, succession

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

NASA Applied Science Efforts: Collaborations in Earth Observation Data, Information, Models and Tools Supporting Wildland Fire Management

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and **Lawrence Friedl**, NASA Applied Science Program, Earth Science Division, Science Mission Directorate, Washington, DC

In 2011, NASA solicited applications and applied research projects using Earth observations (EO) to improve decisionmaking activities and actions on topics related to wildland fires. Nine projects were selected; these projects were focused on advancing organizations' use and application of Earth observations in analysis and assessments, management strategies and actions, business practices, and policy analysis and decisions associated with wildland fires. Those nine projects were focused on fire prediction modeling, active fire monitoring capability enhancements, and post-fire rehabilitation and recovery assessment and modeling. The projects employed various Earth observation data, including orbital and airborne assets to support modeling and improve wildfire management and assessment practices. The focus of the efforts were to engage with fire management communities and develop capabilities to high Applications Readiness Levels (ARL; an adaptation of Technology Readiness Levels (TRL)) and transition those capabilities / models to operational use in the fire community. The investigator teams engage with the fire management communities throughout the 4-5 years of the efforts to ensure that the partner agencies could integrate the practices into their fire management processes.

Additionally, the NASA Applied Science—Wildland Fire Program supported four separate efforts that focused on assessment of the socio-economic impacts of EO data in support of fire management practices. Those projects highlight the importance and added value of EO to the community.

In 2018, the NASA Wildfire program is concluding, and the presentations that follow this Special Session opening presentation will highlight these nine projects which have made significant advances in the integration of EO in tools and decision support endeavors of the wildland fire management community.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

How 10 Years of Physical Assumptions Led to the Development of the Balbi Model, From Laboratory Scale to Field Scale

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Abstract—This work deals with the construction of a fire behavior model that can be easily used by people involved in firefighting or in environmental planning. The model has to provide the main physical characteristics of the fire front (rate of spread, flame tilt angle, flame height, flame length, flame temperature etc.). As this model has to be a universal one, it can be applied to any surface fire configuration without any change in the model.

Keywords: physical model, radiation, convection, rate of spread

INTRODUCTION

Ten years ago, the main part of fire propagation models was split up in empirical models (e.g. the well-known Rothermel model, Rothermel 1972) and complete physical models (the so called multiphase models incorporated into simulators such as Firestar, Firetec or WFDS Linn et al. 2007; Mell et al. 2005; Morvan et al. 2009; Morvan 2014). Simplified physical models were yet another type of model (for instance Koo et al. 2005; Pagni and Peterson 1973) which were physics-oriented enough with a computational time close to zero.

Our goal, at the University of Corsica, was to build a simplified surface fire propagation model (no crown fire model) that could be used by people involved in firefighting or in fire-management. This model had to be physics-oriented, three-dimensional, faster than real time and provide a good accuracy. The use of simplified physical laws had to give the main physical characteristics of a fire front (rate of spread, flame tilt angle, flame temperature, etc.) as a function of the wind speed, the terrain slope angle, the fuel moisture content and other fuel characteristics. This model was built in five steps from a simple model to a complete model working at the field scale.

In order to obtain a simplified physical model, the first important thing is to avoid using partial differential equations, which need strong assumptions on the gas phase. Then we have to consider average values of the variables (e.g., the mean flame temperature). Next, we have to consider simplified physical laws (e.g., simplified mass or energy or preheating balance). Finally, the ROS appears to be the solution of an algebraic equation.

A RADIATIVE ONLY SIMPLIFIED PHYSICAL MODEL

2007—The First Operational Model

This first operational model took into account three energy transfer modes:

1. Flame base radiation (radiation from the fuel burning particles area). The burning fuel/unburnt fuel interface is assumed to be a black radiant panel and we use a usual Stefan-Boltzman modeling.
2. Flame radiation with the flame as a grey radiant panel.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

3. Convective cooling in front of the flame. This cooling leads to a strong assumption: the flame radiation only impinges the unburnt fuel under the flame.

This model (Balbi et al. 2007) was tested in litter experiments with success but some weaknesses remain. Indeed, some equations of the model come from empirical laws (for instance, the flame height is computed with the McCaffrey correlation). Another weakness lies in the definition of flame radiation. And last but not least, the simplified model has 3 model parameters.

2010—Model Improvements

Three years later, three improvements were made. First, we changed the McCaffrey correlation for a physical law obtained with a simplified vertical momentum balance. We also came up with a better modeling for the radiative fraction and we introduce a fresh cooling which models the backfire better. The two main equations of the model are the following (Balbi et al. 2009; Balbi et al. 2010):

$$R = R_b + A\,R\,\frac{1+\sin\gamma-\cos\gamma}{1+\frac{R\cos\gamma}{r_0}} \qquad (1)$$

$$\tan\gamma = \tan\alpha + \frac{U}{u_0} \qquad (2)$$

where R is the rate of spread, R_b is the flame base radiation, A is a radiant coefficient, r_0 is a model parameter, α is the terrain slope angle, U is the normal component of the wind speed and u_0 is the upward gas velocity.

This improved model was applied to a set of laboratory experiments with strong winds (up to 11 m s^{-1}) and non-parallel wind & slope. However, this model still neglects convection and then poorly represents laboratory experiments with well-ordered, vertically-oriented fuel bed.

2011-2014—Model Developments

The improved model has been used in several manners over 4 years. The first one concerns its incorporation into the ForeFire simulator (http://forefire.univ-corse.fr). It also acted as input data for our analytical model for acceptable safety distance (Rossi et al. 2010; Rossi et al. 2011). Thanks to the model, we were able to find two non-propagation criteria, a condition on the extinction moisture and another on the packing ratio (Balbi et al. 2014a). Finally, the last development concerns eruptive fires. We believe, as Viegas did, that the convective flow induced by the fire is responsible for eruption's triggering. We produced a physical modeling of what we called induced wind, and our model is able to compute the threshold terrain slope angle from which eruption is sure (Balbi et al. 2014b).

A RADIATIVE-CONVECTIVE SIMPLIFIED PHYSICAL MODEL

2016—A Convective Model

The point is to determine the flow of the hot gases so as to check the validity of a convective model, this model has to be confronted to experiments with well-ordered and vertically-oriented fuel beds. Indeed, many authors, from Wolff, carrier and Fendell (Wolff et al. 1991) to Finney (Finney et al. 2013) proved that convection is the dominant heat transfer mode in this type of experiments. So, with those specific fuel beds, radiation from the flame base is still considered but is expected to be not very important because of the well-ordered fuel particles.

As flame radiation impinges a very small surface of the fuel bed because of the verticality of fuel particles, it will be neglected. As several authors did, we consider that the flame is quasi laminar in its first half above the vegetal stratum and then it acts as a barrier to the air flow. So, we take into account the flow inside the flame base. A gas particle inside the flame base is subjected to wind speed and upward gas velocity. Some gas particles go out of the flame base through its top and then go into the flame but some gas particles go out of the flame base through the burning/unburnt fuel interface. This hot gas flow creates a contact flame which ignite the unburnt fuel. This contact flame is the modeling of the fingers of fire observed by Rothermel and Anderson (Rothermel and Anderson 1966).

The convective model has been applied to 172 laboratory fires as found in the literature (Chatelon et al. 2017).

We can observe (fig. 1, left) the good agreement between predicted and observed ROS with a very small Normalized Mean Square Error, a Fractional

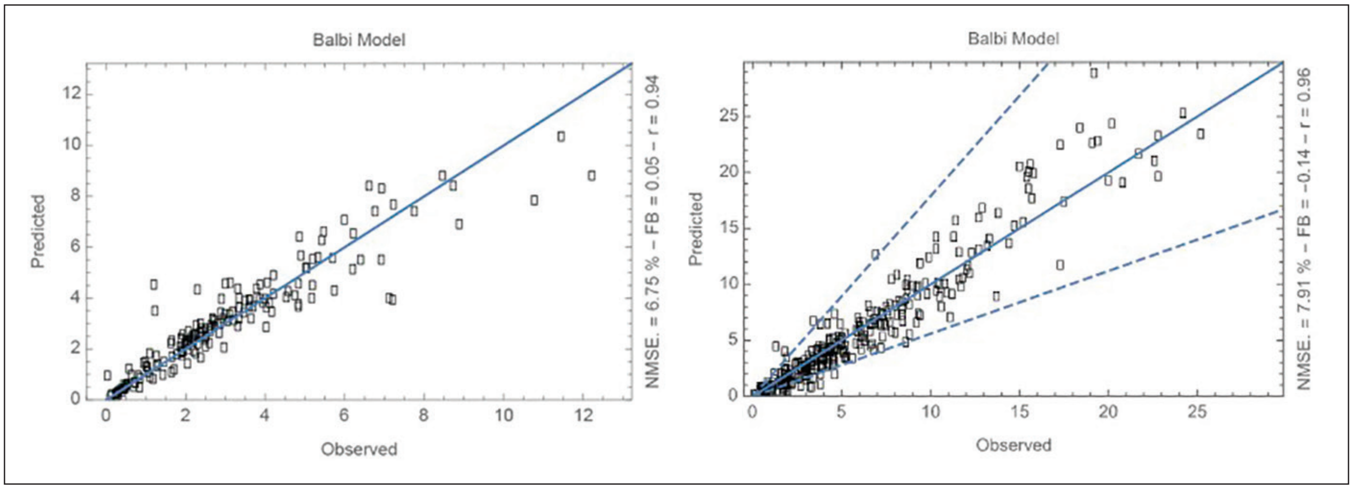

Figure 1—Predicted ROS given by the convective model versus observed ROS for the 172 fires spreading in well-ordered and vertically-oriented fuel beds (left) and Predicted ROS given by the radiative convective model vs observed ROS for the 357 fires carried out by Catchpole et al. 1998 (right). NMSE = Normalized Mean Square Error, FB = Fractional Bias, *r* = Pearson's correlation coefficient.

Bias close to zero and the Pearson's correlation coefficient close to Unity. But the most important thing is that the model has no model parameters. The only changing characteristics from one experiment to another are wind velocity, terrain slope angle and fuel characteristics.

2017—The Radiative-Convective Model

The combination of the convective and radiative models allows us to obtain a complete model. Note that the radiative model was improved with the removal of all the model parameters. The ROS is an increasing function of the wind velocity. After a fast increase, the ROS reaches a plateau which is obtained for a threshold value of the wind speed. Below this value, we can say that flame radiation is negligible. Above this value, the competition between flame radiation and convection involves a negligible flame base radiation.

The main equation of the model is the following definition of the rate of spread:

$$R = R_b + R_f + R_c = R_b + A\,R\,\frac{1+\sin\gamma-\cos\gamma}{1+\frac{R\cos\gamma}{r_0}} + b\,U\,e^{-K\,R} \qquad (3)$$

where R_f is the flame radiation, R_c is the convective effects, K is a drag forces coefficient and b is a convective coefficient which depends on fuel characteristics.

This complete model was confronted to the 357 laboratory fires carried out by Catchpole et al. (1998). We can observe (fig. 1, right) a small error (less than 8%) a light underestimation and a Pearson's correlation coefficient close to Unity.

2018—The Field Scale Model

This year, we confronted our model to the field scale. When the fuel bed is a homogeneous vegetal stratum, the model gives very good results (see fig. 2, left, for the results on the fires performed by Gould 1991). But when the vegetal stratum is composed of dead and living particles, we need to make a new assumption. Indeed, the dead part of the fuel is the mainspring of the spread, whereas the living part of the fuel acts as a brake for the spread. So convection will be changed in this case. Actually, in order for the living part of the fuel to be dried out and pyrolyzed, a flame must exist in the base. So, this new following assumption is made with no convection in case of flame depth (e_c) equal to zero:

$$R_c = \begin{cases} 0 & if\ e < e_c \\ b\,U\,e^{-K\,R}\left(1-\frac{e_c}{e}\right) & if\ e \geq e_c \end{cases} \qquad (4)$$

where e is the fuel thickness and e_c is the depth of the flame into the flame base.

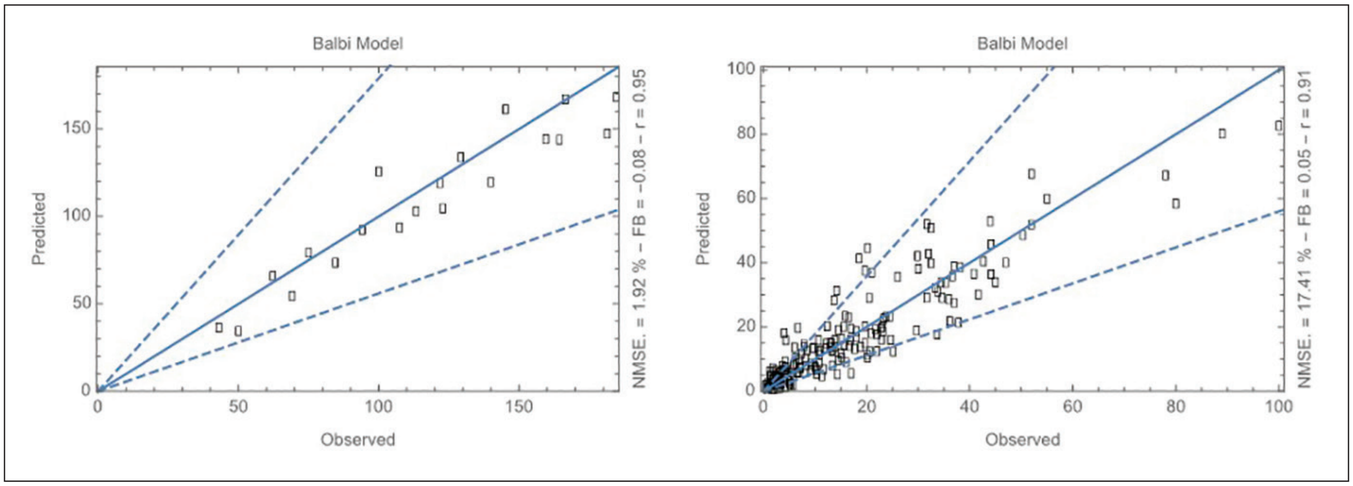

Figure 2—Predicted ROS given by the field scale model versus observed ROS for the fires performed by Gould 1991 (left) and sets of field scale experiments (193 fires), mainly shrublands and grasslands (right).

This field scale model was applied to almost 200 fires (mainly shrubland and grassland fires) and the results are encouraging (see fig. 2, right) with an error below the 20 percent level and a good correlation.

CONCLUSION

Ten years ago, we started with a simplified semi-physical surface fire propagation model with many weaknesses and we finished with a simplified physical model which takes into account radiation and convection and, above all, without any model parameters.

The radiant coefficient is an example of this work: from a fitted parameter, it gained a physical meaning. Obviously, taking convection into account and the removal of all the model parameters (thanks to physical modeling) are the two major improvements.

The radiative-convective model has been confronted to several fires with an average error of 8 percent at the laboratory scale and about 20 percent at the field scale.

REFERENCES

Balbi, J.H.; Rossi, J.L.; Marcelli, T.; Santoni, P.A. 2007. A 3D physical real-time model of surface fires across fuel beds. Combustion Science and Technology. 179(12): 2511–2537.

Balbi, J.H.; Morandini, F.; Silvani, X.; Filippi, J.B.; Rinieri, F. 2009. A physical model for wildland fires. Combustion and Flame. 156: 2217–2230.

Balbi, J.H.; Rossi, J.L.; Marcelli, T.; Chatelon, F.J. 2010. Physical modeling of surface fire under nonparallel wind and slope conditions. Combustion Science and Technology. 182: 922–939.

Balbi, J.H.; Viegas, D.X.; Rossi, J.L.; Rossa, C.; Chatelon, F.J.; Cancellieri, D.; Simeoni, A.; Marcelli, T. 2014a. Surface fires: no wind, no slope, marginal burning. Journal of Environmental Science and Engineering A. 3: 73–86.

Balbi, J.H.; Chatelon, F.J.; Rossi, J.L.; Simeoni, A.; Viegas, D.X.; Rossa, C. 2014b. Modelling of eruptive fire occurrence and behavior. Journal of Environmental Science and Engineering B. 3: 115–132.

Catchpole,W.R.; Catchpole, E.A.; Butler, B.W.; Rothermel, R.C.; Morris, G.A.; Latham, D.J. 1998. Rate of spread of free-burning fires in woody fuels in a wind tunnel. Combustion Science and Technology. 131: 1–37.

Chatelon, F.J.; Balbi, J.H.; Morvan, D.; Rossi, J.L.; Marcelli, T. 2017. A convective model for laboratory fires with well-ordered vertically-oriented fuel beds. Fire Safety Journal. 90: 54–61.

Finney, M.A.; Forthofer, J.; Grenfell, I.C.; Adam, B.A.; Akafuah, N.K., Saito, K. 2013. A study of flame spread in engineered cardboard fuelbeds. Part I: Correlations and observations. In Proceedings of Seventh International Symposium on Scale Modeling. Hirosaki, Japan, Aug 6-9. 11p.

Gould, J.S. 1991. Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. In: Cheney, N.P.; Gill, A.M., eds. Proceedings of a Conference on Bushfire Modelling and Fire Danger Rating Systems. 11-12 July 1988. Canberra, Australia:CSIRO: 51–64.

Koo, E.; Pagni, P.; Woycheese, J.; Stephens, S.; Weise, D.; Huff, J. 2005. A simple physical model for forest fire spread rate. Fire Safety Science-Proceedings of the Eighth International Symposium: 851–862.

Linn, R.; Winterkamp, J.; Edminster, C.; Colman, J.J.; Smith, W.S. 2007. Couples influences of topography and wind on wildland fire behaviour. International Journal of Wildland Fire. 16: 183–195.

Mell, W.; Charney, J.J.; Jenkins, M.A.; Cheney, P.; Gould, J. 2005. Numerical simulations of grassland fire behaviour from the LANL—FIRETEC and NIST—WFDS models. In: For EastFIRE Conference. Fairfax, VA: George Mason University.

Morvan, D.; Meradji, S.; Accary, G. 2009. Physical modelling of fire spread in grasslands. Fire Safety Journal. 44: 50–61.

Morvan, D. 2014. Wind effects, unsteady behaviors and regimes of propagation of surface fires in open field. Combustion Science and Technology. 186(7): 869–888.

Pagni, P.J.; Peterson, G. 1973. Flame spread through porous fuels. In: Proceedings of 14th Symposium (International) on Combustion. Pittsburgh, PA: The Combustion Institute: 1099–1107.

Rossi, J.L.; Chetehouna, K.; Collin, A.; Moretti, B.; Balbi, J.H. 2010. Simplified flame models and prediction of the thermal radiation emitted by a flame front in an outdoor fire. Combustion Science and Technology. 182: 1457–1477.

Rossi, J.L.; Simeoni, A.; Moretti, B.; Leroy-Cancellieri, V. 2011. An analytical model based on radiative heating for the determination of safety distances for wildland fires. Fire Safety Journal. 46: 520–527.

Rothermel, R.C.; Anderson, H.E. 1996. Fire spread characteristics determined in the laboratory. Res. Paper INT-30. Ogden, UT: USDA Forest Service, Intermountain Forest & Range Experiment Station. 34 p.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Paper INT-115. Ogden, UT: USDA Forest Service, Intermountain Forest & Range Experiment Station. 40 p.

Wolff, M.F.; Carrier, G.F.; Fendell, F.E. 1991. Wind-aided firespread across arrays of discrete fuel elements. II. Experiment. Combustion Science and Technology. 77: 261–289.

Evaluating and Optimizing the Use of Logistic Regression for Tree Mortality Models in the First Order Fire Effects Model (FOFEM)

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BACKGROUND

Wildland fires burn millions of forested hectares annually around the world, affecting biodiversity, carbon storage, hydrologic processes, and ecosystem services largely through fire-induced tree mortality (Bond-Lamberty et al. 2007; Dantas et al. 2016). In spite of this widespread importance, the underlying mechanisms of fire-caused tree mortality remain poorly understood, (Hood et al. 2018). Post-fire tree mortality has been traditionally modeled as an empirical function of tree defenses (bark thickness) and fire injury (crown scorch, stem char) (Ryan and Amman 1996; Woolley et al. 2012). Empirical models are commonly used in fire management to predict fire effects (Reinhardt et al. 1997), from the fine-scale software tools for fire management planning, to process-based succession models (Keane et al. 2011), and global models of the terrestrial carbon cycle (Hantson et al. 2016). Nevertheless, many fire-caused tree mortality models have undergone little evaluation.

We evaluated fire-caused tree mortality models used in the First Order Fire Effects Model (FOFEM) software package (Reinhardt et al. 1997). FOFEM predicts fire-induced tree mortality for 219 tree species in the United States. We evaluated 31 models for 17 tree species using a database we developed that combines fire-induced tree mortality observations from independently collected datasets across the United States. FOFEM uses logistic regression models, which predict the probability of mortality based on tree traits (e.g., bark thickness) and injury levels (e.g., percent of crown volume scorched). A second step, in which trees that have a probability of mortality above a user-defined threshold (e.g., "cutoff", "decision criteria") is used to code individual trees as live or dead and predict post-fire stand density and basal area. Land managers who use FOFEM may be interested in optimizing accuracy in predictions of either mortality or survival (Ganio and Progar 2017; Grayson et al. 2017). For example, for post-fire hazard tree removal around recreation sites, may require high accuracy in mortality predictions, so that trees likely to die and become hazards could be identified and removed. Conversely, managers planning a prescribed fire in a long-unburned, old growth stand, may want higher certainty that large legacy trees will survive fire. In a modeling context, we can help support these objectives by identifying the probability thresholds that provide high model accuracy for either sensitivity (correct prediction of dead trees) or specificity (correct prediction of live trees). Thus the objectives of this paper are two-fold. First we evaluate FOFEM performance for species with over 300 individual-

Keywords: : post-fire tree mortality; model evaluation; sensitivity, specificity; threshold; decision criteria; roc analysis; auc; proc package

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

tree observations with a portion of the dataset that we currently have cleaned and standardized. Second, we demonstrate how the choice of thresholds can be used to optimize the accuracy of predicting either tree survival or tree death.

METHODS

We created a tree mortality data set via published studies and outreach, with the goal of creating a database of fire-caused mortality observations at the tree-level to formally evaluate existing fire-caused tree mortality models. We posted inquiries on numerous mailing lists about unpublished monitoring data, and conducted a literature search of published data on fire injury and mortality and contacted all corresponding authors requesting collaboration and data sharing. This effort produced 40 contributed datasets from state, federal, and university researchers in the United States. Our database currently includes observations of fire injuries and survival or mortality of individual tree observations and site location data from 20 states collected in approximately 400 fires (prescribed and wild) from 1974 to 2016. We are currently standardizing data and documenting metadata for the creation of a publicly available, database of U.S. fire-induced tree mortality. The final database will include observations of approximately 150 tree species, and more than 170,000 trees.

We conducted initial model evaluation using a subset of the final data set that had been standardized, combined, and quality-checked (n = 125,980). Currently, there are 62 species with over 50 observations in our dataset (table 1). The most numerous species in our current database are: *Pinus ponderosa* (ponderosa pine; n = 40,851); *Pinus contorta* (lodgepole pine; n = 15,972); *Pseudotsuga menziesii* (Douglas-fir; n = 14,717); *Abies concolor* (white fir; n = 12,688); *Abies lasiocarpa* (subalpine fir; n = 4,399); and *Calocedrus decurrens* (California incense-cedar; n = 3,079). We limited our model evaluation to species with over 300 individual-tree observations that also included the measurements of fire injury—such as percent crown volume scorched, percent crown length scorched—used in FOFEM (table 2). We evaluated the basic FOFEM logistic regression model (hereafter the “fofem5” model) (Ryan and Amman 1994):

$$P_m = 1 \Big/ \left(1 + e^{\left(-1.941+6.316\left(1-e^{-0.3937BT}\right)-0.000535\left(CVS^2\right)\right)}\right) \qquad (1)$$

where P_m is the probability of mortality, BT is bark thickness, and CVS is the percent of crown volume scorched. We evaluated the above model separately for each individual species.

For some conifer species, there are additional logistic regression equations implemented in FOFEM that have additional or different predictor variables because they were specifically developed for predicting mortality either prior to prescribed fire (“pre-fire”) or after wildfire for salvage logging decisions (“post-fire”) (Hood and Lutes 2017). We also evaluated these pre-fire and post-fire models; equations for each model are in table 2. The pre-fire models often use projected percent crown scorch (either percent of crown length or percent of crown volume), which cannot be observed prior to the fire. Instead, users either enter anticipated flame length or scorch height, as well as tree height and crown ratio; percent crown scorch is then calculated from these inputs using additional empirical equations. We did not address uncertainty in these other empirical equations, as we used post-fire measurement of percent crown length scorched or percent crown volume scorched in this evaluation.

For each species-model combination we created receiver operating characteristic (ROC) curves, which evaluate sensitivity (i.e., correctly classified positive outcomes/actual positive outcomes; positive outcomes are dead trees) and specificity (i.e., correctly classified negative outcomes/actual negative outcomes; negative outcomes are live trees). We calculated the area under the ROC curve (AUC) for each species-model combination. AUC values ≤0.5 suggest that the model does not perform better than random chance, values between 0.5-0.6 are poor, values between 0.7-8.0 are acceptable, 0.8-0.9 are excellent, and >0.9 are outstanding (Hosmer and Lemeshow 2000). The ROC curve was calculated over a range of probability thresholds at which a tree is classified as dead or alive. We identified the threshold at which the model performed best, based on combined specificity and sensitivity, using the package pROC (Robin et al. 2011) in R (R Development Core Team 2017). For each of these three thresholds we calculated model performance statistics, including the specificity,

Table 1—Species with at least 50 observations in the current dataset.

Species	n	Species	n
Pinus ponderosa	40,851	*Pinus edulis*	337
Pinus contorta	15,972	*Nyssa sylvatica*	315
Pseudotsuga menziesii	14,717	*Pinus elliottii*	313
Abies concolor	12,688	*Quercus gambelii*	305
Abies lasiocarpa	4,399	*Pinus flexilis*	278
Calocedrus decurrens	3,079	*Pinus attenuata*	268
Picea engelmannii	2,830	*Quercus nigra*	266
Pinus lambertiana	2,558	*Prunus serotina*	258
Pinus taeda	2,066	*Juniperus osteosperma*	249
Pinus palustris	1,215	*Pinus resinosa*	240
Pinus albicaulis	1,194	*Quercus stellata*	220
Abies grandis	1,159	*Pinus monticola*	205
Pinus jeffreyi	1,071	*Quercus velutina*	205
Larix occidentalis	1,057	*Acer saccharum*	185
Acer rubrum	1,030	*Pinus coulteri*	182
Quercus garryana	824	*Cornus florida*	158
Tsuga heterophylla	814	*Sequoiadendron giganteum*	156
Juniperus scopulorum	811	*Liriodendron tulipifera*	151
Populus tremuloides	799	*Picea pungens*	142
Quercus prinus	731	*Cornus florida*	140
Quercus laurifolia	638	*Sassafras albidum*	136
Oxydendrum arboreum	628	*Cornus nuttallii*	119
Abies magnifica	577	*Abies amabilis*	111
Pinus echinata	559	*Quercus rubra*	100
Quercus alba	535	*Diospyros virginiana*	93
Quercus kelloggii	469	*Juniperus occidentalis*	74
Quercus falcata	442	*Chamaecyparis lawsoniana*	69
Liquidambar styraciflua	411	*Carya tomentosa*	61
Tsuga mertensiana	376	*Quercus laevis*	61
Quercus coccinea	371	*Alnus incana*	59
Pinus virginiana	370	*Juniperus virginiana*	50

sensitivity, the true positive rate (i.e., correctly classified positive outcomes/predicted positive outcomes), true negative rate (i.e., correctly classified negative outcomes/predicted negative outcomes), and overall accuracy (i.e., correctly classified positive and negative outcomes/total sample size). Using pROC, we also identified two other probability thresholds: the best threshold with ≥80% sensitivity and the best threshold with ≥80% specificity, and calculated model performance statistics for each.

Table 2—Model validation results for species with at least 300 observations in alphabetical order that included relevant predictor variables. Results in bold denote when the best threshold with ≥80 sensitivity or specificity are the same as the best overall threshold. Thres. =Threshold; Sens. = Sensitivity; Spec. = Specificity; TPR= true positive rate; TNR = true negative rate; Acc. = accuracy.

			Best threshold							Sensitivity of at least 0.8				Specificity of at least 0.8			
Species	**n**	**Model**	**AUC**	**Thres.**	**Sens.**	**Spec.**	**TPR**	**TNR**	**Acc.**	**Thres.**	**Sens.**	**Spec.**	**Acc.**	**Thres.**	**Sens.**	**Spec.**	**Acc.**
Abies concolor	10,294	Equation 1, see notes below	0.902	0.77	0.78	0.88	0.89	0.77	0.83	0.72	0.8	0.86	0.83	0.77	0.78	0.88	0.83
Abies grandis	1,071	Equation 1, see notes below	0.79	0.78	0.55	0.95	0.94	0.56	0.7	0.23	0.81	0.49	0.69	0.78	0.55	0.95	0.7
Abies lasiocarpa	338	Equation 1, see notes below	0.862	0.81	0.79	0.94	0.96	0.7	0.84	0.72	0.8	0.83	0.81	0.81	0.79	0.94	0.84
Abies magnifica	516	Equation 1, see notes below	0.813	0.96	0.55	0.91	0.78	0.78	0.78	0.7	0.86	0.55	0.66	0.96	0.55	0.91	0.78
Calocedrus decurrens	2,714	Equation 1, see notes below	0.968	0.95	0.88	0.96	0.96	0.88	0.92	0.95	0.88	0.96	0.92	0.95	0.88	0.96	0.92
Larix occidentalis	1,053	Equation 1, see notes below	0.794	0.31	0.75	0.72	0.31	0.94	0.72	0.2	0.81	0.58	0.61	0.63	0.6	0.87	0.83
	1,053	Equation 2, see notes below	0.793	0.26	0.58	0.91	0.52	0.93	0.86	0.05	0.81	0.62	0.65	0.26	0.58	0.91	0.86
	865	Equation 3, see notes below	0.849	0.15	0.7	0.89	0.51	0.95	0.87	0.07	0.8	0.78	0.78	0.15	0.7	0.89	0.87
Oxydendrum arboreum	321	Equation 1, see notes below	0.519	0.85	0.8	0.29	0.15	0.9	0.36	0.85	0.8	0.29	0.36	0.58	0.07	0.94	0.82
Pinus contorta	4,136	Equation 1, see notes below	0.818	0.78	0.6	0.92	0.94	0.53	0.71	0.7	0.8	0.63	0.74	0.78	0.6	0.92	0.71
	4,144	Equation 4, see notes below	0.828	0.35	0.73	0.76	0.86	0.59	0.74	0.33	0.8	0.66	0.76	0.57	0.6	0.89	0.7
	2,275	Equation 5, see notes below	0.922	0.89	0.84	0.92	0.9	0.87	0.88	0.89	0.84	0.92	0.88	0.89	0.84	0.92	0.88

(continued on next page)

Table 2 (continued)—Model validation results for species with at least 300 observations in alphabetical order that included relevant predictor variables. Results in bold denote when the best threshold with ≥80 sensitivity or specificity are the same as the best overall threshold. Thres. =Threshold; Sens. = Sensitivity; Spec. = Specificity; TPR= true positive rate; TNR = true negative rate; Acc. = accuracy.

			Best threshold							Sensitivity of at least 0.8				Specificity of at least 0.8			
Species	**n**	**Model**	**AUC**	**Thres.**	**Sens.**	**Spec.**	**TPR**	**TNR**	**Acc.**	**Thres.**	**Sens.**	**Spec.**	**Acc.**	**Thres.**	**Sens.**	**Spec.**	**Acc.**
Picea engelmannii	592	Equation 6, see notes below	0.649	0.74	0.4	0.94	0.94	0.42	0.57	0.26	0.8	0.27	0.64	0.74	0.4	0.94	0.57
	499	Equation 7, see notes below	0.774	0.65	0.65	0.8	0.87	0.51	0.7	…	…	…	…	0.7	0.61	0.82	0.68
	592	Equation 1 or Equation 8, see notes below	0.898	0.73	0.81	0.83	0.92	0.66	0.82	0.73	0.81	0.83	0.82	0.73	0.81	0.83	0.82
Pinus jeffreyi	671	Equation 1, see notes below	0.906	0.57	0.86	0.85	0.8	0.9	0.85	0.57	0.86	0.85	0.85	0.57	0.86	0.85	0.85
	671	Equation 1, see notes below	0.916	0.4	0.8	0.93	0.88	0.87	0.87	0.4	0.8	0.93	0.87	0.4	0.8	0.93	0.87
Pinus lambertiana	2,298	Equation 1, see notes below	0.892	0.52	0.7	0.92	0.92	0.69	0.8	0.25	0.82	0.8	0.81	0.52	0.7	0.92	0.8
	859	Equation 9, see notes below	0.938	0.83	0.84	0.98	0.99	0.81	0.9	0.83	0.84	0.98	0.9	0.83	0.84	0.98	0.9
Pinus ponderosa	29,552	Equation 1, see notes below	0.862	0.8	0.76	0.85	0.63	0.91	0.83	0.67	0.8	0.8	0.8	0.8	0.76	0.85	0.83
	18,659	Equation 10, see notes below	0.827	0.27	0.71	0.82	0.49	0.92	0.8	0.12	0.8	0.68	0.7	0.27	0.71	0.82	0.8
	1,914	Equation 11, see notes below	0.906	0.14	0.83	0.83	0.57	0.95	0.83	0.14	0.83	0.83	0.83	0.14	0.83	0.83	0.83
	31,190	Equation 12, see notes below	0.823	0.35	0.67	0.88	0.71	0.86	0.82	0.07	0.81	0.6	0.66	0.35	0.67	0.88	0.82
	1,914	Equation 13, see notes below	0.91	0.12	0.87	0.8	0.54	0.96	0.81	0.12	0.87	0.8	0.81	0.13	0.86	0.81	0.82

(continued on next page)

Table 2 (continued)—Model validation results for species with at least 300 observations in alphabetical order that included relevant predictor variables. Results in bold denote when the best threshold with ≥80 sensitivity or specificity are the same as the best overall threshold. Thres. =Threshold; Sens. = Sensitivity; Spec. = Specificity; TPR= true positive rate; TNR = true negative rate; Acc. = accuracy.

			Best threshold							Sensitivity of at least 0.8				Specificity of at least 0.8			
Species	**n**	**Model**	**AUC**	**Thres.**	**Sens.**	**Spec.**	**TPR**	**TNR**	**Acc.**	**Thres.**	**Sens.**	**Spec.**	**Acc.**	**Thres.**	**Sens.**	**Spec.**	**Acc.**
Pinus taeda	325	Equation 1, see notes below	0.667	0.57	0.41	0.9	0.64	0.77	0.74	0.35	0.81	0.31	0.46	0.57	0.41	0.9	0.74
Populus tremuloides	493	Equation 1, see notes below	0.705	0.53	0.5	0.81	0.54	0.79	0.72	0.39	0.82	0.39	0.52	0.53	0.5	0.81	0.72
Pseudotsuga menziesii	10,456	Equation 1, see notes below	0.913	0.77	0.78	0.94	0.91	0.85	0.87	0.65	0.81	0.9	0.86	0.77	0.78	0.94	0.87
	10,495	Equation 14, see notes below	0.923	0.69	0.78	0.96	0.94	0.85	0.88	0.48	0.82	0.92	0.87	0.69	0.78	0.96	0.88
	1,442	Equation 15, see notes below	0.902	0.38	0.78	0.87	0.78	0.87	0.84	0.3	0.82	0.82	0.82	0.38	0.78	0.87	0.84
Quercus kelloggii	343	Equation 1, see notes below	0.77	0.89	0.56	0.91	0.78	0.77	0.77	0.65	0.83	0.53	0.64	0.89	0.56	0.91	0.77
Tsuga heterophylla	813	Equation 1, see notes below	0.75	0.34	0.7	0.71	0.83	0.55	0.71	0.28	0.81	0.57	0.73	0.47	0.55	0.83	0.64

Notes:

Equation 1—$P_m = 1/(1 + e^{(-1.941+6.316(1-e^{-0.3937BT})-0.000535(CVS^2))})$

Equation 2—$P_{m(pre)} = 1/(1 + e^{(-(-1.6594+0.0327CVS-0.0489DBH))})$

Equation 3—$P_{m(post)} = 1/(1 + e^{(-(-3.8458+0.1387CVS-0.0004CVS^2+0.6266CKR))})$

Equation 4—$P_{m(pre)} = 1/(1 + e^{(-(-0.3268+0.1387CVS-0.0033CVS^2+0.000025CVS^3-0.0266DBH))})$

Equation 5—$P_{m(post)} = 1/(1 + e^{(-(-1.4059+4.459e^{-6}CVS^3+0.2843CKR^2-0.0485DBH))})$

Equation 6—$P_{m(pre)} = 1/(1 + e^{(-(-0.0845+0.0445CVS))})$

Equation 7—$P_{m(post)} = 1/(1 + e^{(-(-2.9791+0.0405CVS+1.1596CKR))})$

Equation 8—$P_m \geq 0.80$

Equation 9—$P_{m\ (pre)} = 1/(1 + e^{(-(-2.0588+0.000814PCLS^2))})$

Equation 10—$P_{m(pre\ blackhills)} = 1/(1 + e^{(-(1.104-0.156DBH+0.013+PCLS+0.001(DBH)(PCLS)))})$

Equation 11—$P_{m(post\ kill)} = 1/(1 + e^{(-(-3.5729+0.000567(CVK^2)+0.4573CKR+1.6075BTL))})$

Equation 12—$P_{m(pre)} = 1/(1 + e^{(-(-2.7103+0.000004093(CVK^3)))})$

Equation 13—$P_{m(post\ scorch)} = 1/(1 + e^{(-(-4.1914+0.000376(CVS^2)+0.5130CKR+1.5873BTL))})$

Equation 14—$P_{m(pre)} = 1/(1 + e^{(-(-2.0346+0.0906CVS-0.0022(CVS^2)+0.000019(CVS^3)))})$

Equation 15—$P_{m(post)} = 1/(1 + e^{(-(-1.8912+0.07CVS-0.0019(CVS^2)+0.000018(CVS^3)+0.5840CKR-0.031DBH-0.7959BTL+0.0492(DBH)(BTL)))})$

RESULTS AND DISCUSSION

For the 31 models we evaluated, AUC values for most models were ≥0.7, defined as "acceptable" or better, with 20 of the 31 models with AUC values in the good to excellent range (ACU≥0.08) (table 2). Exceptions were an AUC of 0.519 for *Oxydendrum arboreum* (sourwood) using the fofem5 model. This model had notably low specificity and a low true positive rate, meaning that live trees were often classified as dead. *Pinus taeda* (loblolly pine) also had a low AUC of 0.667, and low model sensitivity, meaning that dead trees were often classified as alive. Finally the basic FOFEM model for spruces, which sets mortality to be at least 80%, performed poorly for *Picea engelmannii* (Engelmann spruce) with and AUC of 0.660. Overall model performance was poorer for the deciduous species we assessed (*Oxydendrum arboretum* AUC=0.519; *Populus tremuloides* AUC = 0.705; *Quercus kelloggii* AUC = 0.77).

The pre-fire and post-fire *P. engelmannii* models in FOFEM had higher AUCs of 0.774 and 0.898, respectively. For some species, such as *Larix occidentalis* (western larch), *P. contorta*, *Pinus jeffreyi* (Jeffrey pine), and *P. engelmannii*, *Pinus lambertiana* (sugar pine), the species-specific pre-fire and post-fire models had greater overall accuracy than the fofem5 model (table 2). Species-specific models including those for *P. ponderosa*, and *P. menziesii* did not show distinct improvement over the fofem5 model (table 2). Finally, by adjusting the thresholds, it was possible to get sensitivities above 80% and specificities above 80% for all models except the *P. engelmanni* post-fire model (table 2).

NEXT STEPS

We plan to validate the FOFEM post-fire mortality models for all species with ≥50 observations, once the dataset is fully clean and standardized. Thus we expect to be able to conduct model validation for approximately 70 species. Additional data standardization and data checking will be completed, including for the species-model combinations we presented here, and we will explore whether models perform well or poorly for clades of species or within differing geographic regions. Thus our results should highlight species and regions where new data collect or new model development is needed. Furthermore, we will test whether additional climatic predictors—specifically pre- and post-fire climatic water deficit, precipitation, and vapor pressure deficit—can improve mortality predictions (van Mantgem et al. 2013). For common species for which we have a large number of observations, such as *P. ponderosa* and *P. menziesii*, we will also investigate whether model performance varies regionally or among subspecies, potentially suggesting a need for regionally specific models. Our approach to identifying thresholds and model evaluation results will be incorporated into FOFEM, providing managers with guidance on how to set threshold values to optimize prediction accuracies in a way that mirrors their objectives, and quantifying uncertainty of this widely used decision support tool.

ACKNOWLEDGMENTS

We thank the following people for contributing data to this project: M.C. Agne, R.A. Andrus, M.P. Ayres, J. Bakker, M. Battaglia, C. Breece, B. Bentz, J.K. Brown, D.R. Cluck, T.W. Coleman, R.G. Corace, D. Cram, R. Davis, D. Dickinson, E.A. Engber, M. Finney, A. Graves, J. Hanula, B. Harvey, T. Keyser, L. Kobziar, K. Kopper, J.P. Lerch, V. McDaniel, J.D. McIver, M. North, J. O'Brien, D. Perrakis, S. Prichard, R. Progar, J.P. Roccaforte, B.M. Rogers, H. Safford, C. Sieg, B. Smith, J. Stevens, M.C. Stuever, A. Das, N. Vaillant, D. Westlind. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. government.

REFERENCES

Bond-Lamberty, B.; Peckham, S.D.; Ahl, D.E.; Gower, S.T. 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature. 450: 89–92. doi: 10.1038/nature06272.

Dantas, V.L.; Hirota, M.; Oliveira, R.S.; Pausas, J.G. 2016. Disturbance maintains alternative biome states. Ecology Letters. 19: 12–19.

Ganio, L.M.; Progar, R.A. 2017. Mortality predictions of fire-injured large Douglas-fir and ponderosa pine in Oregon and Washington, USA. Forest Ecology and Management. 390: 47–67. doi: 10.1016/j.foreco.2017.01.008.

Grayson, L.M.; Progar, R.A.; Hood, S.M. 2017. Predicting post-fire tree mortality for 14 conifers in the Pacific Northwest, USA: Model evaluation, development, and thresholds. Forest Ecology and Management. 399: 213–226. doi: 10.1016/j.foreco.2017.05.038.

Hantson, S.; Arneth, A.; Harrison, S.P.; [et al.]. 2016. The status and challenge of global fire modelling. 3359–3375. Biogeosciences. 13 11: 3359–3375. doi: 10.5194/bg-13-3359-2016.

Hood, S.; Lutes, D. 2017 Predicting post-fire tree mortality for 12 western U.S. conifers using the first order fire effects model FOFEM. Fire Ecology. 13: 66–84. doi: 10.4996/fireecology.130290243.

Hood, S.M.; Varner, J.M.; van Mantgem, P.; Cansler, C.A. 2018. Fire and tree death: understanding and improving modeling of fire-induced tree mortality. Environmental Research Letters. 13: 113004. doi: doi.org/10.1088/1748-9326/aae934

Hosmer, D.W.; Lemeshow, S. 2000. Applied logistic regression. New York: John Wiley and Sons.

Keane, R.; Loehman, R.; Holsinger, L. 2011. The FireBGCv2 landscape fire succession model: A research simulation platform for exploring fire and vegetation dynamics. Gen. Tech. Rep. RMRS-GTR-255. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 65 p.

R Development Core Team. 2017. R: A language and environment for statistical computing. Version 3.4.3.

Reinhardt, E.; Keane, R.E.; Brown, J.K. 1997. First Order Fire Effects Model: FOFEM 4.0 User's Guide. Gen. Tech. Rep. INT-GTR-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 65 p.

Robin, X.; Turck, N.; Hainard, A.; [et al]. 2011. pROC: An open-source package for R and S+ to analyze and compare ROC curves. BMC Bioinformatics. 12: doi: 10.1186/1471-2105-12-77

Ryan, K.; Amman, G. 1994. Interactions between fire-injured trees and insects in the Greater Yellowstone Area. In: Despain, D.G., ed. Plants and their environments : Proceedings of the First Biennial Scientific Conference on the Greater Yellowstone Ecosystem. USDI National Park Service Technical Report NPS/NRYELL/NRTR-93/xx: 259-271.

Ryan, K.C.; Amman, G.D. 1996. Bark beetle activity and delayed tree mortality in the greater yellowstone area following the 1988 fires. In: Keane, R.E.; Ryan, K.C.; Running, S.W., eds. Ecological implications of fire in Greater Yellowstone Proceedings. International Association Wildland Fire, Fairland, WA: 151–158.

van Mantgem, P.J.; Nesmith, J.C.B.; Keifer, M. [et al]. 2013. Climatic stress increases forest fire severity across the western United States. Ecological Letters. 16: 1151–1156. doi: 10.1111/ele.12151

Woolley, T.; Shaw, D.C.; Ganio, L.M.; Fitzgerald, S. 2012. A review of logistic regression models used to predict post-fire tree mortality of western North American conifers. International Journal of Wildland Fire. 21: 1. doi: 10.1071/WF09039.

Faster Rate of Fire Spread Algorithm Does Not Fundamentally Change the Relative Unimportance of Fuel Treatment for Limiting Simulated Wildfire Area in South-Eastern Australia

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Understanding effectiveness of prescribed burning for limiting unplanned fire is central to wildland fire management worldwide. Insights have been derived from simulation experiments exploring the relative importance of fuel treatment, ignition management and weather for total wildfire area. These findings could be highly sensitive to assumptions about key model mechanisms such as rate of fire spread. For example, earlier simulation investigations of fuel treatment effectiveness in FIRESCAPE implemented in southeastern Australia invoked McArthur's Mark 5 Forest Fire Danger Meter rate of fire spread. However, it has been shown that this model underpredicts rate of spread of experimental summer fires by a factor of two-to-three; the Dry Eucalypt Forest Fire Model (DEFFM) rate of spread model of Cheney and others is recommended. We explored the effect of these differences in rates of fire spread on wildfire area in a computer simulation design incorporating fuel treatment rate (varying from 0 to 30% of landscape treated), ignition management effort (varying from 0 to 75% of ignitions prevented or extinguished) and inter-annual weather variation (included by 10 distinct years of daily weather representative of observed inter-annual variation).

Overall, our objective was to determine whether earlier simulation experiments based on McArthur's rate of spread, and the resultant conclusion that fuel treatment is relatively unimportant in determining wildfire area, remain valid or should be revised in light of the newer, faster rate of spread model. On average, around 18 times more area was burned by the FIRESCAPE model incorporating an approximation of the faster DEFFM rate of fire spread compared to the otherwise identical model incorporating McArthur's rate of fire spread. Given that this equated to more than three-quarters of the simulation landscape, we cut ignition rate to one-eighth and determined relative importance of management and weather factors on area burned when it was much less constrained by simulation landscape size. Weather and ignition management effort was much more important than fuel treatment rate in determining total simulated wildfire area for this case of the FIRESCAPE model incorporating an approximation of the DEFFM rate of fire spread. High levels of ignition management effort reduced the area burned by 60 percent on average, whereas high levels of fuel treatment effort reduced that response metric by 35 percent.

The results show that our understanding of the relative importance of factors determining wildfire area in landscapes does not fundamentally change as a function of modelling with very different rate of spread algorithms.

Keywords: prescribed burning, rate of fire spread, simulation, weather, wildfire

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Upslope Fire and Eruptive Fires

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Abstract—This work deals with a fire spreading upslope under either no-wind conditions or weak wind velocities. The surface fire propagation model developed at the University of Corsica is used; this model takes into account convective and radiative effects. The model is based on the coupling of the properties of the spreading fire with other conditions (wind, topography) and consists of a feedback effect caused by the flow induced by the fire in the presence of a positive slope. The expression of this induced wind, coupled to the propagation model gives an algebraic relationship for the rate of spread (ROS) which depends on the terrain slope angle. For operational matters, the main goal consists in obtaining very simple conditions necessary to eruption triggering. A simplification of the ROS relationship leads to a triggering condition which only depends on fuel characteristics and the threshold slope angle.

Keywords: steady-state model, rate of spread, fire eruption, convective flow, induced wind.

INTRODUCTION

Eruptive fires are characterized by a sudden and unpredictable acceleration of the ROS, even under low wind speeds or small slope angle conditions. So eruptive fires are extremely dangerous for firefighters and they are the cause of several human losses.

In the literature, there are some empirical models that describe fire behavior during such eruptions (Dold et al. 2011; Viegas 2006), but to our knowledge, none of them are able to predict the eruption's onset.

The main question regards the explanation of the phenomenon. Among several explanations found in the literature, we considered the pioneering interpretation proposed by Viegas (2004a), because it has never been refuted by an example of eruptive fire accident. It consists of a feedback effect caused by the convective flow induced by the fire to compensate for the draft caused by the hot gases moving upwards. This induced wind was proved with laboratory experiments (Viegas and Pita 2004) and was observed at the field scale in the Gestosa fire experiments (Viegas and Pita 2004), and also measured in the Freixo accident (Viegas 2004b).

Thanks to a simplified mass balance, a physical modeling of the convective induced wind is coupled to the radiative physical propagation model developed at the University of Corsica. The coupling of the induced wind modeling and the surface fire propagation model gives an analytical condition of danger (Balbi et al., 2014). As long as this relationship is satisfied, a fire cannot erupt. But when the relationship is no longer satisfied, eruption is possible, but it is not assured. Then it depends on the value of the terrain slope angle. Unfortunately, it is not possible to find an analytical condition which gives the threshold value from which eruption is sure. We have to solve the model numerically.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Extended abstracts published in these proceedings were submitted by authors in electronic media. Editing was done for readability and to ensure consistent format and style. Authors are responsible for content and accuracy of their individual papers and the quality of illustrative materials. Opinions expressed may not necessarily reflect the position of the U.S. Department of Agriculture.

THE RADIATIVE-CONVECTIVE SIMPLIFIED PHYSICAL MODEL

The previous condition of danger (Balbi et al. 2014) has been established thanks to the radiative-only simplified physical model developed at the University of Corsica.

ROS With External Wind

This year, the fire modeling team of the University of Corsica elaborated a radiative-convective simplified physical model without any model parameters. The ROS is defined as the sum of three contributions: radiation from the flame base R_b (fuel burning particles area), flame radiation R_f and convection R_c (Balbi et al., 2018).

$$R = R_b + R_f + R_c \tag{1}$$

The ROS is an increasing function of the wind speed (see fig. 1). After a fast increase, the ROS reaches a plateau which is obtained for a threshold value of the wind speed. The ROS curve could be approximated by three segments (see fig. 1). As the analytical expressions of these three segments are known, it is easy to find the values of $R_{c\infty}$, U_c, and p_∞. Note that (fig. 1) pc is the slope of the straight line which pass through the two points (0,0) and (U_c, $R_{c\infty}$).

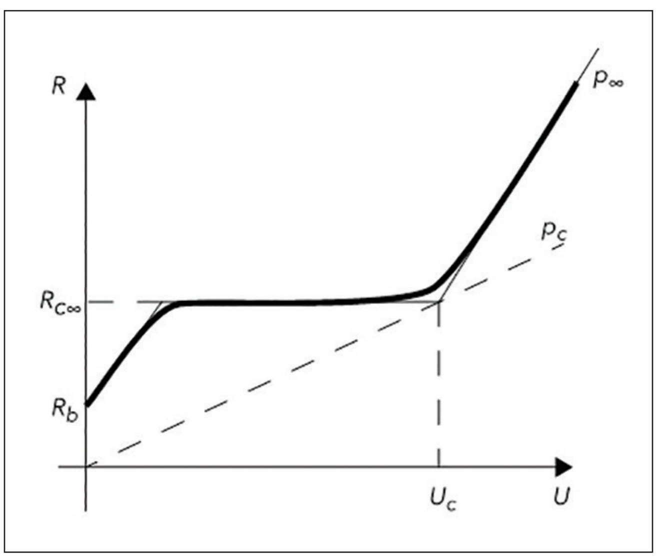

Figure 1—A qualitative illustration of the rate of spread given by equation 1 of the Balbi model.

Convective Flow Induced by the Fire, i.e. 'Induced Wind'

A fire eruption may occur when the external wind is weak or under no wind conditions with a slope. In this case, the fire creates an induced airflow in order to compensate for the draft caused by the hot gases moving upwards. A physical modeling of this "induced wind" is obtained by setting a stoichiometric coefficient st (air/pyrolysis gases):

$$\rho_a \, h \, U = s_t \, L \, \dot{\sigma} \tag{2}$$

where ρ_a is the air density, h is the fuel thickness, U is the normal component of the wind speed, L is the flame depth and $\dot{\sigma}$ is the mass loss rate.

After some calculations, we obtain the following expression of the rate of spread:

$$R = p\,U \tag{3}$$

Equation (3) is a linear function of the wind speed and p is its slope.

Fire Behavior

The solution of the two coupled equations (1) and (3) is the intersection of the straight line given by (3) and the increasing function given by (1). Two different cases may occur:

First case: $p > p_c$

We begin with no wind ($U = 0$) and rate of spread equal to R_b. We can see in figure 2 (left) that induced wind involves the next value U_1 of the wind speed which then gives the new rate of spread R_1. By following, the coupled system (1, 3) leads to a stable solution (U_∞, $R_{c\infty}$) which is a steady state solution and the fire cannot erupt.

Second case: $p < p_c$

With the same process, we can observe on figure 2 (right) that the fixed-point method diverges. So, the regime is an unsteady one and eruption is sure.

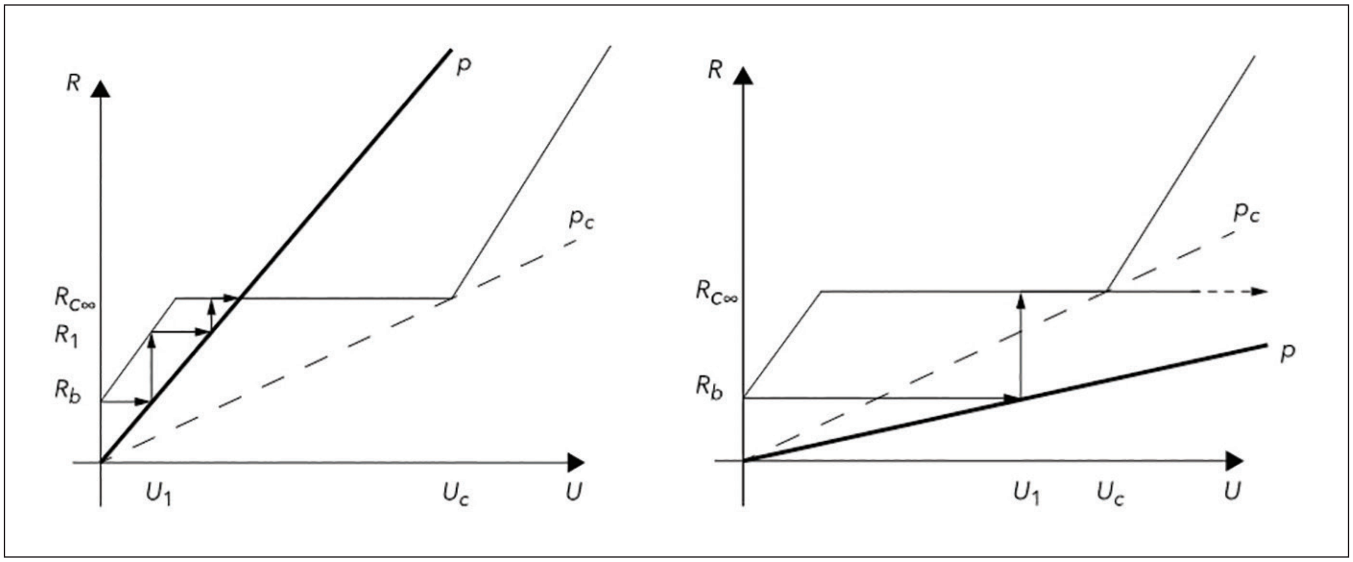

Figure 2—A qualitative illustration of the rate of spread given by equation 1 of the Balbi model and equation 3 obtained with a physical modeling of induced wind (with $p > p_c$ on the left and $p < p_c$ on the right).

Eruptive Conditions

The threshold value is obtained when $p = p_c$. This condition leads to an analytical value of the threshold terrain slope angle denoted by α_{th} which depends on fuel characteristics and fire front width in the following manner:

$$\tan \alpha_{th} = \frac{A}{2A-1} + 10^4 \left(\frac{\Delta H}{\rho \tau_0 K u_{00}}\right)^{\frac{1}{2}} \frac{1}{s\beta} \left(\frac{4}{2A-1} - \frac{s\beta}{\upsilon}\right) \quad (4)$$

where A is a radiant coefficient which depends on fuel characteristics and on fire dynamics properties (fire front width and flame length), ΔH is the heat of combustion of the pyrolysis gases, ρ is the fuel density, K is a drag forces coefficient, s is the surface area to volume ratio, β is the packing ratio, ν is the fuel absorption coefficient, τ_0 is the Anderson's model residence time coefficient and u_{00} is a coefficient of the upward gas velocity.

CONCLUSION

In conclusion, we can say that according to our model, all the situations favorable to a fire eruption are those in which the fire front width remains important. Obviously canyons have very dangerous geometries; the famaliçao accident or the laboratory experiments conducted by Viegas and Pita (2004) are other examples. Finally, as it was proved by Sharples et al. 2010 and Dold and Zinoviev 2009, trenches or corridors are very dangerous situations.

In this work, we presented a steady state propagation model only designed to predict the eruption's onset. If we want to know the behavior of the ROS during the eruption, we have to use the unsteady version of the propagation model because a fire eruption is obviously an unsteady phenomenon. We can find the threshold slope angle from which eruption will occur but in fact, thanks to a very fast code, we are able to find the value of any of the parameters involved in the model which can cause an eruption.

We are not able to take into account a heterogeneous vegetation (but this limitation can be solved using an equivalent fuel model) or eruptive crown fires because the propagation model is only designed for surface fires.

REFERENCES

Balbi, J.H.; Chatelon, F.J.; Rossi, J.L.; Simeoni, A.; Viegas, D.X.; Rossa, C. 2014. Modelling of eruptive fire occurrence and behavior. Journal of Environmental Science and Engineering B. 3: 115–132.

Balbi, J.H.; Chatelon, F.J.; Rossi; J.L.; Marcelli, T. 2018. How ten years of physical assumptions led to the development of the Balbi model, from laboratory scale to the field scale. 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.

Dold, J.W.; Zinoviev, A. 2009. Fire eruption through intensity and spread rate interaction mediated by flow attachment. Combustion Theory and Modelling. 13: 763–793.

Dold, J.W.; Zinoviev, A.; Leslie, E. 2011. Intensity accumulation in unsteady firelines: A simple model for vegetation engagement. Fire Safety Journal. 46: 63–69.

Sharples, J.J.; Gill, A.M.; Dold, J.W. 2010. The trench effect and eruptive wildfires: Lessons from the King's Cross underground disaster, Proceedings AFAC 2010.

Viegas, D.X. 2004a. On the existence of a steady state regime for slope and wind driven fires. International Journal of Wildland Fire. 13: 101–117.

Viegas, D.X. 2004b. A mathematical model for forest fire blowup. Combustion Science and Technology. 177(1): 27–51.

Viegas, D.X.; Pita, L.P. 2004. Fire spread in canyons. International Journal of Wildland Fire. 13: 253–274.

Viegas, D.X. 2006. Parametric study of an eruptive fire behaviour model. International Journal of Wildland Fire. 15: 169–177.

Results and Application of the National Wildfire Risk Assessment

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INTRODUCTION

Spatial wildfire risk assessments that account for both the probability and consequences of wildfire events are becoming an important element of strategic wildland fire and fuels planning (Calkin et al. 2011; Finney 2005; Gilbertson-Day et al. 2017, 2018; Thompson et al. 2013, 2016a). Using a standardized framework (Scott et al. 2013), these assessments can be scaled from local communities up to the continental scale. Inputs, spatial resolution, and methodology considerations change with different assessment scales, as do the types of questions that can be addressed with the results. The Fire Modeling Institute (FMI), a unit of the Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture, recently completed analysis for a national-scale risk assessment for all National Forest System (NFS) lands in the conterminous U.S. (CONUS). This assessment is known as the National Wildfire Risk Assessment for Forest Service Lands (or NaWRA-FS, for short). We present here some brief results from that analysis as well as intended applications, including a Wildfire Risk Index that the Forest Service plans to use to monitor performance toward the agency's broad objective of mitigating wildfire risk.

What Is A Wildfire Risk Assessment?

The term "risk" is used in many contexts in relation to wildland fire. It is important to clarify that we are dealing here with risk in a strategic context that considers the potential effects of fire on things of value on the landscape, not with operational risks to firefighters. We use the following definition of wildfire risk: a measure of the probability and consequences of uncertain future wildfire events (Thompson et al. 2016b). There are three fundamental components involved in a quantitative assessment of risk: (1) the likelihood of fire occurrence, (2) the potential intensity of wildfire if it occurs, and (3) the susceptibility of highly-valued resources and assets (HVRAs) to fire of different intensities.

Why A National Risk Assessment?

The reasons for doing a national-scale assessment are inherently different than reasons for doing more local assessments. From a national perspective, having risk metrics calculated consistently across all units of the Forest Service is very valuable for national-level decisions about wildfire policy and resource allocation. Funding for hazardous fuels reduction work, for example, is allocated from the national budget to each of eight Forest Service regions in CONUS. Nationally-consistent risk metrics can help to inform allocation of this funding. The level of detail in a national assessment, however, is necessarily coarse and is not intended to inform placement or design of specific project areas; those decisions need to be informed by more detailed assessments at finer scales.

From a policy perspective, a national risk assessment can help to broadly articulate agency-wide perspectives on wildfire management. National risk assessment results can highlight, in a scientifically-based and spatially-specific way, the potential risks and benefits from wildfire across NFS lands. They can also help to tie national wildfire policy to overarching guidance such as the Forest Service Strategic Plan

Keywords: : wildfire risk, National Forest System, United States

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Extended abstracts published in these proceedings were submitted by authors in electronic media. Editing was done for readability and to ensure consistent format and style. Authors are responsible for content and accuracy of their individual papers and the quality of illustrative materials. Opinions expressed may not necessarily reflect the position of the U.S. Department of Agriculture.

(USFS 2015) and the national cohesive strategy (WFLC 2014). In fact, in 2016 the USDA Office of the Inspector General completed an audit of the hazardous fuels program in the Forest Service and recommended the agency "fully develop and implement a national risk assessment model," (OIG 2016). Notably, the first iteration of a national risk assessment was completed several years earlier. Known as the "first approximation", that assessment established a proof-of-concept that risk assessment methodologies could be applied nationally (Calkin et al. 2010). The assessment presented here represents a revision that capitalizes on significant advances in recent years.

NATIONAL-SCALE METHODS

The discussion of assessment methods is intentionally brief here, and more detailed information about our methods are available online at: https://www.firelab.org/project/national-wildfire-risk-assessment. The main elements of the risk assessment methodology (Scott et al. 2013) include wildfire simulation, HVRA characterization, and effects analysis. In the sections below, we briefly address how we dealt with each.

The spatial scope of this assessment was all NFS lands in the conterminous U.S. This includes a total of approximately 170 million acres of land in Forest Service ownership. However, to include the potential effects of wildfire on developed adjacent lands, we included all area within 5 km of NFS lands. This totaled just over 330 million acres.

Wildfire Simulation

For wildfire simulation inputs, we used the national mosaics of burn probability and flame-length probabilities produced by the Forest Service, Rocky Mountain Research Station (Short et al. 2016). These data include CONUS 270-m raster mosaics of burn probability (annual likelihood of fire occurrence) and conditional probability of six fire intensity levels (0 to 1 for each of six flame length classes; all six sum to one for any pixel).

HVRA Characterization

To characterize HVRAs at the national level, we selected five primary HVRAs: (1) Communities, (2) Infrastructure, (3) Surface Drinking Water, (4) Ecosystem Function, and (5) Air Quality. In the risk assessment framework, these represent things on the ground that are of value, could be potentially affected by wildfire (negatively or positively), and are important enough that they could influence fire management decisions. Another critically important criterion is that quality, nationally comprehensive and consistent GIS data must exist for each HVRA. Some HVRAs that are common in assessments at finer scales were considered, but excluded from this assessment because they did not meet one or more selection criteria. Habitat for specific plant and animal species and commercial timber resources are examples.

Most of the five primary HVRAs were sub-divided into finer categories for the purposes of estimating fire effects and relative importance. In consultation with Forest Service personnel at the national and regional levels, we assigned response functions for each sub-HVRA and calculated weighting factors based on relative importance and relative extent of each, following methods outlined in Scott et al. (2013).

Effects Analysis

The primary focus of this risk assessment has been on producing effects analysis outputs. These outputs include metrics of wildfire risk such as conditional Net Value Change (cNVC) and expected Net Value Change (eNVC). We can also break these metrics into their component parts of conditional or expected benefits and losses. We followed methods for these calculations outlined in other publications (Scott and Thompson 2015; Scott et al. 2013; Thompson et al. 2016a)

Given the objectives of this assessment, we also summarized all calculated metrics by each of the eight Forest Service regions. For each region, we calculated both the mean and sum of cNVC, eNVC, and conditional and expected benefits and losses. We evaluated each of these for use as a Wildfire Risk Index that could track changes over time.

Lastly, we summarized the calculated risk metrics by each of 109 separate National Forest units. While these forest-level summaries are not intended as the primary use of this assessment, they can help to provide nationally-consistent information for national-level decision making.

RESULTS AND APPLICATION

We present the results of our effects analysis in two categories: conditional versus expected. Conditional measures are exactly that – they reflect likely changes at any location *if a fire occurs there*. Returning to the three primary components of risk (likelihood, intensity, and susceptibility), conditional measures account for only two of them—the intensity of fire and the susceptibility of (or effects on) HVRAs. Conditional risk metrics are very useful for response planning, where you need to prepare for what to do once you have a fire.

Expected measures of risk account for all three components of risk, integrating the conditional metrics with the overall likelihood of fire occurrence, or burn probability. Expected risk metrics are useful for most other purposes besides response planning, particularly resource allocation. Expected risk measures most closely meet our objective of creating a relative measure of overall wildfire risk among Forest Service regions, specifically to help guide resource allocation and policy questions.

We present a sample of maps (fig. 1) and charts (fig. 2) depicting some of our results. More results are available online at: https://www.firelab.org/project/national-wildfire-risk-assessment. The maps reflect the spatial sum, by National Forest, for both the cNVC and eNVC metrics, with regional boundaries overlaid as bold lines. The difference between cNVC (which does not include burn probability) and eNVC (which does include burn probability) is evident in these maps. Several forests in the southeastern U.S., for example, have strongly negative cNVC values but once burn probability is factored in they have relatively mild to moderate eNVC values. This is because burn probability values are much lower in the southeastern U.S. compared to most western regions. However, many factors are combined into the summaries depicted in these maps. It is important to consider these contributing factors to fully understand and give context to the NVC results.

The charts in figure 2 help us to pull apart the NVC numbers into their component parts of benefits versus losses, and also help with further understanding of conditional versus expected metrics. In the bar charts (fig. 2a, 2b), we present the sum of cNVC and eNVC across each Forest Service region (gray bars). As wildfire can have a mix of positive and negative outcomes, depending on the HVRA and fire intensity, these measures truly represent the "net" outcome. The red and green bars show the negative outcomes (potential losses) and positive outcomes (potential benefits), respectively. We strongly encourage managers interpreting results such as this to consider these potential losses and benefits, and not just the NVC values.

The pie charts (fig. 2c, d), also should give managers and policy-makers an understanding of why there are uses for both conditional and expected risk metrics. The conditional losses for each region (red bars in fig. 2, wedges in fig. 2c) show that each region has the potential for a fair amount of loss from wildfire when fires occur there. Each region has roughly 10 percent to 20 percent of the total potential losses across all NFS lands. The expected losses, on the other hand, show that when burn probability is factored in, some regions have a much greater proportion of the total expected losses than others.

A National Risk Index

We evaluated several possible metrics, including all those shown in figure 2, as candidates for a Wildfire Risk Index and ultimately chose expected losses. While eNVC would seem like the best option, we found it problematic as an index because it can get almost zeroed out in regions that have more potential benefits. Given the objective in the Forest Service Strategic Plan (USFS 2015) to "mitigate wildfire risk," we felt that using potential losses focuses on what the agency can possibly mitigate. Potential wildfire benefits, as accounted for in this assessment, are an inherent property of ecosystems and can't be changed by management actions.

To use expected losses as an index, we will use the analysis presented here, based on 2012 landscape conditions, as a baseline. The index value for any area (e.g., region, all NFS) at any point in time will always be the sum of expected losses for the area divided by the baseline sum of expected losses for the area. The initial index value for any area, therefore, is 100. That will become the reference, making it straightforward to assess changes to index values in the future.

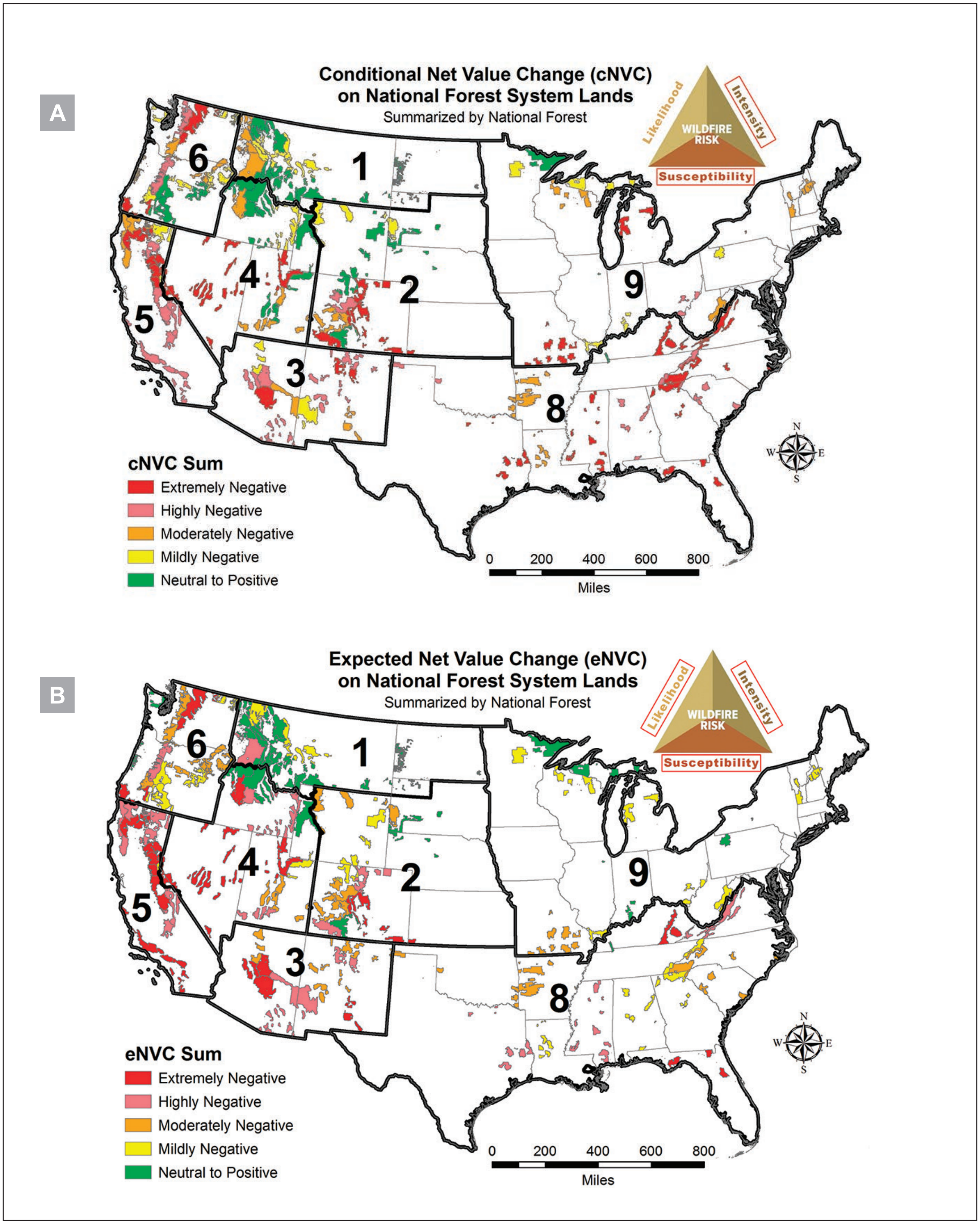

Figure 1—Maps showing cNVC (A) and eNVC (B) results summarized by National Forest. Forest Service regions are shown in bold outlines, with region numbers labeled. Classes shown reflect even quintiles of the data. Inset risk triangle shows which components of risk are included.

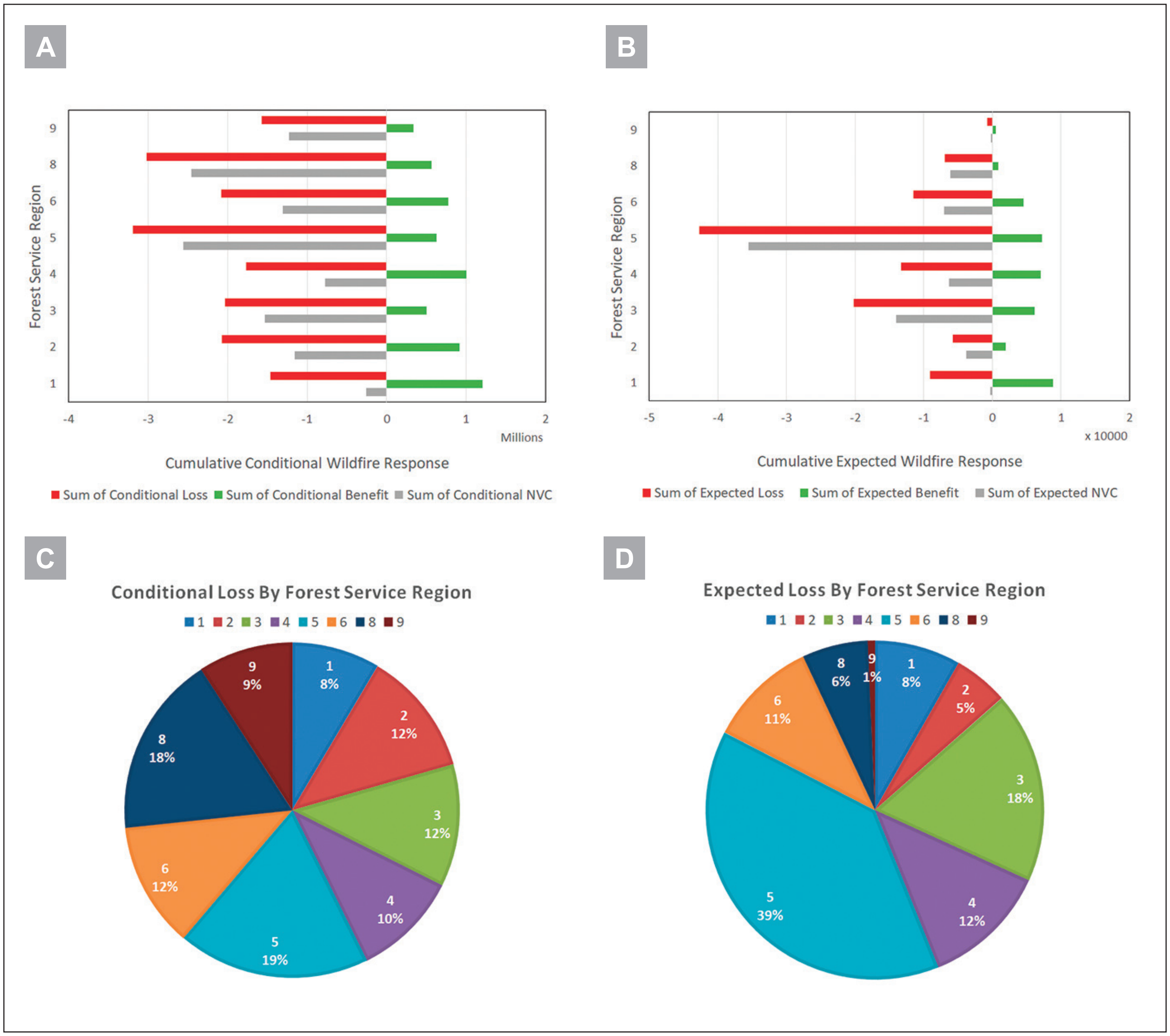

Figure 2—Regional summaries of conditional (A, C) and expected (B, D) risk metrics (regional sums; means not shown). We chose the sum of expected losses (red bars in B) as the basis for a risk index.

REMAINING WORK

Much work remains to fully understand the results and potential applications of this national risk assessment. Upcoming work includes further testing and analysis to better understand the sensitivity of each metric, and particularly the risk index, to landscape changes caused by both management actions and natural disturbances. We also must develop protocols for regular updates on an annual or bi-annual basis. Lastly, we plan to expand the analysis to all lands, to the extent possible, to further guide decision making consistent with principles of the cohesive strategy (WFLC 2014).

REFERENCES

Calkin, D.E.; Ager, A.A.; Gilbertson-Day, J.W., eds. 2010. Wildfire risk and hazard: procedures for the first approximation. Gen. Tech. Rep. RMRS-GTR-235. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 62 p.

Calkin, D.E.; Ager, A.A.; Thompson, M.P., eds. 2011. A comparative risk assessment framework for wildland fire management: the 2010 cohesive strategy science report. Gen. Tech. Rep. RMRS-GTR-262. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 63 p.

Finney, Mark A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management. 211: 97-108.

Gilbertson-Day, Julie; Scott, Joe H.; Vogler, Kevin C.; [et al.]. 2017. Northern Region Wildfire Risk Assessment: Methods and Results. Unpublished report prepared for Brenda Wilmore, U.S. Forest Service, Northern Region. Sept. 2017. 72 p.

Gilbertson-Day, Julie; Scott, Joe H.; Vogler, Kevin C.; [et al.]. 2018. Pacific Northwest quantitative wildfire risk assessment: Methods and results. Unpublished report prepared for Rick D. Stratton, U.S. Forest Service. April 2017. 86 p.

Scott, Joe H.; Thompson, Matthew P. 2015. Emerging concepts in wildfire risk assessment and management. In: Keane, R.E.; Jolly, M.; Parsons, R.; and Riley, K., eds. 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: 196-206.

Scott, J.H.; Thompson, M.P.; Calkin, D.E. 2013. A wildfire risk assessment framework for land and resource management. Gen. Tech. Rep. RMRS-GTR-315. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 92 p.

Short, Karen C.; Finney, Mark A.; Scott, Joe H.; [et al.]. 2016. Spatial dataset of probabilistic wildfire risk components for the conterminous United States. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0034.

Thompson, M.P.; Bowden, P.; Brough, A.; [et al.]. 2016a. Application of wildfire risk assessment results to wildfire response planning in the Southern Sierra Nevada, California, USA. Forests. 7(3): 64. https://doi.org/10.3390/f7030064.

Thompson, M.P.; Scott, J.; Langowski, P.G.; [et al.]. 2013. Assessing watershed-wildfire risks on national forest system lands in the Rocky Mountain region of the United States. Water. 5: 945–971.

Thompson, M.P.; Zimmerman, T.; Mindar, D.; [et al.]. 2016b. Risk terminology primer: Basic principles and a glossary for the wildland fire management community. Gen. Tech. Rep. RMRS-GTR-349. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 13 p.

USDA Forest Service [USFS]. 2015. USDA Forest Service Strategic Plan: FY 2015–2020. Rep. FS-1045. Washington, DC: U.S. Department of Agriculture, Forest Service. https://www.fs.fed.us/sites/default/files/strategic-plan%5B2%5D-6_17_15_revised.pdf. [Accessed 2018 June 27].

USDA Office of Inspector General [OIG]. 2016. Forest Service wildland fire activities—Hazardous fuels reduction. Audit Rep. 08601-0004-41. Washington, DC: U.S. Department of Agriculture. https://www.usda.gov/oig/webdocs/08601-0004-41.pdf. [Accessed 2018 June 27].

Wildland Fire Leadership Council [WFLC]. 2014. The National Strategy: The final phase in the development of the National Cohesive Wildland Fire Management Strategy. Washington, DC: Wildland Fire Leadership Council. http://www.forestsandrangelands.gov/strategy/documents/strategy/CSPhaseIIINationalStrategyApr2014.pdf. [Accessed 2018 June 27].

Characterizing Fire Behavior Across the Globe

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Abstract—Wildfire environmental impacts and the threat they pose to human live and values depend of how fast it spreads, how much biomass is consumed, and how much energy it releases and at what rate. Nearly every feature of contemporary fire management relies upon the understanding and prediction of fire behavior characteristics and a number of tools have been developed for such purpose. However, no attempts have been made so far to provide an overall worldwide picture of fire behavior characteristics, patterns and drivers. These are the general objectives of the BONFIRE project, requiring compilation of the available fire behavior information from field experimental fires, wildfires, and prescribed fires in a global database and subsequent integrated analysis of variation in fire behavior characteristics. We describe the methodology used to build the database, examine data partition by country, climate, biome and fuel complex categories, and mention the difficulties inherent to the process.

Keywords: wildland fire, experimental burning, fire modeling, pyromes, fire-climate relationships

INTRODUCTION

The environmental effects (on ecosystems, geosystems and the atmosphere) and societal impacts of any given fire depend on how fast it spreads, how much biomass it consumes, and how much energy it releases and at what rate (Albini 1984; Reinhardt et al. 2001). These are fire behavior attributes, and are determined by the fire environment, i.e. the combined influences of fuel (burnable vegetation) structure, topography, atmospheric weather, and drought (Countryman 1972). Nearly every feature of contemporary fire management, from fire prevention and fire control operations to the appraisal of its ecological effects relies upon the understanding and prediction of fire behavior characteristics (Scott et al. 2014). This has prompted the development of models capable of predicting with reasonably accuracy the most relevant fire behavior characteristics, namely rate of spread and flame size.

Data from outdoors experiments and other sources resulted in fire behavior models and fire danger rating systems specific to various vegetation types in Australia, Canada, and Europe (e.g., Anderson et al. 2015; Cheney et al. 1998, 2012; Cruz et al. 2005; Fernandes et al. 2009; Forestry Canada Fire Danger Group 1992). These models are empirically based i.e., the dependent variables are statistically related to environmental variables, but can perform acceptably outside the range of observed conditions if the embedded relationships are robust enough (Cruz and Alexander 2013). A distinct approach has been pursued in the U.S.A., resulting in a semi-empirical fire

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

spread model usable in any vegetation type provided that its fuel properties are described as a fuel model (Rothermel 1972). However, attaining satisfactory predictions depends on whether the fuel models have been calibrated with observed fire behavior data or not (Ascoli et al. 2015; Cruz and Fernandes 2008; Hough and Albini 1978).

Wildland fire science has been expanded to analyze fire activity and effects at the global scale, including fire-climate interactions and the contribution to carbon emissions (e.g., Archibald et al. 2013; Moritz et al. 2012; van der Werf et al. 2010). Uncertainty in large-scale estimates of fuel consumption and carbon release by fire persists because of the importance of site-specific influences (Kasischke and Hoy 2008). In fact, sufficiently accurate fire behavior prediction for operational and management purposes is currently limited to specific vegetation types (Cruz and Alexander 2013). The incomplete understanding of global fire behavior patterns and drivers is an important knowledge gap that constrains: (1) adequate prediction of fire activity at different temporal and spatial scales; (2) foreseeing the response of fire activity to global change; and (3) formulating and enacting fire management policies to cope with fire regime changes.

This paper introduces the BONFIRE project, which intends to provide an overall worldwide picture of fire behavior patterns and drivers. Achieving these goals requires compiling the extant fire behavior data in a global database. Here, we describe the data acquisition process and first results.

DATA COLLECTION METHODS

The BONFIRE fire behavior database is being established by collecting information from various sources, namely the peer-reviewed literature, technical reports and grey literature (often addressing wildfire case studies), online databases (http://www.fbkb.ca; https://www.fs.usda.gov/rds/archive/), and unpublished data. Whenever the actual data was unavailable in the publications the respective authors were contacted and asked to share it. Data originates from outdoors fires in natural or activity (slash and masticated) fuels, the former comprising both flaming and smoldering (peat) fires. We restricted data collection to headfires spreading in the absence of interaction between fire fronts. When multiple observation periods were available, wildfire data collection was limited to the period of maximum rate of spread in a given vegetation type.

Ancillary data for each fire observation comprised the respective literature reference, country, location (name and geographic coordinates), observation type (experimental fire, prescribed fire, wildfire), Koppen-Geiger climate classification (Peel et al. 2007), mean annual temperature and rainfall (1970-2000) from the WorldClim 2 database (Fick and Hijmans 2017), biome and ecoregion (Olson et al. 2001), NCAR LSM surface type (e.g. cool broadleaved deciduous forest) (Bonan 1996), generic vegetation type (i.e., forest, woodland, shrubland, or grassland), and dominant species.

Fire behaviour was described in terms of:

1. Type of fire type, i.e., surface, intermittent or passive crowning, or active crowning.
2. Characteristics of the forward section of the fire front, i.e., rate of spread, flame characteristics (height, length, tilt angle), and Byram's fireline intensity.
3. Fuel consumption (absolute and relative) by fuel layer, size class, or condition (dead or live), supplementing a previous database (van Leeuwen et al. 2014) but retaining only those fires for which fuel moisture contents were known.

Additional fire characteristics (flame depth, flame residence time, combustion time) were seldom available and were not included in the database.

The corresponding fire environment was described through:

1. Terrain slope.
2. Atmospheric conditions, i.e., wind speed, relative humidity, and air temperature.
3. Fuel moisture contents by fuel layer, size class or condition, or its Canadian Forest Fire Weather Index System (Van Wagner 1987) surrogates (Fine Fuel Moisture Code, Duff Moisture Code, Drought Code).

4. Nature of the surface fuel complex (litter, grass, shrub, moss-lichen, slash, masticated, and their combinations), and whichever fuel characteristics were available, namely height and cover percent by fuel layer, fuel loads (by layer, size class, or condition), dead fuel percent, curing percent, and forest canopy fuel descriptors (height to live crown base, canopy bulk density).

Each fire entry was assigned an ignition mode (point or line), ignition line length or fire width, and reliability scores (Cheney et al. 2012) for fire behavior characteristics and weather and fuel conditions.

DATA COLLECTION RESULTS

As of the end of May 2018, the BONFIRE database includes about 6000 individual entries from 33 countries, of which three-quarters constitute experimental fires. As expected, countries with long-standing wildland fire research histories and established fire management policies and practices contributed a disproportionately amount to the database, namely Australia (25.6% of the total number of records), USA (17.2%), and Canada (8.1%); South Africa is also well represented (21.1%), however, most of its data comes from the Kruger National Park long-term fire ecology research program (Biggs et al. 2003). The location map (fig. 1) highlights the concentration of experimental fire and wildfire sites in North America, temperate Australasia, and southwestern Europe. Note the scarcity of locations in Russia, Asia and the other regions of Africa and, to a lesser degree, central and South America.

Fully humid warm temperate climates (Cfa, Cfb) accounted for 28.9 percent of the observations, closely followed¬25.7 percent of observations– by warm temperate climates with a dry summer (Csa, Csb) or a dry winter (Cwa). The hot steppe/desert variant of steppe climates (Bsh) ranked next (18.7%), with fully humid snow climates (Dfc, Dfb) and dry-winter equatorial savannah (Aw) being also relevant, respectively 12.1 and 5.0 percent of the observations. Four biomes dominate the database, respectively tropical and subtropical open vegetation types (30.0%), temperate broadleaf and mixed forests (25.7%), temperate conifers (13.7%), and Mediterranean forests, woodlands, and scrub (13.2%), but boreal forests (5.0%) and temperate open types (4.9%) are also relevant. In regards to vegetation

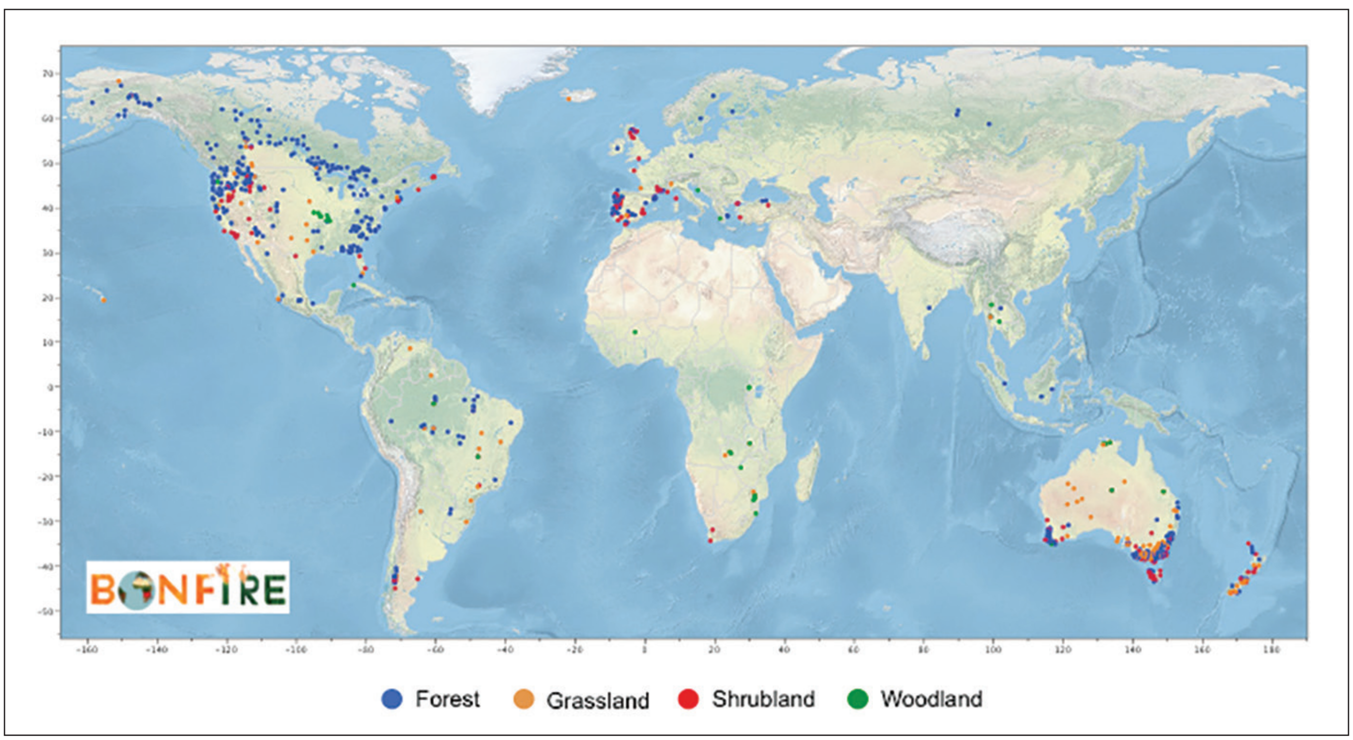

Figure 1—BONFIRE database locations by generic vegetation type as of the end of May 2018.

type, the number of observations decreased in the forest–grassland–shrubland–woodland direction, with respective shares of 44.4, 25.2, 17.5, and 12.8 percent.

The surface fuel complex is either made up of grass or dominated by grass in 50.6 percent of the cases. Litter-dominated fuel complexes rank next (23.9%), followed by shrubs (11.0%), slash alone or in combination with other types (8.5%), and dominance by mosses and/or lichens (4.8%). Table 1 additionally emphasizes the ubiquity of grass-dominated fuel complexes, while dominance by litter or shrubs is more represented in temperate and Mediterranean climates.

A number of issues and difficulties became readily apparent during the process of compiling and organizing the database, starting by uneven data collection and reporting. Field methods are understandably highly variable, as they reflect each study context and objectives, which has impacts on datasets comparability and the completeness of the description of the fire environment variables. For example, wind speed measurements can take place within the 1.2-2 m height range or at a height of 6 or 10 m in the open. The metrics used to describe the fuel complex vary widely, from qualitative descriptions (e.g. fuel type), to fuel hazard scores, to thorough quantitative assessments of fuel structure and load that distinguish between fuel layers, size classes, and dead or live condition. Similarly, fuel moisture and fuel consumption can be available for just the fine dead fuels that often drive fire spread or be detailed by categories, as defined by layer, size, and condition.

CONCLUSION

Completion and analysis of the database will require standardization to the extent possible, which implies derivation of estimates through common methods for some key variables (wind speed, dead fuel moisture content); parts of the database have already been used to validate the results of laboratory-based modeling of fire spread rate (Rossa 2017; Rossa and Fernandes 2018). Then we will be able to characterize and synthesize fire behavior patterns and assess how they vary with top-down and bottom-up environmental drivers, expanding the current options for empirically-based estimation of fire behavior characteristics, developing calibrated fire behavior fuel models for global use in Rothermel's based software, and establishing links with fire danger rating systems.

The BONFIRE project will hopefully provide a sounder foundation for fire management and fire research applications, including a data repository available for further research, and will increase the understanding of fire regime shifts in relation to global change. To keep up with BONFIRE developments,

Table 1—Surface fuel complexes distribution (%) by climate type. Combinations accounting for <1.5% of the total number of observations are not displayed.

Koppen-Geiger climate classification	Grass	Grass + litter	Grass + shrub	Litter	Litter + shrub	Shrub
Equatorial savannah with dry winter	3.1					
Steppe climate - Hot steppe / desert	3.6	10.4	3.8			
Desert climate - Hot steppe / desert	1.9					
Warm temperate climate, fully humid - Hot summer	1.7	2.2	1.5	1.9		
Warm temperate climate, fully humid - Warm summer	6.1			2.6	1.6	3.9
Warm temperate climate with dry summer - Hot summer				2.6		2.5
Warm temperate climate with dry summer - Warm summer				3.2	1.7	2.7
Warm temperate climate with dry winter - Hot summer		5.8				
Snow climate, fully humid - Warm summer	2.5					

visit https://www.researchgate.net/project/BONFIRE-gloBal-scale-analysis-and-mOdelliNg-of-FIRE-behaviour-potential-PTDC-AAG-MAA-2656-2014.

ACKNOWLEDGMENTS

Work funded by the R&D Project BONFIRE - gloBal-scale analysis and mOdelliNg of FIRE behavior potential (PTDC/AAG-MAA/2656/2014), financed by the Foundation for Science and Technology (FCT) and co-financed by the European Regional Development Fund (ERDF) through COMPETE 2020 - Operational Program for Competitiveness and Internationalization (POCI).

REFERENCES

Albini, F.A. 1984. Wildland Fires: Predicting the behavior of wildland fires—among nature's most potent forces—can save lives, money, and natural resources. American Scientist. 72(6): 590–597.

Anderson, W.R.; Cruz, M.G.; Fernandes, P.M.; [et al.]. 2015. A generic, empirical-based model for predicting rate of fire spread in shrublands. International Journal of Wildland Fire. 24: 443–460.

Archibald, S.; Lehmann, C.E.R.; Gómez-Dans, J.L.; [et al.]. 2013. Defining pyromes and global syndromes of fire regimes. Proceedings of the National Academy of Sciences. 110(16): 6442–6447.

Ascoli, D.; Vacchiano, G.; Motta, R.; [et al.]. 2015. Building Rothermel fire behaviour fuel models by genetic algorithms optimization. International Journal of Wildland Fire. 24(3): 317–328.

Biggs, R.; Biggs, H.C.; Dunne, T.T.; [et al.]. 2003. Experimental burn plot trial in the Kruger National Park: History, experimental design and suggestions for data analysis. Koedoe. 46(1): 1–15.

Bonan, G.B. 1996. A land surface model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide. NCAR Technical Note NCAR/TN-417+STR. Boulder, CO: National Centre for Atmospheric Research. 150 p.

Cheney, N.P.; Gould, J.S.; Catchpole, W.R. 1998. Prediction of fire spread in grasslands. International Journal of Wildland Fire. 8(1): 1–13.

Cheney, N.P.; Gould, J.S.; McCaw, W.L.; [et al.]. 2012. Predicting fire behaviour in dry eucalypt forest in southern Australia. Forest Ecology and Management. 280: 120–131.

Countryman, C.M. 1972. The fire environment concept. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 15 p.

Cruz, M.G.; Alexander, M.E. 2013. Uncertainty associated with model predictions of surface and crown fire rates of spread. Environmental Modelling and Software. 47: 16–28.

Cruz, M.G.; Fernandes, P.M. 2008. Development of fuel models for fire behaviour prediction in maritime pine (*Pinus pinaster* Ait.) stands. International Journal of Wildland Fire. 17: 194–204.

Cruz, M.G.; Alexander, M.E.; Wakimoto, R.H. 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Canadian Journal of Forest Research. 35(7): 1626–1639.

Fernandes, P.M.; Botelho, H.S.; Rego, F.C.; [et al.]. 2009. Empirical modelling of surface fire behaviour in maritime pine stands. International Journal of Wildland Fire. 18: 698–710.

Fick, S.E.; Hijmans, R.J. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International Journal of Climatology. 37(12): 4302–4315.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Information Report ST-X-3. Ottawa, ON: Forestry Canada. 63 p.

Hough, W.A.; Albini, F.A. 1978. Predicting fire behavior in palmetto-gallberry fuel complexes. Res. Pap. SE-174. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 44 p.

Kasischke, E.S.; Hoy, E.E. 2012. Controls on carbon consumption during Alaskan wildland fires. Global Change Biology. 18(2): 685–699.

Moritz, M.A.; Parisien, M.-A.; Batllori, E.; [et al.]. 2012. Climate change and disruptions to global fire activity. Ecosphere. 3(6): art49.

Olson, D.M.; Dinerstein, E.; Wikramanayake, E.D.; [et al.]. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. BioScience. 51(11): 933–938.

Peel, M.C.; Finlayson, B.L.; McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and Earth System Sciences Discussions. 4(2): 439–473.

Reinhardt, E.D.; Keane, R.E.; Brown, J.K. 2001. Modeling fire effects. International Journal of Wildland Fire. 10(4): 373–380.

Rossa, C.G. 2017. The effect of fuel moisture content on the spread rate of forest fires in the absence of wind or slope. International Journal of Wildland Fire. 26(1): 24–31.

Rossa, C.; Fernandes, P.M. 2018. Empirical modelling of fire spread rate in no-wind and no-slope conditions. Forest Science. doi:10.1093/forsci/fxy002.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Scott, A.C.; Bowman, D.M.; Bond, W.J.; [et al.]. 2014. Fire on Earth: an introduction. Chichester, UK: Wiley-Blackwell. 434 p.

van der Werf, G.R.; Randerson, J.T.; Giglio, L.; [et al.]. 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmospheric Chemistry and Physics. 10(23): 11707–11735.

van Leeuwen, T.T.; van der Werf, G.R.; Hoffmann, A.A.; [et al.]. 2014. Biomass burning fuel consumption rates: a field measurement database. Biogeosciences. 11: 7305–7329.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. For. Tech. Rep. 35. Ottawa, ON: Government of Canada, Canadian Forestry Service. 35 p.

Fire Regime Analysis of Army Garrison Camp Williams

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BACKGROUND AND RESEARCH QUESTIONS

Army Garrison Camp Williams (AGCW) is a military based located south of Herriman, UT. The base serves primarily as a training area for the Utah National Guard and is a fire-prone landscape located adjacent to urban development. The fire regime at Army Garrison Camp Williams (AGCW) was described in terms of fire frequency, annual area burned, sources of wildfire ignition, and historical fire patterns based on an analysis of historical fire perimeters (table 1). Additionally, Landscape Fire and Resource Management Planning Tools (LANDFIRE) data (Rollins and Frame 2006) were utilized to develop spatially explicit maps summarizing mean fire return interval, fire regime category, general vegetation type, and fire behavior fuel model type (Reeves et al. 2009). Using this data we addressed the following questions: 1) what is the typical pattern of fire in vegetation over time, including historical fire perimeters and the total area burnt per year, and 2) what is the predicted fire return interval?

LARGE AND SMALL FIRE MAPS

Sources of fire ignition at AGCW form 1985 to 2012 were driven primarily by training (49 percent), lightning (28 percent), and humans (15 percent). The fire history map (fig. 1) reveals that the eastern half of the AGCW base has experienced several large fires within the past 30 years (e.g., Big Fire of ’87, the ’95 Fire, Big Fire, Redwood Road Fire, Welder’s Fire, Mustang, Pinion Fire). Large fires (burned area greater than 40 hectares) have also occurred on the western portion of the base, most notably the 2010 Machine Gun Fire. The large fires on the steep slopes of the northeast portion of the base are typified by shrubby Gambel oak (*Quercus gambelii*, Nutt.) and drier climatic conditions relative to the western portion of the AGCW base. Gambel oak sprouts vigorously following fire and has reburned over identical areas in as few as six years, exemplified by the ’95 Fire in August of 1995 and the Big Fire in July of 2001.

MEAN FIRE RETURN INTERVAL AND FIRE REGIME GROUP

In the western portion of AGCW referred to as the “impact area”, overlapping fires have occurred in grassland and shrub fuel types in 1996 (Impact Area Sage), 2006 (Impact Area), 2010 (Machine Gun), and 2012 (Nacho). The average fire return interval for this fuel type and geographic area is about once every four years. The extreme western portion of the base contains some of the steepest topography and most mature stands of Gambel oak and Utah juniper (*Juniperus osteosperma* (Torr.)Little). This area is higher in elevation than the eastern portion of AGCW with higher annual precipitation, which appears to influence the growth and maintenance of these mature stands. This area has experienced very little fire since 1978, except for the 1978 Sheps Fire and the 1991 Shep’s Ridge West Fire. Low fire frequency in the extreme western portion of the base is likely linked to cool and moist climatic conditions experienced in the area coupled with the minimal live-fire training activity that occurs in this area.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Extended abstracts published in these proceedings were submitted by authors in electronic media. Editing was done for readability and to ensure consistent format and style. Authors are responsible for content and accuracy of their individual papers and the quality of illustrative materials. Opinions expressed may not necessarily reflect the position of the U.S. Department of Agriculture.

Table 1—List of large fires (greater than 40 hectares) by name, year of occurrence, start date (if available), area burned, ignition source, and any significant highlights associated with wildfires depicted in Figure 1.

Fire name	Year	Start date	Area (ha)	Ignition source	Significant highlights
Pre-1985 Tickville	1985	Unknown	56	Unknown	
Big Fire of '87	1987	Unknown	1508	Unknown	
Shep's Ridge-West	1991	Unknown	49	Unknown	
Impact Area-Sage2	1992	Unknown	88	Unknown	
The '95 Fire	1995	8 Aug.	1111	Lightning	Burned off base
Impact Area-Sage	1996	Unknown	78	Unknown	
Known Distance Range	2001	Unknown	48	Training	
Redwood Road	2001	17 June	271	Human	
The Big Fire	2001	16 July	3244	Training	Burned off base
Welders Fire	2003	8 July	478	Human	
South of Area 51	2005	Unknown	42	Lightning	
M31 Fire	2006	12 June	54	Training	
Impact Area Fire	2006	19 Sep.	278	Training	
Juniper Ridge Fire	2007	8 July	63	Lightning	
Mustang	2010	16 July	96	Human	
Machine Gun	2010	19 Sep.	1498	Training	Destroyed 3 homes off base
Nacho	2012	23 July	53	Lightning	
Pinion	2012	5 Aug.	2334	Lightning	Burned off base

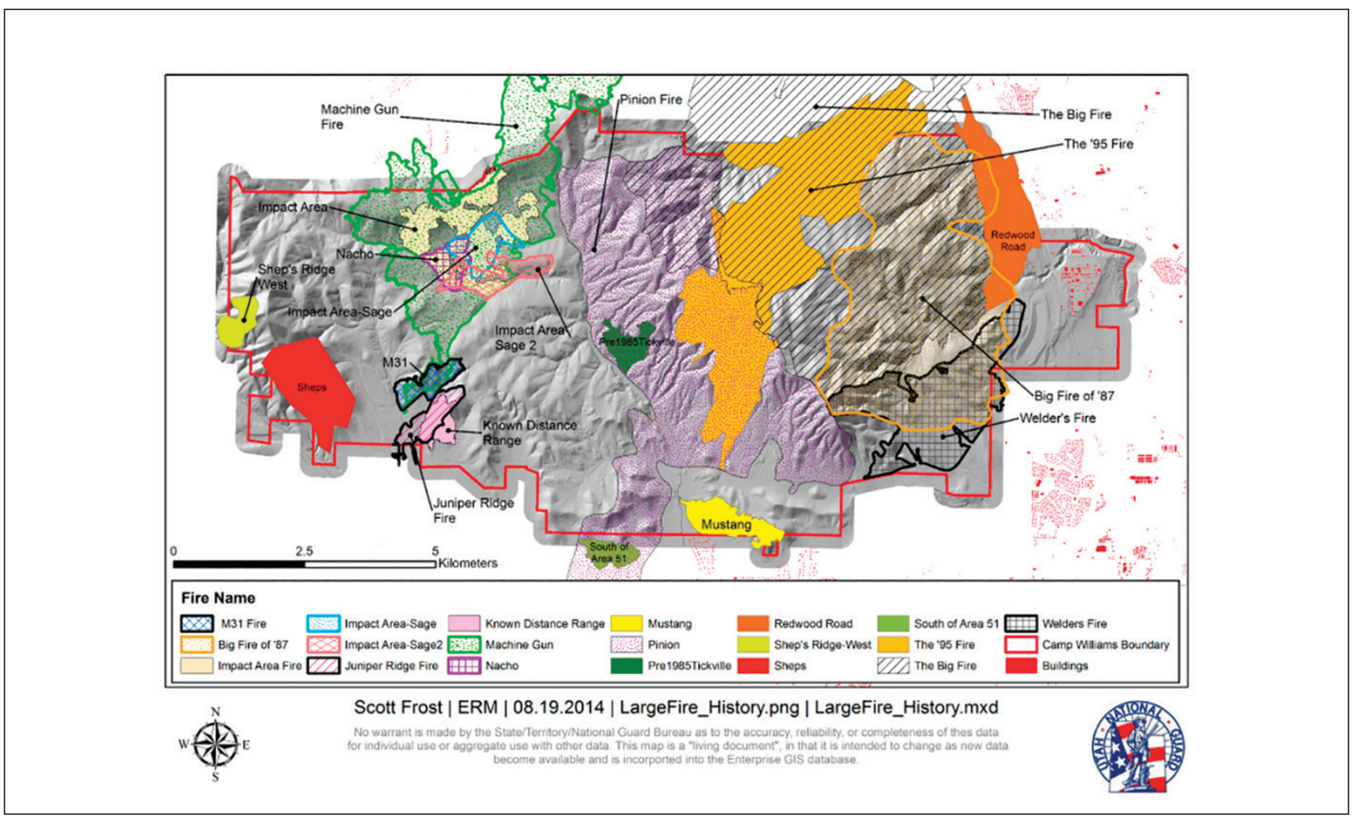

Figure 1—The "large fire" (40 hectares and above) history map for Army Garrison Camp Williams, 1978-2012.

The Mean Fire Return Interval (MFRI) map produced by LANDFIRE, indicates return intervals ranging from five to about 22 years at AGCW. The most widespread category is the interval from 9 to 12 years. The map also indicates that along the northwestern boundary of AGCW, intervals are classified as predominantly in the range of five to eight years. Meanwhile, in the extreme western portion of AGCW the map corroborates the recent fire history data, indicating that the longest fire return intervals are from 18 to 22 years. Regardless of the MFRI class, the LANDFIRE map product suggests that wildfire has and continues to be a frequent visitor across the AGCW landscape. The fire regime was classified into two predominant categories, namely Fire Regime groups three (35–200 year fire return interval, low and mixed severity) and four (35–200 year fire return interval, replacement severity). There are small linear, mostly creek or valley bottom areas that are categorized into fire regime group five (greater than 200 year fire return interval, any severity). The lower elevation terrain is categorized almost entirely as fire regime group four, indicating that fire is both frequent and of a replacement severity type. Meanwhile, higher elevation areas are typically categorized as fire regime group three, indicating frequent fire, but of low to moderate severity. Lastly, a small area on the western portion of the base, likely in mature Gambel oak and Utah juniper is categorized into fire regime group one (less than or equal to 35 year fire return interval, low and mixed severity). Thus, only a small portion of the land area at AGCW is categorized into an exclusively low severity category. More in depth analysis of the topic is available in Chapter 3 of Frost (2015).

ACKNOWLEDGMENTS

Thanks is owed to Wesley Page of the Missoula Fire Lab for excellent technical review and edits, and to Army Garrison Camp Williams for funding this research.

REFERENCES

Frost, S.M. 2015. Fire environment analysis of Army Garrison Camp Williams in relation to fire behavior potential for gauging fuel modification needs. Thesis. Logan, UT: Utah State University. 183 p. https://digitalcommons.usu.edu/etd/4560/. [Accessed 2018 July 2].

Reeves, M.C.; Ryan, K.C.; Rollins, M.G.; Thompson, T.G. 2009. Spatial fuel data products of the LANDFIRE project. International Journal of Wildland Fire. 18: 250–267.

Rollins, M.G.; Frame, C.K. 2006. The LANDFIRE prototype project: Nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins, CO: U.S. Department of Agriculutre. Forest Service, Rocky Mountain Research Station. 416 p.

Wildfire Behavior Case Study of the 2010 Machine Gun Fire, Army Garrison Camp Williams

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BACKGROUND AND RESEARCH OBJECTIVES

A case study is presented for the major run of the Machine Gun Fire on September 19, 2010, which started within the confines of Army Garrison Camp Williams (AGCW) and spread beyond installation boundaries to the north, destroying three homes and requiring an evacuation of approximately 1600 people in an adjacent community. This fire was selected for a wildfire behavior case study analysis because of its large size and destructive nature in relation to the wildland urban-interface area adjoining the base. Alexander and Thomas (2003) suggest that a wildland fire behavior case study should include, at the minimum, introduction remarks regarding the significance of the fire, fire chronology and development, detailed description of the fire environment (i.e., topography, fuels, and fire weather), an analysis of fire behavior, and concluding remarks regarding lessons learned and significant contributions, if any, to the broader general fire behavior knowledge database.

FIRE CHRONOLOGY AND DEVELOPMENT

The Machine Gun Fire started at approximately 1237 hours on September 19, 2010; all times given are Mountain Daylight Time (MDT). An initial attack fire suppression crew employed by the Utah National Guard stationed at AGCW were initially dispatched to the fire. Two distinct surges in the fire's forward advance subsequently occurred, the first at 1330 hours and a second at 1400 hours were stopped at firebreaks in grass and sparse shrub cover northeast of the fire's point of ignition (fig. 1). Near 1500 hours, high winds gusting to at least 28 km hr-1 produced spot fires north of the firebreaks that had initially stopped fire spread. After 10 minutes of extensive spotting the fire advanced 706 m and jumped yet another set of firebreaks in grass at 1530 hours.

In the next 30 minutes, from 1530 to 1600 hours, the fire spread forward an additional 800 m, and breached a trail at 1600 hours (fig. 1). From 1601 to 1625 hours, fire spread continued at a rapid pace until it jumped a set of trails at the EQA pad area. For the next 20 minutes (from 1626-1645 hours), a large portion of the fire's edge moved upslope in a northwesterly direction. At 1646 hours, the fire jumped two sets of firebreaks, each approximately 8-m wide, and spread rapidly upslope in a north-northeast direction until running into a goat-maintained fuelbreak (Lovreglio et al. 2014) in Gambel oak (*Quercus gambelii*, Nutt.) where the fire was stopped.

At 1656 hours, spot fires were observed developing on the other side of the fuelbreak that eventually spread beyond the northern boundary of AGCW. Meanwhile, the northwestern portion of the fire continued spreading from 1626-1645 hours (fig. 1), eventually breaching the same set of firebreaks at 1700 hours. From 1700 to 2000 hours, the fire burned northward until spotting over the goat-maintained fuelbreak at 2000 hours. In addition, the fire burned

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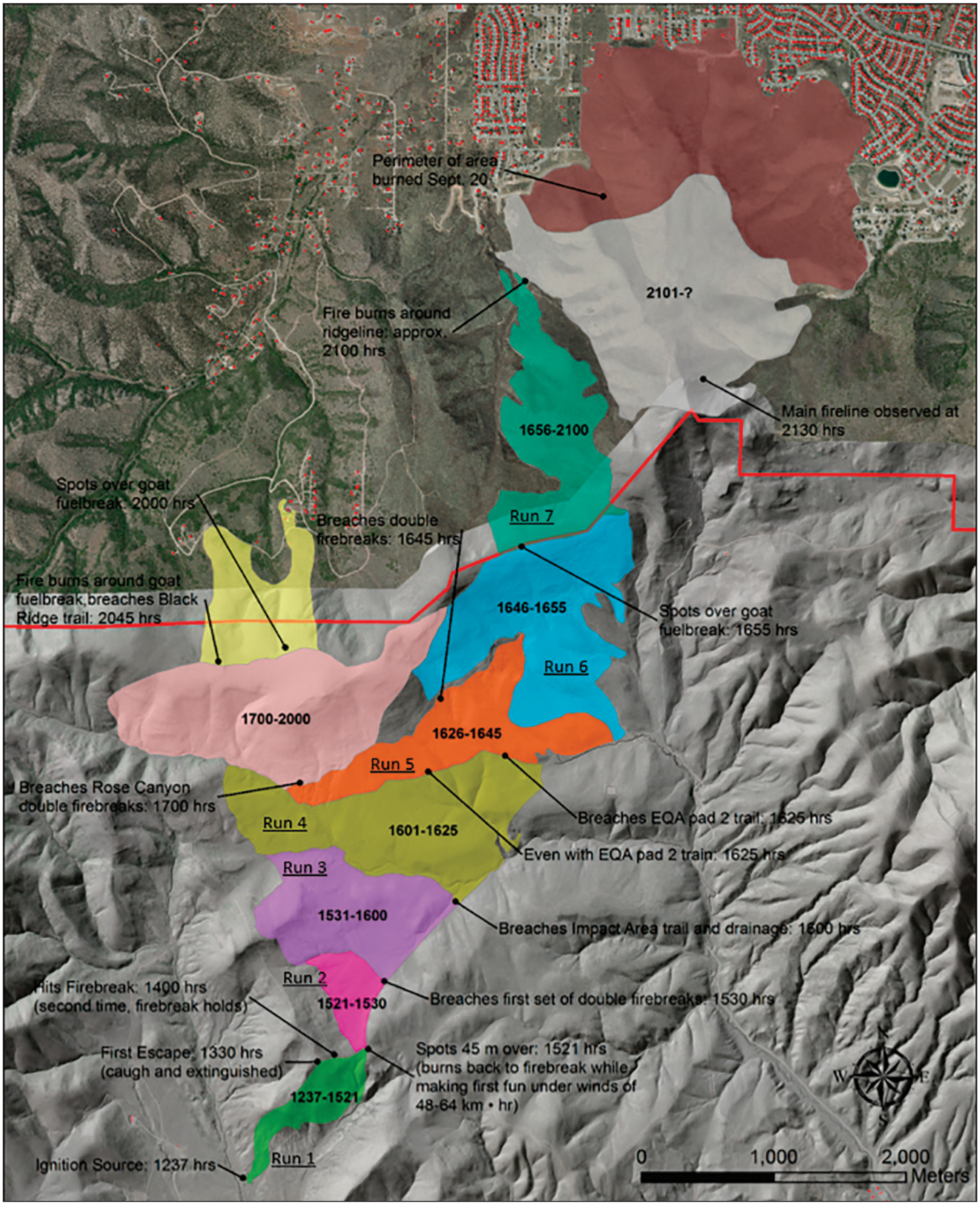

Figure 1—Progression map and narrative of events associated with the major run of the Machine Gun Fire on September 19, 2010.

along the fuelbreak towards the west and subsequently hooked around the fuelbreak at 2045 hours, eventually coalescing with the spot fire activity that developed at 2000 hours. The fire then burnt farther northward and consumed one home before being stopped along roads and property boundaries later the night of September 19. At the northeastern portion of the fire, spread continued through the evening of September 19 and on into the morning of hours of September 20.

DESCRIPTION OF THE FIRE ENVIRONMENT

Information on vegetation and fuel type at the time of the 2010 Machine Gun Fire was acquired via LANDFIRE (Reeves et al. 2009) for existing vegetation type (EVT) and fire behavior fuel model (FBFM) classifications as per Anderson (1982). EVT is a baseline LANDFIRE data product that represents species composition at a given site. The EVT map for AGCW was mapped, with the perimeter of the Machine Gun Fire overlaid onto LANDFIRE data compiled in 2008. Using general vegetation groups, the EVT map indicates that within the boundaries of AGCW, the Machine Gun Fire burned predominantly through shrubland vegetation and small patches of grassland. Once the fire crested Black Ridge on the northern boundary of AGCW, the vegetation type transitions to hardwoods, which on the ground is represented by Gambel oak. The FBFM map for AGCW at the time of the Machine Gun Fire in 2010 indicates that the shrubland vegetation is primarily FBFM 5 and secondarily FBFM 2. Grasslands are modeled as FBFM 1, while Gambel oak stands were modeled as FBFM 8 and possibly FBFM 2.

The ICS-209 report filed at 2100 hours (MDT) on September 19, 2010 briefly mentions a peak or gust wind speed observed at 56 km h-1 and rapid, wind-driven rates of fire spread. The Remote Automated Weather Station (RAWS) hourly weather data indicates similar high wind speed observations with average 6.1-m open wind speeds of 22 to 32 km h-1 from 1400 to 2200 hours. Wind speed in the morning hours on September 19, 2010 were fairly high, with readings consistently between 12-15 km h-1 from 0000 to 0900 hours. Average wind speed decreased slightly from 1000 to 1300 hours, varying from 6 to 14 km hr-1. At approximately 1400 hours, peak temperatures for the day and relative humidity lows coincided with a dramatic increase in average wind speed ranging from 22 to 32 km h-1 for all of the afternoon and evening weather observations. Relative humidity dropped from a morning high of 34 percent at 0800 hours to 7 percent by 1400 hours. Wind direction from 1000 hours onward was a constant southeast to south to southwest. The dead timelag fuel moistures were very low throughout the day ranging from one to four percent for 1-h fuels, two to six percent for 10-h fuels, and six to ten percent for 100-h fuels.

FIRE BEHAVIOR ANALYSIS—OBSERVED VS. PREDICATED RATE OF SPREAD USING BEHAVEPLUS

Observed rates of spread for seven different fire run segments compiled by AGCW personnel in the form a fire progression map were compared to predicted rates of spread using BehavePlus v. 5.0 (Heinsch and Andrews 2010). The required inputs were obtained from a LANDFIRE fuel model classification map, digital terrain model data, and weather observations from the Tickville RAWS. Of the seven different fire run segments compared (table 1), three of the predicted segments were within 60 percent of the observed fire spread rates, while the other four were drastically different. It's of note that the maximum rate of fire spread, as observed over a 9-minute period, was 164 m min-1. Major differences in ROS estimates in the present case study could be due to inaccuracies related to fire progression timelines and generalizations of slope and fuel model type when input into BehavePlus. Fire progression interval 6, which exhibited very high ROS, could be an example of this kind of inaccuracy or of a transition area from surface to crown fuels.

LESSONS LEARNED AND RECOMMENDATIONS

Butler and Reynolds (1997) in their wildfire behavior case study comparison of observed and predicted rate of spread (ROS) values using BehavePlus found that, even in shrub fuel types, transition from a surface fire to crown fire was an abrupt occurrence and was under predicted by BehavePlus. However, once the fire

Table 1—Observed versus predicted rates of spread tabulation for the major run of the Machine Gun Fire of September 19, 2010 patterned after Butler and Reynolds (1997). Predicted rates of spread were computed with BehavePlus using Fire Behavior Fuel Model 5 as per Anderson (1982). The live woody fuel moisture content was set as a constant at 69%, the value obtained from a nearby live fuel sampling location for Wyoming big sagebrush on September 1, 2010.

Fire progression segment	Time interval (duration)	Slope steepness (%)	Spread distance (m)	Avg. 6.1-m open wind (km h^{-1})	Observed ROS (m min^{-1})	Predicted ROS (m min^{-1})
1	2h 50m	8.8	1284	13	22	8
2	10m	-4.8	706	30	78	24
3	30m	-3.0	798	30	28	24
4	25m	3.5	1043	32	43	26
5	20m	3.2	310	32	16	26
6	9m	13.1	1478	32	164	27
7	Unknown	-3.2	2142	32	9	26

reached a quasi-steady state in the crowns of the shrub fuels, the ROS predictions produced by BehavePlus were much more in alignment with the observed values. Major differences in ROS estimates in the present case study could be due to inaccuracies related to fire progression timelines and generalizations of slope and fuel model type when input into BehavPlus. Fire progression interval 6, which exhibited very high ROS, could be an example of this kind of inaccuracy or of a transition area from surface to crown fuels.

It is difficult to ascertain a definitive reason for the differences in observed and predicted ROS from the data available on the Machine Gun Fire. There could be any number of reasons (Alexander and Cruz 2013; Cruz and Alexander 2013). The present wildfire behavior case study represents the first such effort at AGCW. Findings from the present completed case study underscores the need for rigorous protocols to make fire behavior observations in the future in order to evaluate fire behavior models more thoroughly (Haines et al. 1986; Alexander and Taylor 2010) and ultimately to better evaluate fuel treatment effectiveness, amongst other purposes. More in depth analysis of the topic is available in Chapter 3 of Frost (2015).

ACKNOWLEDGMENTS

Thanks is owed to Wesley Page of the Missoula Fire Lab for excellent technical review and edits, and to Army Garrison Camp Williams for funding this research.

REFERENCES

Alexander, M.E.; Cruz, M.G. 2013. Limitations on the accuracy of model predictions of wildland fire behaviour: A state-of-the-knowledge overview. Forestry Chronicle. 89: 370–381.

Alexander, M.E.; Taylor, S.W. 2010. Wildland fire behavior case studies and the 1938 Honey Fire controversy. Fire Management Today. 70(1): 15–25.

Alexander, M.E.; Thomas, D.A. 2003. Wildland fire behaviour case studies and analyses: Other examples, methods, reporting standards, and some practical advice. Fire Management Today. 63(4): 4–12.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Butler, B.W.; Reynolds, T.D. 1997. Wildfire case study: Butte City Fire, southeastern Idaho, July 1, 1994. Gen. Tech. Rep. INT-GTR-351. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 15 p.

Cruz, M.G.; Alexander, M.E. 2013. Uncertainty associated with model predictions of surface and crown fire rates of spread. Environmental Modelling & Software. 47: 16–28.

Frost, S.M. 2015. Fire environment analysis of Army Garrison Camp Williams in relation to fire behavior potential for gauging fuel modification needs. Thesis. Logan, UT: Utah State University. 183 p. https://digitalcommons.usu.edu/etd/4560/. [Accessed 2018 July 2].

Haines, D.A.; Main, W.A.; Simard, A.J. 1986. Fire danger rating and observed wildfire behavior in the northeastern United States. Res. Pap. NC-274. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 23 p.

Heinsch, F.A.; Andrews, P.L. 2010. BehavePlus fire modeling system, version 5.0: Design and Features. Gen. Tech. Rep. RMRS-GTR-249. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 111 p.

Lovreglio, R.; Meddour-Sahar, O.; Leone, V. 2014. Goat grazing as a wildfire prevention tool: A basic review. Journal of Biogeosciences and Forestry. 7: 260–268

Reeves, M.C.; Ryan, K.C.; Rollins, M.G.; Thompson, T.G. 2009. Spatial fuel data products of the LANDFIRE project. International Journal of Wildland Fire. 18: 250–267.

Role of Ornamental Vegetation in the Propagation of the Rognac Fire, 2016

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Abstract—In August 2016, a fire caused by negligence during leisure activities started in the wildland-urban interface (WUI) of Rognac (NE of Marseille, southeast France). The fire was driven by a strong wind and exceptionally dry and warm climatic conditions, burning almost 3,000 ha, mostly in an urbanized area, in a few hours. These severe meteorological conditions led to difficult firefighting operations, already hampered by a lack of resources due to several aircraft being grounded for maintenance and by six other fires burning at the same time in the area. The fire impacted seven communities, ending up in the outskirt of Marseilles, some 15 km away from its ignition point. The Rognac Fire mostly spread in WUI burning primarily ornamental vegetation such as hedges located along the roads that led to buildings. Homes were damaged or destroyed often because of the poor positioning of ornamental vegetation, sometimes combined with a lack of clear-cutting (however mandatory in WUI). This exceptional fire event underlines the need to better understand fire propagation through WUI vegetation. In order to improve fire prevention in WUI under climatic conditions more and more conducive to fire, it is thus necessary to adapt the fire behavior modelling to ornamental vegetation.

Keywords: large fire; fire propagation, ornamental vegetation, wildland-urban interface, fire damage

INTRODUCTION

Around the world, and especially in the Mediterranean region, concerns about the impact of wildland fires are increasingly focusing on the wildland-urban interface (WUI) (Cohen 2000; Lampin-Maillet 2009). Because this region's climate conditions (dry and warm summers, often with strong winds) favor fire ignition and propagation, plants were selected by the influence of fire for thousands of years (Keeley 2012) and thus, today, the resulting fire-prone ecosystem is characterized by fire-prone species (pyrophytic species). Furthermore, in this high fire risk area, human population has considerably increased wildfire frequency (Syphard et al. 2007), especially in the WUI. These areas are constantly increasing in several parts of the world with growing urbanization (Keeley et al. 1999; Lampin-Maillet 2009) and where the risks to human lives and property, and thus the assets to defend, are greatest (Bar Massada et al. 2009). Southeastern France is one of these regions and is also the area most affected by wildfires compared to the rest of the country (Ganteaume and Guerra 2018); most fires here are human-caused (Ganteaume and Jappiot 2013) and occur in the WUI (Ganteaume and Long-Fournel 2015). WUI vegetation differs from that of typical wildland, especially by its structure, which is heterogeneous, composed of isolated plants and of groups of plants, sometimes lining up thereby providing horizontal fuel continuity. This WUI vegetation is also called ornamental vegetation as it is located around housing. It is composed of both native and strictly ornamental species and can act as a vector for fire propagation from the wildland to housing in WUI, and then from house to house, possibly entailing

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

significant damage to structures. Furthermore, the ongoing higher incidence of extreme climate events (e.g. high summer temperatures, strong winds, and drought) is expected to worsen under climate change and will increase the fire risk, with more catastrophic fires such as those that happened in Portugal in 2017.

This work describes one of these severe fires that has occurred in the WUI in southeast France and highlights the major role of the ornamental vegetation in fire propagation, as well as the damage to structures. Some insights are also provided, attempting to explain the scale reached by this fire.

THE FIRE DETAILS

The Rognac Fire ignited in the afternoon on August 10, 2016 and spread mostly in the wildland-urban interface (2,200 ha burned in WUI and urban area) and was caused by sparks emitted by an electric saw used by a resident working outdoors (i.e., negligence during private works). The fire burned almost 3,000 ha, threatening more than 2,000 buildings located at less than 50m from the flame front.

The largest fire size obtained every year in southeast France shows a decreasing trend since 1973, especially since the 1990s. The Rognac Fire is actually the largest fire that occurred in 2016. Its size is in the same range as that of the fires in 2009 and 2010 but its impact on structures was much higher, and more or less similar to that of the fires in 2003.

Study Area

The fire area is located in the Département Bouches du Rhône which is one of the 15 administrative districts composing southeast France (fig. 1a). This département is one of the most affected by wildfires and the fire area has already been impacted by six large fires (≥ 300 ha) since 1967, most of them occurring in the Arbois forested massif located east of the fire area. The 2004 fire perimeter overlapped the North of the Rognac Fire perimeter.

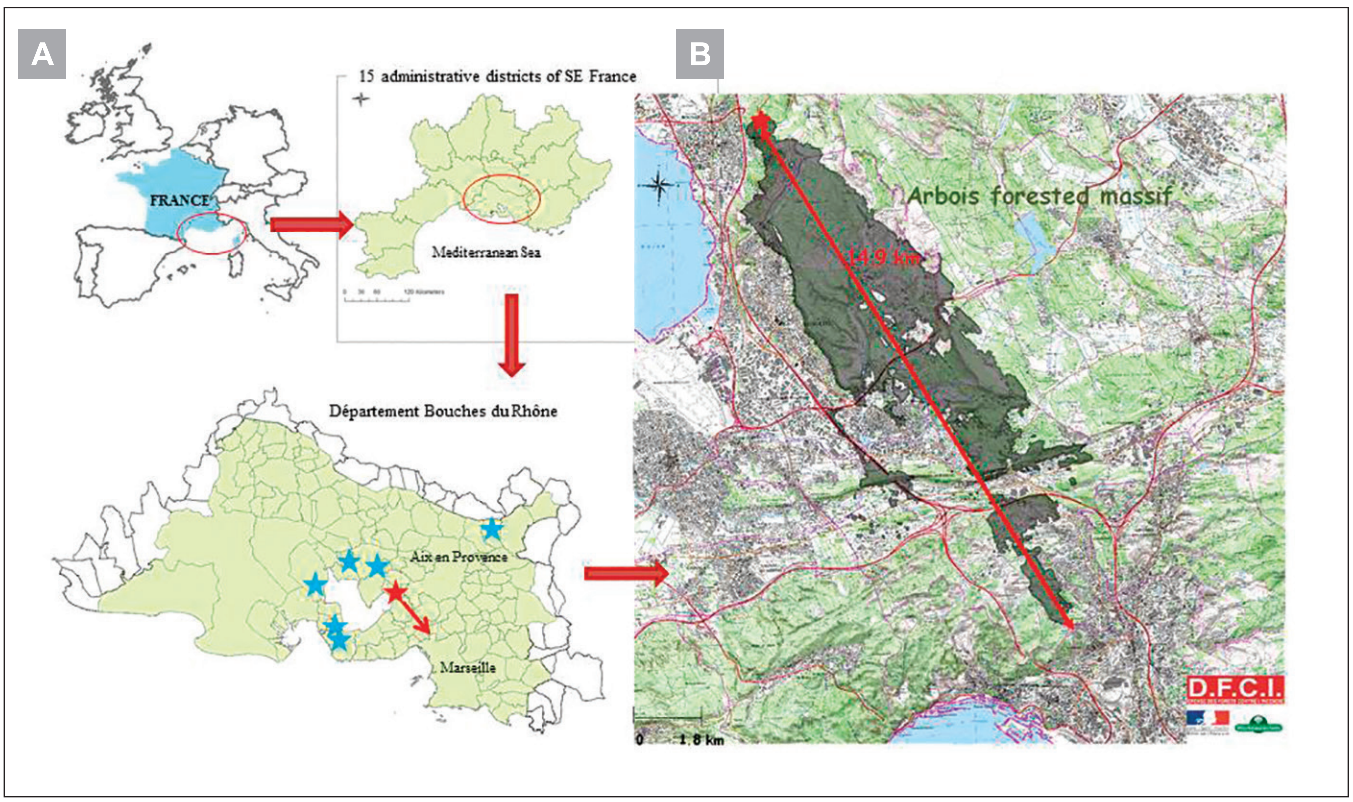

Figure 1—(A) Location of the Rognac Fire (red star and arrow showing the fire spread) and of the other concomitant ignitions that occurred nearby the same day (blue stars), and (B) fire perimeter (dark gray) highlighting that most of the fire propagation occurred in WUI and in urban areas.

The fire spread in the wind direction with a maximum rate of spread of 5.3 kmh^{-1} and ended up 15 km from its initial ignition zone, affecting seven communities, especially Vitrolles (1648 ha) and Les Pennes-Mirabeau (676 ha).

The Context

Different reasons can explain the extent of the fire size and of the subsequent damage: (1) a limited suppression force, (2) extreme weather conditions and (3) high proportion of WUI.

When the fire ignited, the firefighting force available was limited due to unexpected firefighting aircraft maintenance that grounded most aircraft, but also because of several other fires that burned the same day in nearby locations (fig. 1a), including the critical fire in Fos/Mer (more than 1,000 ha burned) that threatened the oil terminals (one of the main assets of the area). These concomitant fire outbreaks caused the splitting of the firefighting force to different locations. Because of this cascade of events, the fire was not contained soon enough as the early and full attack on the fire could not be achieved (usually the firefighting tactic consists of attacking the fire within the first 10 minutes after ignition with full force).

With the attack delayed, the fire grew rapidly due to the extreme weather conditions occurring that day. At the time of the ignition, temperature was at the highest (around 26 °C) and the relative humidity at the lowest (25%) generating a high fire weather index. Moreover, a very strong Mistral wind, blowing from the northwest and gusting at 85 km/h, allowed the fire propagation to increase and the fire to spot in several locations. This high wind speed varied spatially in the fire area, mostly due to topography, making it even more difficult and dangerous for the firefighters.

HOW THE FIRE SPREAD AND IMPACTED THE WUI

History of the Fire

Besides the large size of the fire, what mostly characterized the Rognac Fire was its propagation through WUI to the core of an urban area, becoming sometimes more an "urban fire" than a "WUI fire." The fire ignited at 3:09 pm and spread quickly in the direction of the wind, then to the flanks, reaching the highway to the west of the fire area, and spotting several times. About 4 hours and 50 minutes after ignition, the fire had already burned 2,000 ha. One hour later, the fire spotted over the highway located South of Les Pennes-Mirabeau and spread towards Marseille where it was extinguished, almost 10 hours after ignition, having burned 2,669 ha and impacted more or less severely seven communities (fig. 1b).

Fire Severity and Damage

The fire severity varied spatially within the fire perimeter; the area showing higher severity mostly corresponded to pine forest, but in some areas it was due to damage to structures in WUI.

In total, 181 structures were impacted by the fire (fig. 2), mostly in the two communities of Vitrolles and Les Pennes-Mirabeau. The damage varied in severity from outside damage, which was the most frequent and consisted of burned vegetation around houses or burned vehicles located close to housing, to houses impacted without being destroyed (burned wooden decks or sheds, window glass broken, PVC gutters and shutters melted, for instance). The fire completely destroyed 26 structures, mostly in Les Pennes-Mirabeau. These structures belonged mostly to residents living in the WUI area, but schools and a car dealership were also destroyed.

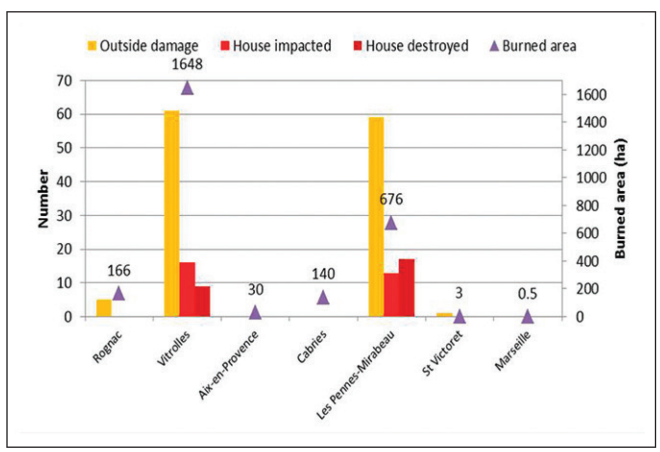

Figure 2—Number of buildings damaged by the fire according to the type of damage and total burned area in each community affected by the Rognac Fire.

Role of Ornamental Vegetation in Fire Propagation and Damage to Structures

The role of the ornamental vegetation in fire propagation was clear as the fire spread using the horizontal fuel continuity provided by the ornamental hedges around residents' properties and along the roads, damaging and even destroying buildings when they were located to close to this vegetation. The role of the ornamental vegetation was sometimes combined with a lack of clearing vegetation around housing, which is mandatory for the buildings located less than 200 m from forest/shrubland areas. The Rognac Fire was characterized by its propagation mostly throughout WUI, even reaching the urban area using this network of vegetation (76% of the burned area was located outside the wildland areas).

The role of this vegetation in the damage to structures was also very clear and often highlighted that the vegetation was too close to the houses. One of the most significant examples was the Chateau des Barnouins, which was completely destroyed because of large trees overhanging the roof in several places and two huge cypress hedges located on each side of the house. The damage resulted from strong radiant heat emitted by the burning vegetation surrounding the buildings as well as to the massive shower of firebrands generated by this vegetation, eventually provoking the collapse of the roof and the burning of the mansion. To worsen the situation, the vegetation was poorly maintained around the property. In several other cases, the destruction of buildings was also due to large trees (usually pines) overhanging the roof or being located very close to the house (usually Italian cypress). In one case, the house was destroyed because of a window left open, this allowed the firebrand shower to reach the inside of the building and set it on fire.

Why Did This Happen?

This fire provoked such an extent of damage because most of the people living in the WUI lacked awareness of the fire risk. Residents, but also land planners, need to be more educated about the fire risk as very often they simply do not understand the role of the mandatory brush-clearing (in force in WUI areas of southeast France) on fire mitigation. Consequently, this regulation is often not well implemented, resulting at times in catastrophic consequences during a fire.

Besides this lack of awareness, people need a better knowledge of the ornamental vegetation they can use and how to use it around their home. They need to know how it burns in order to be able to choose the less flammable species for "firewise" landscaping and to avoid planting species that present a large amount of dead fuel, such as Italian cypress. Because of this dead fuel, this plant results in a high intensity fire when burning, which thus damages or destroys the structures if they were too close, as often has been witnessed by the firefighters.

CONCLUSIONS

The Rognac Fire was one of the most destructive since the fires of 2003, spreading through ornamental vegetation and damaging or destroying structures from the WUI to the city center. This exceptional fire event, both in terms of burned area and damage to structures, underlines the need to better understand fire propagation through WUI vegetation. This propagation differs from that in wildland vegetation especially because of its strong heterogeneous structure and of the presence of exotic species whose fire behavior, for the most part, is unknown. In order to improve fire prevention in WUI areas under climatic conditions more and more conducive to fires because of ongoing global change, it is necessary to adapt fire behavior modelling for this type of vegetation.

During this fire, the limited suppression force hampered firefighting, but the extreme fire spread was mainly the result of extreme weather conditions. Even with a full firefighting force, this large fire would have been very difficult to contain, as sadly happened in Portugal with the extreme fires that occurred in 2017.

REFERENCES

Bar Massada, A.; Radeloff, V.C.; Stewart, S.I.; Hawbaker, T.J. 2009. Wildfire risk in the wildland-urban interface: a simulation study in northwestern Wisconsin. Forest Ecology and Management. 258: 1990–1999. doi:10.1016/J.FORECO.2009.07.051.

Cohen, J.D. 2000. Preventing disaster: home ignitability in the wildland-urban interface. Journal of Forestry. 98: 15–21.

Ganteaume, A.; Guerra, F. 2018. Explaining the spatio-seasonal variation of fires by their causes: The case of southeastern France. Applied Geography. 90: 69–81.

Ganteaume, A.; Long-Fournel, M. 2015. Driving factors of fire density can spatially vary at the local scale in south-eastern France. International Journal of Wildland Fire. 24: 650–664. doi.org/10.1071/WF13209.

Keeley, J.E. 2012. Ecology and evolution of pine life histories. Annals of Forest Science. 69: 445–453.

Keeley, J.E.; Fotheringham, C.; Morais, M. 1999. Reexamining fire suppression impacts on brushland fire regimes. Science. 284: 1829–1832.

Lampin-Maillet, C. 2009. Caractérisation de la relation entre organisation spatiale d'un territoire et risque d'incendie: le cas des interfaces habitat-forêt du sud de la France. PhD thesis, Université de Provence, Marseille.

Syphard, A.D.; Radeloff, V.C.; Keeley, J.E.; Hawbaker, T.J.; Clayton, M.K.; Stewart, S.I.; Hammer, R.B. 2007. Human influence on California fire regimes. Ecological applications. 17: 1388–1402.

Fire Emission Measurements Using Lightweight Sensors and Samplers on Unmanned Aerial Systems

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Emission measurement systems making use of miniaturized sensors and samplers have been developed for portable and aerial sampling from aerial platforms. Small, shoebox-sized systems called "Kolibri", weighing 3–4.5 kg, have been deployed on USGS- and NASA-flown unmanned aerial systems (UASs, or "drones," fig. 1) to characterize plume emissions from open area combustion sources. A 5 m diameter, tethered, helium-filled aerostat (balloon) has been used to loft a larger instrument system (20+ kg) called the "Flyer" into combustion plumes (fig. 2). Both the Kolibri and Flyer use sensors to measure CO and CO_2 and miniature samplers for $PM_{2.5/10}$, PAHs, VOCs, SVOCs, carbonyls, black/elemental/organic carbon (BC/EC/OC), inorganic halogens, and real time BC. New capabilities are being added including IR cameras, NOx sensors, and a real time sampler for particle size distributions. Telemetry systems on both the Kolibri and Flyer transmit data to the ground crew to enable flight, battery, and sample monitoring. The Flyer has been used to determine emission factors from a variety of open burning sources including oil burns, waste pile burns, agricultural field burning, prescribed wildland fires, and open burning/open detonation of military ordnance. The Kolibri has been successfully and safely deployed in five campaigns to determine emission factors from prescribed fires and open burning and detonation demilitarization processes.

Figure 1—NASA Unmanned Aerial System (UAS) with EPA Kolibri" gas and particle sampler.

Figure 2—EPA tethered aerostat and "Flyer" gas and article sampler (inset).

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Anticipating Interactions Between Forest Management and Wildfire as Private Forestland Owners Adapt to Climate Change

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Abstract—Climate change will influence wildfire on private forest lands via two pathways: (1) changes in temperatures and precipitation will induce direct changes in wildfire likelihood and severity; and (2) changes in management by forest landowners seeking to adapt to climate change will result in shifts in species composition and harvest timing and intensity, which act as additional indirect influences on wildfire. We examined private forest landowners' management behavior in the context of climate change and wildfire, to anticipate how forest landowners in California, Oregon, and Washington (USA) are likely to adapt to climate change and how their adaptation could influence wildfire in the region. Drawing on fine-scaled panel data describing forest conditions, climate, wildfire, and private forest management, we estimated empirical models characterizing forestland owners harvest and replanting decisions in response to climate and wildfire variables. We used our empirical models to simulate forestland owners' future harvest and replanting decisions, and the likelihood and severity of future wildfires, as private forest landowners shift their management in response to changing climate. Our results suggest that climate change will induce moderate shifts away from Douglas-fir in favor of hardwoods and ponderosa pine, with associated increases in wildfire, particularly in the western Cascades.

Keywords: private forest landowners, climate change adaptation, wildfire

INTRODUCTION

A coupled human and natural systems (CHNS) approach to evaluating private management of fire-prone landscapes proposes a conceptual model in which forest landowners and managers respond to biophysical landscape conditions (e.g., vegetation, fuel conditions) and the existing fire regime via management actions, such as thinning, harvest, and replanting (e.g., Kline et al. 2016, 2017). These management actions alter biophysical characteristics and influence the fire regime that landowners and managers face in subsequent years (fig. 1). Both the human and biophysical systems also are influenced by exogenous factors, such as climate change, while landowners also are influenced by market forces, policies, and other socioeconomic factors.

A key reason for taking a coupled systems approach to wildfire and climate change, when private land is involved, is because human-caused disturbance is the primary source of tree mortality on private forest lands. In Washington, Oregon, and California, for example, harvesting accounts for between 71 and 87 percent of mortality on non-federal land, versus 5 to 16 percent on federal lands. Vegetation growth models typically presume some type of forest disturbance that links current and future landscapes, but these models often do not explicitly model forest management by landowners. As a result, analysts may

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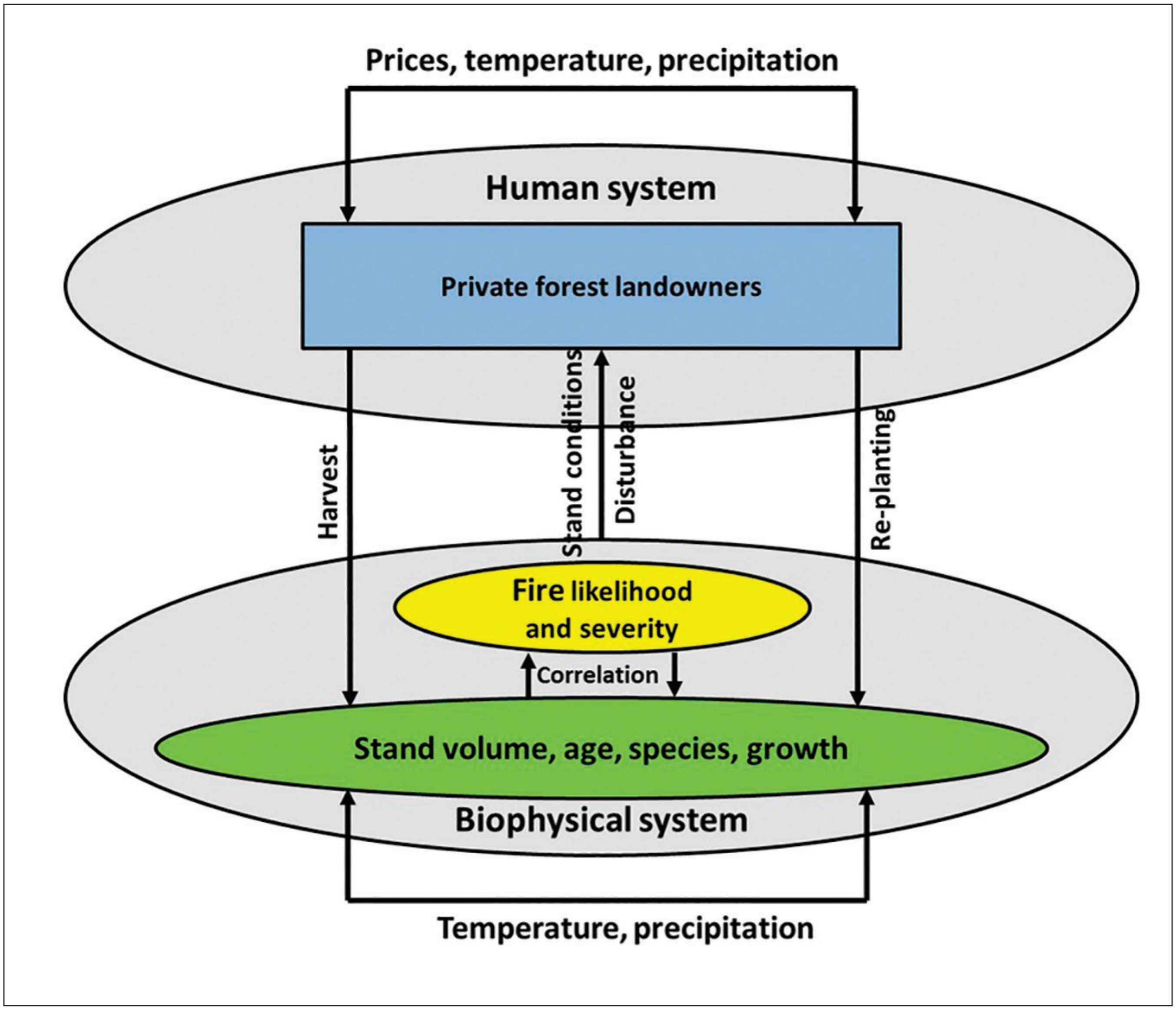

Figure 1—Coupled human and natural systems conceptual model of private forest landowners and their interactions with biophysical landscape features and wildfire, including climate influences (adapted from Kline et al. 2016, 2017).

miss opportunities for understanding the role that various biophysical and socioeconomic factors play in influencing landscape change.

We examined how private landowners might adapt to changing climate and what that would imply for future landscape change. We modeled three processes: (1) the timing and intensity of timber harvests; (2) the choice of tree-species replanted following harvest; and (3) what these landowner behaviors—in reaction to climate change and wildfire risk—could mean for future landscape conditions and disturbance. We also examined the influence of carbon pricing policies to mitigate climate change on these landscape changes.

METHODS

Study Area

Our study area included Washington, Oregon, and California, and our primary data were the Forest Inventory and Analysis (or FIA) data for these States. A key task was anticipating how private forest landowners' adaptation to climate change would influence future spatial distributions of forest species. Current distributions of species include the Douglas-fir forest type largely on the western portions of Washington and Oregon, interspersed with hardwoods, with ponderosa pine and other softwoods prevalent east of the Cascades, and extensive regions of hardwoods in portions of California, for example. Different species thrive in different locations and under different climatic conditions. If landowners are adapting to a changing climate, their post-harvest replanting choices conceivably would be influenced by expectations concerning the viable ranges of different species under those changing climatic conditions. A key difference in species viability is the juxtaposition of Douglas-fir, preferring moist conditions with moderate temperatures, versus hardwoods which tolerate warmer and drier conditions, for example. These differences in viability influence the profitability of growing different species under changing climatic conditions, and thus the choices that landowners are likely to make as they adapt.

Empirical Modeling

We used the historical FIA data to estimate four regression equations in a nested logit framework. One equation evaluated the likelihood that landowners elected to harvest via clear-cut or partial cut, or choose not to cut, between successive FIA inventories. For harvested plots, a second equation evaluated which species (or forest type) landowners chose to replant. For unharvested plots, a third equation evaluated the likelihood that the plot experienced natural disturbance, including wildfire. Lastly, for plots experiencing specifically wildfire, a fourth equation evaluated fire severity. Our analysis was based on the work of Hashida (2017). A complete description of our methods is provided in Hashida and Lewis (2017).

The specific variables that factored into each equation varied. Harvest was modeled as a function of current harvest revenue (prices, species, volume, age), as well as potential future yield—characterized as change in volume according to an expected growth curve, climate variables including expected future temperatures and precipitation, and disturbance likelihood. Similarly, post-harvest replanting was modeled as a function of potential future revenue, characterized by future timber prices, tree growth, site productivity, and expected future temperatures and precipitation. Natural disturbance and fire severity were modeled as functions of species, volume, and future temperatures and precipitation.

Additional data informs the modeled replanting choice set available to landowners who harvest, to account for spatial changes in the viability of different forest species in the future under climate change. We used "plant viability scores" developed by the USDA Forest Service (Crookston et al. 2010), combined with climate projections, to reflect the likelihood that future climate at any given location would be suitable for each species. Projections of future temperatures and precipitation under climate change, combined with plant viability scores, suggest a gradual reduction in the viable growing range of Douglas-fir, and gradual expansion of the viable growing range of ponderosa pine, for example, with shifts in viable ranges for other species as well.

Simulations

Using these estimated equations, we simulated landowners' future harvest and replanting choices under climate change using down-scaled (1 km resolution) climate data for representative concentration pathway (RCP) 8.5 from the National Center for Atmospheric Research's (NCAR), Community Climate System Model (CCSM) (Wang et al. 2012). The RCP-8.5 scenario is a business as usual scenario that anticipates a 5 degree Celsius increase in average global temperature through 2100. This is expected to result in warmer and drier conditions for most of the western portions of Oregon, Washington, and northern California; and warmer and wetter conditions for eastern portions of those States.

Simulation steps involved: (1) estimating harvest as either clear-cut, partial cut, or no cut; then (2) for harvested plots, estimating the replanted species choice; and then (3) in the no-cut cases, estimating the incidence of natural disturbance; and finally (4) in the case of wildfire, estimating fire severity. These outcomes were then used to update forest attributes, which were then combined with climate projections to inform simulation of the next time period. Tree growth models estimated for each forest type enable updating of tree volumes at each simulation step. We repeated the simulation process through 2100. The result of these simulations was a set of predicted outcomes determined by interactions between landowners' harvest and replanting choices, and the biophysical factors of tree growth, climate change, and natural disturbance.

RESULTS

Forest Types and Natural Disturbance

Our simulations anticipate reductions in Douglas-fir on private forest land in the prime coastal Douglas-fir regions of Oregon and Washington, largely due to the warmer and drier conditions anticipated under RCP-8.5. Our simulations also anticipate increases in ponderosa pine for California, and increases in hardwoods for Oregon and Washington. Hardwoods, in particular, are projected to become a prevalent re-planting choice by 2090, largely due to their viability in the warmer temperatures anticipated. This is notable from a profitability standpoint, since hardwoods tend not to earn as much revenue for private forest landowners compared to other forest types, but under current climate projections would appear to offer greater viability in the future. The extent of all of these landscape changes are fairly subtle, even under the fairly pessimistic RCP-8.5 climate scenario. Because harvesting and replanting tend to occur infrequently, we can expect that adaptation could be a fairly slow process.

Our simulations also anticipate changes in natural disturbance. Recalling the warmer and drier conditions expected for coastal Oregon under RCP-8.5, for example, our projections anticipate elevated disturbance incidences throughout much of western Oregon and northeastern California. Changes in both climate and species choices also are expected to induce changes in harvest choices. For example, our simulations anticipate reduced prevalence of clear-cutting in much of Oregon and Washington, and higher prevalence of clear-cutting in northern California.

The spatial distributions of expected forest type changes suggest fairly dramatic declines of Douglas-fir in coastal Oregon and Washington from 10 to 25 percent, with those declines coming in favor of hardwood expansion. Our simulations also anticipate modest hardwood declines in California, with increases in ponderosa pine. These shifts in forest type could include increased natural disturbance, since FIA data indicate that hardwoods tend to have a higher incidence of natural disturbance than Douglas-fir. We would expect that this increased natural disturbance incidence would be exacerbated by the drier conditions expected under climate change.

Carbon Policy Interactions

An advantage of explicitly modeling landowner behavior when anticipating landscape change under climate change is that it enables simultaneously accounting for the influence of socioeconomic and other factors on landscape change. To demonstrate this, we used our model to examine the combined influence of climate change and carbon pricing on landowners' adaptation responses. Carbon pricing is a policy approach to mitigating climate change by providing payments to forest landowners who alter management of their forest lands in ways that store additional carbon above and beyond what would be stored based on their past management.

We found that implementation of carbon pricing would likely induce faster landscape changes in line with those that would occur under climate change alone. Specifically, with carbon pricing we would see even faster declines in Douglas-fir in coastal Oregon and coastal Washington, for example, and more rapid increases in hardwoods. Although carbon uptake for Douglas-fir typically exceeds that of hardwoods, the difference in total carbon absorbed (?) is negligible in young stands. Moreover, hardwoods exceed Douglas-fir in carbon uptake on low site-class plots, enabling landowners to earn greater carbon payments with hardwoods if carbon prices rise sufficiently. These factors cause the revenue premium of Douglas-fir over hardwood to decline as carbon prices rise, adding to the incentive some private forest landowners may have to shift from Douglas-fir to hardwoods under climate change.

CONCLUSIONS

Our empirical analysis of private forest landowners' harvest and replanting choices under climate change suggests that landowners will alter their harvest and replanting choices, resulting in shifts away from Douglas-fir toward hardwoods in Oregon and Washington; and expansion of ponderosa pine in California at the expense of hardwoods there. Resulting landscape changes could effect changes in natural disturbance regimes, including wildfire, beyond those induced by climate change alone. Accounting for the manner in which private landowners are likely to adapt to climate change helps to improve landscape analysis, by enabling additional analyses of the influence of socioeconomic factors, including policy effects. It is important to remember that landowners are always adapting, whether to climate, prices, policies, or some other factor that happens to be changing. When landscapes involve private landowners, we cannot fully understand how and why a landscape might be changing without examining the factors motivating landowners to manage in the ways they do.

REFERENCES

Crookston, N.L.; Rehfeldt, G.E.; Dixon, G.E.; Weiskittel, A.R. 2010. Addressing climate change in the forest vegetation simulator to assess impacts on landscape forest dynamics. Forest Ecology and Management. 260: 1198–1211.

Hashida, Y. 2017. How does climate change adaptation and carbon price policy affect forested landscapes? An empirical analysis of forest management under climate change on the U.S. west coast. Dissertation. Corvallis, OR: Oregon State University, Department of Applied Economics. http://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/2j62s9767.

Hashida, Y.; Lewis, D.J. 2017. The intersection between climate adaptation, mitigation, and natural resources: An empirical analysis of forest management. Working Paper. Corvallis, OR: Oregon State University, Department of Applied Economics. http://www.science.oregonstate.edu/~lewisda/Hashida_Lewis.pdf.

Kline, J.D.; Ager, A.A.; Fischer, A.P. 2016. A conceptual framework for coupling the biophysical and social dimensions of wildfire to improve fireshed planning and risk mitigation. 13th International Wildland Fire Safety Summit & 4th Human Dimensions of Wildland Fire Conference, proceedings. Missoula, MT: International Association of Wildland Fire: 204-212. https://www.fs.fed.us/pnw/pubs/journals/pnw_2016_kline001.pdf.

Kline, J.D.; White, E.M.; Fischer, A.P.; Steen-Adams, M.; Charnley, S.; Olsen, C.; Spies, T.A.; Bailey, J.D. 2017. Integrating social science into empirical models of coupled human and natural systems. Ecology and Society. 22(3): 25. https://www.fs.fed.us/pnw/pubs/journals/pnw_2017_kline001.pdf.

Wang, T.; Campbell, E.M.; O'Neill, A.; Aitken, S.N. 2012. Projecting future distributions of ecosystem climate niches: uncertainties and management applications. Forest Ecology and Management. 279: 128-40.

What We Know About Mountain Big Sagebrush Fire Ecology, Postfire Recovery Rate, and Fire Regimes

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INTRODUCTION

The area occupied by mountain big sagebrush (*Artemisia tridentata* subsp. *vaseyana*) communities has been greatly reduced since European-American settlement and is likely to be further reduced due to ongoing threats including land use and development, woodland expansion, nonnative plant invasions, altered fire regimes, and climate change. These threats and the recent federal listing review of greater sage-grouse (*Centrocercus urophasianus*) make conservation and proper management of sagebrush communities key priorities.

New publications in the Fire Effects Information System (FEIS, www.feis-crs.org/feis/) include a Species Review of mountain big sagebrush fire ecology (Innes 2017) and a Fire Regime Synthesis of the frequency, severity, pattern, and size of fires in mountain big sagebrush communities before and after European-American settlement (Innes 2018). These publications summarize hundreds of publications by researchers and managers and compliment the recent FEIS Species Review on sage-grouse (*Centrocercus* spp.) (Innes 2016), which are obligate species that require sagebrush communities for food and cover. This obligate relationship may suggest the need to protect remaining sagebrush ecosystems from disturbances such as fire, but sage-grouse habitat requirements vary seasonally. Thus, the species may be best served by a mosaic of sagebrush successional stages that provide diverse, productive forage near security and thermal cover. Such mosaics are beneficial to many wildlife species. Fire was an important driver in creating and maintaining these mosaics historically, so understanding fire ecology, postfire recovery dynamics, and fire history of mountain big sagebrush and other sagebrush taxa is critical for making sound management decisions and avoiding long-term negative impacts to sagebrush communities and associated wildlife. In this extended abstract, we summarize the information on mountain big sagebrush fire ecology and fire regimes reported in these two FEIS publications, which includes the results of our analyses on postfire recovery from over 300 sites. Primary citations used in FEIS publications are not included in this abstract. See the FEIS publications for detailed information and citations.

FIRE ECOLOGY

Regeneration Processes

Mountain big sagebrush plants are easily killed by fire and do not sprout, although hybrids of mountain big sagebrush × silver sagebrush (*Artemisia cana*) may sprout after fire. Postfire establishment is exclusively from seeds, which may be present in the soil seed bank or come from unburned plants in and adjacent to burns. The rate of recovery (i.e., the length of time necessary for canopy cover to reach unburned (or prefire) levels) is driven by timing and abundance of postfire seedling establishment.

Keywords: conifer expansion, fire ecology, fire regimes, mountain big sagebrush, nonnative annual grasses, postfire recovery, regeneration processes, prescribed fire, succession

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Seedling establishment during the first few postfire years is highly variable because it is influenced by many interacting factors including the abundance of viable seeds in the soil seed bank, location of and seed production by unburned plants, postfire moisture availability and weather, and postfire herbivory. Fire timing, severity, size, and pattern affect soil-stored seeds and the amount and distribution of unburned, seed-producing plants. Establishment from soil seed banks may be limited because seeds are vulnerable to lethal temperatures during fire. Unburned mountain big sagebrush plants in and adjacent to burns are important seed sources for postfire establishment; however, seed production is highly variable and depends on weather, site, and plant characteristics (e.g., size, age, and genetics). Most mountain big sagebrush seeds disperse within 3 m of parent plants, so the distance from parent plants to the burn affects the rate and distribution of postfire seedling establishment. Seeds from unburned plants ripen and disperse during fall and winter, typically after wildfire season.

Postfire Succession

Most mountain big sagebrush seedling establishment occurs within the first 4 postfire years, although postfire seedling establishment may be absent or limited on some sites for many years, especially when available moisture is low. Mountain big sagebrush seedling establishment typically slows after the first few postfire years because soil seed banks are depleted and seedlings must compete with other vegetation for resources. Secondary peaks in establishment occur when mountain big sagebrush individuals that established soon after fire mature and produce seeds (anywhere from 2 to >13 years old). Thereafter, establishment may be episodic.

In the absence of fire or other disturbances (e.g., heavy browsing, freeze-kill, snow mold, and drought), mountain big sagebrush can dominate shrub steppe communities indefinitely. However, when the interval between fires is long enough for junipers (*Juniperus* spp.), pinyons (*Pinus* spp.), and other conifers to establish and mature, woodlands may expand into adjacent mountain big sagebrush communities. The rate of woodland expansion varies with conifer species and site characteristics. Woodland expansion is most common on sites with frigid to mesic soil temperature regimes and xeric soil moisture regimes. Cover of mountain big sagebrush and native grasses and forbs declines as cover of trees increases during succession. Succession of mountain big sagebrush communities to late-successional woodlands causes changes in wildlife habitat, fuel characteristics, and fire behavior.

POSTFIRE RECOVERY RATE

Due to concerns regarding habitat requirements for sagebrush obligates, postfire recovery rate has been the focus of numerous studies. We obtained data from 306 burned sites examined in 20 studies to synthesize information on mountain big sagebrush recovery. To assess changes in postfire recovery across all sites over time, we averaged these data within 5-year, time-since-fire bins and plotted recovery versus time-since-fire (fig. 1), and we used a binary logistic regression model to estimate the overall probability of recovery over time (fig. 2). Sites were classified as “recovered” when mean canopy cover equaled or exceeded unburned (or prefire) canopy cover and “not recovered” when mean canopy cover was less than unburned (or prefire) cover. We then explored whether changes in recovery over time differed geographically by plotting postfire recovery by time-since-fire for each of eight ecoregions.

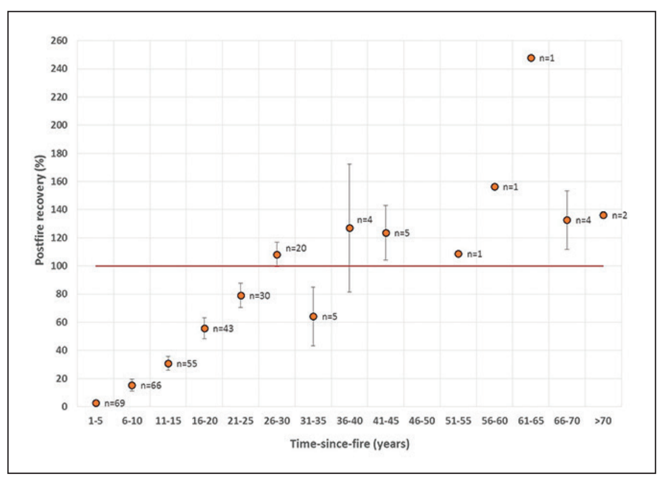

Figure 1—Percent mean ratio (±SE) of burned to unburned (or prefire) canopy cover (i.e., “postfire recovery”) of mountain big sagebrush averaged within 5-year, time-since-fire bins. The red line indicates recovery to unburned (or prefire) canopy cover.

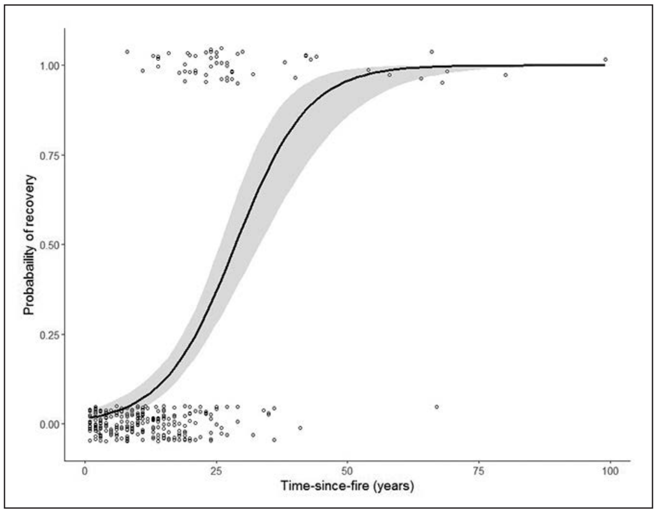

Figure 2—Binary logistic regression analysis of mountain big sagebrush postfire recovery as a function of time-since-fire (n = 306 burned sites). Circles around the “1” line on the y-axis indicate recovered sites, and circles around the “0” line indicate sites that had not recovered to unburned canopy cover. The solid line represents the probability function derived from the prediction equation and the gray area shows the 95% confidence interval.

Our analyses showed that mountain big sagebrush canopy cover and postfire recovery increased fairly consistently during the first 30 postfire years. On average, mountain big sagebrush sites began reaching full recovery around 26 to 30 years after fire (fig. 1), when mountain big sagebrush canopy cover averaged 28 percent, although variability among sites is high. On average, a given site has little chance of recovery (12%) within 15 years, a 50 percent chance of recovery in 29 years, and a high chance of recovery (95%) in 49 years ($P < 0.0001$) (fig. 2); however, the certainty around these probabilities varies. Based upon 95% confidence intervals (shown by the gray area in fig. 2), uncertainty of recovery is greatest for sites about 25 to 50 years after fire, due to a similar number of recovered and unrecovered sites in that age range.

Mountain big sagebrush postfire recovery may be faster on some sites and in some ecoregions than in others; however, differences in unburned cover values (i.e., the recovery threshold) among study sites and in the number of study sites among ecoregions complicate comparisons of postfire recovery within and among ecoregions. Overall, sites in the Middle Rockies appeared slowest to recover, in part due to heavy postfire browsing; however, exceptions occurred and a site with sprouting mountain big sagebrush hybrids recovered relatively fast, reaching 20 percent canopy cover 15 years after fire. These results emphasize the importance of postfire land use and prefire plant community composition in estimating postfire recovery rates.

FIRE REGIMES

Presettlement fires in the sagebrush biome were both lightning- and human-caused. Peak fire season occurred between April and October and varied geographically. Wildfires were high-severity, stand-replacement fires. Fire frequency was influenced by site characteristics, and frequency estimates range from decades to centuries, depending on the applicable scale, methods used, and metrics calculated. Because mountain big sagebrush steppe communities occur over a productivity gradient driven by soil moisture and temperature regimes, fire regimes likely varied across the gradient, with more frequent fire on more productive sites that supported more continuous fine fuels. Sites with mountain big sagebrush burned more frequently than sites with Wyoming big sagebrush (*A. t.* subsp. *wyomingensis*) because the former tend to be more productive. Mountain big sagebrush communities adjacent to fire-prone forest types (e.g., ponderosa pine (*Pinus ponderosa*)) may have had more frequent fires than sites adjacent to less fire-prone types (e.g., pinyon-juniper) and those far from forests and woodlands. Most fires were likely small (less than ~500 ha), and large fires were infrequent. Large fires were most likely after one or more cool, wet years that allowed fine fuels to accumulate and become more continuous.

Since European-American settlement, fuel and fire regime characteristics in many big sagebrush (*A. tridentata*) steppe communities have shifted outside the range of historical variation. Settlement generally began in the mid-1800s and caused changes in ignition patterns and fuel characteristics, although the timing and magnitude of these changes varied among locations. Since then, fuels and fire regimes in many sagebrush ecosystems have changed due to a combination of interrelated factors, including land development for agriculture and energy, urbanization and infrastructure development, proliferation of nonnative invasive plants, woodland expansion, overgrazing by livestock, fire exclusion, and climate changes. Since 1980, the number of fires each year and total annual area burned have increased in the sagebrush biome. However, in most mountain big sagebrush communities, available data suggest that fire frequency has either not changed or has been reduced, with the exception of an area in the Colorado Plateaus ecoregion where fire frequency may have increased due to frequent prescribed burning.

MANAGING MOUNTAIN BIG SAGEBRUSH COMMUNITIES

Creating and maintaining sufficient habitat and forage for wildlife, especially sagebrush obligates, are primary objectives of managing mountain big sagebrush communities. This involves increasing resilience to stress and disturbance and enhancing resistance to establishment and spread of nonnative species. Resilience and resistance differ among big sagebrush communities, and generally increase with increasing soil moisture availability and decrease with increasing soil temperature; thus, researchers emphasize the importance of site-specific management. Fire management considerations are covered in the following sections.

Wildlife Considerations

Challenges of managing mountain big sagebrush communities for wildlife include maintaining sufficient mountain big sagebrush cover and native herb abundance while reducing opportunities for conifer and nonnative plant establishment and spread. Mountain big sagebrush provides important forage and cover for many wildlife species, particularly in winter, and fire reduces its abundance for many years. Conversely, prescribed burning may increase the abundance and productivity of native herbs for up to 10 postfire years, providing important forage for sage-grouse and wild ungulates. A landscape mosaic of successional stages provides wildlife habitats with diverse, productive forage near areas with security and thermal cover, but effects depend on the ratio of forage to cover over time.

Conifer Management

Prescribed fire is sometimes recommended to reduce conifer establishment in mountain big sagebrush communities because cover of mountain big sagebrush and native herbaceous species decline with increasing conifer cover, which is detrimental to sagebrush obligates. Because conifers are important habitat components for many facultative wildlife species, especially if tree density is low enough to allow a healthy understory of shrubs and grasses, researchers generally only advocate conifer removal in areas where trees were historically absent or where tree density has increased since European-American settlement. Several researchers recommend that priority for conifer removal be given to mountain big sagebrush sites in early to middle stages of woodland succession, before trees become dominant, because they are likely to have more native plants in the understory and more native seeds in the soil seed bank, making them more resilient than sites in later stages of woodland succession.

Nonnative Plants

Of the nonnative plants present in mountain big sagebrush ecosystems, annual grasses pose the biggest threat because they alter fuel characteristics in invaded communities and have the potential to increase the frequency, size, spread rate, and duration of wildfires. Among nonnative annual grasses of concern in big sagebrush communities, cheatgrass (*Bromus tectorum*) has been the most harmful. While mountain big sagebrush communities are among the least susceptible of big sagebrush communities to invasion by cheatgrass, cheatgrass can dominate mountain big sagebrush communities after fire, especially if pre- and postfire cover of native herbs is low and weather is favorable for cheatgrass establishment and growth. Areas with a history of overgrazing by livestock or a high density of conifers are likely to have low cover of native perennial grasses and therefore less resistance to the establishment and spread of cheatgrass after fire. In areas where native perennial plant cover is depleted, seeding after fire may help stabilize soils, increase recovery of native plants, and prevent establishment and spread of cheatgrass and other nonnative plants. Prescribed fire is recommended only in areas where postfire dominance by nonnative plants is unlikely and plans include postfire monitoring and invasive plant management.

Postfire Grazing

Livestock tend to concentrate on burned mountain big sagebrush communities. To protect regenerating plants, many authors recommend excluding livestock for at least 1 or 2 years after fire, or until perennial grasses have recovered and are producing viable seeds in numbers equal to that of unburned levels.

Prescribed Fire

In general, fire is considered an appropriate and effective tool only on sites where mountain big sagebrush is abundant, native perennial grasses and forbs are present, nonnative plants are absent or sparse, and plans include postfire monitoring and invasive plant management.

Authors recommend that fires in mountain big sagebrush communities be frequent enough to prevent tree establishment and succession to conifer woodland, but not more frequent than the amount of time required for mountain big sagebrush to recover (~26 to 30 years, on average, although use of site-specific estimates is critical). Postfire recovery of mountain big sagebrush communities is likely to be faster if fires are small or patchy, with unburned plants inside burn perimeters. Authors recommend burning when plants are dormant, either in the spring or fall, if the objective is to produce a patchy burn that reduces big sagebrush cover and increases herbaceous plant production.

CONCLUSIONS

The FEIS publications on mountain big sagebrush fire ecology and fire regimes help land and resource managers locate and apply the best available science to planning and management decisions because they synthesize information from hundreds of sources and describe management implications.

REFERENCES

Innes, Robin J. 2016. *Centrocercus minimus*, *C. urophasianus*, sage-grouse. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: www.fs.fed.us/database/feis/animals/bird/cent/all.html.

Innes, Robin J. 2017. *Artemisia tridentata* subsp. *vaseyana*, mountain big sagebrush. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: https://www.fs.fed.us/database/feis/plants/shrub/arttriv/all.html.

Innes, Robin J. 2018. Fire regimes of mountain big sagebrush communities. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: https://www.fs.fed.us/database/feis/fire_regimes/mountain_big_sagebrush/all.html.

Modeling Fire Severity in Eastern Washington Using Mapped Surfaces of Climate, Weather, and Topography

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Wildfire is the most important disturbance agent affecting forest landscape structure across the inland western United States. In recent decades, rates of annual area burned have outpaced restorative treatments across the region, and there is a need for more reliable models of fire severity and associated ecological impacts. Such tools would be useful for strategically focusing management efforts. We used remotely-sensed burn severity, topography, climate, and weather data to identify predictors of fire severity for 284 wildfires that burned in eastern Washington between 1985 and 2015. Our study domain included the Colville and Okanogan-Wenatchee National Forests.

We modeled fire severity as measured by remotely sensed burn severity indices derived from Landsat satellite imagery. We used machine learning, via random forest modeling, to (1) quantify variable importance of fire severity predictors, (2) examine the response functions of each predictor with respect to burn severity, and (3) evaluate relations between predictors and fire severity, and how they vary by topography, local climate and weather. We used principal coordinates of nearest neighbor modeling (PCNM) and variance partitioning to reveal the strength of influence of spatial autocorrelation among our predictors and to help assess individual and shared variance components of our model predictors.

Our results showed that spatial patterns in the model were quite strong, accounting for 38 percent variance explained by itself. Variance partitioning analysis revealed considerable overlap between spatially explained variance and variance explained by our non-spatial covariates (fig. 1). In particular, climate and weather variables had considerable overlap with spatial variance. We believe this raises questions about the true strength of the relationship between biophysical variables and fire severity.

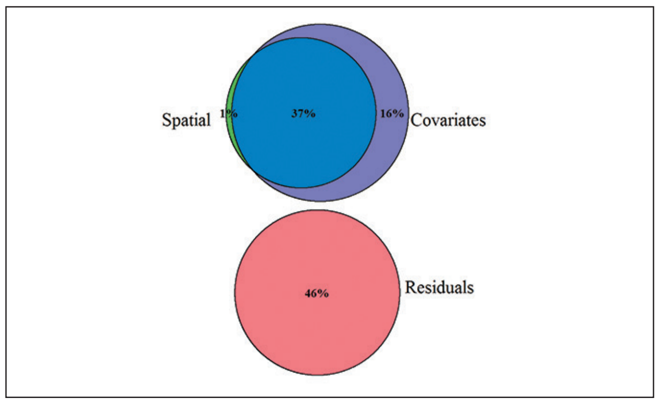

Figure 1—A venn diagram displaying variance decomposition of our random forest model of fire severity. The green circle is the portion of variance explainable by spatial patterns, the blue circle is the portion explainable by biophysical covariates, and the red circle is residuals. The overlap between the green and blue circles indicates the variance explainable either spatially or with the biophysical covariates. The area of the circles and overlap is to scale, and are labeled with their precise values.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Wildfire Hazard Assessment for Community Land Use Planning: A Case Study in Chelan County, WA

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INTRODUCTION

Federal wildland fire agencies are increasingly reaching across jurisdictional boundaries to their state, county, and local partners to better manage the unwanted effects of wildland fire, guided, in part, by the National Cohesive Wildfire Strategy. This collaborative and inclusive fire management strategy includes efforts to promote fire adapted communities through improved land use planning via a program called Community Planning Assistance for Wildfire (CPAW, http://planningforwildfire.org/). CPAW provides communities with professional assistance from land use planners, foresters, economists, and wildfire modelers to integrate wildfire mitigation into the development planning process. Communities apply to participate and implementation of recommendations is under the authority of local jurisdictions. We report on the collaborative CPAW process between federal research and management with county and local representatives in Chelan County, WA, to map wildfire hazard as the basis for identifying areas where existing and proposed development may require regulation that safeguards life and property.

Together, maps of wildfire hazard, wildland-urban interface (WUI), and mitigation difficulty provide spatial context to delineate land use planning regulations, like requirements for fire-resistant building materials or defensible space. We summarized burn probability outputs from fire behavior models to quantify wildland fire hazard at two spatial scales, as relevant to Chelan County community wildfire risk management interests. We emphasize the importance of an iterative and collaborative process of modifying methods according to local input, and we highlight the value of discussions about the mapping process in bringing diverse stakeholders together to fortify relationships around community wildfire risk reduction.

CHARACTERIZING WILDFIRE HAZARD

Wildfire hazard is a measure of the likelihood that an area will burn and the likely intensity of the burn, given that a fire occurs. For this community assessment in Chelan County, we used established wildfire risk assessment methodology (Scott et al. 2013) to develop wildfire hazard maps for two scales: "landscape" and "local."

Landscape-level Wildfire Hazard

We integrated wildfire likelihood and intensity information from 120-m cell size fire behavior modeling outputs from the Large Fire Simulator (FSim; Finney et al. 2011), originally produced for a wildfire risk assessment for OR and WA (Stratton 2017), to characterize "landscape" wildfire hazard, or the hazard due to large fires. Landscape level fire likelihood (i.e. burn probability), is the FSim-modeled annual likelihood that a wildfire will burn a given point or area. FSim can apportion burn probability into wildfire intensity levels and produce estimates of the probability of a certain flame length, given a fire

Keywords: wildfire hazard assessment, Chelan County, fire behavior modeling, community land use planning, CPAW (Community Planning Assistance for Wildfire)

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burns a pixel. Conditional flame length is the weighted average of all flame length probabilities that FSim simulated for each 120-m pixel. We multiplied the burn probability by the conditional flame length raster to produce the landscape wildfire hazard raster.

To summarize the spatial metrics of likelihood, intensity and hazard for the "landscape" analysis, we chose subwatersheds ("HUC12"; Watershed Boundary Dataset, USDA-NRCS et al. 2017) as the polygon summary unit within which we assigned the mean of all pixel values. The HUC12 unit is based on the areal extent of surface water draining to a point, is commonly used to summarize landscape attributes, and is "administratively-neutral", as it is not related to administrative or political boundaries. Using a biophysically-based summary unit is important because fire spread is inherently dynamic and fire moves across landscapes without respect to political boundaries. Additionally, summarizing pixel-based information to polygons allows for broad-scale patterns to emerge that may not be immediately obvious in the raw pixel datasets. We classified the mean landscape wildfire hazard into three classes (Moderate, High, and Very High) based on quantiles in the distribution of values within the analysis area (fig. 1A). We did not include a "Low" wildfire hazard category, as every pixel on the landscape is within 1.5 miles of burnable vegetation, and as such, we assumed that everywhere in the county is potentially exposed to fire branding.

Local-level Wildfire Hazard

While the "landscape"-level hazard assessment characterizes the large fires which account for the majority of area burned, we also represented local fire events, which can have a devastating impact on a community. Chelan County experienced such an event in 2015 when the Sleepy Hollow fire destroyed 29 homes and several commercial buildings within the city of Wenatchee. At our hazard mapping workshop in 2017, this event was still fresh in the minds of those who experienced it, so community stakeholders wanted to capture the potential for what is often referred to as a "problem fire."

To represent wildfire hazard for a "problem fire" situation, we used the Minimum Travel Time (MTT) option within FlamMap 5.0 (Finney 2006) to generate burn probabilities and flame length probabilities under 97th percentile weather conditions. Performing a custom simulation for the county also allowed us to

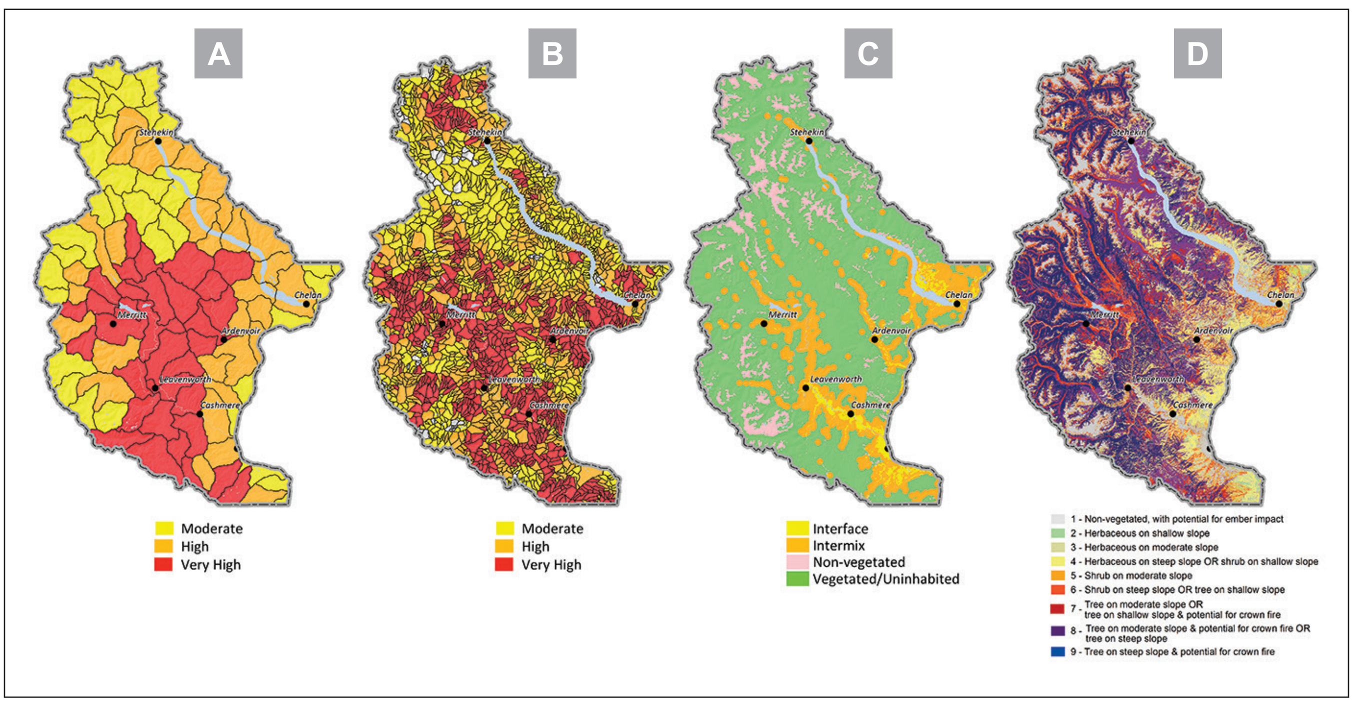

Figure 1—Maps needed to provide spatial context to Chelan County CPAW land use planning recommendations: (A) "Landscape" wildfire hazard; (B) "Local" wildfire hazard; (C) Wildland urban interface; (D) Mitigation difficulty.

tailor landscape and fuels simulation inputs to reflect local conditions at a finer spatial resolution. We used the same 30-m resolution landscape files (including all topography and fuels spatial data necessary to parameterize FlamMap 5.0; LANDFIRE 2014) that were the basis for the "landscape" assessment, but we modified them to represent local conditions. We made the following changes to the input fuel model layers to reflect input from subject matter experts (SMEs):

- Past fires and fuel treatments—we devised rulesets in collaboration with SMEs to change the fuel model, canopy height, canopy cover, and canopy bulk density layers to represent how the landscape changed as a result of these disturbances. Rules depended on factors such as time since disturbance, existing fuel conditions, elevation, land ownership type, and treatment type.
- Ravines—heavy fuel commonly accumulates in ravines adjacent to homes and orchards due to landowners discarding landscaping debris. SMEs reported that these fuels contributed to extreme fire behavior that caused structure loss during the Sleepy Hollow fire. We used a derivative of a digital elevation model and other GIS techniques to identify ravines near homes and orchards, and we changed the fuel model in those areas to a slash/blowdown model that produces high intensity fire behavior.
- Orchards—in Chelan County, SMEs reported that orchards are typically irrigated and thus do not contribute to fire behavior. We obtained an agriculture GIS layer from the county and represented orchards as non-burnable fuels.

We initialized the MTT module within FlamMap5.0 with 54,044 fire ignitions whose locations were random, but informed by locations where wildfires have occurred during the period of 1992 through 2015 (Short 2017). Using FlamMap5.0 outputs, we created a set of six flame length probability rasters (one for each flame length class: 0-2 ft , 2-4 ft, 4-6 ft, 6-8 ft, 8-12 ft, >12 ft), and calculated a conditional flame length raster as the sum-product of the probability and the flame length across all flame length classes. Finally, we calculated the final local wildfire hazard raster as the product of the burn probability and conditional flame length rasters.

To summarize the spatial metrics of likelihood, intensity and hazard for the "landscape" analysis, we chose National Hydrography Dataset Plus V2 catchments (USEPA and USGS 2012). Catchments are local level drainage areas and typically subdivide HUC12 watersheds into smaller polygon units. Following the same approach used in the "landscape" level analysis, we classified the mean "local" wildfire hazard into three classes (Moderate, High, and Very High) based on quantiles in the distribution of values within the analysis area (fig. 1B).

MAPPING WILDLAND URBAN INTERFACE

We mapped categories of structure density integrated with wildland vegetation to characterize where structures exist within or adjacent to burnable wildland vegetation in Chelan County. Though we generally followed methods that mimic Federal Register Wildland Urban Interface definitions (USDA and USDI 2001) as adapted by Martinuzzi et al. 2015, we customized our mapping to include representation of structures in rural areas.

Conventionally, WUI is mapped using census data for population density information and census blocks as the summary unit. In Chelan County, the size of the census blocks range from less than an acre to over 265,000 acres and though structures may exist in the larger blocks, the value attributed to the entire block will be a "low structure density" class, with no spatial delineation as to where the structures exist within the larger unit. Since the county has accurate and up-to-date address point data for all structures, we were able to use these points, instead of census data, to represent structures for our WUI mapping effort. We input the point data into a Kernel Density tool (ESRI 2015) to create a 30-m resolution raster surface of structure density, which we then sliced into the ranges of values specified in the Federal Register definition (structures per km2): < 6.18, 6.18 – 49.42, 49.42 – 741.32, and > 741.32, to represent Very Low, Low, Medium, and High structure density, respectively.

To map the vegetation conditions as specified in the WUI definition, we assumed wildland vegetation as anything that is classed with a "burnable" fuel model in the same fuel model raster data that we used as input to our fire behavior modeling. We used Focal Statistics (ESRI 2015) to create a raster surface in which 30-m pixel values represent the percentage of burnable fuel within a 40 ac window, which we then classified into two levels: 50 percent and 75 percent vegetation. Finally, we combined the structure density and vegetation rasters so that the final WUI map included the following categories: Interface, Intermix, Non-WUI Vegetated, and Non-Vegetated or Agriculture (fig. 1C). One modification we made to the rules outlined in Martinuzzi et al. 2015 was to include the "Vegetated Very Low Density" category (structure density < 6.18 structures/km^2 and wildland vegetation >50%) in the Intermix category. This decision reflects our intent to include isolated structures in rural areas as WUI.

MAPPING MITIGATION DIFFICULTY

As a complement to the "landscape" and "local" wildfire hazard assessments, we calculated an index that characterizes the difficulty and effort involved in modifying landscape characteristics in a way that could reduce wildfire hazard. To create the components necessary to map mitigation difficulty, we developed three 30-m resolution raster datasets, as follows:

- Vegetation Life form—We classified the Existing Vegetation Type (LANDFIRE 2014) data set into four life form classes: 1. Barren/Developed/Sparsely Vegetated/Irrigated Agriculture, 2. Grass, 3. Shrub, 4. Tree.
- Slope—We classified the same slope dataset that we used in our fire behavior modeling landscape (LANDFIRE 2014) into three classes: 1. Steep (≥ 30%), 2. Moderate (15-30%), and 3. Shallow (≤ 15%).
- Crown Fire Activity—We used the Crown Fire Activity (CFA) raster output layer from our Basic FlamMap modeling to represent the potential for crown fire. CFA characterizes the potential for fires burning in surface fuels to transition into tree crowns, based on mapped fuel characteristics and modeled wind speeds and indicates if a pixel could experience passive or active crown fire. For the mitigation difficulty index, we collapsed CFA values into two categories: 1. No crown fire potential, and 2. Potential for either active or passive crown fire.

We integrated the spatial layers described above to create map categories representing the difficulty of mitigating wildfire hazard, with difficulty increasing from 1 to 9 (fig. 1D):

1—Non-vegetated, with potential for ember impact

2—Herbaceous on shallow slope

3—Herbaceous on moderate slope

4—Herbaceous on steep slope OR shrub on shallow slope

5—Shrub on moderate slope

6—Shrub on steep slope OR tree on shallow slope

7—Tree on moderate slope OR tree on shallow slope with potential for crown fire

8—Tree on moderate slope with potential for crown fire OR tree on steep slope

9—Tree on steep slope with potential for crown fire.

IMPACT OF THE MAPPING PROCESS

During the CPAW process in Chelan County, team members met with community stakeholders, evaluated community conditions and existing planning documents, and ultimately provided the community with a set of voluntary recommendations to more effectively address the WUI through appropriate land use planning strategies. The hazard, WUI and mitigation difficulty maps aid planners in assessing an existing or future development area for wildfire exposure and also guide implementation of a wildland urban interface code, which delineates standards that might apply depending on levels of exposure and mitigation difficulty. As part of the final CPAW package of products, we delivered a geodatabase containing the final map products, and we provided demonstrations and explanations of data limitations and "best practices" to empower users to take ownership of the data.

Not only do the maps provide spatial context for planning recommendations, but during site visits with stakeholders and SMEs, we found that the discussions that we had about the mapping process were also critically important. Community members affirmed the value of convening multidisciplinary professionals from various agencies to work together on the development of community wildfire hazard maps, ultimately fostering collaborative wildfire risk reduction in Chelan County.

REFERENCES

ESRI. 2015. ArcGIS for Desktop. Version 10.3.1. Redlands, CA: Environmental Systems Research Institute.

Finney, M. 2006. An overview of FlamMap fire modeling capabilities. Andrews, P.L.; Butler, B.W., comps. Fuels management-How to measure success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 213–220.

Finney, M.; McHugh, C.; Grenfell, I.; Riley, K.; Short K. 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stochastic Environmental Research and Risk Assessment. 25: 973–1000.

LANDFIRE. 2014. LCP layers, LANDFIRE 1.4.0. Washington, DC: U.S. Department of the Interior, Geological Survey.

Martinuzzi, S.; Stewart, S.; Helmers, D.; Mockrin, M.; Hammer, R.; Radeloff, V. 2015. The 2010 wildland-urban interface of the conterminous United States. Research Map NRS-8. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 124 p.

Scott, J.; Thompson, M.; Calkin, D. 2013. A wildfire risk assessment framework for land and resource management. Gen. Tech. Rep. RMRS-GTR-315. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 83 p.

Short, K. 2017. Spatial wildfire occurrence data for the United States, 1992-2015 [FPA_FOD_2010508]. 4th Edition. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2013-0009.4.

Stratton, R. 2017. Quantitative wildfire risk assessment for Oregon and Washington. USFS Pacific NW & Alaska Regions/BLM State Office. Portland, OR. Project Manager: Rick Stratton.

USDA and USDI. 2001. Urban wildland interface communities within vicinity of Federal lands that are at high risk from wildfire. Federal Register 66: 751–777.

USDA-NRCS, USEPA, USGS. 2017. National Hydrography Dataset (NHD) Best Resolution 20170517 for Washington State or Territory FileGDB 10.1 Model Version 2.2.1.

USEPA and USGS. 2012. National Hydrography Dataset Plus—NHDPlus. Edition 2.10.

Using Landscape Simulation Modeling to Develop an Operational Resilience Metric

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Abstract—Ecological resilience is a concept that is now being used to guide U.S. land management into the uncertain future. However, there are few operational means of assessing the resilience of a landscape or ecosystem. We present a new method for quantifying resilience that uses simulated historical range and variation (HRV) time series as the benchmark or reference to compare to contemporary conditions to assess resilience. However, managing for resilience based on historical conditions is somewhat tenuous in this era of climate change, therefore we integrate projected future conditions with HRV to inform the management of ecosystems and landscapes for resilience. We use simulation results from the FireBGCv2 landscape model applied to a large landscape in western Montana USA to illustrate the methods presented here.

Keywords: historical range and variation (HRV), future range of variability (FRV), landscape modeling, ecosystem management, climate change, land management, landscape ecology, historical ecology

INTRODUCTION

Managing for "ecological resilience" is mandated by U.S. policies to guide publicly-owned landscapes into a future made uncertain due to the anticipated complex and sometimes novel interactions of anthropogenic climate change; exotic plant, insect, and pathogen invasions; and industrial, agricultural, and urban development (Moritz and Agudo 2013; Schoennagel et al. 2017). The National Cohesive Wildland Fire Management Strategy, for example, specifies *creating resilient landscapes* as one of its three major goals (USDOI and USDA 2014) and the U.S Forest Service is mandated to restore natural resources to be "more resilient to climate change" (USFS 2012). However, there are few standard metrics available to easily evaluate or quantify resilience using existing theory (Angeler and Allen 2016; Falk 2016). To manage for ecological resilience, land managers must have a standardized and scientifically credible method of quantifying resilience that is based on tangible concepts that can be included in land planning analyses (Stephens et al. 2016; Colavito 2017).

We suggest that the first step towards moving from resilience theory to its application in land management is to create a simple operational method. In this paper we present a method to quantify resilience within a

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

specific area, defined as a single ecosystem, a planning area, or an entire landscape. The primary assumption of this proposed method is that ecosystems are most resilient when they are within the broad of historical range and variation (HRV; Morgan et al. 1994) because HRV represents those conditions under which most of the biota has evolved. However, rapid climate change, land use actions, exotic species invasions, and a host of other human impacts into the future requires a broader assessment than HRV alone. Therefore, we have integrated a companion FRV (future range of variation) expression into this method to help inform future land management targets. Overlaps between HRV and FRVs may provide possible targets for specific management-oriented environmental variables. We show examples of how to deploy this method into operational use, even in cases where there is little apparent overlap between the HRV and FRV.

HRV-RESILIENCE METHOD

Creating HRV and FRV Time Series

To demonstrate our HRV-based resilience method, we use simulation modeling to derive time series representing historical and future ranges of variability. We recognize the limitations of a simulation approach to quantify HRV—mainly that all models simplify reality and are subject to bias from input parameters and model mechanics (Keane 2012; Loehman et al. 2016). But simulations can provide the necessary temporally deep, spatially-explicit, and rich historical data that can be difficult to obtain elsewhere (Humphries and Bourgeron 2001). Moreover, modeling provides a single, consistent platform for generating the required data to characterize HRV for multiple ecological attributes and for generating projections of FRV under future climates.

All examples presented in this paper were generated from the mechanistic landscape model FireBGCv2 (Keane et al. 2011b) as implemented for the 128,000 ha East Fork of the Bitterroot River (EFBR) watershed on the Bitterroot National Forest, Montana, USA. The lower elevations of the EFBR are dry, mixed-conifer ecosystems of ponderosa pine (*Pinus ponderosa* var. *ponderosa*) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) generally with a primarily frequent, low-severity fire regime (Holsinger et al. 2014). Vegetation at montane elevations are mixed conifer forests (primarily lodgepole pine, Douglas-fir, and subalpine fir (*Abies lasiocarpa*)) with mixed severity fire regimes, while high elevations are whitebark pine (*Pinus albicaulis*), subalpine fir, and spruce (*Picea engelmannii*) forests with a long fire-free interval, high-severity fire regimes. The EFBR has been used in past FireBGCv2 simulation studies with its initialization, parameterization, calibration, and validation described in various papers for the EFBR and other landscapes (Clark et al. 2017; Holsinger et al. 2014; Loehman et al. 2011). We illustrate the HRV- and FRV-resilience procedures using simulations of historical conditions and three future scenarios that incorporate one future climate and three levels of wildfire suppression (0%, 50%, and 98% fires suppressed) under a climate scenario (CRM-C5 RCP 8.5) that represents continuation of current global emissions trends (Rupp et al. 2013). The EFBR landscape's current conditions circa 2010 were used as the initial conditions at the beginning of the simulation; these conditions were measured in the field in 2009-2010 (Holsinger et al. 2014). We output a suite of landscape response variables (table 1) at ten-year intervals for five replicates of 500-year long simulations (using only the last 400 years of output to eliminate the influence of initial conditions for a total of 200 observations).

Quantifying Resilience Using Single and Multiple Response Variables

We use tree basal area (BA, m2 ha-1), often used to represent forest biomass and is commonly used in management, in the box-and-whisker diagrams that show median, 25th, and 75th percentile BA for each 10-year observation interval for the five, 400-year simulations (fig. 1). The comparative range of variation in BA among the four scenarios is immediately evident: the current BA ("Present"; the line on the graph in fig. 1) is well within the HRV interquartile range (IQR, 25th to 75th percentile); indicating it is not departed from the simulated, historical baseline ($p<0.001$). The FRV3 scenario has a significantly smaller IQR and higher median BA (pairwise t-test against FRV1 and FRV2 respectively, $p<0.001$ and $p<0.001$) than the other scenarios because the high (98%) level of fire suppression implemented

Table 1—Response variables output from the FireBGCv2 model and used in the multivariate analysis to determine a metric for resilience.

Variable	Code	Description	Units
Composition	FA-Spp, FS-Spp	Proportion of the landscape occupied by the fire-adapted species (FAD) and fire-sensitive species (FSS), respectively	%
Structure	Seed, Sap, Pole, Mat, Lrg, VLrg	The proportion of the landscape occupied by each of five structural stages	%
Basal Area	BA	Average basal area across all stands on the landscape	$m^2\ ha^{-1}$
Coarse woody debris	CWD	Average loading of CWD (logs greater than 8 cm in diameter) across all stands in the landscape	$kg\ m^{-2}$
Fine woody debris	FWD	Average loading of FWD (woody fuel particles less than 8 cm diameter) across all stands in the landscape	$kg\ m^{-2}$
Outflow	OUTFLOW	Amount of surface water that flows out of a stand each year averaged across all stands	kg water m^{-2}
Net Primary Productivity	NPP	Average biomass production of the stand across the landscape	kg C m^{-2}
Area burned	BURN	Average annual area burned	ha

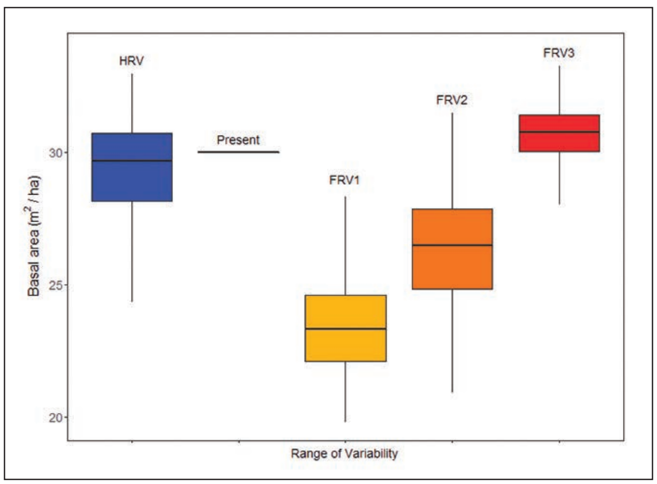

Figure 1—An illustration comparing historical (HRV) and future (FRV) ranges of variability in basal area ($m^2\ ha^{-1}$) compared with current conditions (Present; the initial conditions at the start of the simulation) of the EFBR landscape. There appears to be a zone of overlap between HRV and FRV2 and FRV3, which may provide a possible reference for management. FRV1, FRV2, and FRV3 are future simulations with RCP4.5 climates with zero, 50 percent and 98 percent of the fire ignitions suppressed respectively. The box in this figure are the 25th and 75th interquartiles and the whiskers represent the range of the data.

in this scenario maintains high biomass on the landscape and minimizes fire-caused biomass loss. Its median BA falls within the IQR of the historical reference. The FRV2 scenario has a lower median BA, consistent with a lower implemented suppression level (50%), and a smaller zone of overlap with the historical reference, in which BA is departed for at least half of the simulation years ($p<0.001$). There is little overlap between HRV and FRV1: most observations are outside of the historical reference, where tree mortality from frequent fires and climate stress result in persistently lower BA than the historical reference With this this limited univariate example, it is interesting that greater fire suppression in the future (FRV3) may keep stands within HRV under new climates.

In the univariate method, a simple percentile number can be used as a metric for resilience. In our example above, we would calculate the percentile in which the current (Present) landscape BA resides within the HRV distribution of BA and use that as a relative score to describe resilience (Present was in the 64th percentile or a score of 64 where 50 would be high resilience and below 25 and above 75 would be low resilience, for example). Central tendency statistics that define the variability of the historical envelope and standard probability tests (e.g. one-sample t-test, or one-sample Wilcoxon test for non-normal data) can be used to determine where in the HRV BA probability distribution is the current value for BA and if it is significantly different (departed) from the HRV value. The probability of the current condition in HRV distribution can also be used as a score (Steele et al. 2006), where anything above an alpha significance level of 0.05, for example, could be considered resilient. For current BA in the EFBR, the probability of the current landscape condition in the HRV distribution is 0.69 which is less than our designated alpha level (p>0.05) so this landscape could be considered resilient. Keane et al. (2011a) evaluated several similarity indices for use in HRV comparisons and found that the Sorenson's Index performed best for this task. The Sorenson's Index (number between 1 and 100) is computed for each instance in a time series and the average is compared against current conditions.

We used the PCA approach to assess the importance of multiple variables in the expression of HRV (fig. 2) the first two principal components, which together explained around 45 percent of the variance in the simulation variables, Comparison of the PCA results across all FRV climate-management scenarios provides insight into the potential impacts of changing climate and fire regimes on future landscape resilience (fig. 2). Unlike results from the single variable BA (Figure 1), all three fire management scenarios (0, 50, 98% suppression, respectively) under the RCP8.5 climate depart from HRV, especially FRV3. Moreover, the state of the contemporary landscape (green asterisk) is well outside of HRV and all three FRVs, indicating that it has low resilience when multiple variables are used, regardless of climate or fire management scenario, in contrast to the univariate case. This illustrates the value of using multiple variables when evaluating resilience. The zones of overlap among the three future fire management scenarios and HRV become smaller as suppression increases. Also notice that the zone of overlap for FRV1 and FRV2 (figs. 2B, 2D, 2F) includes all of the HRV "ellipse" so any treatment that moves the landscape towards HRV will also be viable in the future.

Creating a resilience metric from multivariate time series is more difficult. A statistical approach, such as MANOVA, might be used to determine if the current condition is significantly outside the PC1-PC2 centroid, and the magnitude of that distance relative to the acceptable distance could be the metric. In our example, we set the confidence ellipse of HRV at 0.68 or an ellipse containing 68% of the observations. We then computed the ellipse probability that encompassed the current EFBR landscape (Present) at 0.995. If we assume that a 95 percent confidence level ellipse represents a resilient landscape, this test would indicate that the present landscape is in a non-resilient condition. The multivariate PCA HRV-resilience approach can also employ box-and-whisker diagrams using the scores of PC1 from the HRV time series to compare to current conditions similar to our use of BA above. We can also average Sorenson's Index calculations for each variable against the current conditions across all points in the HRV time series to obtain a resilience metric that encompasses multiple variables.

Managing For Resilience

Enhancing resilience, especially in fire-excluded forests, will probably entail some degree of either ecosystem restoration or acceptance of change (Stephens et al. 2016). Other things being equal, restoration treatments should be designed to move the current landscape in the direction of HRV but with an eye towards anticipated future conditions (Falk 1990). For example, the current landscape BA in figure 1 is well within HRV but FRV1 and FRV2 scenarios have significantly less BA. Silvicultural thinnings combined with prescribed fire treatments could be used to reduce BA of fire-sensitive species to enhance the vigor and growth of fire-adapted species in stands in the EFBR landscape to make the restoration treatment more effective into the future. Alternatively or in combination, a higher proportion of natural ignitions could be allowed to burn without full suppression, reducing the effect of fire exclusion as illustrated in our simulation results (figs. 1, 2). Designing treatments using the multi-variate PCA results may be a bit more difficult, but based on the results in figure 2 and the

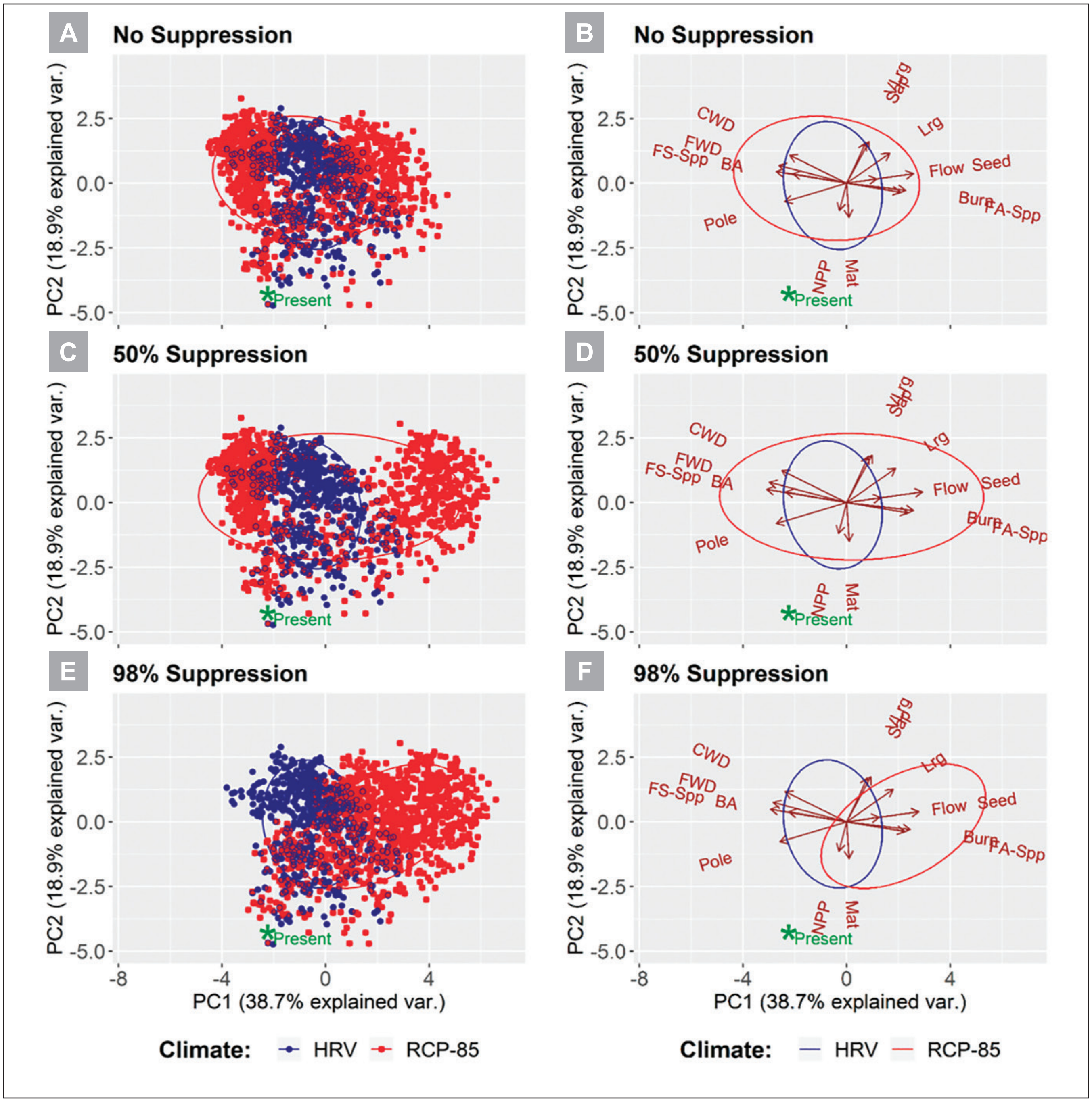

Figure 2—Results of the PCA analysis of the FireBGCv2 simulations for the EFBR landscape for the historical scenario (HRV; blue dots, reference) and for the future RCP8.5 climate (FRV1, FRV2, FRV3) under three fire suppression scenarios (no suppression, 50% ignitions suppressed, 98% ignitions suppressed) showing the simulation years (A,C,E) and the circles that contain 60 percent of the variation in the spread of the points (B,D,F). The green asterisk at the lower left of graphs A, C, E represents the condition of the landscape today. FRV1 is shown in A and B, FRV2 is C and D, and FRV3 is E and F. The variable names in B, D, and F are defined in table 1 and indicate the importance of the variables in the PC1 and PC2 scores.

variables in table 1, possible restoration goals may be to increase large (Lrg) and very large (VLrg) diameter structural stages on the landscape by thinning or prescribed burning in overly dense stands to ensure that smaller diameter pole stands eventually grow into the large structural stages.

REFERENCES

Angeler, D.G.; Allen, C.R. 2016. Quantifying resilience. Journal of Applied Ecology. 53: 617–624.

Clark, J.A.; Loehman, R.A.; Keane, R.E. 2017. Climate changes and wildfire alter vegetation of Yellowstone National Park, but forest cover persists. Ecosphere. 8:e01636.

Colavito, M.M. 2017. Utilising scientific information to support resilient forest and fire management. International Journal of Wildland Fire. 26: 375–383.

Falk, D. 1990. Discovering the future, creating the past: Some reflections on restoration. Restoration and Management Notes. 8(2): 71–72.

Falk, D.A. 2016. Resilience dilemma: Incorporating global change into ecosystem policy and management. Ariz. St. LJ. 48: 145.

Holling, C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology & Systematics. 4: 1–23.

Holsinger, L.; Keane, R.E.; Isaak, D.J.; Eby, L.; Young, M.K. 2014. Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a Rocky Mountain watershed. Climatic Change. 124: 191–206.

Humphries, H.C.; Bourgeron, P.S. 2001. Methods for determining historical range of variability. In: Jensen, M.E.; and Bourgeron, P.S., eds. A guidebook for integrated ecological assessments. New York: Springer-Verlag: 273–291.

Keane, R.E. 2012. Creating historical range of variation (HRV) time series using landscape modeling: overview and issues. In: Wiens, J.A.; Hayward, G.D.; Stafford, H.S.; and Giffen, C., eds. Historical environmental variation in conservation and natural resource management. Hoboken NJ: John Wiley and Sons: 113–128.

Keane, R.E.; Holsinger, L.; Parsons R.A. 2011a. Evaluating indices that measure departure of current landscape composition from historical conditions. Res. Pap. RMRS-RP-83. Fort Collins CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 19 p.

Keane, R. E.; Loehman, R.A.; Holsinger, L.M. 2011b. The FireBGCv2 landscape fire and succession model: A research simulation platform for exploring fire and vegetation dynamics. Gen. Tech. Rep. RMRS-GTR-255. Fort Collins CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 137 p.

Loehman, R.A.; Clark, J.A.; Keane R.E. 2011. Modeling effects of climate change and fire management on western white pine (Pinus monticola) in the Northern Rocky Mountains, USA. Forests. 2: 832-860.

Loehman, R.A.; Keane, R.E.; Holsinger, L.M.; Wu, Z. 2016. Interactions of landscape disturbances and climate change dictate ecological pattern and process: Spatial modeling of wildfire, insect, and disease dynamics under future climates. Landscape Ecology. 2: 1447–1459.

Morgan, P.; Aplet, G.H.; Haufler, J.B.; Humphries, H.C.; Moore, M.M.; Wilson, W.D. 1994. Historical range of variability: a useful tool for evaluating ecosystem change. Journal of Sustainable Forestry. 2: 87–111.

Moritz, C.; Agudo, R. 2013. The future of species under climate change: Resilience or decline? Science. 341: 504–508.

Rupp, D.E.; Abatzoglou, J.T.; Hegewisch, K.C.; Mote, P.W. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research: Atmospheres. 118: 10,884–10,906.

Schoennagel, T.; Balch, J.K.; Brenkert-Smith, H.; Dennison, P.E.; Harvey, B.J.; [et al.]. 2017. Adapt to more wildfire in western North American forests as climate changes. Proceedings of the National Academy of Sciences. 114(18): 4582–4590.

Steele, B.M.; Reddy, S.K.; Keane, R.E. 2006. A methodology for assessing departure of current plant communities from historical conditions over large landscapes. Ecological Modelling. 199: 53–63.

Stephens, S.L.; Collins, B.M.; Biber, E.; Fulé, P.Z. 2016. U.S. federal fire and forest policy: Emphasizing resilience in dry forests. Ecosphere. 7: e01584-n/a.

USDOI and USDA. 2014. The national strategy: The final phase in the development of the National Cohesive Wildland Fire Management Strategy. Washington, DC: U.S Department of Agricultur Forest Service and U.S. Dept. of Interior.

USFS. 2012. National Forest System land management planning. Washington, DC: U.S Forest Service: 123.

Assessing the Work of Wildfires with Post-Fire Landscape Evaluations

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Wildfires across the western U.S. are modifying the structure and composition of forests at rates far exceeding the footprint of mechanical thinning and prescribed fire treatments. Although the pace and scale of management is increasing, the reality is that wildfire is and will continue to be the primary agent affecting vegetation and fuels across forests of the American West. This underscores the need to deliberately incorporate the occurrence and effects of contemporary wildfires into landscape analysis and planning. The "work" of wildfires can be beneficial in terms of reducing fuel loads, enhancing fire resistant species and structure, and creating early-seral habitat. However, many recent wildfires are creating large, high-severity patches in dry forests that were historically dominated by low- and mixed-severity fires. These conditions carry potential risks of elevated fuel loads and shifts in ecosystem states and disturbance regimes. These large fires present managers and collaborative stakeholder groups with the huge challenge of assessing the need for post-fire management and reprioritizing the remaining unburned landscape matrix for green restoration treatments.

We introduce here a framework to quantify and analyze the degree to which wildfires move forest structure and composition towards or away from desired conditions by evaluating wildfire effects relative to historical reference conditions at watershed scales. The landscape evaluation system involves comparison of photo-interpreted pre-fire and post-fire attributes with early twentieth-century historical aerial photographs. Watersheds are photo-interpreted following the Interior Columbia Basin Ecological Management Project (ICBEMP) protocol using imagery collected immediately prior to and after a fire. The departure of the pre-fire and post-fire conditions are then compared against the range of conditions from the historical dataset for the same ecological sub-region (historical range of variation [HRV]) and the next warmest/driest ecological sub-region (future range of variation [FRV]). Effects of the fire are evaluated in terms of moving watershed conditions closer to or further from the reference conditions. We use the fires of 2014 and 2015 in North Central Washington as a model system to test this approach; current work is focused in two sub-watersheds on the Colville National Forest that were burned by the large Stickpin Fire in 2015.

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Within our study area, the Stickpin Fire reduced the amount and patch size of the fire-intolerant subalpine fir cover type to levels closer to, but still above reference conditions. Fire had nominal effects on the amount, and reduced patch size of fire-tolerant conifer species cover, which often resulted in conditions matching reference target windows. Fire increased the amount and patch size of herb and shrub cover to be outside HRV conditions while remaining within FRV conditions. Fire also increased cover of early seral and open canopy structure stages, while reducing high density and vertically diverse structural stages. This generally had the effect of moving current conditions further into the reference condition windows (fig. 1).

Patch density was reduced for nearly all cover types and structural stages, but remained above historical reference conditions (fig. 2). Mean patch size had nominal changes across cover types and structure classes, and remained low relative to reference condition windows. It is likely that reductions in patch density represent the conversion of forested patches into herb and shrub cover, rather than a reduction in fragmentation. Patches of different cover types and structural stages remained overly fragmented post-fire compared to reference conditions, as they were pre-fire.

Generally, fire tended to move conditions closer to reference targets. However, conditions were often not fully restored. Furthermore, major uncertainties remain regarding the future trajectories of the newly created herb and shrub cover patches. If left unmanaged, it is likely that these patches will return to a subalpine cover type. This represents a unique opportunity to leverage the work of these wildfires by replanting with fire-tolerant species. Managers are currently utilizing this information to design landscape prescriptions for both post-fire and green treatments that integrate the work of wildfire with mechanical and prescribed fire.

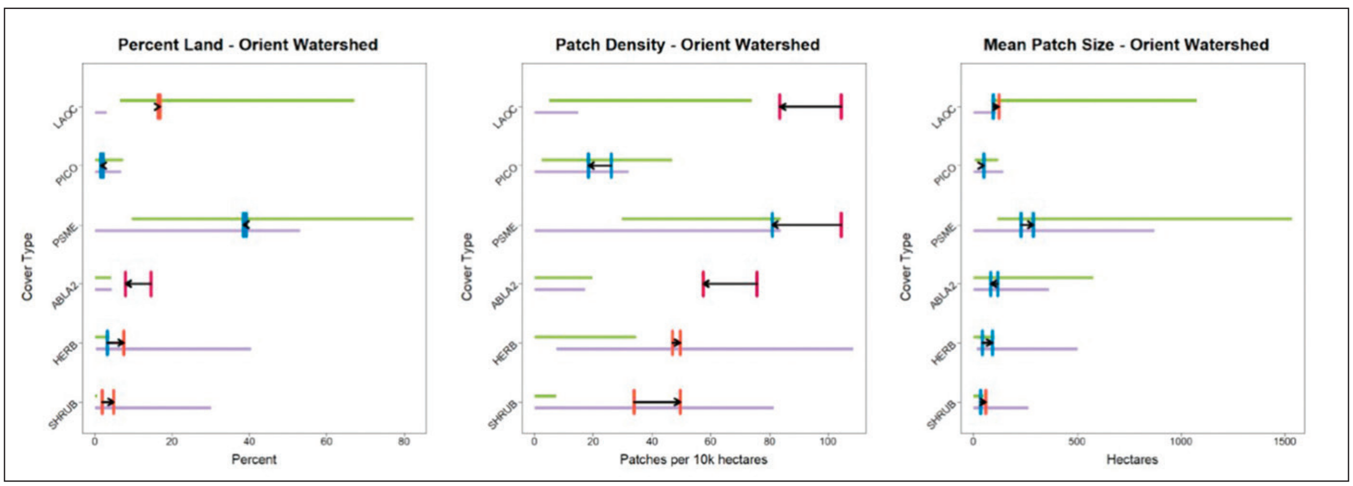

Figure 1—Effects of wild fire on forest cover type in the Orient watershed relative to regional historical and projected future reference conditions. Green bars represent the historical range of variation (HRV), while purple bars represent the future range of variation (FRV). Vertical bars represent the observed conditions of the Orient watershed, with blue indicating overlap of HRV and FRV conditions, orange indicating overlap of only one reference condition, and red indicating no overlap of reference conditions. The black arrow indicates the direction of change from pre-fire to post-fire conditions. Percent land (left) is the proportion of the entire watershed occupied by patches of each cover type. Patch density (center) is a normalized measure of the number of patches of each cover type. Mean patch size (right) is a measure of the average patch size of each cover type.

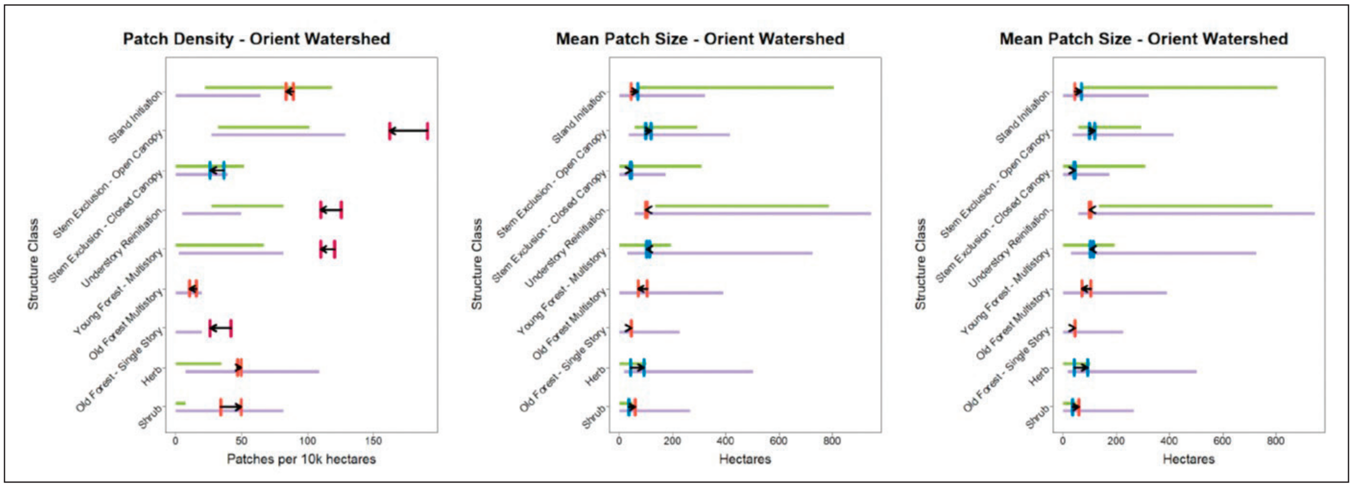

Figure 2—Effects of wild fire on forest structure class in the Orient watershed relative to regional historical and projected future reference conditions. Green bars represent the historical range of variation (HRV), while purple bars represent the future range of variation (FRV). Vertical bars represent the observed conditions of the Orient watershed, with blue indicating overlap of HRV and FRV conditions, orange indicating overlap of only one reference condition, and red indicating no overlap of reference conditions. The black arrow indicates the direction of change from pre-fire to post-fire conditions. Percent land (left) is the proportion of the entire watershed occupied by patches of each structure class. Patch density (center) is a normalized measure of the number of patches of each structure class. Mean patch size (right) is a measure of the average patch size of each structure class.

A Synthesis and Meta-Analysis of Ponderosa Pine Fire Regimes From Five U.S. Regions

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BACKGROUND

A fire regime describes the role fire plays in an ecosystem for a given location and over a specific time period (Agee 1993). The concept is multivariate in nature (Krebs et al. 2010) and therefore is best described by a combination of parameters including fire frequency, severity, extent, seasonality, and relationship with climate. How these parameters vary across space and time and with environmental factors (e.g., elevation and latitude) reveals the underlying dynamics that constitute the fire regime for a given ecosystem. Fire regimes of forest communities are commonly described as high frequency-low severity, low frequency-high severity, or variable frequency-mixed severity; emphasizing the central role of fire frequency and severity in fire regime characterization and suggesting an inverse relationship between these two key parameters.

Fire history studies quantify the values of fire regime parameters, most often fire frequency, but despite an appreciable amount of fire history research within dominant forest types, individual studies are constrained in their scope of inference and restricted in their ability to identify fundamental patterns and relationships across broad scales. Moreover, studies conducted in the same ecosystem may arrive at different conclusions regarding characteristics of a fire regime, yet it is difficult to determine whether differences are driven by underlying natural processes, or by variability in researcher approach (e.g., methods, sampling design, terminology, etc.). For example, fire history studies in ponderosa pine (*Pinus ponderosa*) ecosystems of the Colorado Front Range provide estimates of historical fire frequency (mean fire-return interval, MFI) that range from 3 years (Gartner et al. 2012) to 66 years (Laven et al. 1980), and fire-severity estimates (i.e., the proportion of events that are classified as low, mixed, and high severity) that range from 0 percent (Schoennagel et al. 2011) to 90 percent for low-severity class fires (Ehle and Baker 2003), and 0 percent (Sherriff et al. 2014) to 64 percent for high-severity class fires (Williams and Baker 2012). Understanding the role of natural variability in determining fire regime characteristics of a given forest type is even more challenging across broad spatial extents than within a specified region. Literature reviews coupled with a quantitative assessment of the distribution of fire regime parameter values from individual studies can help explain variability among studies, identify areas where disagreement is largely due to researcher approach, and reveal fundamental patterns from natural relationships.

A wealth of research has been conducted on fire history in ponderosa pine ecosystems over the past five decades, leading to multiple interpretations on the characteristics and driving mechanisms of the distribution of key fire regime parameters. We synthesized and quantified this information from five U.S. regions: Northern Rocky Mountains (Fryer 2016),

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Black Hills and surrounding areas (Murphy 2017), Blue Mountains (Juran 2017), Colorado (McKinney, submitted), and East Cascades (Juran and Zouhar, in preparation). Our objective in this current paper is to describe what the collective research indicates about the distribution of fire frequency values within and among the five regions, and to address whether and how fire frequency varies with elevation—a key environmental factor broadly believed to contribute to variability in fire regime parameter values (e.g., Johnson and Larsen 1991 and references therein).

METHODS

We performed a systematic review to address our study objective. We searched several citation databases for relevant literature from each of the five regions using keywords such as fire history, fire regime, ponderosa pine, and geographic location (e.g., Colorado). We also examined the literature cited in relevant studies identified by the initial search to find other relevant publications, including published and unpublished studies that did not turn up in the initial search. Papers were reviewed and included in our analysis if they met the following inclusion criteria: research occurred within one of the five regions in a ponderosa pine-dominated ecosystem, were empirically based, and reported numeric results for fire frequency values. Sixty studies met the inclusion criteria and formed the population of studies for the meta-analysis. When a study included multiple, independent sites, site-level values were extracted and entered in our database.

We extracted mean, minimum, and maximum fire-return interval (years) values, associated time period, elevation (m), and latitude and longitude (decimal degrees) from 60 studies comprising 200 independent sites. Fire-return interval estimates in these studies were based almost exclusively on fire-scars, which provide a record of low- to moderate-severity surface fires. Site elevation, latitude, and longitude were derived using mapping software and were based on site descriptions or maps from the studies when values were not explicitly provided. In cases where there was not enough information to delineate site-specific values, we used study-level values provided in the papers. When only minimum and maximum elevation values were given in papers, we calculated the mid-point value and entered it as the site elevation.

We performed graphical analysis to explore and describe patterns in fire frequency and elevation within and among regions by creating histograms and box plots of all MFI and elevation values. We then plotted MFI value by corresponding site elevation and calculated Pearson's correlation coefficient between MFI and elevation to assess the strength of the linear relationship between the two variables within each region and for the complete data set. Finally, we calculated summary statistics of central tendency and variability to compare MFI and elevation within and among regions.

RESULTS

The mean MFI for all 200 sites was 18.2 years (± SE 0.7 years) and ranged from 3 to 66 years. Mean elevation was 1,818 m (± SE 43.4 m) and ranged from 550 m to 3,078 m. Despite the broad spread between minimum and maximum values for both variables, the standard errors relative to the means (RSE) were quite low (RSE MFI = 4.1 percent, RSE elevation = 2.4 percent). Site-level MFI increased with elevation across the 200 sites ($r = 0.36$, $P < 0.05$).

The spread of MFI values varied among regions, but median MFI values were similar among regions, except for East Cascade sites, where the 95 percent confidence interval for the median was shorter than all other regions except the Northern Rockies (fig 1a). Variability in the range of elevation values among the five regions was much larger compared to MFI values (fig 1b). Median elevation was significantly greater in Colorado than all other regions; Black Hills and Blue Mountains were not different from each other, but were significantly higher in elevation than East Cascades and Northern Rockies (fig 1b). Likewise, the strength of the relationship between elevation and MFI varied broadly among the regions (fig 2). We found a significant relationship ($P < 0.05$) between elevation and MFI in the Black Hills, Northern Rockies, and Colorado, while elevation at sites in the East Cascades and Blue Mountains had positive, but weak associations with MFI (fig. 2).

Elevation range within regions explained variability in the strength of the relationship between elevation and MFI among regions except for the East Cascades where the correlation was the second lowest ($r = 0.14$)

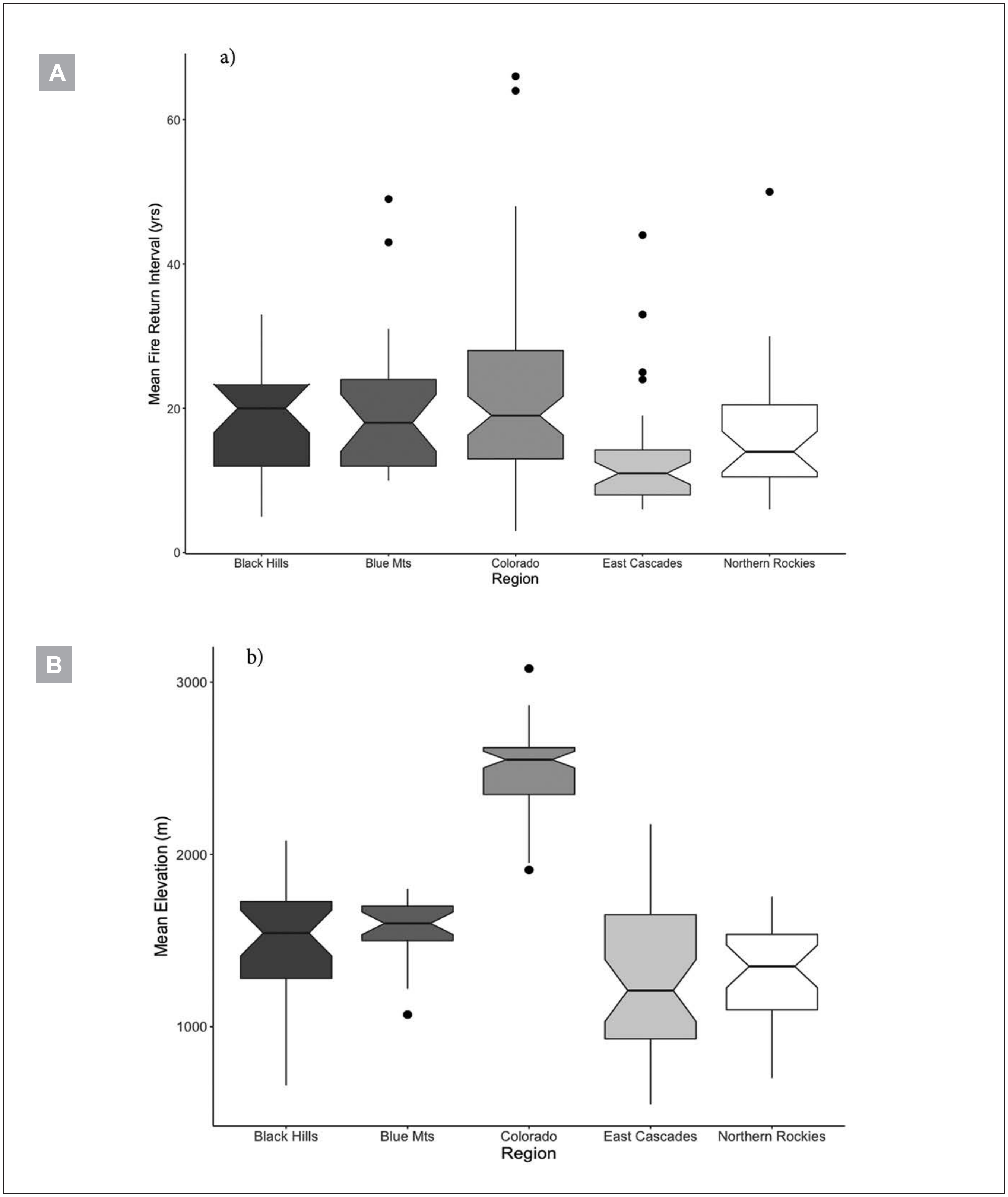

Figure 1—Variability in site-level mean (A) fire-return interval and (B) elevation by five geographic regions from 60 fire history studies on ponderosa pine (Pinus ponderosa) dominant communities. The line in the middle of each box represents the median value (50th percentile), the ends of the boxes are the first (Q1) and third (Q3) quartiles, which cover the central 50% of the data, and the difference between Q3 and Q1 is the interquartile range (IQR). Vertical lines extend to the most extreme data points that are no more than ± 1.5 x IQR, and outliers beyond the vertical lines are individually displayed as circles. Regions whose notches do not overlap have median values that are not different with 95 percent confidence.

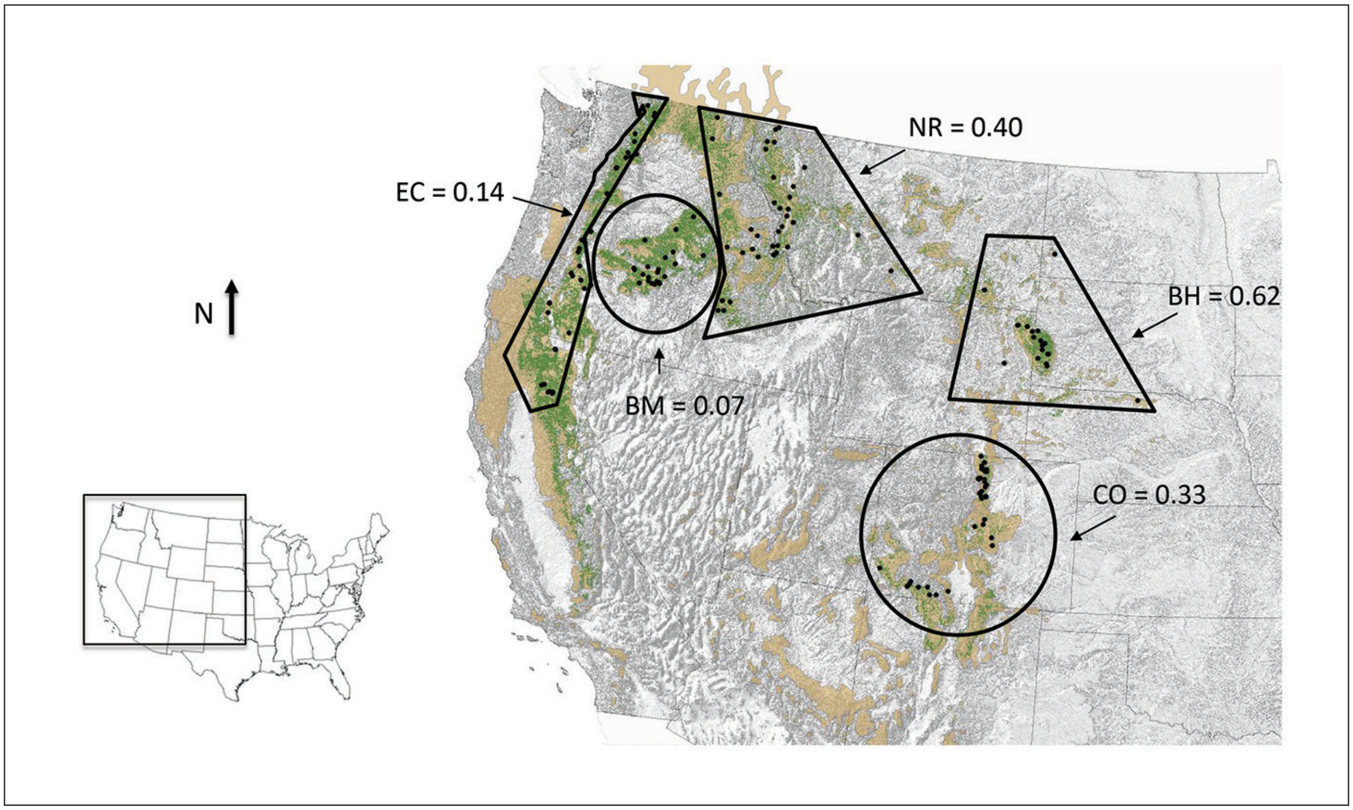

Figure 2—Distribution of ponderosa pine (tan = species (Little 1971), green = Biophysical Settings within study regions (LANDFIRE 2008)). Black dots indicate approximate location of study sites used in this meta-analysis. The five study regions are delineated with black polygons, with study region abbreviation and associated correlation coefficient value between site-level mean fire return interval (years) and elevation (m) given. Abbreviations: EC = East Cascades, BM = Blue Mountains, NR = Northern Rockies, BH = Black Hills and surrounding area, and CO = Colorado.

but elevation range was largest (1,625 m). The value of the correlation coefficient increased steeply with elevation range among the four other regions from a low in the Blue Mountains (r = 0.07, elevation range = 730 m) to a high in the Black Hills (r = 0.62, elevation range = 1,420 m).

The strongest and most consistent relationship between elevation and MFI was evidenced at the regional level (r = 0.79, n = 5). The East Cascades had the shortest MFI (12.9 years) and lowest mean elevation (1,287 m), followed by the Northern Rockies (15.7 years, 1,301 m), Black Hills (18.4 years, 1,514 m), Blue Mountains (19.7 years, 1,565 m), and Colorado (21.3 years, 2,479 m).

CONCLUSIONS

Our analysis of data from 200 ponderosa pine community sites in five regions suggests that variability in fire frequency and the strength of its relationship with elevation are dependent on the spatial scale of analysis. Our understanding of both the variability in fire frequency and its relationship with elevation is limited at the site level, where other factors can strongly affect variability in fire frequency values. Mean fire return interval values will be difficult to predict based only on site elevation, therefore. Indeed, myriad other factors, including history of grazing, logging, mining, and fire suppression activity likely contributed to the wide range of site-level MFI we encountered in the literature.

At broader spatial extents (i.e., among regions), more consistent patterns emerge. Ponderosa pine mean fire frequency is not too variable at the regional level, and the variation present can be largely explained by changes in elevation. The consistent median MFI values among regions contrasted with the broad spatial and elevational distribution of the sites. The data spanned 11.8° latitude and 23.4° longitude, and were distributed along 2,528 m of elevation, yet the range in regional-level MFI was only 8.4 years. This suggests that at the regional level the conditions that favor ponderosa pine occurrence provide for a reasonably consistent environment for high frequency-low severity fire.

Elevation can reflect a change in environmental conditions, where, in general, precipitation increases and temperature decreases with increasing elevation. These changes can manifest into variability in fire frequency through complex relationships with fuel dynamics. For example, in Colorado, lower elevation sites can be fuel limited and require moist conditions to generate fine fuels to carry fires, while higher elevation sites can have sufficient fuel to carry fires but the likelihood of fire is affected by the dryness, and not the lack of abundance, of those fuels (Gartner et al. 2012; Sherriff and Veblen 2008). Elevation provided one explanation for variability in fire frequency at coarse scales across the broad study area, demonstrating that this key variable can be a useful indicator of fire frequency within the species' environmental space.

REFERENCES

Agee, James K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.

Ehle, Donna S.; Baker, William L. 2003. Disturbance and stand dynamics in ponderosa pine forests in Rocky Mountain National Park, USA. Ecological Monographs. 73(4): 543–566.

Fryer, Janet L. 2016. Fire regimes of Northern Rocky Mountain ponderosa pine communities. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: www.fs.fed.us/database/feis/fire_regimes/Northern_RM_ponderosa_pine/all.html.

Gartner, Meredith H.; Veblen, Thomas T.; Sherriff, Rosemary L.; Schoennagel, Tania L. 2012. Proximity to grasslands influences fire frequency and sensitivity to climate variability in ponderosa pine forests of the Colorado Front Range. International Journal of Wildland Fire. 21(5): 562–571.

Johnson, E.A.; Larsen, C.P.S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. Ecology. 72(1): 194–201.

Juran, Ashley G. 2017. Fire regimes of conifer forests in the Blue Mountains. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: https://www.fs.fed.us/database/feis/fire_regimes/Blue_Mts_conifer/all.html.

Juran, Ashley G.; Zouhar, Kris. [In preparation]. Fire regimes of ponderosa pine and montane mixed-conifer communities in the East Cascades. In: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer).

Krebs, Patrik; Pezzatti, Gianni B.; Mazzoleni, Stefano; Talbot, Lee M.; Conedera, Marco. 2010. Fire regime: history and definition of a key concept in disturbance ecology. Theory in Biosciences. 129: 53–69.

LANDFIRE. 2008. CONUS refresh (LANDFIRE 1.1.0). Biophysical settings layer, LANDFIRE data distribution site, [Online]. In: LANDFIRE. U.S. Department of the Interior, Geological Survey (Producer). Available: https://landfire.cr.usgs.gov/viewer/.

Laven, R.D.; Omi, P.N.; Wyant, J.G.; Pinkerton, A.S. 1980. Interpretation of fire scar data from a ponderosa pine ecosystem in the central Rocky Mountains, Colorado. In: Stokes, Marvin A.; Dieterich, John H., technical coordinators. Proceedings of the fire history workshop; 1980 October 20-24; Tucson, AZ. Gen. Tech. Rep. RM-81. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 46–49.

Little, Elbert L., Jr. 1971. Atlas of United States trees. Volume 1. Conifers and important hardwoods. Misc. Publ. 1146. Washington, DC: U.S. Department of Agriculture, Forest Service. 320 p.

McKinney, Shawn T. [Submitted May 2018]. Fire regimes in Colorado ponderosa pine ecosystems. In: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer).

Murphy, Shannon K. 2017. Fire regimes of ponderosa pine communities in the Black Hills and surrounding areas. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (Producer). Available: https://www.fs.fed.us/database/feis/fire_regimes/Black_Hills_ponderosa_pine/all.html.

Schoennagel, Tania; Sherriff, Rosemary L.; Veblen, Thomas T. 2011. Fire history and tree recruitment in the Colorado Front Range upper montane zone: implications for forest restoration. Ecological Applications. 21(6): 2210–2222.

Sherriff, Rosemary L.; Veblen, Thomas T. 2008. Variability in fire-climate relationships in ponderosa pine forests in the Colorado Front Range. International Journal of Wildland Fire. 17: 50–59.

Sherriff, Rosemary L.; Platt, Rutherford V.; Veblen, Thomas T.; Schoennagel, Tania L.; Gartner, Meredith H. 2014. Historical, observed, and modeled wildfire severity in montane forests of the Colorado Front Range. PLOS ONE. 9(9): 1–17.

Williams, Mark A.; Baker, William L. 2012. Comparison of the higher-severity fire regime in historical (A.D. 1800s) and modern (A.D. 1984-2009) montane forests across 624,156 ha of the Colorado Front Range. Ecosystems. 832(5): 832–847.

Assessing Fuel Treatment Effectiveness During Wildfires Under Future Climate Conditions in Southern California

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The wildland-urban interface (WUI) is one of the fastest growing land-use types in the United States resulting in increased populations directly vulnerable to wildfire hazards. One way to mitigate fire danger near the WUI is through adjacent fuel reduction treatments. While there is a national priority to reduce fire risk through fuel treatments, the efficacy of such treatments to mitigate fire behavior in a changed climate is unknown. One place impacted by a large expanding WUI, human-altered fire regime, and changing climate is the Angeles National Forest in southern California. The Charlton-Chilao fuel treatment was completed in 2009 in ponderosa pine-dominated forest on the Angeles National Forest; the treated area was intersected by the Station Fire on September 1, 2009. We compared the change in fire behavior between historic and future climate conditions to assess how the Charlton-Chilao fuel treatment would have altered a fire analogous to the Station Fire, but under future climatic extremes. We used FlamMap to conduct a change analysis of flame length, fire line intensity, and crown fire activity using either the 97th or 3rd percentile weather and fuel moisture representative of historical and projected mid-21st century conditions. We used Rothermel's (1982) charts for interpreting wildland fire behavior characteristics, commonly accepted in wildland fire management for interpreting the effectiveness of a fuel treatment during fire interception. We reclassified flame length (FL) into 5 classes: Class 0 = 0m; Class 1 = 1m; Class 2 = 2m; Class 3 = 3m; and Class 4 = ≥4m; and fire line intensity (FLI) into 5 classes: Class 0 = 0 kw/m/s; Class 1 = 1 – 1,100 kw/m/s; Class 2 = 1,101 – 5,500 kw/m/s; Class 3 = 5,501 – 11,000 kw/m/s; and Class 4 = ≥11,001 kw/m/s; to represent each Rothermel category of fire suppression interpretation. We conducted an absolute change analysis within each class between modeled future and modeled historic climate conditions for each fuel treatment and fire line intensity. FlamMap classifies crown fire activity (CFA) into 4 categories: 0 = no data; 1 = surface fire; 2 = passive crown fire; and 3 = active crown fire. We reclassified the future crown fire activity prior to conducting the change analysis to determine the absolute change between the starting CFA value and the ending CFA value using modeled future and modeled historic climate conditions. Overall, we found little change in FL, FLI, and CFA within the fuel treatment area under future conditions (fig. 1). These results have important implications to increase cost-effectiveness of long-term fuel treatment programs by providing suggestions on strategic areas to focus that require further reduction of fuels to allow for safe fire management operations, protection of property, life, and egress.

Keywords: Climate change, fuel treatment, wildfire, FlamMap, WUI

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

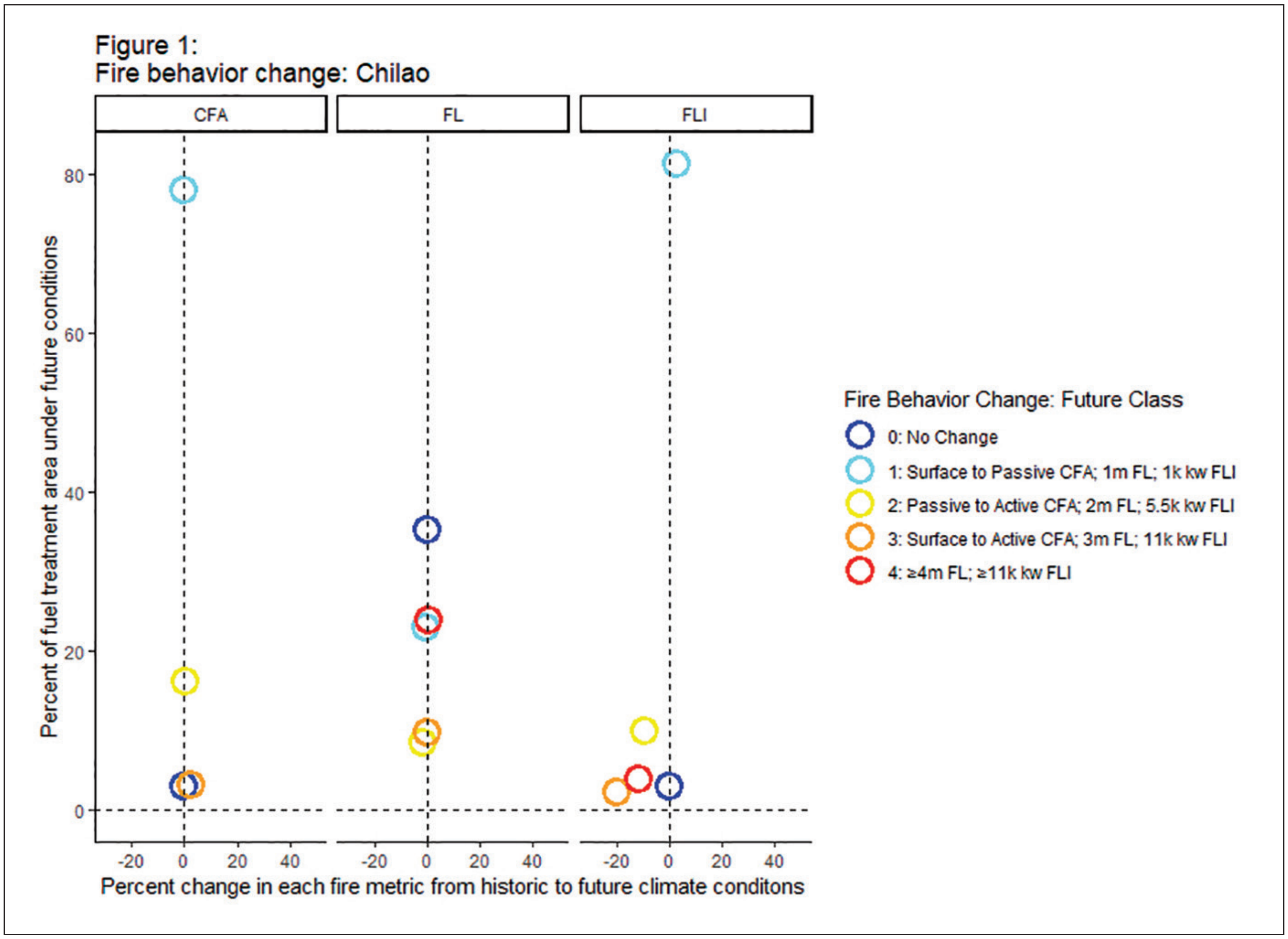

Figure 1—Fire behavior change metric per class where x-axis is relative percent change in each fire behavior class from historic to future conditions per fire behavior class and y-axis is relative percent change of the fuel treatment area under mid-21st century conditions for each fire behavior class where CFA is crown fire activity, FL is flame length, and FLI is fire line intensity.

Demographic Analysis of Transboundary Wildfire Exposure in the Western U.S.

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INTRODUCTION

Wildfire risk mitigation research has focused on either its biophysical or social components, with few studies attempting to integrate both. Studies that have coupled social and biophysical systems have not considered the source of fire risk (Cutter et al. 2003; Davies et al. 2018; Oliveira et al. 2017; Parisien et al. 2016; Rappold et al. 2017; Wigtil et al. 2016), or were applied at limited geographic scale (Fischer et al. 2014; Olsen et al. 2017) leaving a gap in our knowledge about how and where biophysical fire risk is transmitted and affects populations. Vulnerable populations, in terms of economic abilities, social structure and evacuation capabilities have lower capacity to protect their property, with limited access to public and private recovery assets (Peacock and Ragsdale 1997). Identification of these populations is critical for allocating official aid to minimize the loss of lives and property to wildfire.

In this study we examined social vulnerability to large wildfires using a transboundary exposure framework that accounts for the transmission of exposure from public to private lands and communities. Understanding the spatial linkage between an ignition and subsequent wildfire spread to communities allows social vulnerability to be related to the source of exposure, rather than the in-situ hazards. We examined two hypotheses:

H1: Populated places with high social vulnerability received disproportionately more fire and exposure from national forest.

H2: There are zones inside national forests that affected multiple high vulnerability populated places, creating disproportionate exposure compared to their size.

METHODS

This study was applied on three sites (Wenatchee, Washington; Central Sierra, California; Santa Fe, New Mexico) that included large areas of national forest land managed by the U.S. Forest Service (FS), with estimated high fire transmission and exposure to neighboring communities. Using social variables from the American Community Survey (ACS) at the scale of census block groups (hereafter referred to as “blocks”), a composite index of social vulnerability was estimated and related to biophysical fire transmission and exposure data. This coupling enabled us to understand which land tenures expose communities of high social vulnerability, and whether specific social indicators receive a disproportionate

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

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amount of exposure (hypothesis 1). For hypothesis 2, simulated ignitions were clustered to form high structure exposure zones inside national forests, where fuel treatments can be more effective in protecting multiple communities.

To estimate fire exposure, we used probabilistic wildfire risk components simulated with FSim (Short et al. 2016). Simulated perimeters were used to quantify the area burned on each land tenure and the structures affected within each community (Ager et al. 2014; 2018). Community polygons were intersected with the FSim fire perimeter layer. Intersections provided the parts of each perimeter that extend beyond the boundaries of each community or block, with the sum of those intersected parts characterized as either incoming (ignited on another land tenure) or non-transmitted (ignited and burned inside the same land tenure).

By using all simulated ignitions causing structure exposure, we applied a kernel density interpolation to get the ignition density and create community exposure clusters (hereafter referred to as "clusters"). These clusters produce at least 80 percent of all structure exposure generated from national forests within each study area. After identifying the exposed communities from national forest clusters, we identified all other ignitions that affected these communities but ignited on other land tenures. All blocks intersecting these ignitions were used to define each study area.

The ACS 5-year estimates for the period 2011-2015 were used to select variables that were linked with socially vulnerable populations (Cutter et al. 2003; Flanagan et al. 2011; Wigtil et al. 2016; Wright et al. 2012). We formed six broad groups that describe a similar social vulnerability aspect: households and population, socioeconomic status, household composition and disability, minority status and language, housing and transportation and occupation. For each block group, we estimated the percentages of each variable based on different population or household metrics.

The Social Vulnerability Index (Cutter et al. 2003) is an inductive approach to reduce a large set of social variables into a smaller set of uncorrelated latent factors using principal components analysis (PCA), aggregated to build the index (Tate 2012). All variables were estimated at the scale of blocks. The social vulnerability index (SOVI) was constructed with all variables for the entire dataset of each state. Each block's score was categorized into low (values < -0.5), moderate (-0.5 to 0.5) and high (>0.5) social vulnerability. Community social vulnerability was estimated by their areal percentage on each SOVI class: communities with >25 percent area in high SOVI class characterized as high; >40 percent area in moderate SOVI class and not high, as moderate; all the rest as low.

RESULTS

Most blocks in Wenatchee were of low SOVI, with only 3 percent in high and 25 percent in moderate SOVI classes (fig. 1). Central Sierra had less moderate (15%) but similar percentage of high SOVI blocks. About 76 percent of Santa Fe blocks had moderate SOVI values, followed by high (13%) and low SOVI values (11%). Regarding communities in Wenatchee, 33 were classified with low, 24 with moderate, and seven with high social vulnerability. Most communities in Santa Fe had moderate (n=53), followed by high (n=40) and low (n=15) social vulnerability. Lastly, in Central Sierra 79 communities had low, 26 moderate and 20 high social vulnerability.

Cluster Transmission and Exposure

The Central Sierra cluster covered 8.5 percent of the study area (fig. 1) and caused 13 percent of the total (all-lands) estimated structure exposure to blocks, affecting mostly low (72%) and moderate (28%) SOVI blocks. The Wenatchee cluster also covered 8.5 percent of the study area but caused 41 percent of all structure exposure to blocks, affecting low (49.3%) and moderate (50.7%) SOVI blocks. The Santa Fe cluster covered 10 percent of the study area and caused 22 percent of all structure exposure to blocks, affecting low (26%), moderate (58.5%) and high (15%) SOVI blocks.

Community Structure Exposure and Fire Received

In Wenatchee, 61 percent of the community area was exposed to fire. When we compared the percentage

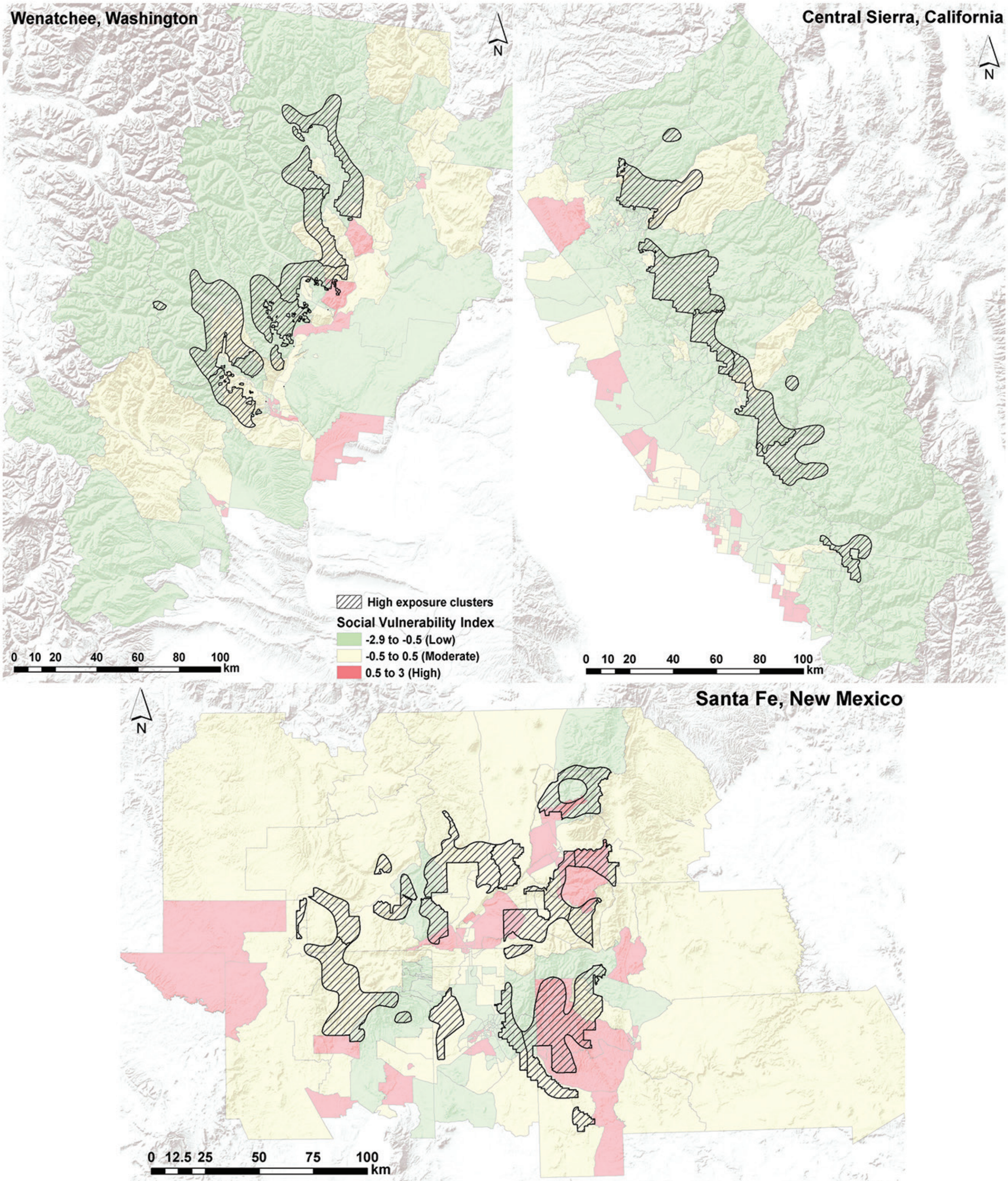

Figure 1—Classification of the social vulnerability index values for the Block Groups of the three study areas. Ignition clusters are shown as dashed polygons.

of exposure that each SOVI class received to its percentage area cover, high SOVI block exposure was disproportionately higher by 0.5 times (4.4% of total exposure vs. 2.9% cover); moderate SOVI block exposure was 1.1 times more (53.8% exposure vs. 24.9% cover); and low SOVI block exposure was 0.4 times less (41.8% exposure vs. 72.2% cover). There was a balance between structure exposure and the proportion of national forest area in Wenatchee (41.7% of all exposure vs. 47.5% cover), like private lands (19% exposure vs. 21.5% cover) and State lands (10% exposure vs. 13% cover). Communities comprise 8.7 percent of the Wenatchee study area but created 27 percent of exposure; on the contrary, tribal lands comprise 4.7 percent but created only 0.9 percent of exposure. The major structure exposure contributor in high SOVI communities were communities (46%) (non-transmitted fire), private lands (21%), and FS managed lands (17%) (fig. 2).

For Santa Fe, 74 percent of community area was exposed. High SOVI block exposure was disproportionately higher compared to its percentage area cover by 0.5 times (19.3% exposure vs. 13% cover), moderate SOVI block exposure was 0.3 times less (54.9% exposure vs. 75.8% cover), and low SOVI block exposure was 1.3 times more (25.8% exposure vs. 11% cover). Forest Service managed lands exposure was proportionate to their area (24.7% exposure vs. 23% cover in Santa Fe), similar to tribal lands (12.5% exposure vs. 12.7% cover). Disproportionately, private, Bureau of Land Management (BLM), and State lands cover 41.5 percent, 11.5 percent and 4.5 percent of the Santa Fe study area respectively, but caused only 15 percent, 6 percent and 2.5 percent of exposure respectively. Communities comprised only 6.4 percent of the Santa Fe study area but caused the 37.5 percent of all structure exposure. For high SOVI communities, exposure originated mostly from communities (35.9%), FS (18%) and private lands (15.5%) (fig. 2).

Lastly, 61.5 percent of the community area in Central Sierra was exposed. High SOVI block exposure was disproportionately higher compared to their percentage area cover by 0.25 times (4.7% exposure vs. 3.8% cover), moderate SOVI block exposure was 1.2 times higher (33% exposure vs. 15% cover), and low SOVI block exposure was 0.2 times less (62.4% exposure vs. 81.3% cover). Forest Service managed lands created

Figure 2—Fire received (left panels) and structure exposure (right panels) by land tenure for the high social vulnerability communities of the three study areas. FS: Forest Service (M: manageable; P: Protected); BLM: Bureau of Land Management.

disproportionately lower structure exposure compared to their area (13% exposure vs. 41% cover in Central Sierra), while private and BLM lands were more balanced (27% and 3.1% exposure vs. 25.6 percent and 3 percent of cover in Central Sierra respectively). National Park Service (NPS) lands (18% of Central Sierra) created less than 1 percent of exposure; on the contrary, communities (16.2% of Central Sierra) created 55 percent of exposure. The major structure exposure contributors in high SOVI communities were communities (53%) and private lands (45%) (fig. 2).

DISCUSSION

One of the main findings of this study was that exposure clusters on national forests, compared to their percentage area within each study site, affected disproportionally more communities and blocks, but only in Santa Fe did exposure affect some highly vulnerable communities. Forest Service managed lands had a strong fire and exposure contribution to the total problem but affected the highest vulnerability blocks proportionate to their area. The bulk of structure exposure originated from communities and private lands.

More than half of the total fire problem for all study areas originated from communities and private lands. Most community lands were private and created disproportionate exposure compared to their areal percentage. This finding can alter the perception of who is responsible for taking mitigation actions (e.g., the landowner vs. a local, State or Federal agency). It also suggests that homeowners and communities should initiate collaborations with adjacent land and homeowners and take actions towards reducing fire risk within their firesheds, an approach aligned with the recently announced shared stewardship initiatives of the U.S. Forest Service (USDA Forest Service 2018). Furthermore, our results showed that even though the FS is the major land owner in Central Sierra and Wenatchee, and the second largest in Santa Fe, it created proportionate exposure to its areal percentage. There was no evidence that the Forest Service contributes more exposure compared other land tenures to high vulnerability communities, while for Central Sierra it did not expose any high vulnerability communities. These findings reject hypothesis #1 and suggest that the problem was distributed among three key land tenures (Communities, Private, Federal/FS), supporting the need for further collaboration.

Ignitions on national forests, or on any other large landowner, can expose several communities to the same fire and there are large spatial clusters (sources) that can affect multiple communities (sinks). Most of the area within the Wenatchee clusters was close or inside moderate social vulnerability blocks, receiving half of cluster exposure. Since ignition clusters are managed by the Forest Service, implementation of additional fuel treatments (7% of cluster area was treated during 2009-2017) can reduce the amount of transmitted fire and exposure that moderate vulnerability blocks received. On the contrary, Central Sierra clusters were mostly close or inside low vulnerability blocks (receiving three quarters of cluster exposure), with high vulnerability blocks being far west of them (8.5% of these clusters has been treated during 2009-2017). Santa Fe clusters are mostly inside moderate vulnerability blocks, receiving half of the exposure that clusters caused. Since a forth of total exposure and transmission came from clusters, this suggests potential opportunities for greater federal investments there (2% already been treated during 2009-2017). Although clusters caused disproportionately more exposure compared to their size, we reject hypothesis #2 since they had a minor effect on high social vulnerability communities.

CONCLUSION

Without estimating and interpreting cross-boundary wildfire transmission it is difficult to implement “all lands” risk management policies (USDA Forest Service 2014) and the planning areas around communities will likely be substantial lower than it takes to reduce their exposure (Ager et al. 2015). This study provided new methods for prioritizing community wildfire protection investments with a coupled social-biophysical approach, targeting at reducing suppression costs, protect vulnerable populations, and leverage fuel management and firewise activities investments in underserved communities.

REFERENCES

Ager, A.A.; Day, M.A.; McHugh, C.W.; Short, K.; Gilbertson-Day, J.; Finney, M.A.; Calkin, D.E. 2014. Wildfire exposure and fuel management on western US national forests. Journal of Environmental Management. 145: 54–70.

Ager, A.A.; Kline, J.; Fischer, A.P. 2015. Coupling the biophysical and social dimensions of wildfire risk to improve wildfire mitigation planning. Risk Analysis. 35(8): 1393–1406.

Ager, A.A.; Palaiologou, P.; Evers, C.R.; Day, M.A.; Barros, A.M.G. 2018. Assessing transboundary wildfire exposure in the southwestern United States. Risk Analysis. 38(10): 2105–2127.

Cutter, S.L.; Boruff, B.J.; Shirley, W.L. 2003. Social vulnerability to environmental hazards. Social Science Quarterly. 84(2): 242–261.

Davies, I.P.; Haugo, R.D.; Robertson, J.C.; Levin, P.S. 2018. The unequal vulnerability of communities of color to wildfire. PLoS One. 13(11): e0205825.

Fischer, A.P.; Kline, J.D.; Ager, A.A.; Charnley, S.; Olsen, K.A. 2014. Objective and perceived wildfire risk and its influence on private forest landowners' fuel reduction activities in Oregon's (USA) ponderosa pine ecoregion. International Journal of Wildland Fire. 23: 143–153.

Flanagan, B.E.; Gregory, E.W.; Hallisey, E.J.; Heitgerd, J.L.; Lewis, B. 2011. A social vulnerability index for disaster management. Journal of homeland security and emergency management. 8(1).

Oliveira, S.; Zêzere, J.L.; Queirós, M.; Pereira, J.M. 2017. Assessing the social context of wildfire-affected areas. The case of mainland Portugal. Applied Geography. 88: 104–117.

Olsen, C.S.; Kline, J.D.; Ager, A.A.; Olsen, K.A.; Short, K.C. 2017. Examining the influence of biophysical conditions on wildland-urban interface homeowners' wildfire risk mitigation activities in fire-prone landscapes. Ecology and Society. 22(1): 21.

Parisien, M.A.; Miller, C.; Parks, S.A.; DeLancey, E.R.; Robinne, F.N.; Flannigan, M.D. 2016. The spatially varying influence of humans on fire probability in North America. Environmental Research Letters. 11(7): 075005.

Peacock, W.G.; Ragsdale, A.K. 1997. Social systems, ecological networks and disasters: Toward a socio-political ecology of disasters. In: Peacock, W.G.; Morrow, B.H.; Gladwin, H.; eds. Hurricane Andrew: Ethnicity, gender, and the sociology of disasters. Routledge: 20–35.

Rappold, A.G.; Reyes, J.; Pouliot, G.; Cascio, W.E.; Diaz-Sanchez, D. 2017. Community vulnerability to health impacts of wildland fire smoke exposure. Environmental Science and Technology. 51(12): 6674–6682.

Short, K.C.; Finney, M.A.; Scott, J.H.; Gilbertson-Day, J.W.; Grenfell, I.C. 2016. Spatial dataset of probabilistic wildfire risk components for the conterminous United States. Fort Collins, CO: Forest Service Research Data Archive.

Tate, E. 2012. Social vulnerability indices: a comparative assessment using uncertainty and sensitivity analysis. Natural Hazards. 63(2): 325–347.

USDA Forest Service. 2014. The National Strategy: The final phase in the development of the National Cohesive Wildland Fire Management Strategy. Washington, DC: USDA Forest Service: 93.

USDA Forest Service. 2018. Towards shared stewardship across landscapes: An outcome-based investment strategy. Washington, DC: USDA Forest Service.

Wigtil, G.; Hammer, R.B.; Kline, J.D.; Mockrin, M.H.; Stewart, S.I.; Roper, D.; Radeloff, V.C. 2016. Places where wildfire potential and social vulnerability coincide in the coterminous United States. International Journal of Wildland Fire. 25(8): 896–908.

Wright, J.D.; Rossi, P.H.; Pereira, J.A.; Weber-Burdin, E. 2012. Victims of the environment: Loss from natural hazards in the United States, 1970–1980. New York: Springer Science & Business Media. 238 p.

Obstacles to Improving Wildfire Risk Governance in Greece

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INTRODUCTION

A sequence of catastrophic wildfires that occurred during the past decades in Greece point to the need to re-examine the established wildfire risk governance policies. The most important regulations for fire suppression and fuel/forest management were established four decades ago (Law 998/1979). Wildfire suppression is now led by the Greek Fire Service, while pre-suppression vegetation management is supervised by the Greek Forest Service. The limited available budget is clearly distributed in favor of fire suppression (about $410 million annually), with minor funding remaining for fuel management and ignition prevention programs (about $25 million annually). Since a substantial improvement of fire suppression effectiveness is not anticipated to occur in the near future due to economic restrictions, fire prevention that includes managing landscape fuel conditions (quantity and spatial arrangement) might be the only available option for Greece to aid fire suppression and reduce the number of potential harmful fire events in a cost-effective way. Successful application and experiences from North America and South Europe proved that investing more in prevention provides the means to cope with the upcoming challenges that emerge from climate change and, typical to Greece, the effects of land abandonment on fuel patterns.

Few studies have explained the current trends and beliefs of the Greek society on wildfire related issues (Henderson et al. 2005; Kalabokidis et al. 2008; Morehouse et al. 2011). One of the main objectives of this study was to understand the prevailing trends and perspectives of engaged stakeholders who can influence risk governance policies through their job position. Several questions were focused on prescribed fire use for fuel management and backfires for suppression, while others on evaluating the current policies and the role of state agencies in reducing the most important wildfire related problems. We hypothesized that prescribed fire use is lacking consensus and support, and that engaged stakeholders are more favorable on promoting suppression related policies, rather than adopting preventive fuel management measures.

FIRE AND SOCIETY IN THE GREEK LANDSCAPE

Radical population movements during the past 70 years shaped the Greek landscape, altering vegetation conditions and ownership patterns, mostly due to

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

land abandonment and vegetation encroachment into formerly cultivated lands. Cultural reasons caused a remarkable land ownership fragmentation on private lands, with 80 percent of all private holdings be less than five hectares (Kasimis et al. 2012). This highly fragment landscape, with thousands of small ownerships without any regular activity makes their management difficult, especially in mountainous and rugged areas. In addition, private lands fragmentation makes management costlier and more laborious. The problem of illegally built structures in the wildland-urban interface increase suppression complexity and landscape fragmentation (Palaiologou et al. 2018). Regarding forest ownerships, 65 percent belongs to the state and 12 percent to local communities, 10 percent are of mixed ownership (i.e. public with private), 8 percent are private, and 5 percent belong to the church or other non-government organizations. On about 35 percent of all forests, some form of management is applied, mainly for timber production. Grasslands are mostly state owned and suitable for sheep and goat grazing, composed of grasses and short shrubs.

During 1974-2012, 180 wildfires burned between 500 to 2,000 ha, 99 wildfires burned between 2,000 and 7,000 ha, and 35 events evolved into large scale fires burning more than 7,000 ha. Only half of wildfires have a verified ignition cause, with most significant be the burning of agricultural lands and grassland for clearing unwanted vegetation (33%, arsons (23%), negligence (12%), lightning (8%) and landfill fires (6%).

VEGETATION AND FUEL MANAGEMENT CULTURE

Greece implements a minimalistic application of fuel treatments (limited in extent, size and efficiency) that require in addition “active” fire suppression for benefits to be realized. The temporal scale of treatment effectiveness is usually ignored (i.e. treated areas are revegetated after a location based or vegetation type specific period), and the strategic allocation of treatments is narrowed only to fuel breaks that empirically consider the dominant travel paths of possible wildfires in the landscape.

Fuel reduction and timber production are regulated by the Greek Forest Service on both state and large privately-owned forested lands, but with limited application to non-forested private lands. The main obstacles for increasing management on private forests are their small size and owner’s reluctance to invest due to reduced prospects for profit, in addition to conflicts caused by joint ownerships that can paralyze management decisions. Officially, regulated forest management is centered on harvesting for industrial timber production, mainly in northern Greece where productive forests of true-fir (*Abies* spp.), spruce (*Picea abies*), high-elevation pines (*Pinus nigra* and *Pinus sylvestris*), beech (*Fagus* spp.) and deciduous oaks (*Quercus* spp.) grow (Xanthopoulos 2004). The annual timber production is 1.1 million m^3, 30 percent of which comes from private forests; one third is produced from conifers, with the majority of production (~65%) used as fuelwood.

Fire-prone low elevation conifer forests and evergreen shrublands are largely left unmanaged and prone to fuel build-up due to funding shortages and lack of fire risk management culture. Despite these, management activities or disturbances are applied by farmers or livestock producers, sometimes unofficially, with traditional land use practices on agroforestry systems, including resin collection from conifers, grazing on silvopastoral systems, fuelwood collection, honey production and forage products. These traditional management practices are threatened by degradation, either through abandonment or intensification, which leads to their conversion to woodlands and crop monocultures, respectively (Papanastasis et al. 2009); or through repeated wildfires that change the landscape characteristics (changes in dominant vegetation types and land uses, erosion/desertification, livestock and farming activity reduction).

Current laws do not allow any intentional fire use, neither prescribed burns nor backfires during fire suppression. Prior to the major postwar-era land abandonment, fire was a widespread practice of local populations employed to clear forests from unwanted vegetation, the absence of which (through legal ban) has caused forest encroachment in formerly agricultural lands (Tedim et al. 2015; Zakkak et al. 2014). Reintroducing fire as a management tool may be an important strategy in resolving several ecological and management challenges on the Greek landscape, but it can only be applied after a substantial legislative reform and strict guidelines.

KEY INFORMANT SURVEY

We conducted a web-based survey of a sample comprised of professionals in wildfire management and research and other engaged stakeholders interested in wildfires (local government officials, NGO's, community members etc.). The survey was conducted during the winter of 2017-2018 (December through February). We received 106 properly completed responses, from people living in 28 different municipalities in Greece, reaching approximately a 33 percent response rate. The questionnaire consisted of 22 questions, forming three different groups: general questions about the respondent status/expertise; beliefs about fire management and suppression; ranking/comparison of different fire effects. Respondents were asked to rate the questions based on the situation, conditions and perceptions they have for the place of residence where they lived longest during their lives (place-based knowledge). We defined as experts those respondents that have experienced at least three fire incidents during their lives, and with good or excellent working experience on at least two of the following fire related activities: suppression, fuel management, research and study, post-fire rehabilitation and wildfire effects. The questionnaire was constructed with Qualtrics (Qualtrics, Provo, UT) using different question types (multiple choice, five-point Likert-scale, ranking order).

RESULTS

In this write-up, we focused on responses describing beliefs about fire management and suppression, and not on those received for the different fire effect categories. Our sample was comprised by mostly male respondents (80%), with one third of all respondents being younger than 35 years old and the majority (52%) between 35-54 years old. Experts comprised 45 percent of all respondents. One third of all respondents were working for the Fire Service.

A 28 percent of all respondents experienced more than ten fires, 30 percent less than two, and 50 percent more than five fires (fig. 1A). Most respondents believed that in their home region wildfires are caused due to people's negligence, by arsonists pursuing specific objectives, or by the way the society/people function and live (fig. 1B). Only a minority of people (8% of all responses) believed that ignitions are from natural causes (lightning). When the question was framed differently, i.e. "when multiple wildfires occur across Greece who is responsible?" (fig. 1C), respondents rated higher the "arsonists pursuing specific interests", while they attributed additional influence on weather/natural phenomena. Negligence was also rated high, while some respondents stated that arsonists with psychological disorders are those causing most of wildfires.

Respondents believed that improved collaboration among the fire management agencies is the most capable approach on reducing the wildfire related problems (fig. 1D), while better education and access to information for individuals and communities can play a major role in achieving this goal. There was limited support for fuel reduction since only a small percentage (9%) believed that fuel reduction activities can play a major role in dealing with wildfire related problems (fig. 1D), while responses related to increased fire suppression capacity (better patrolling or surveillance, acquisition of new firefighting resources and hiring of more firefighters) were also relatively few (15% of all responses).

In figure 2A, we noticed two main conflicting issues, the first on if all fires must remain illegal, and the second on allowing some natural fires to burn to achieve ecological objectives, with a slightly higher acceptance on allowing some of them to burn than remaining illegal. Respondents were very reluctant on fire use without a strict supervision and training, although they overwhelmingly agreed (~80%) on tolerance and protection of people involved in a possible accident. Most respondents (~75%) agreed that fire can effectively control and protect forests, and that fires are an inexpensive method for firefighting and removal of unwanted fuels (~65%), but with strong minorities disagreeing on the above issues (~25% and ~35%, respectively). Such strong minorities can be importantly influential, especially in issues regarding fires and legislative reforms to allow its use.

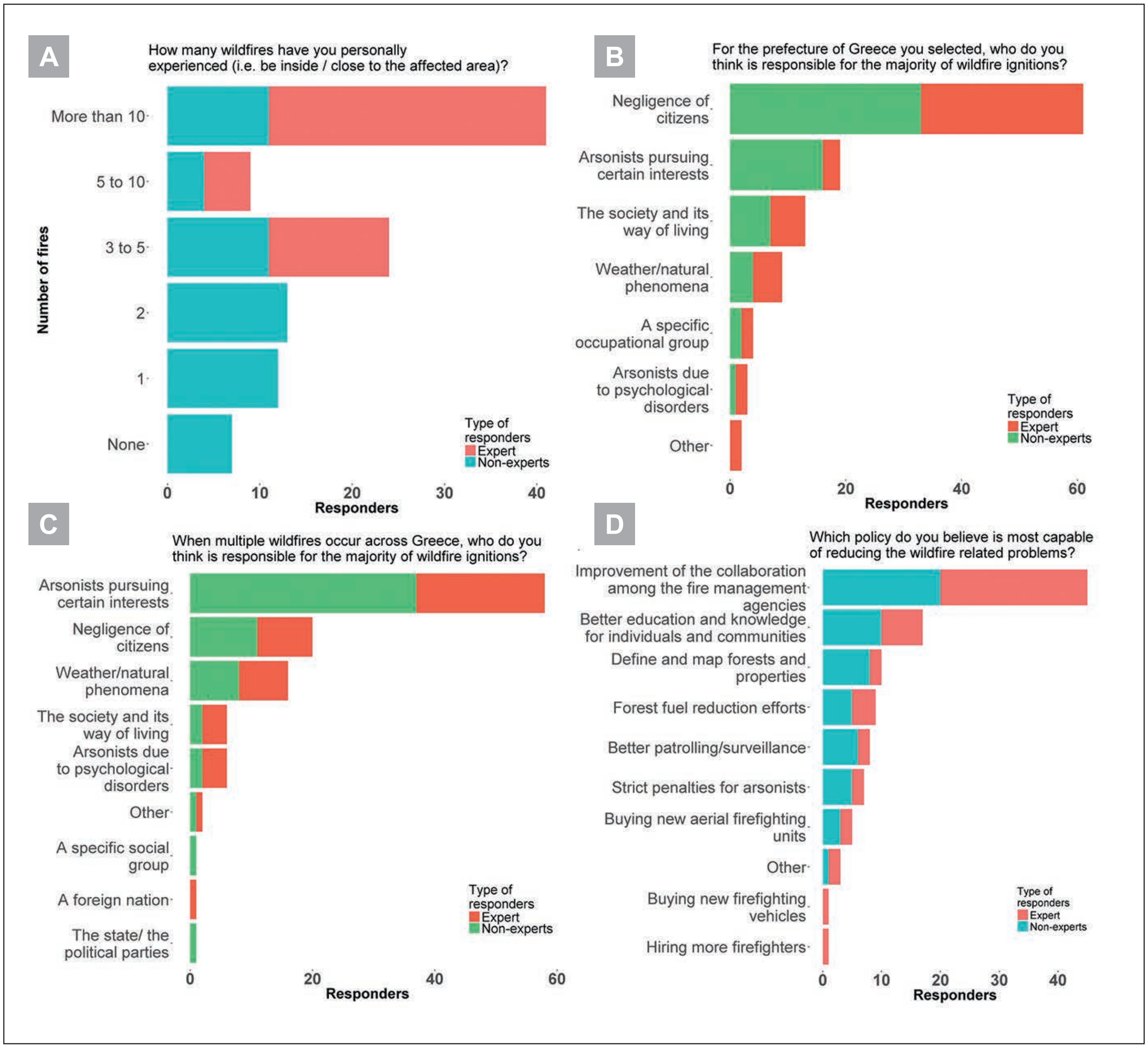

Figure 1—Questions about the respondent beliefs on fire ignition responsibility, wildfire management policy and experience with wildfires.

Respondents overwhelmingly agreed that societies can do much to confront wildfire (fig. 2B), a finding that is in accordance with the responses in figure 1D, where most respondents believed that socially related improvements can reduce wildfire related problems (e.g. collaboration, education and officially defined ownership boundaries). In general, wildfires were not seen as a natural process and part of ecosystem functioning (fig. 2B), since almost 45 percent of the respondents stated that wildfires cause only negative impacts and effects, with more than 75 percent disagreeing that there is a fire deficit in Greek landscapes. There is little tolerance for uncontrolled fires and the clear majority agreed that they should be extinguished as soon as possible. Regarding climate change, most of the respondents (>90%) agreed that it can increase the number, intensity and area burned by wildfires. About 80 percent of the respondents agreed that it is people's responsibility to remove vegetation and fuels from their property. Respondents also acknowledged that the Greek Forest Service, which currently has little involvement in the field, should become more engaged on all stages of wildfire management.

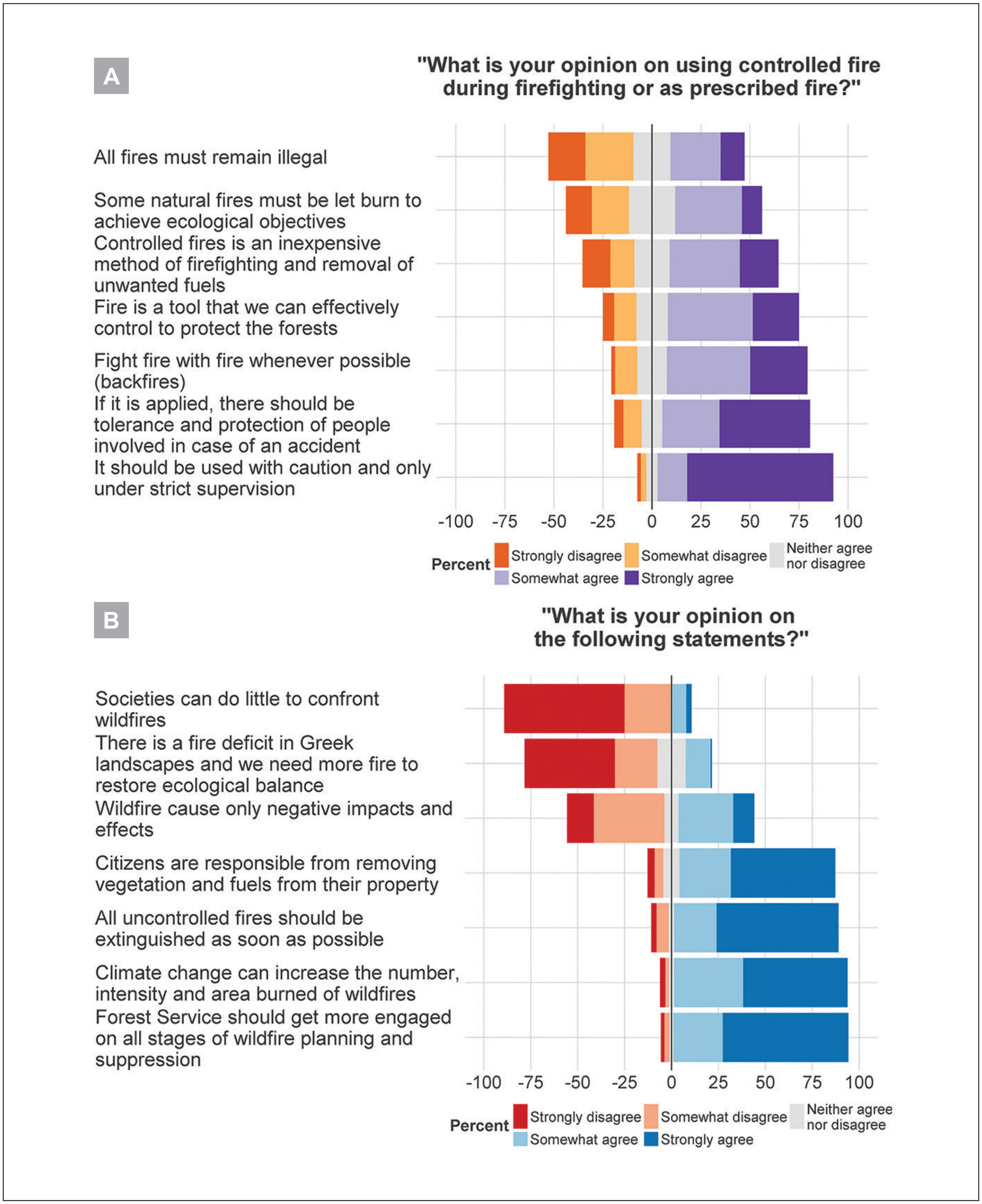

Figure 2—Likert scale questions about the respondents' opinions on controlled fire use and their perceptions on several wildfire related issues.

DISCUSSION

Analysis of questionnaire responses revealed that landscape fragmentation, legal barriers for wildland fire use and prescribed fires, weak collaboration among the major stakeholders and agencies, the lack of fuel management culture, funding unavailability and lack of knowledge on the spatial scale of risk (where fires start, how they spread and who can be potentially affected) are major obstacles on improving wildfire risk governance in Greece.

A legal reform to allow fire to be used as a tool during fire suppression and fuel management can encounter strong opposition. Results revealed that respondents tend to have a negative attitude towards wildfire and uncontrolled burns, with most people expressing a strong belief that fires are causing negative effects. There is weak support to legitimize some fires and respondents strongly agreed that all uncontrolled fires should be extinguished as soon as possible. Any wildfire has the potential to burn into some private property scattered in the highly fragmented land tenure system, and this is probably one of the reasons that societies want all fires to be confronted. However, results suggested that respondents can possibly accept the use of controlled fire, under the condition that it will be used with caution and strict supervision, with a weak majority of people in favor of fire use for resource benefits (although, they disagree that there is a fire deficit).

Most experts believed that an effective wildfire policy should account for the way society and agencies function and interact. Respondents acknowledged that the lack of a national cadaster and the fuzzy boundaries among ownerships was one of the major sources of wildfire related problems. There was also a strong belief that arsonists are behind most ignitions, but negligence of citizens accounts for more ignitions in local spatial scales.

CONCLUSION

The challenge of confronting large wildfire events in Greece will require the adoption of holistic approaches that will consider the new socioeconomic reality and incorporate recent advancements in wildfire science, targeted at reducing the wildfire spread rate and intensity by modifying the fuel patterns at a landscape level. Negative views on some policy change reforms (e.g., fire use) can be dealt with improved education and campaigns that will showcase success stories of implementation. Finally, training of the Forest Service personnel on the results of successful fuel management projects in Europe and elsewhere may help towards fuel management in places and scales that can create a change in Greece's future wildfire trajectory.

REFERENCES

Henderson, M.; Kalabokidis, K.; Marmaras, E.; Konstantinidis, P.; Marangudakis, M. 2005. Fire and society: a comparative analysis of wildfire in Greece and the United States. Human Ecology Review. 12(2): 169–182.

Kalabokidis, K.; Iosifides, T.; Henderson, M.; Morehouse, B. 2008. Wildfire policy and use of science in the context of a socio-ecological system on the Aegean Archipelago. Environmental Science & Policy. 11(5): 408–421.

Kasimis, C.; Venturas, L.; Ziomas, D. 2012. Social impact of emigration and rural-urban migration in Central and Eastern Europe. Final Country Report: Greece. European Commission, DG Employment, Social Affairs and Inclusion.

Morehouse, B.J.; Henderson, M.; Kalabokidis, K.; Iosifides, T. 2011. Wildland fire governance: perspectives from Greece. Journal of Environmental Policy & Planning. 13(4): 349–371.

Palaiologou, P.; Ager, A.A.; Nielsen-Pincus, M.; Evers, C.R.; Kalabokidis, K. 2018. Using transboundary wildfire exposure assessments to improve fire management programs: a case study in Greece. International Journal of Wildland Fire. 27(8): 501–513.

Papanastasis, V.P.; Mantzanas, K.; Dini-Papanastasi, O.; Ispikoudis, I. 2009. Traditional agroforestry systems and their evolution in Greece. In: Rigueiro-Rodróguez, A.; McAdam, J.; Mosquera-Losada, M.R.; eds. Agroforestry in Europe: Current status and future prospects. Dordrecht, The Netherlands: Springer Netherlands: 89–109.

Tedim, F.; Xanthopoulos, G.; Leone, V. 2015. Chapter 5 - Forest fires in Europe: Facts and challenges. In: Paton, D., ed. Wildfire hazards, risks and disasters. Oxford, UK: Elsevier: 77–99.

Xanthopoulos, G. 2004. Who should be responsible for forest fires? Lessons from the Greek experience. In: González-Cabán, Armando, tech. coord. II International Symposium on Fire Economics, Planning and Policy: A Global View. Gen. Tech. Rep. PSW-GTR-208. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture: 19–22.

Zakkak, S.; Kakalis, E.; Radović, A.; Halley, J.M.; Kati, V. 2014. The impact of forest encroachment after agricultural land abandonment on passerine bird communities: The case of Greece. Journal for Nature Conservation. 22(2): 157–165.

Ignitions for Peat Fires in Indonesia: A Critical Look

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Fires in the peatlands of Kalimantan and Sumatra in Indonesia are significant sources of greenhouse gases (GHG). Ignitions for these fires are widely regarded as occurring because of land clearing associated with palm oil and timber production and smallholder agriculture. The scale of peat forest degradation has led to intra- and inter-governmental, academic, and NGO efforts to monitor, document and reduce GHG emissions. Laws and policies are emerging as a result of these efforts. However, naming broad economic reasons for fire use in peatlands is inadequate for formulating land management policies and for implementing programs to reduce GHG emissions from peatlands. A more detailed understanding of the biophysical conditions and human activities associated with peatland fires is needed.

GHG emissions depend on the amount and type of fuel that is consumed and on how it is burned (Stockwell et al. 2014, 2016). Monitoring and documentation of GHG emissions is limited by the failure to adequately distinguish between surface fires that consume predominantly woody and herbaceous fuels via flaming combustion versus peat fires that consume organic soil and buried wood predominantly via smoldering combustion. Depending upon a suite of environmental conditions, peat consumption can vary by orders of magnitude if and when surface fires transition into burning peat soils. Once established, peat fires can persist for weeks, initiating new surface fires whenever relative humidity and wind are favorable.

From a fire environment perspective, i.e., the union of weather-climate, vegetation-fuels, and terrain-hydrology, it is critical to understanding the surface fire-ground fire continuum and how this plays out on the peat-swamp landscape. Fire is a rare occurrence in pristine peat-swamp forests due to the lack of fine, dry surface fuels and the high peat moisture content. However, as the degree of degradation increases, both surface fuels (principally ferns, graminoids, sclerophyllous shrubs, and non-woody litter) and organic soil (figs. 1A, B) become increasingly susceptible to burning (Graham et al. 2014; Siegert et al. 2012). Unlike the pristine forest, the degraded peat swamp is highly heterogeneous with varying surface fuels, concentrations of woody debris, and micro relief that affect fire potential. Our observations suggest that people have a good sense as to when fire will spread as a function of the vegetation-fuels, relative humidity and wind. It is common to see recently burned areas with well-defined boundaries borders, as well as people igniting fires during mid-day optimum conditions. However, many fires are ignited without clear boundaries borders and become unregulated, free-burning fires. Once ignited, surface fire spreads as long as there are continuous fine fuels that are dry enough to burn. In degraded peat-swamp forests, afternoon relative humidity and wind commonly favor surface fire spread during the dry season (Usup et al. 2004) (fig. 2). These fires wander haphazardly across the landscape. They often spot across roads and canals. Surface ignition of peat from embers has been observed (figs. 1C, D). While it was found in

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

Figure 1—Surface characteristics of degraded peat (A-D). Dry, cracked and fissured peat and exposed rotten wood form favorable conditions for peat fire initiation (A, B). Ember-initiated spot fire in degraded peat roughly 50 meters from an active surface fire (C, D). (Photos by Kevin C. Ryan, March 5, 2014, Riau, Sumatra).

Figure 2—Surface fire–ground fire transition dynamics (A-D). Surface fire ignited by smoldering peat (A). Minimum surface fire spread rates exceed 100 times maximum ground fire smoldering rates. Thus, areal coverage by fire is dominated by surface fuel conditions. Surface fires ignite ground fuels preferentially through rotten, partially buried wood, cracks and fissures, and root channels (B). Once established, they provide "hold-over" ignition sources for adjacent surface fuels (A). Transitions commonly occur on a diurnal cycle during the dry season (C, mid morning – B, mid afternoon) but sustained smoldering combustion has been observed (kcr) eight weeks into the rainy season and intense nighttime flaming is commonly observed during droughts. (KFCP file photo, Central Kalimantan).

some Central Kalimantan studies (Usup et al. 2004) that surface vegetation fires burning in slashed grass did not transition to ground fires, our observations indicate that such transitions do commonly occur in other fuels, typically leading from surface fires to smoldering combustion in the peat as a result of the ignition of partially buried and decayed wood. Ground fires reemerge as surface fires whenever relative humidity and wind favor flaming combustion (fig. 2A). These fires (fig. 2B) can persist for weeks and may not self-extinguish until the water table rises as the rainy season develops. The flaming-smoldering transition dynamics are easily observed (figs. 2C, D) but remain to be rigorously documented. The process confounds fire detection, for example, via multiple, same-pixel MODIS hot-spot detections, and fire causation investigations. Given the scope and complexity of the fire problem, i.e., the sheer number of fires and their remoteness, the fire management organization in Indonesia, currently lacking the capacity to effectively suppress fire, limits actions to 'point protection' of rural homes.

To be successful, programs to reduce emissions from peatland fires must: 1) recognize the diverse human activities and objectives associated with fire use which, in addition to those mentioned above, include: asserting land-rights and improving access and habitat for hunting and fishing; 2) accept that some of these activities may be difficult to regulate because of being transient and occurring in remote locations; and 3) recognize that not all ignitions in and around peatlands lead to sustained peat fires. A better understanding is needed of not only the human activities associated with the ignitions, but also their timing, locations, methods, and the biophysical conditions under which they occur.

In accord with the preceding paragraph, our research, carried out in a peatland area of Central Kalimantan over an extended period, identified a wide array of human actions involving fire use in and around peatlands. In addition to ignitions for agricultural land clearing, which tend to be confined mainly to mineral soils and shallow-peat areas close to human settlements, we found numerous instances of ignitions in or close to deep-peat areas for such purposes as setting vegetation on fire to facilitate access to salvageable logs or fishing grounds or to provide fresh browse to attract deer and other game. Unlike the agriculture-associated ignitions that have a fairly predictable spatial and temporal distribution based on such factors as land tenure, soils suitability, and the seasonal "window" for land preparation early in the dry season, ignitions for the other purposes identified by us in degraded peat areas are transient, ephemeral, widely scattered, and, accordingly, less conspicuous. Such ignitions are less amenable to management, and, in accord with this, fire management, policy, rhetoric, and even research have been biased to focus primarily on the use of fire in agriculture and to neglect other uses that may result in peat fires.

To illustrate the operation of this bias in research, we cite here an article by Gaveau et al. (2014). The authors claim that most fires in their 2013 study area in Riau in Sumatra were for the purpose of agricultural land clearing, but they do not support their claim with any data resulting from observations of actual ignitions and their consequences. Instead they write, "Burn locations [within plantation concessions partially occupied by smallholders] suggest ignition by both communities and companies." This suggestion is followed by the assertion that "most fires are lit in order to prepare land for cultivation," (p. 5), citing Murdiyarso et al. (2010). But the cited article is a general review of GHG emissions from tropical peatlands, not specific to the study area in Riau. Nor does the review by Murdiyarso et al. (2010) cite any empirical studies of how peat fires start or of how surface fires spread—the distinction between causes of the start of fires and causes of their spread being a significant one (cf. Vayda 2006, emphasizing this point for fires in tropical moist forests). Rather, the authors of the review write, "land clearing by fire was *assumed* to be part of the land management system," (emphasis added); and "After clearing the forest, the land is prepared for cultivation, and fire is often used," (Murdiyarso et al. 2010, p. 19658). Even if we accept the general statement that fire is often used for agricultural clearing in tropical peatlands, that is not the same as saying that most peatland fires start from land clearing for agriculture or, even more unjustifiably, that most peatland fires transitioning from surface fires to underground peat fires start with ignitions for land clearing. Nevertheless, many have accepted these unjustified notions as conventional wisdom not requiring any further direct, evidentiary support even in specific cases where fire causes and burning methods are ostensibly of interest (see, for example, Harrison et al. 2009; Page et al. 2009; and Someshwar n.d.). Far from bearing out these notions, a recent remote-sensing study by Cattau et al. (2016) concluded that only 1-2 percent of the tens of thousands of fires detected by the MODIS satellite from 2000 through 2010 in a 2.5 Mha study area in Central Kalimantan peatland were fires that started either within oil-palm concessions or within 5 km of settlements and their nearby farms.

The difficulties in implementing a policy of fire control in peatlands by means of controlling fires from the sort of transient, ephemeral, scattered, and less conspicuous ignitions described by us argue for a policy that gives less priority to fire suppression and instead devotes more effort and resources to restoring the pre-agricultural hydrology and vegetation that made the peatlands previously much less vulnerable to fire than they are today. We therefore welcome the recent regulatory actions taken by the Indonesian government to initiate a policy of peatland protection, rehabilitation, and sustainable management (Mongabay 2015).

REFERENCES

Cattau, M.E.; Harrison, M.E.; Shinyo, I.; [et al.]. 2016. Sources of anthropogenic fire ignitions on the peat-swamp landscape in Kalimantan, Indonesia. Global Environmental Change. 39: 205–219.

Gaveau, D.L.; Salim, M.A.; Hergoualc'h, K.; [et al.]. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Scientific Reports 4. DOI 10.1038/srep06112.

Graham, L.; Manjin, S.; Tri Juni, E.; [et al.]. 2014. KFCP heavy fuel load assessment—Line intersect method and heavy fuel load results. Kalimantan Forests and Climate Partnership. 27 p.

Harrison, M.E.; Page, S.E.; Limin, S. 2009. The global impact of Indonesian forest fires. Biologist. 56: 156–163.

Mongabay. 2015. Indonesia bans peatlands destruction. http://news.mongabay.com/2015/11/indonesia-bans-peatlands-destruction/

Murdiyarso, D.; Hergoualc'h, K.; Verchot, L.V. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. Proceedings of the National Academy of Science. 07(46): 19655–60.

Page, S.E.; Hoscilo, A.; Langner, A.; [et al.]. 2009. Tropical peatland fires in Southeast Asia. In: Cochrane, M., ed. Tropical fire ecology. Springer-Praxis, UK.

Siegert, F.; Franke, J.; Ballhorn, U. [et al.]. 2012. LiDAR-based peat surface lowering estimation and historical burned area analysis for the Kalimantan Forests and Climate Partnership (KFCP) project. Baierbrunn/München, Germany: RSS-Remote Sensing Solutions GmbH. Isarstr. 57 p.

Someshwar, S.; Boer, R.; Conrad, E. n.d. World Resources Report case study. Managing peatland fire risk in Central Kalimantan, Indonesia. Washington, DC: World Resources Report. http://www.worldresourcesreport.org.

Stockwell, C.E.; Yokelson, R.J.; Kreidenweis, S.M.; [et al.]. 2014. Trace gas emissions from combustion of peat, crop residue, domestic biofuels, grasses, and other fuels: Configuration and Fourier transform infrared (FTIR) component of the fourth Fire Lab at Missoula Experiment (FLAME-4). Atmospheric Chemistry and Physics. 14(18): 9727–9754.

Stockwell, C.E.; Jayarathne, T.; Cochrane, M.A. [et al.]. 2016. Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño. Atmospheric Chemistry and Physics. 16: 11711–11732. https://doi.org/10.5194/acp-16-11711-2016, 2016.

Usup, A.; Hashimoto, Y.; Takahashi, H.; Kayasaka, H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. Tropics. 14(1). 19 p.

Vayda, A.P. 2006. Causal explanation of Indonesian forest fires: Concepts, applications, and research priorities. Human Ecology. 34: 615–635.

Human Performance Optimization: A Holistic Approach to Improve Wildland Firefighter Performance, Well-Being, and Safety

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INTRODUCTION

To perform optimally, a wildland firefighter needs a diverse skillset. In addition to mastering firefighting tactics, the job requires a high level of physical fitness, proper nutrition, mental acuity, and self-awareness. These human performance factors are vital because, unlike other professions, failure to perform optimally in wildland firefighting can result in serious injury or death. Yet despite the job requirements and potentially fatal consequences, human performance is overlooked in wildland firefighting training.

In 2011, the Wildland Firefighter Apprenticeship Program (WFAP) began to address this gap in training with the Human Performance Optimization Course (HPO). This is a three-hour course providing a brief overview of exercise physiology, nutrition, and performance psychology. HPO expanded to a three-day course covering all elements of human performance through a variety of pedagogical methods (i.e., lectures, interactive workshops, exercise and relaxation demonstrations, small and large group activities, experiential exercises, and question and answer sessions). Currently, HPO is held each year during the first three days of WFAP's Foundational Academy. The apprentices are full time wildland firefighters and generally have less than five years of experience.

CURRICULUM AND STRUCTURE

HPO's mission is to increase understanding and application of the factors leading to optimal human performance and safety among wildland firefighters working in high risk, complex environments. To accomplish this task, instructors teach an integrated curriculum that includes exercise physiology, nutrition, performance psychology, and leadership. Although there are other leadership trainings provided by the U.S. Forest Service, HPO's approach is unique. Grounded in Authentic Leadership principals, HPO's leadership style emphasizes self-awareness and values. These concepts require mindfulness and self-compassion, topics that are often absent from other leadership training.

HPO begins with The Amazing Race, a critical component of the curriculum intended to quickly connect the apprentices and provide a foundation for the rest of the HPO curriculum. The Amazing Race—an extensive team building activity— requires small groups to work together efficiently and effectively to complete mental and physical challenges that push individuals beyond their comfort zones.

After The Amazing Race, the first two days consist of 30- to 45-minute sessions that include a variety of interactive activities, discussions, and hands-on demonstrations. The instructors and topics continually rotate throughout the day. The apprentices spend the last day of HPO in small groups, attending a series of 50-minute workshops based on the information taught

Keywords: : fitness, leadership, nutrition, psychology, teaching, training

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

the previous two days. The smaller group environment provides an opportunity to apply the information through discussions and activities (e.g., developing a fitness plan, calculating caloric expenditure, taking a personality assessment). Although the a key aim of the curriculum is to increase performance and safety while fighting wildland fires, the skills learned at HPO are transferable to all domains of life. This is heavily emphasized because firefighting does not occur in a vacuum; challenges and stress experienced in all aspects of life affect performance, safety and well-being on the fire line.

CHALLENGES AND FUTURE OPPORTUNITIES

Despite HPO's success and popularity among apprentices, several challenges are limiting its growth and effectiveness. First, is the length of the course. All parties agree the current three-day model is not long enough to adequately cover the curriculum. Extending or increasing HPO to four or five days would allow instructors to add supplemental information, expand on current content, and/or incorporate more interactive activities. Another option to address the length is to create an Advanced HPO to be held in WFAP's advanced academy (Core).

Second is HPO's scalability and reachability. Currently, HPO is taught at WFAP's Foundational Academy in Sacramento, CA. Expansion of HPO to other areas of the Forest Service has been discussed, but logistical and financial challenges have prevented it. The National Fallen Firefighters Foundation (NFFF) has, however, recognized HPO's value and potential for all firefighters. NFFF is actively working with HPO instructors to modify the concepts, design, and course availability for structural firefighters.

Third is a lack of instructors. The growing demand for HPO has also resulted in a shortage of qualified instructors. Instructors hold advanced degrees and certifications in their areas of expertise, and most also have several years of wildland firefighting experience. Furthermore, they bring a contagious mix of energy and passion for the content, and firmly believe in HPO's mission. However, each instructor is also a full-time professional in his or her field, making it difficult to secure instructors for multiple HPO sessions in a single year. Therefore, more instructors must be recruited and vetted for HPO to expand beyond WFAP's Foundational Academy, but the unique combination of requirements makes them difficult to find.

The final challenge is quantifying HPO's impact on performance and safety. No long-term assessment of HPO's impact on wildland firefighter's performance, safety, and well-being has been conducted. While the apprentices continually provide overwhelmingly positive feedback, it is unknown how effective they are at implementing what they learned. It is also unknown what additional tools and/or support are needed to bolster their performance in the field. The NFFF is currently supporting the first year of a multi-year research study to answer these questions. Their support comes at a critical time, as demand grows, so does the need to quantify HPO's long-term impact.

CONCLUSION

The Human Performance Optimization Course's mission is to improve firefighter performance, safety, and well-being by empowering firefighters to think differently, train effectively, and lead compassionately. It does this through an integrated and interactive curriculum that teaches exercise physiology, nutrition, performance psychology, and leadership. By continuing to address the current challenges and expand beyond the Wildland Firefighter Apprenticeship Program's Foundational Academy, HPO will be able to help all firefighters thrive personally and professionally.

A Future Without the Joint Fire Science Program?

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INTRODUCTION

In the Federal Fiscal Year (FY) 1998, appropriation for Interior and related agencies, U.S. Congress established funding and direction to initiate the Joint Fire Science Program (JFSP). Federal wildland fire management agencies developed the Joint Fire Science Plan to provide program direction. Under the guidance of an interagency governing board, the program matured into a full-featured science program utilizing a multi-faceted process to determine research priorities; efficient and open proposal solicitation, review, and funding procedures; and effective, collaborative science delivery and exchange mechanisms.

As documented by four successive independent program reviews since 2002, JFSP has been a highly successful and integral component of the interagency wildland fire management program. With a relatively limited budget, it has improved efficacy and accountability of agency activities by funding research on timely and important topics. These reviews clearly identify the critical role JFSP has played in catalyzing collaborative efforts across management and science boundaries, and in articulating an interagency, management-driven science agenda.

However, as JFSP enters its 21st year, current trends are placing its future at risk. The proposed Federal Fiscal Year 2019 President's Budget provides no funding for JFSP. This paper highlights the unique values and importance of the program and illustrates the magnitude of impacts that will result from implementation of such drastic funding proposals.

BUDGET HISTORY

The JFSP was initially funded in federal FY 1998 at $8 million, half from Department of the Interior (DOI) and half from Forest Service, U.S. Department of Agriculture. This funding was doubled in FY 2001. This funding level held steady until dropping to $14 million in FY 2006, then to $13 million in FY 2012. Funding dropped again in FY 2017 to $9 million, then to $3 million (all DOI) in FY 2018. The proposed FY 2019 President's Budget eliminates the program.

PROGRAM ORGANIZATION AND FOCUS

The JFSP program organization reflects a unique focus on management-driven research questions. A 12-person Governing Board, comprised of employees of the funding agencies, provides guidance and direction to the research questions selected for study; selects specific research proposals for funding; and selects new science and science exchange projects funded by JFSP. In addition, a unique program investment strategy maintains a balance among the types of science investigations, the mix of issues addressed, and short-term versus long-term investments.

Keywords: fire science, fire research, research funding, JFSP

In: Hood, Sharon; Drury, Stacy; Steelman, Toddi; Steffens, Ron, tech. eds. The fire continuum—preparing for the future of wildland fire: Proceedings of the Fire Continuum Conference. 21-24 May 2018, Missoula, MT. Proc. RMRS-P-78. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 358 p.

RESEARCH

JFSP research has been an important and highly efficient component of wildland fire science. JFSP has funded a significant portion of all wildland fire and fuels research conducted in the U.S., averaging 28 studies annually. Most studies are collaborative projects involving Federal land managers and Federal and university scientists. State, private, and NGO scientists and managers have also made important contributions. An important characteristic of JFSP research is that investments directly translate into research accomplishments. The JFSP does not fund salary for permanent employees, including tenured faculty, and in-kind and contributed costs of funded proposals have historically averaged approximately 60 percent of the total requested funds. This means that JFSP capitalizes on the capacity of Federal and university scientists to conduct research.

Another key aspect of JFSP is the open proposal solicitation and independent peer-review processes. Open proposal solicitation means that anyone can submit proposals that address research questions listed in proposal solicitations. Simply put, JFSP has full access to the entire talent pool. Having access to university scientists is significant because Federal science agencies alone do not present the diversity of skills, experience and innovation found within the university system.

Independent peer review is a cornerstone process of high-quality science. The JFSP regularly convenes independent peer-review panels to evaluate scientific merit and management relevance of submitted proposals. Only the highest-rated proposals are considered for funding. This means that a wide range of experience, skills, and knowledge is used to evaluate the research questions identified by managers, and that each study meets a peer-review quality standard.

As an indicator of productivity, JFSP research constitutes a significant portion of published wildfire and fuels research. On average, JFSP research results are published in 44 scientific journal articles annually. It also constitutes 20–40 percent of the U.S. based science papers in the International Journal of Wildland Fire and Journal of Fire Ecology, two of the more important science journals for wildland fire. JFSP research results appear in many other publications including federal science papers, book chapters, and conference proceedings.

Research outputs are important, but not the ultimate goal. The JFSP Governing Board has long sought to evaluate the management-relevant outcomes of JFSP investments. According to an analysis by Hunter (2016), 86 of 122 (71%) of sampled agency fire planning and policy documents cited JFSP results. In a complementary assessment, Hunter (2016) showed that 41 of 48 (85%) of sampled JFSP projects were cited in agency fire planning and policy documents. This emphasizes the continuing value of JFSP research results for managers.

SCIENCE EXCHANGE

Science exchange among scientists and managers has been central to the mission of JFSP since its origin. The first phase of science exchange was viewed as technology transfer and focused on the transfer of science to managers by scientists. Technology transfer was an explicit proposal evaluation criterion and funding decisions by the Governing Board were based in part on planned science delivery.

After an independent program review (Abbey and others 2002) recommended that JFSP do more to promote science delivery, the Governing Board invested in program-level science delivery capabilities. A communications specialist was hired and a science delivery plan was developed. Two important changes resulted from these actions. First, science delivery was recognized as a more complete system of problem and research question development that engaged managers in science implementation and facilitated exchange of science results interpreted and demonstrated in manager-relevant terms. The second change saw development of multiple science delivery products including science briefs, digests, and syntheses. These products have been widely disseminated and broadly used.

A second program review (Jones and others 2009) again emphasized that JFSP needed to do more in terms of science delivery. This time, the Governing Board decided a major change in scope would significantly improve the effectiveness of JFSP science delivery and exchange. This set the stage for creation of the JFSP Fire Science Exchange Network (FSEN). Funded in several rounds of proposal solicitation starting in 2009, the network has grown to include 15 exchanges covering the entire US (figure 1).

The FSEN engages practitioners, scientists and citizens in a wide-ranging set of activities to inform research agendas and accelerate understanding and adoption of fire science. The FSEN reported 12,218 individual activities reaching 417,419 participants in FY 2017, an increase of approximately 50 percent from FY 2014 in both categories. An independent evaluation of FSEN effectiveness conducted by the University of Nevada, Reno (Copp et al. 2017) stated that:

- The FSEN is increasingly achieving intended outcomes as well as outputs.
- Exchange users demonstrate higher levels of confidence in their ability to find, interpret, and apply fire science.
- Exchange users report better engagement with fire scientists, and increased use of fire science by fire managers.

The FSEN has become the ‘go-to’ source of the latest fire science information for many wildland fire and fuels practitioners and citizens throughout the country.

STUDENTS

An often overlooked but important contribution of JFSP has been support for university undergraduate and graduate students. These students are the managers, scientists, and leaders of tomorrow. The management-driven research focus of JFSP exposes students to managers and management issues early in their career, often in ways that directly impact their careers and the agencies that employ them. From 2011 to 2017, 1,000 students were directly involved in JFSP research (594 undergraduate students; 208 masters students; 198 doctoral students).

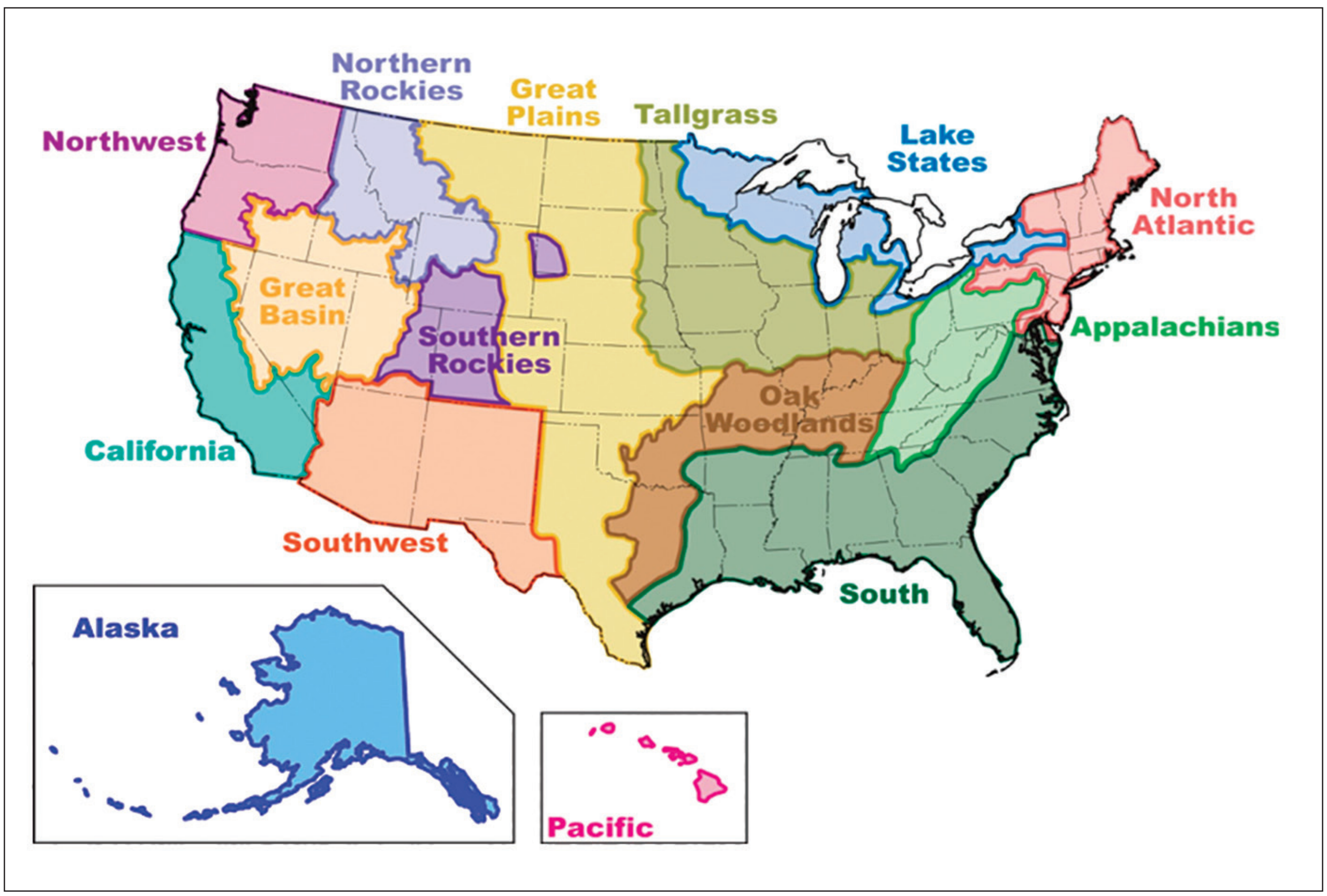

Figure 1—JFSP Fire Science Exchange Networks.

In collaboration with the Association for Fire Ecology (AFE), JFSP developed and sponsors two unique programs that directly support engagement of students with fire and fuels managers. The GRIN (GRaduate INnovation) program provides limited supplemental awards to graduate students to enhance student exposure to wildland fire, fuels management, and policy. GRIN awards produce tools useful for fire and fuels managers. Since 2011, 50 students have successfully competed for GRIN awards (27% award rate). JFSP also sponsors travel grants that support student interaction with managers. Over 230 students from 49 universities have received travel grants (average of $630 per grant).

CAN THE FEDERAL GOVERNMENT MAKE UP FOR THE LOSS OF JFSP?

One assertion is that existing Federal research programs can absorb the loss of JFSP without real consequence, but in reality, this is improbable.

Eliminating JFSP will result in loss of:

- A manager-driven research agenda.
- A strategic approach to science and science exchange investments.
- A significant portion of the total wildland fire and fuels research conducted in the US.
- A highly leveraged and value-added means of conducting research.
- Involvement of university scientists.
- Independent peer review of all funded research.
- Student understanding of management issues.
- The Fire Science Exchange Network.
- Major contributions to wildland fire journals and conferences.

The Forest Service is the only real candidate agency to absorb the loss of JFSP because it is the only agency that has a broad-based research wildland fire appropriation. Other agencies (USGS, NASA, EPA, ARS, NOAA) have scientists engaged in fire and fuels research but are largely dependent on external funding for wildfire research. Forest Service research is also coping with significant budget cuts and not in a position to take on new work without new funds.

Funding trends for Forest Service research are on a long-term downward trajectory. Despite increasing expenditures for wildland fire over the last 20 years, wildland fire research funds show a downward trend. Appropriated wildfire research funds are actually lower now than in FY 2000, and National Fire Plan funds used for research, which have been as high as $22 million dollars (FY 2002) are slated to be eliminated in the proposed FY 2019 President's Budget.

The USGS has a unique role with the DOI management agencies and has many excellent scientists with relevant expertise but is missing expertise in large elements of the JFSP mission (smoke, fire behavior, social science, fire weather, incident management, human health). USGS scientists largely depend on external funding sources for fire research because USGS does not have a wildfire research appropriation.

OPTIONS

Given the potential that JFSP could be eliminated in FY 2019, are there options the wildfire community should be considering? The contributions JFSP has brought to the community are substantial and loss of the program will have significant effects in both the short- and long-terms. These values are not intrinsically associated with the personnel or particular administrative history of the program but the deliberate result of specific values and policies, namely:

- An investment strategy focused on manager's needs.
- Open competition and independent peer-review.
- Limited indirect costs and salary funding.
- Strong commitment to science delivery and exchange.

In theory, any or all of the specific practices that support these policies could be adopted by a new or revised science program. However, it has taken 20 years for JFSP to fully develop the infrastructure and procedures necessary to maximize the value of these practices and to ensure fair and equitable management. Disbanding JFSP and starting a new program in the future with a similar or revised mission will incur significant start-up costs and take time to mobilize.

Options. Some potential options include, but are not limited to:

1. Proposed program elimination—This is proposed in the FY 2019 President's Budget and would eliminate JFSP. But, multiple-year agreements that are already funded mean that JFSP science and science exchange projects would continue for another 2-3 years.
2. Restore full funding—This would restore funding to historical levels so that the program would continue to operate as it has in the past. Full operations could be re-initiated fairly quickly.
3. Reboot with new focus—The intent here is to focus JFSP procedures on a new critical mission as determined by fire and fuels managers. The program could be re-branded to reflect a new theme but retain the critical operating practices that have distinguished JFSP and made it successful.
4. Fund only FSEN—This option would continue funding for FSEN but eliminate new research. At a minimum, this capacity is needed for the next 3–5 years as research already funded by JFSP is completed and enters an active science exchange phase.

In our opinion, JFSP has been a vital component of the fire and fuels community for 20 years and loss of the program would be highly damaging. The JFSP may want to consider a sustained period of enhanced engagement with interagency fire and fuels managers to re-invigorate its mission. Such engagement could help identify and clarify top priority research and science exchange issues facing managers in the next 3–5 years. The program has done this before successfully, and many in the community remain committed to ensuring the success of the program. The FSEN has created valuable relationships among scientists, managers, and citizens at local and regional levels and could sponsor and organize such an activity. The FSEN also has established patterns of working cooperatively as a national network and could facilitate a synthesis of research priorities involving a broad set of stakeholders. Many of these priorities are reasonably well understood, but a period of increased engagement could sharpen the focus of future research and science exchange priorities. A side benefit could be to heighten awareness of the program and create positive energy for the program's future.

CONCLUSIONS

This paper has described the impacts of the loss of JFSP to the wildfire community and presented some options for the future. In our view, without JFSP, links between research and management will be weakened, and a standard for addressing knowledge gaps and meeting research needs will be lost. These losses are significant and wide-ranging and will not be made up by Federal agencies individually, or collectively. In addition, ending this program is not consistent with statements in the Federal Wildland Fire Management Policy and the National Cohesive Wildland Fire Management Strategy Guiding Principles that call for basing fire management plans, activities, and decisions on the best available science, knowledge, and experience. With wildland fire presenting greater challenges to natural resources and society each year, it seems incomprehensible to de-fund indispensable programs that advance overall management capabilities. We urge reconsideration of full funding for JFSP and enhanced engagement of JFSP with interagency managers to ensure future research needs are well understood and articulated.

Author's Note

Both authors have been directly engaged with JFSP in the past and have detailed knowledge of JFSP practices. However, both are now retired and not affiliated with JFSP or Federal government research. The opinions in this paper are strictly that of the authors and do not represent any official input or opinion of JFSP or other government agencies. Most data in this paper are excerpted from agency program reviews and evaluation reports on file at JFSP office, Boise, ID.

REFERENCES

Abbey, R.; Roussopoulos, P.; Beighley, M.; Hartmann, L.; Kearney, M.; [et al.]. 2002. Joint Fire Science Program five year program review report. Boise, ID: DOI/USDA Forest Service. 36 p.

Copp, C.; Davis, B.; Evans, W.; Singletary, L. 2017. Joint Fire Science Exchange Network 2017 evaluation report: A national cluster evaluation of the Fire Science Exchange Network processes and impacts. Reno NV: University of Nevada. 56 p.

Hunter, Molly. 2016. Outcomes of fire research: Is science used? International Journal of Wildland Fire. 25(5): 495–504.

Jones, B.; Joyner, C.; Brandel, K.; Cutter, S.; [et al.]. 2009. Joint Fire Science Program 5-Year program review report. Boise ID: DOI/USDA Forest Service. 20 p.

Field Trips

Confederated Salish-Kootenai Tribal Fire and Forestry Management: Philosophy, Management Strategies, and Working across Boundaries

Monique Wynecoop, Fire Ecologist, Colville National Forest, USDA Forest Service, Colville, Washington

Abstract—Within the ancestral homelands of the Confederated Salish Kootenai Tribes (CSKT), the Fire Continuum Conference (May 2018) discussed the complexity of wildland fire and fuels research and management. The CSKT fieldtrip took place on the Flathead Reservation, about 20 miles north of Missoula, and the presenters addressed many facets of the fire continuum and the CSKT's novel approach towards addressing the complexity challenge. Approximately 53 people, from a variety of different countries, states, and backgrounds, attended the field trip which made for a great opportunity for shared learning and networking. Serra Hoagland, Liason Officer (Biologist), Rocky Mountain Research Station, was the facilitator for the field trip.

Keywords: Confederated Salish Kootenai Tribes, ecosystem-based resource management

OVERVIEW

The Hellgate Treaty of 1855 established the Flathead Reservation, which was further decreased by a half a million acres in 1905 during the Allotment Era (1871-1934) (fig. 1). The remaining reservation was then managed by the Bureau of Indian Affairs, which initially did not incorporate tribal values or opinions into their management strategies and hired what they called Indian Agents (not foresters or tribal people) to administer timber sales. Like many reservations across the U.S., poor timber management by these agents led to the exploitation and illegal harvest of the Confederated Salish Kootenai Tribes' (CSKT) timber resources and prohibition of indigenous fire on the land in the 19th century, with no consideration for sustainability or benefits to the tribal people. When the Indian Self-Determination Act of 1976 (Public Law 93-638) was passed, it allowed the unique opportunity for sovereign tribal governments such as the CSKT to develop a forest management plan that addressed their unique cultural, ecological, and economic values for the best interest of the tribe.

Within their Forest Management Plan (May 2000 version), the CSKT demonstrates how natural resource management can heal the land and the people and adapt to address complex challenges such as increasingly frequent and large wildfires and climate change. This was the bottom line of the field trip. The field trip included presentations at the Gray Wolf Peak Casino by CSKT Employees who discussed ecological and social challenges the tribe is facing and how they are successfully addressing that with their innovative

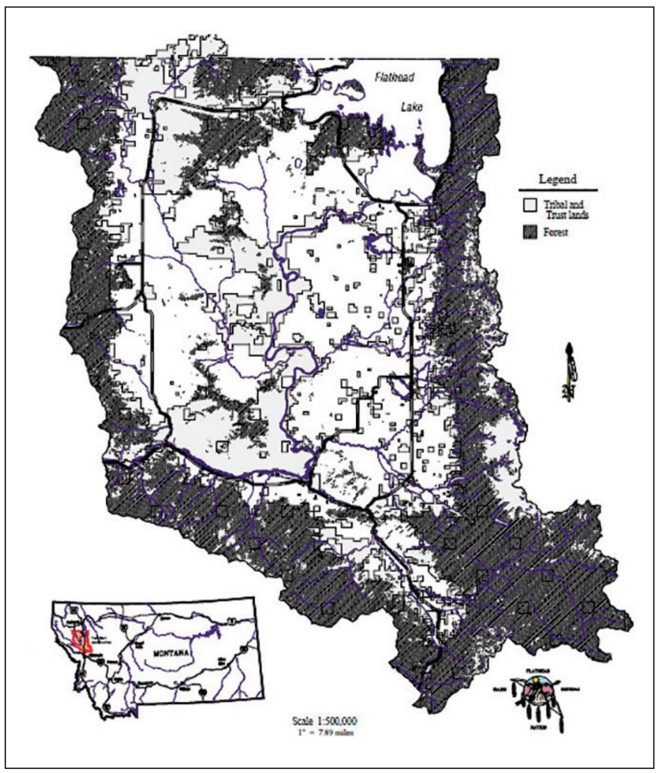

Figure 1—CSKT Reservation (CSKT 2000).

CSKT Forest Management Plan, which is updated every 10 years (CSKT 2000). The presentations were then followed up by a drive out to the Jocko Prairie project area to see the ecological concepts of the resource management plan in practice on a recent prescribed burn.

Some key take-away points from the field trip:

- The management plan follows an ecosystem based approach that is defined in the plan as, "… the integrated use of ecological knowledge at various scales to produce desired resource values, products, services, and conditions in ways that also sustain diversity and productivity of ecosystems. This approach blends physical, biological, cultural, and social needs," (CSKT 2000).
- Management, such as timber removal, mimics natural disturbance.
- Natural fire and indigenous fire have had a significant impact on the CSKT landscape for thousands of years.
- Cultural ideology of the CSKT is incorporated into all facets of management.
- Combining TEK and Western Science are the best ways to address resource management issues today.
- The land is being managed to help and heal the people. Tribe and future generations come first.

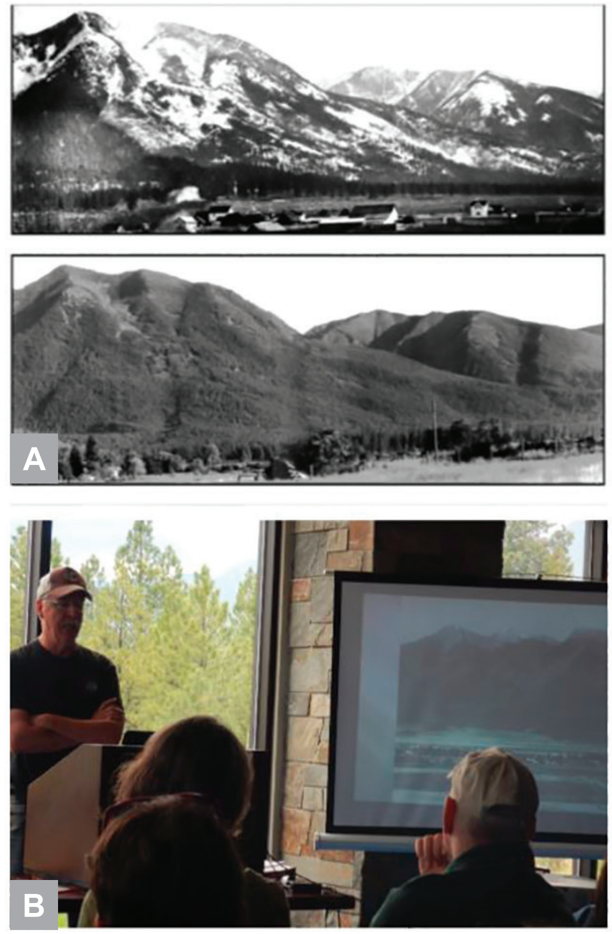

Figure 2—(A) Comparison between photo points taken during 1925 (top) and 1994 (bottom). Photo A courtesy of the CSKT. (B) Tony Hardwood points out that retaking pictures at these historic photo points help demonstrate the loss of diversity and how the removal of fire has caused a monoculture. (Photo B courtesy of Monique Wynecoop, Fire Ecologist, USDA Forest Service.)

CSKT FIRE HISTORY

Between the years 1978 and 1997, the Flathead Reservation had 734 fires totaling 20,933 acres. Between the years 1998 and 2017, there were 1,572 fires and 139,956 acres were burned (fig. 3). Many factors led to the alteration of the forested areas within and surrounding the reservation, such as, "changes in patch size, in species diversity within stands, and increases in tree density within stands," (CSKT 2005). The Tribe's ecosystem based resource management plan is novel in that the tribe redefines fire management units to fit their emphasis on mimicking natural disturbance. In 2005, the CSKT completed a fuels assessment to amend their fuels management plan within their 22,000 wilderness Buffer Zone Management Area and identified four significant fire regime types within the management area:

- "Lethal" Stand-replacement Fire Regime (FRC)—Approximately 2 percent of the buffer zone, these areas are lower elevation even-aged, managed, and shelterwood timber stands, primarily comprised of mature, mixed conifer Douglas-fir (*Pseudotsuga menziesii*), Grand-fir (*Abies grandis*), Western Red Cedar (*Thuja plicata*), and Englemann spruce (*Picea englemannii*). They are cool and moist sites with moderate wind exposure.
- "Mixed" Partial Stand-replacement Fire Regime (FRB)—Approximately 25 percent of the buffer zone, these areas are lower- and mid- elevation timber stands with a dense pine/fir/larch (*Larix occidentalis*) understory.

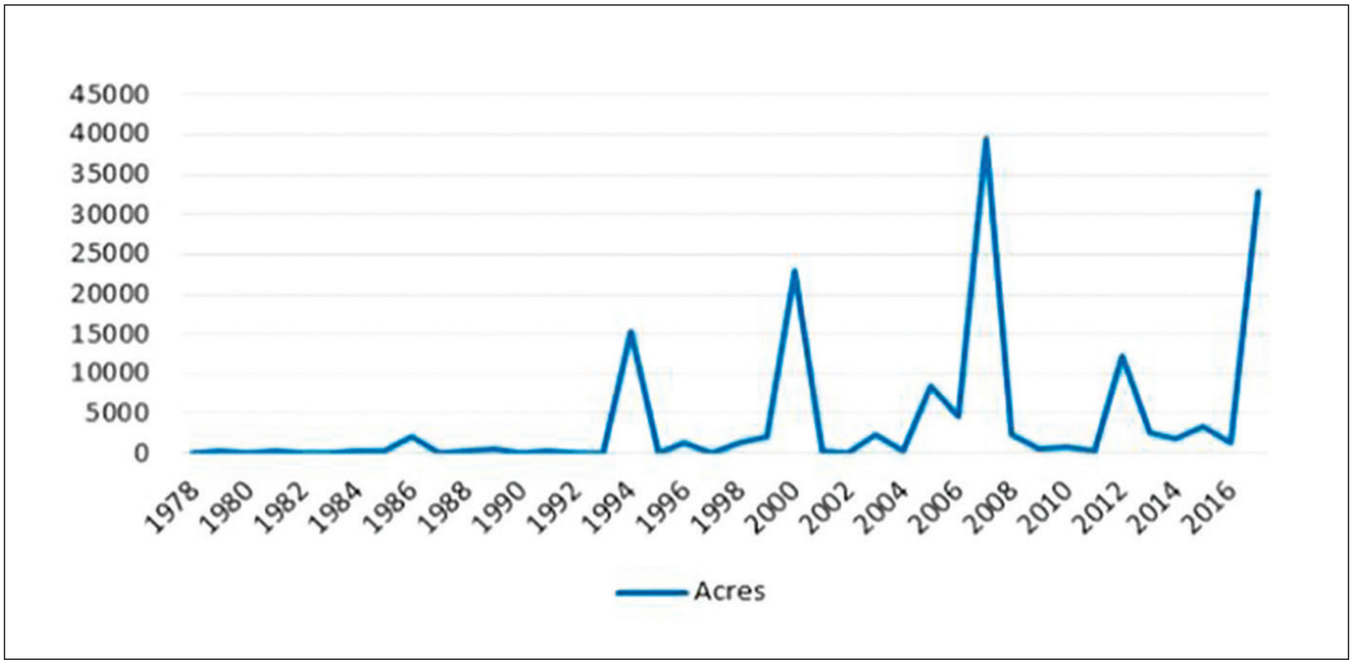

Figure 3—Trend of annual acres burned by wildfires on the Flathead Reservation between 1978 and 2017. Numbers in graph are from the CSKT Division of Fire Management numbers from field trip fire history handout (Graph made by Monique Wynecoop, USDA Colville National Forest).

- Non-lethal Fire Regime (FRA)—Approximately 73 percent of the buffer zone, these areas are uneven-aged treatment areas within low and mid-elevation areas comprised of intermediate and mature ponderosa pine (*Pinus ponderosa*) and Douglas-fir with dense regen understory (CSKT 2005).

JOCKO PRAIRIE PROJECT

The site visit to the Jocko Prairie Project was a great way to end the field trip (fig. 4). The site demonstrated the CSKT management approach utilizing traditional cultural knowledge, thinning, and prescribed fire to return ecological and cultural values of the CSKT to the landscape. One growing season post-fire, the camas returned in abundance to the project area. The visible difference in plant diversity and blue camas (Cammasia quamash) abundance between the untreated, closed-canopy stand directly across the road from the treated, now open-canopy stand was notable.

FIELD TRIP PRESENTERS

Serra Hoagland, Liaison Officer (Biologist), Rocky Mountain Research Station

Stephen McDonald, Forestry, Division Manager of Project Planning, CSKT

Kyle Felsman, Tribal Preservation Officer, CSKT

Casey Ryan, NRD Water Management Project Engineer, CSKT Ronan Office

Tony Hardwood, Consultant, (Former CSKT Fire Management Officer)

Ron Swaney, Fire Management Officer, Division of Fire, CSKT

Mark Couture, Lands Department Specialist, CSKT

Tony Incashola Jr., CSKT Forest Manager

Vernon Finley, Gray Wolf General Manager

Figure 4—Jocko Prairie Project unit, post prescribed fire to reestablish camas and cultural uses of the area. Camas was plentiful in the project area just one growing season post-fire. (Photo courtesy of Monique Wynecoop, Fire Ecologist, USDA Forest Service.)

ADDITIONAL READING AND INFORMATION

Confederated Salish Kootenai Tribes (CSKT) Climate Change Strategic Plan. 2016. Online: http://nrd.csktribes.org/component/rsfiles/download?path=CSKT%2BClimate%2BChange%2BAdaptation%2BPlan%2B4.14.16.pdf. [Accessed 2018 June 10].

Confederated Salish Kootenai Tribes (CSKT) Mission Mountain Wilderness Buffer Zone Reclassification. 2005. Online: http://www.csktribes.org/natural-resources/tribal-forestry/about-forestry. [Accessed 2018 July 2].

Confederated Salish and Kootenai Tribes (CSKT), 2000. Flathead Indian Reservation Forest Management Plan: An Ecosystem Approach to Tribal Forest Management. Online: http://www.csktribes.org/natural-resources/tribal-forestry/about-forestry. [Accessed 2018 June 10].

Intertribal Timber Council (ITC) Indian Forest Management Assessment Team, 2013. Assessment of Indian Forests and Forest Management in the United States: Executive Summary. Online: http://www.itcnet.org/issues.projects/issues_2/forest_management/assessment.html. [Accessed 2018 June 10].

Lolo Peak Field Trip: From the Wilderness to the Wildland Urban Interface

Linda Mutch, Northern Rockies Fire Science Network, National Park Service, Sierra Nevada Network, Three Rivers, California

Abstract—Forty-one participants joined field trip coordinator LaWen Hollingsworth, Fire Behavior Specialist at the U.S. Forest Service Rocky Mountain Research Station, as well as local Forest Service managers, the Type I Incident Commander, and the County Sheriff's office, to learn about management of the 2017 Lolo Peak Fire. At four stops, participants had views of the burn area, heard about management decisions and actions and the Highly Valued Resources and Assets that informed decisions, talked with a local property owner, and saw previous fuel treatments and shaded fuel breaks that were useful in the long-term management of the fire. The Lolo Peak Fire ignited in an area that had not experienced significant fire in many years, and large portions of the area were dominated by lodgepole pine and mixed conifer forests comprising 40 to 50 percent dead trees. Most recent fires had been small or effectively suppressed. Thus, fuels and forest conditions along with remote, rugged terrain made direct line construction unsafe. The location of the primary fireline was based on creating a working zone for firefighting resources that had escape routes and safety zones in areas that were less steep with fewer snags and where fuels were more favorable for successful suppression actions. Indirect line construction combined with burnout operations was chosen as the best strategy to safely manage this fire.

Keywords: Lolo Peak Fire, Selway-Bitterroot Wilderness, firefighter safety, Highly Valued Resources and Assets, Management Action Points, wildland urban interface, fire management planning, LOLO

OVERVIEW

Although most of the spring of 2017 was wet and green in western Montana, numerous consecutive days of 90-plus degree weather with no significant precipitation led to a flash drought, or a rapid-onset drought, as summer progressed. By July 12th, lightning storms had started numerous fires near Missoula, Lolo, and in the Rock Creek drainage. On July 15th, an air attack plane responding to another fire discovered the Lolo Peak Fire burning at high elevation in the Selway-Bitterroot Wilderness (fig. 1). This was one of several fires in the region that contributed to air quality impacts in local communities, and by the time it was contained in late October, it had burned nearly 54,000 acres.

Forty-one participants joined field trip coordinator LaWen Hollingsworth, Fire Behavior Specialist at the U.S. Forest Service Rocky Mountain Research Station, local Forest Service managers, the Type I Incident Commander, and the County Sheriff's office (see list of presenters at the end), to learn about management of the 2017 Lolo Peak Fire. At four stops, participants had views of the burn area, heard about management decisions and actions and the Highly Valued Resources and Assets that informed decisions, talked with a local property owner, and saw previous fuel treatments and shaded fuel breaks that were useful in the long-term management of the fire.

FIREFIGHTER SAFETY—A PRIORITY

The fire ignited in an area where 40-50 percent of trees were dead, and slopes were steep, ranging from 60-70 percent. Local fire managers and the incident management team determined there were no safe places to insert firefighters where they could be readily evacuated if there were a medical emergency. Initially bucket drops of water were used to stall growth but were largely ineffective. These safety issues informed the subsequent strategies used to manage this fire.

Figure 1—View of Lolo Peak in the background and lower elevation burned area visible on the ridge in the foreground.

INFORMED ASSESSMENT AND PLANNING

Forest Service staff and Incident Management Team members focused on planning strategies for indirect attack in areas with more favorable fuel types and topography and communicating their strategy with cooperators, stakeholders, and the Montana Department of Natural Resources, who managed lands in some of the areas proposed for indirect fireline.

Knowledge from prior fire and fuels planning and from previous fires in the area informed early decisions made on this fire. Fire behavior on the 2013 Lolo Creek Complex indicated that wind is funneled through Lolo Creek drainage that can result in significant fire spread from west to east. It was clear that once the Lolo Peak Fire crossed Lantern Ridge northwest of Lolo Peak, it could burn towards the community of Lolo quickly as the fire would be exposed to west winds, potentially making a rapid transition from wilderness to wildland urban interface areas.

Potential indirect fireline locations were scouted in accessible areas adjacent to developed areas across all land ownerships. Structure assessments were done on 904 homes, and negotiations done to determine where the fireline would go. A shaded fuelbreak was established along the primary fireline.

Ultimately, Agency Administrators such as Forest Supervisors help the team managing a fire to prioritize where efforts are focused by identifying values at risk and voicing management priorities. The Lolo National Forest Supervisor's direction to invest in strategies with a high probability of success and emphasize risk management and firefighter safety informed team decisions early on.

WORKING COLLABORATIVELY CRITICAL TO SUCCESS

Large, complex fires burning near wildland-urban interface require collaboration across disciplines, organizations, and property boundaries. On the Lolo Peak Fire, scientists and resource managers worked closely with fire managers to inform decisions and ensure natural resources were protected. The Incident Management Team worked closely with counties, state agencies, local property owners, law enforcement officers, and many others to protect Highly Valued Resources and Assets, such as public and firefighter safety and social and economic values (fig. 2).

Early on, there were as many working in the overhead team's Science Branch on this fire as in Operations and other branches. The positions in the Science Branch included Strategic Operational Planner, Long Term Fire Analyst, Fire Behavior Analyst, Incident Meteorologist, Air Resource Advisors, and Fire Effects Monitor. Fire behavior modeling characterized the fire as a small wilderness fire with great potential to grow, and modeling informed the identification of management action points. Management action points are geographic points on the ground or specific points in time where a management action is warranted based on the location and behavior of the fire. In the Lolo Peak Fire, these were all spatial points, and the action that occurred was usually an evacuation warning or order.

Figure 2—LaWen Hollingsworth, Long-term Fire Analyst on the Lolo Peak Fire, shows maps of Highly Valued Resources and Assets and Vegetation Types and Fire History of the area.

Planning and executing evacuations involved the Incident Management Team working closely with the Missoula and Ravalli County Sheriffs' Offices (fig. 3). The management action points were based on knowledge of expected fire behavior as well as available resources and evacuation authorities. The team worked to keep evacuation terminology simple and consistent. Warnings could turn into orders quickly, and once people were evacuated, their homes had to be kept secure until it was safe for them to return.

Another important area of collaboration was the liaison efforts between the Lolo National Forest and the management team coordinated by the Resource Advisor, a local specialist familiar with resources at risk of impact from the fire or fire management actions. The Lolo NF Resource Management Plan identifies many of the objectives for resource protection, and communication of these to the team helped to prevent or mitigate impacts of fire management activities on resources. Examples of such resources included critical habitat (bull trout), wilderness, and alpine larch in the Research Natural Area. Examples of actions that reduced impacts of suppression efforts included avoiding retardant drops near bull trout habitat, lifting dozer blades when crossing streams, and cleaning equipment to prevent invasive species introductions.

Figure 3—Rob Taylor, Captain at the Missoula County Sheriff's Office, discusses evacuations and the collaborative efforts between the Incident Management Team and the local county sheriffs' offices. LaWen Hollingsworth displays map of fire growth, Management Assessment Points, and evacuation.

PRIOR FUEL TREATMENTS FACILITATE BURNOUT OPERATIONS

In the Bass Creek drainage, the last stop for the field trip, participants looked at open forest stands treated with a thinning project. After the 2000 fires, the Bitterroot National Forest planned and conducted numerous stand treatments, and these, in addition to fuel breaks on privately owned lands, made it more feasible to conduct burnouts that provided “blackline” between the fire front and the wildland-urban interface and helped prevent the fire from burning rapidly down canyons toward properties in the Bitterroot Valley. Fire restoration and WUI protection were priorities for the Bitterroot NF treatment planning. In addition to larger fuel treatments, the work of local property owners to reduce fuels near their homes helped prevent structure loss where the fire did reach WUI zones (fig. 4).

COMMUNICATE EARLY AND OFTEN

Once the decision was made to manage the Lolo Peak Fire by backing off to more favorable fuel types and topography, and planning and establishing shaded fuel breaks and fireline, the Public Information Officers invested significant time in conveying this strategy to the public, cooperators, and other stakeholders. Building relationships and trust was critical, and helped the team more effectively communicate fire management strategy and evacuation warnings and orders as well as respond to questions and information needs.

Figure 4—Retired US Forest Service Ecologist Steve Arno talks about the Lolo Peak Fire from the perspective of a property owner, in addition to sharing his knowledge of the fire history in the area.

SUMMARY

The Lolo Peak Fire ignited in an area that had not experienced significant fire in many years, and large portions of the area were dominated by lodgepole pine and mixed conifer forests comprising 40-50 percent dead trees. Most recent fires had been small or effectively suppressed. Thus, fuels and forest conditions along with remote, rugged terrain made direct line construction unsafe. The location of the primary fireline was based on creating a working zone for firefighting resources that had escape routes and safety zones in areas that were less steep with fewer snags and where fuels were more favorable for successful suppression actions. Indirect line construction combined with burnout operations was chosen as the best strategy to safely manage this fire.

Incident Commander Greg Poncin said that he did not feel good about the number of people impacted by smoke, and emphasized his primary role on the fire was to ensure firefighter safety. While the Lolo Peak Fire had significant smoke impacts, early planning for a long-duration event allowed time to establish and implement a plan to reduce the probability of property damage and loss of life. This contrasts with a fire igniting in August, at a time of year when conditions favor more extreme fire behavior, and managers have fewer choices to influence where and how the fire burns.

FIELD TRIP PRESENTERS

LaWen Hollingsworth, Fire Behavior Specialist, U.S. Forest Service Rocky Mountain Research Station; Long-term Fire Analyst for Northern Rockies Team 1

Jesse Kurpius, Fire Management Officer, Missoula District, Lolo National Forest

Dave Williams, Assistant Fire Management Officer (Fuels), Missoula District, Lolo National Forest; Strategic Operational Planner for Lolo National Forest fires

Greg Poncin, Northwest Area Manager, Montana Department of Natural Resources; Incident Commander on Northern Rockies Team 1 overseeing the Lolo Peak Fire

Shane Hendrickson, Fish Biologist, Lolo National Forest; Wildland Fire Decision Support System (WFDSS) author and lead Resource Advisor for Lolo National Forest

Rob Taylor, Captain, Missoula County Sheriff's Office; Liaison Officer for Northern Rockies Team 1

Steve Arno, Retired U.S. Forest Service Rocky Mountain Research Station Ecologist and local property owner

Warren Appelhans, Fire Management Officer, Stevensville District, Bitterroot National Forest

Western Prescribed Fire Science Research Burn at the Lubrecht Experimental Forest, Montana

Abstract—Twenty-one participants were integrated into the operational incident command structure of a 10-acre prescribed burn on the Lubrecht Experimental Forest in Montana. Sharon Hood, Research Ecologist for the U.S. Forest Service Rocky Mountain Research Station (RMRS) was the facilitator for the field trip. This field trip was the first Western Prescribed Fire Science research burn conducted as an extension of the RxCADRE and Prescribed Fire Science Consortium (RxScience) experiments that have been conducted in the Southwest for the past decade (http://firecontinuumconference.org/field-trips/research-burn/). The research burn was a collaborative effort between the Tall Timbers Research Station, University of Montana, Los Alamos National Lab, and the U.S. Forest Service.

OVERVIEW

Often a prescribed burn requires time sensitive, logistical, and safety precautions that would make it challenging for a non-fire qualified person to observe and ask questions as it is taking place. The Lubrecht field trip, though also requiring the same precautions listed above, was unique in that it was set up for the purpose of shared learning and offered a unique opportunity for people from a variety of fire experience backgrounds to observe a prescribed burn up close from an established safety zone. The burn also offered a chance for participants to learn about the many facets of the Fire Continuum that can play into a prescribed burn. Some topics discussed during the day by managers, academics, and researchers were: operations, fire effects, fire behavior, and fuel characterization methods, which were also demonstrated in the field on the prescribed burn.

HISTORY OF THE LUBRECHT EXPERIMENTAL FOREST

Nineteen-thousand and fifty eight acres of the Lubrecht Experimental Forest were previously owned and logged by the Anaconda Copper Mining Company in the late 1800s, 1916, 1925, 1926 and then donated to University of Montana in 1937. In 1939, another 1,200 acres previously owned by the Northern Pacific Railroad were donated to the University of Montana (www.cfc.umt.edu/lubrecht/about/history.php).

The Lubrecht Experimental Forest serves as a middle ground between fire and academia and offers a unique opportunity to move forward with projects and treatments such as this prescribed burn more quickly than could be achieved on lands managed by a state or federal agency.

THE IMPORTANCE OF COMBINING OPERATIONS AND SCIENCE

Often times, the operational and scientific aspects of wildfire and fuels management are managed separately, and can seem intimidating to an outside party. However, the reality is that they depend heavily upon each other in order to address current challenges. The entire group, managers, researchers, and observers alike, were all incorporated into the command structure of the prescribed burn and took part in the morning briefing (fig. 1), where they were able to learn about the logistical aspects that go into a prescribed burn, such as safety, weather, and goals of the burn. During the briefing the two objectives of the burn were (1) safety and (2) provide a demonstration for the field trip participants.

The day was also ended with an After Action Review (AAR), in which the group was able to share what they learned and how the prescribed burn could go better for future field trips.

Figure 1—Valentijn Hoff gives the group a morning briefing prior to the prescribed burn.

SCIENCE OF PRESCRIBED FIRE

After taking part in the morning briefing the group were able to see the research equipment that would be used during the burn (fig. 2) and then moved to the safety zone of the experimental burn and waited for the test fire on the East side of the 10-acre unit (fig. 3).

The group learned about the fire ecology of the open ponderosa pine (*Pinus ponderosa*) systems of the Rocky Mountain Region and the goal of the past burns within the Lubrecht Experimental Forest (fig. 4), which was to kill the Douglas-fir (*Pseudotsuga menziesii*) in order to promote less shade tolerant species and protect the Ponderosa pine from being killed by a crown fire. He also explained to the group that western larch (*Larix occidentalis*) is more adapted than ponderosa pine to torching and crown fires, since it is deciduous.

The prescribed fire burned enough of the unit for the researchers on the burn to set up their equipment and demonstrate how they collected data and applied that to their models in the lab. During the burn, there was discussion of the power of leveraging models with on-the-ground and same-time data and the importance of looking at multiple scales of fire behavior and effects. Some field demonstrations during the burn included:

- Thermocouples that were measuring internal temperatures of individual trees before, during, and after the fire,
- Thermal Infrared camera that was used to view the burn from the safety zone,
- Demonstrations of different methods and equipment for measuring fire behavior and post-fire effects, and
- A 1 m^2 plot box used to validate models.

Figure 2—Introduction to some research equipment used on wildfires and prescribed burns. Top left: Dan Jimenez explains differences between in-situ measurements of fire energy and remotely sensed thermography using unmanned aerial systems (UAS) to provide real-time, co-located thermographic data. Top right and bottom left: tools used on the ground to collect on-the-ground fuels measurements and thermographic data. Bottom right: Matthew Cunningham showing the group the DGI Matrice 100 UAS prior to it being flown over the prescribed burn.

Figure 3—The test fire on the east side of the 10 acre burn unit.

Figure 4—While the burn crew prepares for the test fire, Ron Wakimoto, retired Fire Ecologist, University of Montana, describes to the group the goals of past burns on the Lubrecht Experimental Forest and fire ecology of the area and how that drives the goals of the field trip prescribed burn.

SUMMARY

Though the wet conditions weren't optimal for burning the entire 10-acre unit, the field trip was a success and an excellent example of shared learning between the many managers, researchers, and scientists involved. The atmosphere was energetic and positive, and the group left excited for the future of collaborative burn experiments in the western United States.

FIELD TRIP PRESENTERS

Sharon Hood, USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Montana

Eric Rowell, National Center for Landscape Fire Analysis, University of Montana

Christopher Keyes, University of Montana, Missoula

Lloyd Queen, Director National Center for Landscape Fire Analysis, University of Montana, Missoula

Valentijn Hoff, National Center for Landscape Fire Analysis, University of Montana, Missoula

Dave Grimm, Tall Timbers Research Station, Tallahassee, Florida

Morgan Varner, USDA Forest Service, Pacific Northwest Research Station, Wenatchee, Washington

Susan Prichard, Research Scientist, UW School of Environmental Sciences, Seattle, Washington

Dan Jimenez, USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, Montana

Nick Skowronski, USDA Forest Service, Northern Research Station, Morgantown, West Virginia

Andy Hudak, USDA Forest Service, Rocky Mountain Research Station, Moscow Fire Science Lab, Missoula, Montana

Marjie Brown, ScienceFire Solutions Inc.

Linda Chapelle, USDA Forest Service, Intermountain Region

Kevin Hiers, Tall Timbers Research Station, Tallahassee, Florida

Rodger Ottmar, USDA Forest Service, Pacific Northwest Research Station, Seattle, Washington

Leda Kobziar, University of Idaho, Moscow

Ron Wakimoto, University of Montana, Missoula

Marshall Woods Restoration Project: Challenges to Building Consensus and Conveying Fire Hazard Mitigation and Ecological Restoration Needs to the Public

Megan Keville, Northern Rockies Fire Science Network, Missoula, Montana

Abstract—Missoula District Ranger Jennifer Hensiek and other field trip presenters (see list of presenters at end) led about 35 participants on a tour through a portion of the Marshall Woods Restoration Project in the Rattlesnake National Recreation Area on the Lolo National Forest (NF). The tour included stops throughout the project area to view thinning and prescribed burn treatments, as well as stops on private land adjacent to the project area to demonstrate the importance of community and partner engagement to project success. The number of unique stakeholders invested in the project area resulted in a lengthy, and at times contentious decision process. The final authorization and implementation of fuel reduction treatments, weed spraying, and other actions did not begin until 2016, almost a decade after initial planning began. Through partnerships with local landowners, Missoula County, and the Montana Department of Natural Resources and Conservation (MT DNRC), the staff of the Lolo NF has observed increased acceptance and expansion of fuel reduction treatments to lands adjacent to the Marshall Woods Restoration project area, thereby increasing both the ecological and social effectiveness of the project.

Keywords: Marshall Woods Restoration Project, Rattlesnake National Recreation Area, wildland urban interface, fuel treatments, prescribed fire

OVERVIEW

Missoula District Ranger Jennifer Hensiek and other field trip presenters (see list of presenters at end) led 35 participants on a tour through a portion of the Marshall Woods Restoration Project in the Rattlesnake National Recreation Area (RNRA) on the Lolo National Forest. The tour included stops throughout the project area to view thinning and prescribed burn treatments, as well as stops on private land adjacent to the project area that demonstrated the importance of community and partner engagement to project success. In addition to the social and ecological aspects of the fuel treatments, participants learned about the unique challenges presented by this project and how they were addressed.

The 28,000-acre RNRA lies immediately northwest of Missoula, Montana, and is a highly popular recreation destination with an estimated 60,000 annual visitors. The immediate area also contains thousands of residences situated within the Wildland Urban Interface (WUI). In 2005, Missoula County's Community Wildfire Protection Plan identified the RNRA as having the second highest wildfire risk in the county, which prompted the early stages of restoration planning in the 13,000-acre Marshall Woods project area (fig. 1). In addition to reducing fire risk, the primary objectives of the project included forest restoration (enhancement of resilient vegetative communities, terrestrial habitats and water quality), reintroduction of fire, opportunities for restoration education, and recreation enhancements (e.g., trail improvements). The number of unique stakeholders invested in the project area resulted in a lengthy, and at times contentious decision process. The final authorization and implementation of fuel reduction treatments, weed spraying and other actions did not begin until 2016. Through partnerships with local landowners, Missoula County, and the Montana Department of Natural Resources and Conservation (MT DNRC), the staff of the Lolo NF has observed increased acceptance and expansion of fuel reduction treatments to lands adjacent to the Marshall Woods Restoration project area, thereby increasing both the ecological and social effectiveness of the project.

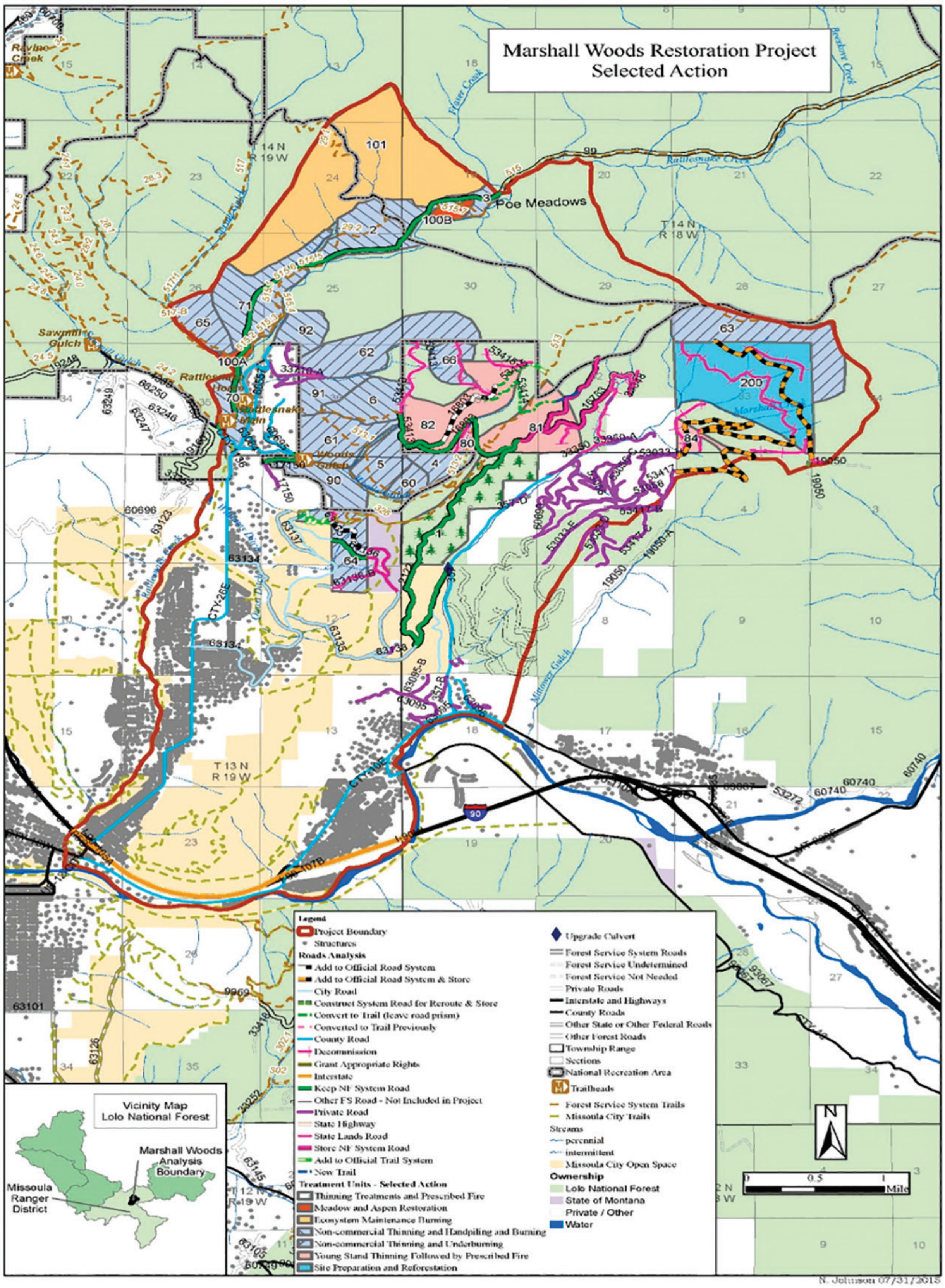

Figure 1—Marshall Woods Restoration Project area map with final decision actions.

ECOLOGY AND HISTORY OF PROJECT AREA

The RNRA is composed primarily of ponderosa pine/Douglas-fir and mixed conifer (western larch, Douglas-fir, ponderosa pine and lodgepole pine) stands. Almost a century of fire suppression has produced an atypically high tree density and heavy fuel loading, and shifted the relative abundance of tree species to favor Douglas-fir over the more fire resilient ponderosa pine and western larch.

The land currently designated within the RNRA has a long history of human habitation stretching back to the 13th century. The area is traditional territory for the Salish, who inhabited the area long before European settlers arrived at Rattlesnake Creek during the 1800s. The settler population in the area peaked at 139 people in 1910, with an operating schoolhouse and phone line serving the community. The entire Rattlesnake Creek drainage and surrounding areas were extensively logged throughout the late 1800s and early 1900s, primarily to provide railroad ties for the Northern Pacific Railroad. A major fire burned through the valley in 1919, the last fire that these forests experienced. Montana Power acquired much of the land in 1936 and halted logging operations in order to protect the watershed, which was the historical municipal watershed of Missoula.

In 1980, Congress designated the RNRA, the only National Recreation Area in the U.S. Forest Service Northern Region (Rattlesnake National Recreation Area and Wilderness Act of 1980, P.L.96-476). This designation includes unique management requirements, some of which were difficult to interpret, and contributed to contentious discussions when the Marshall Woods project planning process began over two decades later.

PROJECT PLANNING AND IMPLEMENTATION: CONSENSUS BUILDING CHALLENGES

In the early 2000s, natural resource management in the Missoula area was marked by polarization among timber and environmental groups. This led to paralysis on the ground, with proposed projects either litigated in court, or potentially too small to have a meaningful ecological impact. All stakeholders were dissatisfied with the status quo system, so in 2006, a group of upper-level officials representing agency, timber, nonprofit and other parties came together to attempt to find a “zone of agreement,” or common ground, that they shared in order to plan and accomplish work on the ground. A year of discussion within the group led to unanimous agreement around 13 Restoration Principles for “ecologically appropriate and scientifically supported forest restoration.” The Montana Forest Restoration Committee formed to promote these Principles, with a focus on National Forest System lands. Local forest- and district-level restoration committees were then established to work with the U.S. Forest Service to “ensure diverse and knowledgeable community engagement resulting in the recommendation of the selection, design and monitoring of restoration projects on National Forest System lands in Montana (MFRC 2013).”

The Lolo Restoration Committee (LRC) formed to assist with projects on the Lolo NF. In 2007 and 2008, LRC members met with Lolo NF employees to discuss project ideas in the Marshall Woods area, with a focus on promoting fire resilient species and the historic role of fire in these ecosystems. No proposed actions were agreed upon, and the start of the U.S. recession in 2008 shifted energy and funds elsewhere. During the recession, turnover in LRC membership and Missoula Ranger District leadership led to a loss of knowledge and trust, both of which needed to be rebuilt when the groups reengaged around the Marshall Woods Restoration Project in 2014 (fig. 2).

Lack of consensus within and among stakeholder groups during the project planning process resulted in a vocal and adversarial comment period when the National Environmental Policy Act (NEPA) Environmental Assessment (EA) detailing the proposed activities and anticipated environmental impacts was released in winter 2015. The EA presented three alternative actions in addition to a no-action alternative. The proposed actions included commercial tree harvest, log hauling and improvements to roads and trails throughout the project area, as well as small-tree cutting and prescribed fire. Disagreement around whether national recreational area management guidelines allowed for commercial harvesting was a

Figure 2—Missoula District Ranger Jennifer Hensiek explains the layout and specifics of the Marshall Woods Project treatments with the help of silviculturist Sheryl Gunn and Assistant Fire Management Officer Shaun Zenner.

major issue for many in the community—in the minds of many, the idea of logging trucks coming and going from their neighborhood or favorite recreation area outweighed the project's potential benefits. This and other views resulted in several letters to the editor of the local Missoulian newspaper, an extension of the public comment period, and eventual changes to the Lolo NF's preferred action for the Marshall Woods Restoration Project.

After taking public comments under consideration, the Lolo NF ultimately made the decision to exclude removal of merchantable trees from the RNRA. Managers concluded that this reduced results in terms of treatment impact, but still achieved some desired ecological and social outcomes. The final decision combined two of the action alternatives, authorizing non-commercial thinning, hand piling and burning, slashing/and or under burning to achieve fuel reduction objectives.

Project implementation began in 2016, with thinning and hand piling along the main Rattlesnake Creek corridor. Managers noted the 8-inch diameter limit for thinning trees within the RNRA constrained the effectiveness of the fuel treatment to a certain extent; however, mortality from root rot and bark beetles provided desired target conditions in some areas. The reduction in tree density following treatment is evident at treatment unit boundaries.

The treatment area around the Main Rattlesnake Trailhead offered its own set of challenges due to its proximity to private landowners and the need to address recreation issues while still achieving treatment objectives. Missoula District Ranger, Jennifer Hensiek, described the implementation on this unit as a "gardening scenario," which the Lolo NF undertook itself rather than contracting out, in order to ensure the elimination and prevention of user-created trails in addition to achieving desired ecological outcomes (fig. 3). The prescribed burn at the trailhead introduced additional social complexity with respect to adequately notifying area residents and recreationists about the burn and potential smoke impacts. Despite door-to-door and posted notifications, road signs well in advance of the burn, and newspaper and other media outreach, the Lolo NF received several public complaints during the burn. Nevertheless, public comments on the areas of the Marshall Woods Restoration Project treated to date have been overwhelmingly positive, and general acceptance of the fuel reduction treatments in such a treasured location has been viewed as a success by Lolo NF managers.

IMPORTANCE OF COMMUNICATION AND PARTNERSHIP WITH COMMUNITY

Field trip presenters suggested that, to truly meet ecological objectives and reduce fire risk at a meaningful scale, the lands adjacent to the Marshall Woods project would also need to undergo restoration treatments. The project has been viewed as a springboard opportunity to have more in-depth discussions and identify priorities with MT DNRC and neighboring landowners. A group of about 20 landowners have come together under MT DNRC

Figure 3—View of the thin and burn treatment at the Main Rattlesnake Trailhead.

leadership to complete fuel treatments on their private property adjacent to the Marshall Woods treatments. Some private landowners have taken on the role of fuel treatment "ambassadors," and have inspired their neighbors to participate in the Hazardous Fuels Reduction Program to do projects on their own property (fig. 4). This has been a particularly encouraging development for the Lolo NF, as project-adjacent private landowners did not participate in the NEPA comment process for the Marshall Woods project.

Missoula County is currently in the process of drafting a new Community Wildfire Protection Plan to assist with prioritization and planning of treatments and to integrate fire and land management objectives. As part of this process, Greg Dillon of the U.S. Forest Service's Fire Modeling Institute, is helping with the identification of strategic fire management zones using spatial risk assessment techniques. These management zones will help land managers prioritize areas for fuel treatments to protect the WUI when a fire occurs.

The above examples of collaborations among agencies, local and state government, and private landowners to reduce fire risk and increase ecosystem resilience have helped move the conversation toward a landscape-level approach to restoration and fuel reduction treatments. This is the ultimate desired outcome for the Marshall Woods project, and one that will require continued collaboration and cooperation across the entire community.

Figure 4—Missoula District Ranger Jennifer Hensiek describes the importance of the private landowners in the background, one of several "sparkplugs" adjacent to the Marshall Woods Restoration project, whose early adoption of fuel treatments educated and inspired other landowners in the area to also treat their property.

FIELD TRIP PRESENTERS

Jennifer Hensiek, District Ranger, Missoula Ranger District, Lolo National Forest, U.S. Forest Service

Sheryl Gunn, East Zone Silviculturist, Ninemile Ranger District, Lolo National Forest, U.S. Forest Service

Mike O'Herron, Area Manager, Southwestern Land Office, MT Dept. of Natural Resources and Conservation

Greg Dillon, Spatial Fire Analyst, Fire Modeling Institute, Rocky Mountain Research Station Fire Sciences Laboratory, U.S. Forest Service

Shaun Zenner, Assistant Fire Management Officer, Missoula Ranger District, Lolo National Forest, U.S. Forest Service

REFERENCES

Community Planning Assistance for Wildfire. 2005 (updated 2018). Community Wildfire Protection Plan—Missoula County, Montana. https://www.missoulacounty.us/home/showdocument?id=30120.

Montana Forest Restoration Committee (MFRC). 2013. Restoring Montana's National Forest System lands: Guiding principles and recommended implementation, 5th Edition. Online: https://drive.google.com/file/d/0B5jrNh3PiR96NzRhdHZsdlZDcVU/view.

Rattlesnake National Recreation Area and Wilderness Act of 1980. Pub. L. 96-476. 19 October 1980. Online: https://www.congress.gov/bill/96th-congress/senate-bill/3072.

U.S. Forest Service. 2015. Marshall Woods restoration project environmental assessment. Missoula Ranger District, Lolo National Forest, Missoula County, Montana. Online: https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3831355.pdf.