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Developments in Wildland Fire Research

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On the Cover:

Cross-section of a shortleaf pine (Pinus echinata) *that grew in the Missouri Ozarks from 1577 to 1934. Shortleaf pine requires frequent fire for regeneration and survival, and land managers commonly use controlled burning to manage shortleaf pine ecosystems. Old fire-scarred trees like this give researchers valuable information about how forests, fire, climate, and people have interacted through time.*

IN THIS ISSUE

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Firefighter and public safety is our first priority.

GUIDELINES for Contributors

Science You Can Use

By Shawna A. Legarza, Psy.D.
Former Director, Fire and Aviation Management USDA Forest Service

Did you know that Gifford Pinchot, the founder of the Forest Service, was one of our earliest fire researchers? In 1899, Pinchot published an article on "the relation of forests and forest fires" (Pinchot 1899). That was well before the Nation's forest reserves were transferred to USDA in 1905 to become the National Forest System. The Bureau of Forestry—the Forest Service's predecessor organization in USDA, headed by Pinchot—had a vigorous research program devoted to forestry and conservation, and Pinchot himself was a contributor.

So it is no surprise that Forest Service Research and Development is so deeply ingrained in the mission of the Forest Service—and so intertwined with our programs for Fire and Aviation Management. The Forest Service's land management and wildland fire management have always been interdependent with our Research and Development mission area. It's a longstanding relationship and a classic case of interdependence as a core value for the Forest Service.

Prescribed fire is of tremendous and growing importance for the Forest Service in improving forest conditions across the Nation.

In this issue of *Fire Management Today,* you can see that interdependence in various ways. Wind and weather effects have long complicated wildland fire management, and you can read about the implications for both fire behavior and smoke dispersion of atmospheric turbulence in wildland fire environments. New techniques for sampling fuel loadings will help fire managers anticipate fire behavior and severity. Another article explores the implications for wildland fire management of forest dieoff in the West due to bark beetle epidemics.

Interest in the evolution of fire regimes in the United States in tandem with Tribal cultures has long been growing, and two articles explore some of the implications. Indigenous knowledge can help identify trigger points, thresholds, and indicators for ecosystems, habitats, and resources of interest; one article is a primer that nonindigenous fire managers can use for thoughtful and respectful engagement with Tribal communities.

Prescribed fire is of tremendous and growing importance for the Forest Service in improving forest conditions across the Nation. Several articles explore fire-related issues in Alabama and Missouri, with useful findings for fire managers across many Southern and Eastern States.

All articles in this issue reflect the spirit of "Science you can use," the slogan of Forest Service Research and Development. Researchers and fire managers have long been strengthening their ties. Increasingly, they are designing projects together, achieving outcomes together, and opening new opportunities for collaborative projects in both fire research and wildland fire management.

In the spirit of "Science you can use," I am pleased and proud to present the developments in wildland fire science contained in this issue.

LITERATURE CITED

Pinchot, G. 1899 [reprinted 1999]. The relation of forests and forest fires. Forest History Today. Spring: 29–32.

The Photoload Technique for Sampling Surface Fuel Loadings

Robert E. Keane, Heather Heward, and Chris Stalling

How many miles of Brown's (1971) transects have you done in your lifetime? Collectively, we estimate that we've established over 500 miles (800 km) of transects in our careers—a distance from Salt Lake City, UT, to Denver, CO. If you have also sampled great distances using planar intersect sampling, then this will really depress you: most operational field sampling efforts probably did not sample at the appropriate intensities to obtain a useful estimate of fuel loadings using planar intersect techniques.

PROBLEMS WITH PLANAR INTERSECT SAMPLING

Although the Brown (1971) method is not wrong, you would need an enormous number of transects—corresponding to long transect lengths—for a realistic estimate of fuel variability. New research has found that surface fuel components vary at different scales (Keane and others 2012; Vakili and others 2016), and because the planar intersect technique samples in only one dimension, it misses much of the variability of fuel loading in a stand or landscape. As a result, more than 800 meters (2,600 feet) of transect might be needed to realistically quantify fine woody fuel loadings in an area of less than a hectare (2.4 acres) (Sikkink and Keane 2008; Keane and Gray 2013).

This realization completely rocked our world because we had ignorantly conducted countless fuel loading inventories using only three to five transects, all less than 30 meters (100 feet) long. We knew there were problems with planar intersect sampling:

- It concerns only down dead woody fuels;
- It is difficult to repeat across samplers;
- It can't easily be meshed with other fixed-area plot sampling procedures; and
- It doesn't provide a visual reference for loading in the field (so you need to convert intersects to loading later on, after leaving the field).

But we didn't know that the planar intersect technique failed to capture the variability of fuel loadings across the appropriate spatial scales (Keane and others 2012).

New research has found that planar intersect sampling might be inappropriate for many operational sampling efforts.

ARE THERE ALTERNATIVES?

The high sampling intensity demanded by planar intersect sampling, coupled with its other shortcomings, certainly begs the question: Are there viable alternatives to this "tried-and-true" sampling method?

Destructive methods, such as clipping and weighing, are too time intensive for most operational applications (Keane 2015). Measuring fuels onsite based on cover, height, length, and width is also time consuming and often no better than planar intersect methods (Keane and Gray 2013). Some believe that photo series, the most common method of estimating loadings, is a good alternative. But many photo series loadings were measured using planar intersects, and the loadings of fine fuels are rarely visible in the oblique photos in the photo series guides (Maxwell and Ward 1980; Sikkink and Keane 2008).

Is there a fuel sampling alternative to planar intersect sampling that not only allows accurate estimates of fuel loadings but also assesses more than down dead woody fuel components, meshes well with other vegetation inventory techniques, and is repeatable?

More than a decade ago, Keane and Dickinson (2007b) developed a visual

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Robert Keane is a research ecologist for the Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT; Heather Heward is a senior instructor at the University of Idaho, Moscow, ID; and Chris Stalling is a fire ecologist for the Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT.

technique to assess fuel loadings from a series of photographs representing the gradient of loadings in the field. Unlike photo series photographs, the photoload technique uses downward-facing photographs of known fuel loadings measured prior to taking the photo (fig. 1). Recent studies have found that this technique is comparable and sometimes superior to planar intersect techniques, given the same level of sampling effort (Sikkink and Keane 2008; Keane and Gray 2013). Keane and Dickinson (2007a) created this new sampling method as an alternative to planar intercept sampling for research and operational applications. This article describes the photoload technique and its recent improvements for more robust and scale-appropriate surface fuel loading sampling.

THE PHOTOLOAD TECHNIQUE

The photoload technique involves matching conditions on the ground with the corresponding conditions in a set of photographs of known loadings (fig. 1). You start with the photograph showing the lowest loading for that fuel component and compare it to conditions on the ground. If they don't match, you move on to the next photo (and so on) until you find the photo showing *more* than the fuel loading on the ground. Then you visually compare the loading on the ground with that photo and the previous photo, and you estimate a loading value that is somewhere in between.

New research has found that wildland fuel components vary at different spatial and temporal scales.

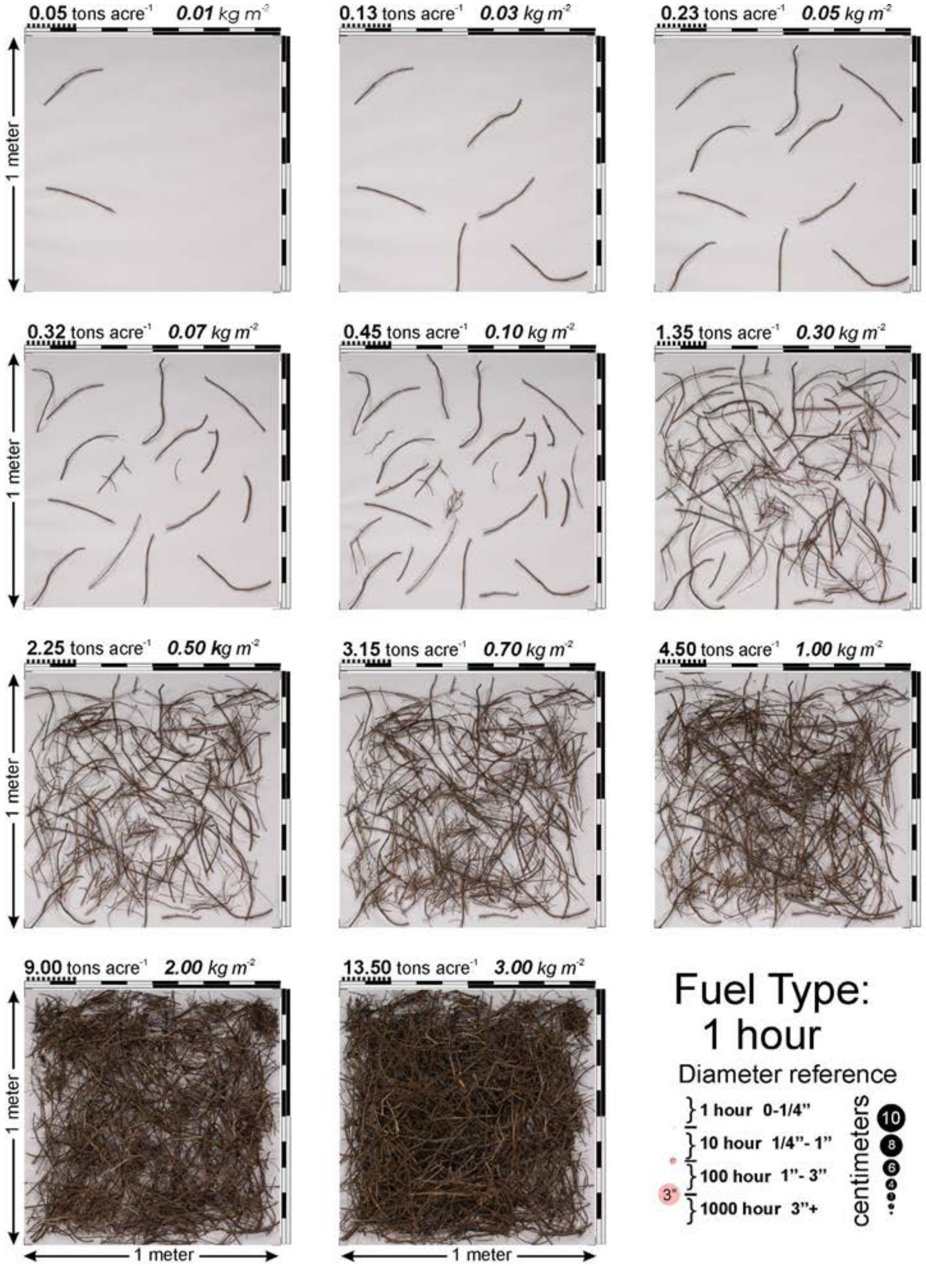

Figure 1—*A sample of photoload loadings for 1-hour down dead woody fuels (woody fuels with diameters less than ¼ inch (7 mm)). Source: Keane and Dickinson (2007b).*

If the fuel component is shrub or herbaceous, then another step is required. You measure or visually estimate the *height* of the shrub or herbaceous layer and then divide the height by the height in the photo within the photoload sequences (fig. 2). You then multiply the estimated fuel loading by this ratio to adjust for the size of the plants.

Estimating loadings for logs (1,000-hour down dead woody fuels) is a bit more complicated. Manipulating log loading in a studio or other controlled environment was impossible because of the immense weight of the logs (Keane and Dickinson 2007a), so we created the original photoload sequences with 6-inch (15-cm) and 10-inch (25-cm) tubes painted brown (fig. 3). The weight of each "log" was calculated as the volume of the tube

Figure 2—*A herbaceous fuelbed photo in the photoload series. Source: Keane and Dickinson (2007b).*

multiplied by the density of Douglas-fir wood (380 kg m^{-3}). Moreover, because logs vary at spatial scales much more than does fine woody debris, Keane and Dickinson (2007a) used a 100-square-meter plot that was designed to be easily photographed.

In subsequent testing of this method using the brown tubes, we found it useful; but there was a great deal of uncertainty in the visual estimates, and it was difficult to obtain consistent results across multiple users (Sikkink and Keane 2008). Therefore, we developed a companion tabular approach as an alternative to photo comparisons: a series of tables where rows are diameters, columns are lengths, and cells are loadings (Keane and Dickinson 2007a). You visually estimate or actually measure the average diameter and length of all logs in a 100-square-meter area and find the right loading value in the table, then reduce it for rot, if needed. The tables are the better option for estimating log loading because the method is highly scalable: you can use the method to compute the weight of each log, a set of similar logs, or all logs in the 100-square-meter area, and you can estimate lengths and diameters by eye, by pacing, or by actually measuring.

Photoload techniques are best used when sampling experience is low and sampling time is limited (Sikkink and Keane 2008). The method is relatively quick and inexpensive, and it allows for moderately precise and reasonably accurate estimates of fuel loadings, especially during operational sampling.

The photoload technique is not intended to replace previous protocols and methods but as a viable alternative when the objectives of sampling and the resources available match the design characteristics of the photoload technique (Keane and Dickinson 2007b; Sikkink and Keane 2008). The technique is perfect for monitoring because it does not alter fuelbed characteristics, and it can be a valuable research sampling technique when paired with double sampling to create correction factors (Catchpole and Wheeler 1992).

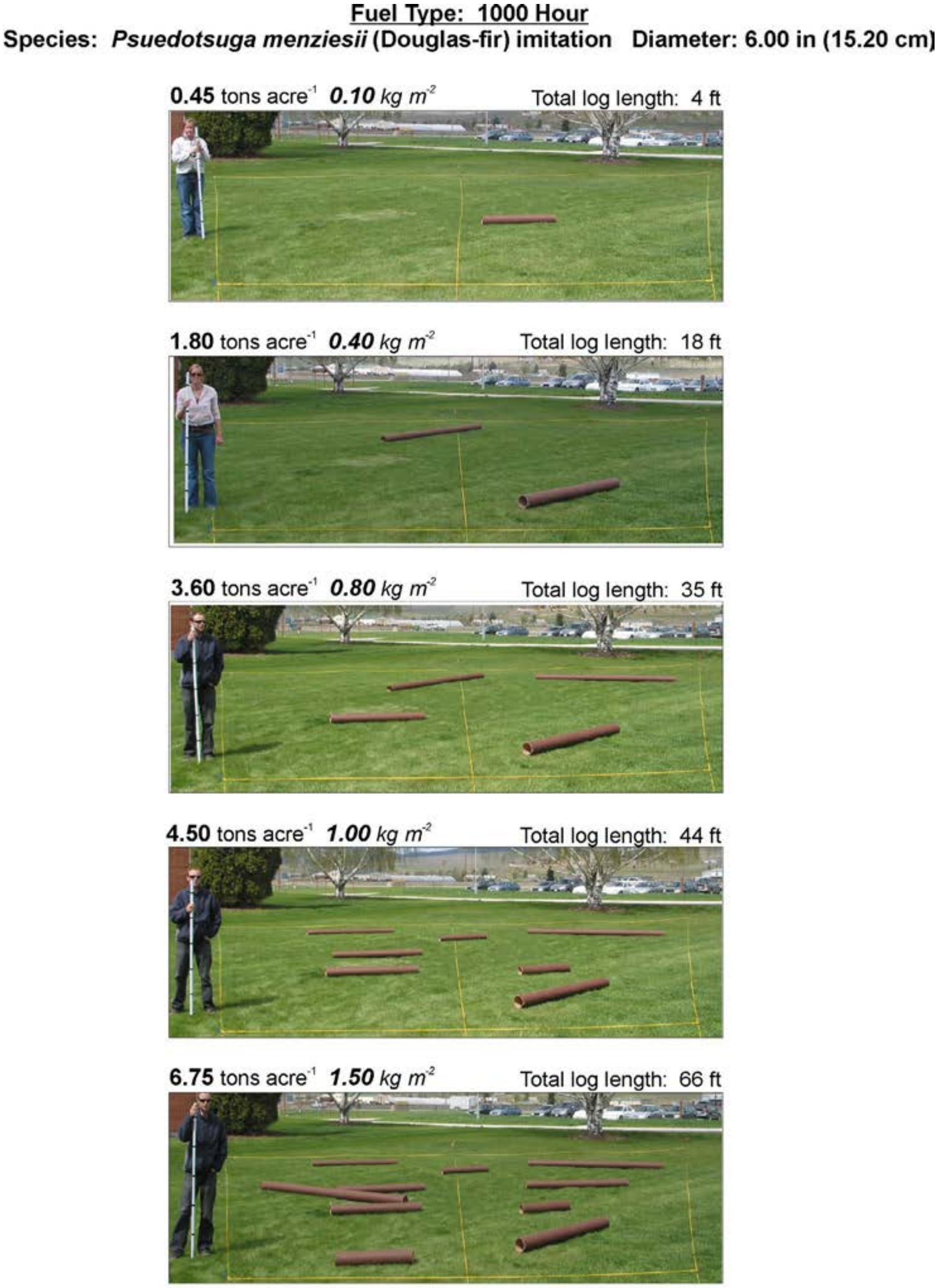

Figure 3—*A sample of photoload loadings for 1,000-hour down dead woody fuels (woody fuels with diameters greater than 3 inches (8 cm)). Source: Keane and Dickinson (2007b).*

The photoload technique is being used around the world for a multitude of reasons. It is most often used to estimate fuel loadings for many purposes, including estimating smoke emissions, fire intensity, and fire hazard. Other uses have included estimating plant species biomass for forage potential, carbon pools, and wildlife habitat. And because it is easy to learn and use and requires little complex equipment, the photoload technique is often used by graduate students, foresters, and interested citizens. The photoload methodology has been integrated into sampling systems, such as FFI (Lutes and others 2009), for estimating surface fuel in wildlands and the wildland–urban interface, and it is also being included as a fuel sampling method in the National

Aeronautics and Space Administration's Globe program for citizen science.

PHOTOLOAD LIMITATIONS

A few limitations need mention. First, like the Brown (1974) protocols, photoloads cannot be used for estimating litter and duff surface fuel loadings, which must still be sampled by measuring the depth of each layer and multiplying by the layer bulk densities. The depth of the litter and especially the duff is not entirely evident in downward-facing photographs, so the photoload approach is inappropriate.

However, depth measurements are easily integrated into photoload sampling procedures; we often take depth measurements at the corners of the microplot frame used for fine fuels. To estimate bulk densities, we are developing a photo guide for selecting the most appropriate bulk densities for the sample site.

Another limitation is that there are photoload series for only six shrub and four herbaceous species. Moreover, these species are primarily found in the northern Rocky Mountains in the United States.

Both logs and fine woody debris pose a challenge for fuel sampling because woody particles are often in different stages of decay and the degree of rot directly influences wood density, which then affects the accuracy of loading estimates. Currently, most sampling techniques for fuel loading use wood densities for sound logs; reduction factors should be developed to account for loss of mass due to decomposition. The photoload method includes a way to reduce loading to account for rot, but the reduction factors are not based on comprehensive research findings.

PHOTOLOAD IMPROVEMENTS

During the initial testing and use of photoloads, Sikkink and Keane (2008) found that people with experience in fuel sampling were better able to make accurate visual estimates of loading than novice samplers. Subsequent trials revealed that photoload users could more accurately estimate loadings if they were given rudimentary training—a 1- to 2-hour training session (fig. 4). Accordingly, the Holley and Keane (2010) training tool was created to give novice users a quick way to improve the accuracy of their visual estimation using photographs of fuelbeds where the loadings were measured afterwards using destructive techniques.

Despite the popularity of photoload methods, many have recognized that the original photoload photographic sequences were taken for a small set of

Figure 4—*Teaching photoload techniques to Forest Service employees at the Wildland Fire Academy in Sacramento, CA. Basic training in the use of photoload techniques improves estimates of fuel loadings. Photo: Heather Heward, University of Idaho (2019).*

Are You Interested in Photoload Sampling?

The following is a list of websites for downloading photoload reference materials and taking a peek at them. We conduct anywhere from 3 to 11 workshops per year at conferences, local offices, universities, and nongovernmental organizations (fig. 4). If you are interested in conducting a workshop, please contact Chris Stalling (*chris.stalling@usda.gov*) or Heather Heward (*hheward@uidaho.edu*).

The sampling manual: *https://www.fs.usda.gov/treesearch/pubs/26755*

The development methods: *https://www.fs.usda.gov/treesearch/pubs/26757*

The training guide: *https://www.fs.usda.gov/treesearch/pubs/36328*

VIDEO: Introduction to the photoload sampling technique

A zip file with presentations and reference materials is also available.

Training crews on photoload sampling. Photos: Heather Heward, University of Idaho (2019).

The photoload technique allows you to quickly and accurately sample loadings of most surface fuel components at the appropriate spatial scales.

fuel components found only in the U.S. northern Rocky Mountains (Tinkham and others 2016). Applying the Keane and Dickinson (2007b) limited set of reference photos to fuel sampling in other ecosystems or geographic areas could result in higher errors due to major differences in fuelbed and plant morphology (McColl-Gausden and Penman 2017). Down woody fuel particle diameter and density distributions, for example, vary greatly across species, ecosystems, biophysical settings, and times since disturbance (Harmon and others 2008; Woodall and Monleon 2010; Russell and others 2013). More importantly, the species that comprise shrub and herbaceous fuels differ across ecosystems. We have recently written a comprehensive guide to quickly, easily, and economically create a set of photoload sequences to represent surface fuel components for local applications, to be published some time in 2020.

ACKNOWLEDGMENT

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LITERATURE CITED

Brown, J.K. 1971. A planar intersect method for sampling fuel volume and surface area. Forest Science. 17(1): 96–102.

Brown, J.K. 1970. A method for inventorying downed woody fuel. General Technical Report INT?16, USDA Forest Service. 24 p.

Catchpole, W.R.; Wheeler, C.J. 1992. Estimating plant biomass: a review of techniques. Australian Journal of Ecology. 17(2): 121–131.

Harmon, M.E.; Woodall, C.W.; Fasth, B.; Sexton, J. 2008. Woody detritus density and density reduction factors for tree species in the United States: a synthesis. Gen. Tech. Rep. NRS–29. Newtown Square, PA: USDA Forest Service, Northern Research Station. 84 p.

Holley, V.J.; Keane, R.E. 2010. A visual training tool for the photoload sampling technique. Gen. Tech. Rep. RMRS–GTR–242. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 234 p.

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

Keane, R.E.; Dickinson, L.J. 2007a. Development and evaluation of the photoload sampling technique. Res. Pap. RMRS–RP–61. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 29 p.

Keane, R.E.; Dickinson, L.J. 2007b. The photoload sampling technique: estimating surface fuel loadings using downward looking photographs. Gen. Tech. Rep. RMRS–GTR–190. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 44 p.

Keane, R.E.; Gray, K.; Bacciu, V.; Leirfallom, S. 2012. Spatial scaling of wildland fuels for six forest and rangeland ecosystems of the northern Rocky Mountains, USA. Landscape Ecology. 27: 1213–1234.

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

Lutes, D.C.; Benson, N.C.; Keifer, M. [and others]. 2009. FFI: a software tool for ecological monitoring. International Journal of Wildland Fire. 18: 310–314.

Maxwell, W.G.; Ward, F.R. 1980. Photo series for quantifying natural forest residues in common vegetation types of the Pacific Northwest. Gen. Tech. Rep. PNW–GTR–105. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. 229 p.

McColl-Gausden, S.; Penman, T. 2017. Visual assessment of surface fuel loads does not align with destructively sampled surface fuels. Forests. 8: 408.

Russell, M.B.; Woodall, C.W.; Fraver, S.; D’Amato, A.W. 2013. Estimates of downed woody debris decay class transitions for forests across the eastern United States. Ecological Modelling. 251: 22–31.

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

Tinkham, W.T.; Hoffman, C.M.; Canfield, J.M. [and others]. 2016. Using the photoload technique with double sampling to improve surface fuel loading estimates. International Journal of Wildland Fire. 25: 224–228.

Vakili, E.; Hoffman, C.M.; Keane, R.E. [and others]. 2016. Spatial variability of surface fuels in treated and untreated ponderosa pine forests of the southern Rocky Mountains. International Journal of Wildland Fire. 25: 1156–1168.

Woodall, C.W.; Monleon, V.J. 2010. Estimating the quadratic mean diameters of fine woody debris in forests of the United States. Forest Ecology and Management. 260: 1088–1093.

The Prescribed Fire Science Consortium

Nicholas Skowronski, Bret Butler, J. Kevin Hiers, Joseph O'Brien, and J. Morgan Varner

Scientists taking measurements during an event at Tall Timbers Research Station in Florida. The Prescribed Fire Science Consortium focuses on integrated fuels, fire behavior, and fire effects measurements and prioritizes coproduction of actionable science working closely with land managers.

Prescribed fire is used on more than 12 million acres (4.9 million hectares) in the United States annually. It is a critical strategic management tool for hazardous fuels reduction and the resilience of fire-adapted landscapes. In recognition of its value, the President's Budget for fiscal year 2020 called for $450 million in funding for hazardous fuels reduction for USDA alone.

RATIONALE

Because managers intentionally choose to introduce fire onto a land management unit for a specific objective or set of objectives, science-based decision making is essential. However, the lion's share of national research investment in fire science has focused on wildfires and suppression needs, neglecting the field of prescribed fire science and leading to a relative paucity of tools for modeling prescribed fire behavior and effects in ways that managers need to safely increase the pace and scale of treatments.

In response, the Prescribed Fire Science Consortium (PFSC) was formed in 2016 by a group of multidisciplinary fire scientists and managers with a focus on the modernization of science, with specific applicability to safe and effective application of prescribed fire.

The PFSC takes a coproduction approach to prescribed fire science, with science discovery and delivery as closely aligned with operational needs as possible. The consortium comprises an ensemble of scientists from across the Nation, including representatives from each Forest Service research station, the Tall Timbers Research Station, the Los Alamos National Laboratory, and numerous academic institutions. In addition, the PFSC is guided and assisted by land managers from the Forest Service and State agencies like the New Jersey Forest Fire Service and the Florida Division of Forestry as well as by private land managers and landowners.

> **The consortium's coproduction events are increasing the pace and scale of prescribed fire across the United States.**

Nicholas Skowronski is a research forester for the Forest Service, Northern Research Station, Morgantown, WV; Bret Butler is a research mechanical engineer for the Forest Service, Rocky Mountain Research Station, Missoula, MT; J. Kevin Hiers is a wildland fire scientist for Tall Timbers Research, Inc., Tallahassee, FL; Joseph O'Brien is a team leader and research ecologist for the Forest Service, Southern Research Station, Athens, GA; and J. Morgan Varner is the director of fire research for Tall Timbers Research, Inc., Tallahassee, FL.

> **The PFSC is one of several models for developing scientist/manager coproduction of actionable science.**

ACTIVITIES

The PFSC has sponsored coproduction events in Florida and Montana that spanned several days and included both experimental and operational prescribed burning. These events served to deepen scientist/manager relationships, conduct fireline experimentation for a variety of objectives, and set the stage for future work. The next coproduction event is planned in the New Jersey Pinelands for September 2020.

The PFSC has aggregated successful prescribed fire research from across the country, building on previous investments in projects at Eglin Air Force Base, in the New Jersey Pinelands, and at other locations to create new soft-funding opportunities. Over the past several years, consortium teams have made 10 successful research proposals to the U.S. Department of Defense Strategic Environmental Research and Development Program. Broadly, their work advances prescribed fire research by:

1. Supporting the next generation of fire dynamics modeling,
2. Improving scientific understanding and modeling of the fluid dynamics of surface fire regimes,
3. Improving scientific understanding of how fire/atmospheric feedbacks determine smoke and emissions production and transport, and
4. Developing advanced understanding of fire effects and responses.

Managers have been involved at every step of the process and will continue to play a critical role in operational applications of the science. The collaboration of researchers and managers through the PFSC has gained international interest and likely represents the largest combined investment in fire science currently underway.

SCIENCE/MANAGEMENT COLLABORATION

The PFSC is one of several models for developing scientist/manager coproduction of actionable science. The consortium's events featuring "elbow-to-elbow" interactions between fire scientists and fire managers are doing much to increase the pace and scale of prescribed fire across the United States. An often-overlooked benefit from the PFSC is building rapport and breaking down barriers between fire practitioners and fire scientists. Fire science and management share a responsibility for encouraging and collectively supporting the consortium and similar activities.

> **The consortium takes a coproduction approach, with science discovery and delivery as closely aligned with operational needs as possible.**

Figure 1—*Goat perched on snag (top) browsing a dogwood on the Mark Twain National Forest in Missouri. Photo: Gina Beebe.*

Can Targeted Browsing Be a Useful Surrogate for Prescribed Burning?

Gina Beebe, Lauren S. Pile, Michael Stambaugh, Brian Davidson, and Daniel Dey

The limitations on prescribed burning are numerous, but fire's ecological role in shaping the health and integrity of our forests is incredibly important. Browsers, such as domesticated goats, prefer to consume woody species. People can use goats and other browsers to help manage ecological communities that are degraded by nonnative invasive shrubs and vines or located in the wildland–urban interface or where smoke impacts are considerable. Furthermore, browsers could supplement prescribed burning by treating forest stands in "off years"or outside of typical burn windows.

> **In the oak and pine woodlands of the Missouri Ozarks, we are testing targeted browsing as a management tool.**

Browsers can constitute an additional and accessible tool in managing fire-maintained landscapes.

TESTING TARGETED BROWSING

"Targeted browsing" is the use of browsing livestock at predetermined levels of intensity and seasonality to achieve desired land management objectives. In the oak and pine woodlands of the Missouri Ozarks, we are testing targeted browsing as a management tool to meet restoration objectives and fuel targets on the Mark Twain National Forest (figs. 1, 2).

Silvicultural prescriptions for woodland restoration require lowering overstory stocking levels and removing the midstory to increase sunlight reaching the forest floor. However, this often results in vigorous sprouting by oaks and hickories as well as less desirable species such as red maple. Furthermore, it can increase the abundance of woody shrubs, including fragrant sumac and blackberry, which compete with herbaceous plants.

This aggressive woody ingrowth into the midstory could be managed effectively with frequent low-intensity surface fire. However, maintaining such levels of disturbance can be complicated on some sites, resulting in the need for other or a combination of approaches. Specifically:

Gina Beebe is a graduate student in the School of Natural Resources, University of Missouri, Columbia, MO; Lauren Pile is a research ecologist at the Northern Research Station, USDA Forest Service, Columbia, MO; Michael Stambaugh is an associate research professor in the School of Natural Resources, University of Missouri, Columbia, MO; Brian Davidson is a botany and invasive species program manager for the Mark Twain National Forest, USDA Forest Service, Rolla, MO; and Daniel Dey is a research forester and project leader at the Northern Research Station, USDA Forest Service, Columbia, MO.

Figure 2—*Browsed (left) and nonbrowsed (right) plots. Photo: Gina Beebe.*

We are interested in the combined effects of targeted browsing and prescribed burning in meeting our restoration objectives.

1. We are investigating browsing season (late winter, spring, and late summer) to determine when we can maximize the impact of browsing on the growth of woody stems while minimizing its impact on ground flora;
2. We are interested in how targeted browsing might stimulate the available seedbank by reducing midstory vegetation (such as dogwoods) and thereby increasing sunlight reaching the forest floor and exposing bare mineral soil through trampling; and
3. We are interested in the combined effects of targeted browsing and prescribed burning in meeting our restoration objectives—that is, a two-layer (ground and canopy) open woodland with a diverse forb- and grass-dominated ground layer that provides critical habitat for important wildlife species.

Finally, we will examine the effects of targeted browsing on fuels, a topic of rising interest to many land managers. Past declines in fire use have led to an accrual of surface fuels, reaching levels of management concern. Surface fuels play a critical role in fire spread, and their removal greatly reduces the likelihood of fire hazard and stand-replacing crown fires as well as the need for recurrent prescribed burns.

RESULTS

Although examples are limited, targeted browsing has been demonstrated to supplement prescribed fire as a fuels management technique. Goat browsing, in particular, can be a highly effective fuels reduction treatment due to the ability of goats to consume a wide variety of plants and to remove shrubs up to 6 feet (2 m) high, reducing both vertical and horizontal fuel continuity.

Goats and other browsers can constitute an additional and accessible tool in managing fire-maintained landscapes.

Targeted goat browsing has a notable impact on litter, 1-hour fuels, and 10-hour fuels. In a study by Tsiouvaras and others (1989), a herd of 113 goats per acre reduced 1-hour dead fuels by 58.3 percent and average litter depth by 27.4 percent in 3 days. Goats' capacity to reduce fine dead fuels is mainly through trampling as the fuels are crushed and incorporated into soils.

To learn more about this project, please visit our project website: *https://www.nrs.fs.fed.us/sustaining_forests/conserve_enhance/biodiversity/goats-fire-woodlands/*

LITERATURE CITED

Tsiouvaras, C.N.; Havlik, N.A.; Bartolome, J.W. 1989. Effects of goats on understory vegetation and fire hazard reduction in a coastal forest in California. Forest Science. 35(4): 1125–1131.

Bark Beetle and Fire Interactions in Western Coniferous Forests: Research Findings

Christopher J. Fettig, Sharon M. Hood, Justin B. Runyon, and Chris M. Stalling

Figure 1—*Tree mortality following a bark beetle outbreak in the Sierra Nevada in California. California experienced a severe drought from 2012 to 2015, stimulating a large bark beetle outbreak in the central and southern Sierra Nevada. Most tree mortality was caused by western pine beetle* (Dendroctonus brevicomis)*, which readily colonizes drought-stressed ponderosa pine* (Pinus ponderosa)*, but other tree and shrub species were also affected. About 89 percent of the ponderosa pines in the three largest diameter classes were killed (Fettig and others 2019), representing the loss of an important structural component of these forests. Mortality of sugar pine* (Pinus lambertiana)*, caused primarily by mountain pine beetle* (Dendroctonus ponderosae)*, was also substantial (48 percent). In total, 49 percent of the trees died between 2014 and 2017. Photo: C. Fettig, USDA Forest Service.*

Native bark beetles and wildfires are important disturbances in western coniferous forests. Bark beetles can colonize and kill trees of all species, ages, and sizes, but each species exhibits unique host preferences and impacts. Some bark beetles cause extensive levels of tree mortality (table 1), as demonstrated by mountain pine beetle *(Dendroctonus ponderosae)* in several pines, western pine beetle *(Dendroctonus brevicomis)* in ponderosa pine *(Pinus ponderosa),* Douglas-fir beetle *(Dendroctonus pseudotsugae)* in Douglas-fir *(Pseudotsuga menziesii),* and spruce beetle *(Dendroctonus rufipennis)* in several spruces. Other bark beetles are secondary agents that colonize stressed, dead, or dying trees. The impacts of these secondary agents often go unnoticed, while the former occasionally drive headlines in large newspapers.

In general, bark beetles require living phloem (the layer of cells within the inner bark that transports photosynthates (sugars) within the tree) to reproduce. When bark beetle populations are low, the beetles create small gaps in the forest canopy by colonizing and killing trees stressed by age or other factors. During bark beetle outbreaks, large numbers of trees can be

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Christopher Fettig is a research entomologist for the Forest Service, Pacific Southwest Research Station, Davis, CA; Sharon Hood is a research ecologist for the Forest Service, Rocky Mountain Research Station, Missoula, MT; Justin Runyon is a research entomologist for the Forest Service, Rocky Mountain Research Station, Bozeman, MT; and Chris Stalling is a biologist for the Forest Service, Rocky Mountain Research Station, Missoula, MT.

Table 1—*Bark beetles recognized as causing substantial levels of tree mortality during outbreaks in the Western United States.*

Common name	Scientific name	Common host(s)	Current knowledge of effects on wildfire behavior and severity[a]
California fivespined ips	*Ips paraconfusus*	Lodgepole pine, sugar pine, ponderosa pine	Low
Douglas-fir beetle	*Dendroctonus pseudotsugae*	Douglas-fir	Moderate
Fir engraver	*Scolytus ventralis*	White fir, grand fir, California red fir	Low
Jeffrey pine beetle	*Dendroctonus jeffreyi*	Jeffrey pine	Low
Mountain pine beetle	*Dendroctonus ponderosae*	Whitebark pine, lodgepole pine, limber pine, sugar pine, western white pine, ponderosa pine	High
Northern spruce engraver	*Ips perturbatus*	White spruce, Lutz spruce	Low
Pine engraver	*Ips pini*	Lodgepole pine, Jeffrey pine, sugar pine, ponderosa pine	Low
Pinyon ips	*Ips confusus*	Pinyon pine(s)	Low
Spruce beetle	*Dendroctonus rufipennis*	Engelmann spruce, white spruce, Lutz spruce	Moderate
Western balsam bark beetle	*Dryocoetes confusus*	Subalpine fir	Low
Western pine beetle	*Dendroctonus brevicomis*	Ponderosa pine, Coulter pine	Low

a. Level (low, moderate, or high) defined in relation to knowledge of the effects imposed by mountain pine beetle outbreaks, which have been most intensively studied.

killed over extensive areas (fig. 1), often adversely affecting timber and wood fiber production, water quality and quantity, fish and wildlife populations, opportunities for outdoor recreation, and biodiversity and carbon storage, among other ecological goods and services (Morris and others 2018).

HISTORIC OUTBREAK LEVELS

The amount of tree mortality caused by bark beetles in the Western United States has exceeded that caused by wildfires in the last 3 decades (Hicke and others 2016), and several recent outbreaks are considered the most severe in history. Since 2000, for example, about 25.5 million acres (10.3 million ha) in the Western United States have been affected by mountain pine beetle. Activity peaked in 2009, with 8,842,698 acres (3,578,513 ha) affected in that year alone.

Bark beetles are cold-blooded organisms highly sensitive to changes in temperature, which influence their survival and population growth (Bentz and others 2010). Drought stress adversely affects the ability of conifers to repel beetle attack (Kolb and others 2016). Accordingly, recent bark beetle outbreaks have been correlated with shifts in temperature and precipitation caused by climate change. In some forests, increases in tree density have exacerbated the effect by providing an abundance of hosts and by increasing competition among hosts for limited resources, making trees more vulnerable to beetle attacks.

Wildfires have sculpted many western forests for millennia, reducing the quantity and continuity of fuels, discouraging establishment of fire-intolerant tree species, and influencing the susceptibility of forests to bark beetle outbreaks and other disturbances. Climate change is increasing the number of large wildfires (fires greater than 1,000 acres (400 ha) in size), the frequency of wildfires, the length of the wildfire season (by up to 90 days in some locations), and the cumulative area burned (Vose and others 2018). Suppression costs and risks to homes and other infrastructure are also increasing (Flannigan and others 2006).

In this article, we consider two common interactions between bark beetles and wildland fires:

1. The effects of fuel reduction treatments (prescribed fire and mechanical thinning) and wildfires on bark beetles; and
2. The effects of bark beetle outbreaks and associated levels of tree mortality on fuels and wildfire behavior and severity.

We briefly describe the current state of knowledge and identify gaps in knowledge needed to make informed management decisions.

EFFECTS OF FUEL REDUCTION TREATMENTS ON BARK BEETLES

Tens of millions of acres of forest in the Western United States are classified as having moderate to high fire hazards. Efforts to lower hazards focus on reducing surface fuels, increasing the height to live crowns, decreasing crown bulk density, and retaining large trees of fire-resistant species such as

A common management concern is that bark beetles might colonize and kill trees injured by prescribed fire.

ponderosa pine (Agee and Skinner 2005). When applied under prescription, planned ignitions and their mechanical surrogates (such as thinning from below) are generally effective in meeting fuel reduction goals (McIver and others 2013; Stephens and others 2012). For example, the effectiveness of prescribed fire for treating surface and ladder fuels to reduce the incidence of passive crown fire (that is, the torching of small groups of trees) is well supported by modeling of predicted fire behaviors (Stephens and others 2009) and by empirical research (Ritchie and others 2007). Furthermore, results from the National Fire and Fire Surrogate Study, the largest study of its kind (*www.frames.gov/ffs/about*), indicate that the incidence of active crown fire is best reduced by combining prescribed fire with mechanical fuel treatments (McIver and others 2013).

The type of fuel reduction treatments and their manner of implementation have different effects on the fuel matrix, which can influence the susceptibility of forests to bark beetles in different ways (Fettig and others 2007). For example, prescribed fire can affect the health and vigor of residual trees; the size, distribution, and abundance of preferred bark beetle hosts; and the physical environment within forests. Associated reductions in tree density can alter microclimates, affecting beetle fecundity (the ability to produce offspring) and fitness as well as the phenology (timing of life cycle events) and voltinism (number of generations per unit of time) of bark beetles and their predators, parasites, and competitors. Tree density reductions can also disrupt pheromone plumes that attract bark beetles to a tree during initial colonization.

Volatiles (volatile organic compounds) released from trees are known to influence the behavior of many bark beetles (Seybold and others 2006). Fettig and others (2006) showed that chipping submerchantable and unmerchantable ponderosa pines and depositing the chips back into treated stands increases the risk of infestation by several species of bark beetles in the Southwestern United States. The effect was due to large amounts of monoterpenes being released during chipping, which enhanced attraction to bark beetles. Impacts were greater from chipping in spring (April–May) than in late summer (August–September) because spring is the time of peak flight activity for several species of bark beetles in the Southwestern United States as they search for new hosts. If possible, chipping should be conducted in fall to minimize tree losses to bark beetles if the chips will remain onsite.

PRESCRIBED FIRE

Following fire, tree mortality can be immediate due to consumption of living tissue or heating of critical plant tissues; or it can be delayed, occurring over the course of a few years as a result of fire injuries to the crown, bole, or roots (Hood and others 2018a). Levels of delayed tree mortality caused by bark beetles depend on numerous factors, including tree species; tree size; tree phenology; degree of fire-caused injuries; initial and postfire levels of tree vigor; the postfire environment; and the scale, severity, and composition of bark beetle populations and other tree mortality agents in the area.

A common management concern is that bark beetles might colonize and kill trees that were injured by prescribed fire and otherwise would have survived. These trees may then serve as a source of beetles and attractive semiochemicals as host volatiles are released by the boring activity of bark beetles. In addition to host volatiles, the pheromones produced by bark beetles might attract other beetles and result in additional levels of tree mortality over time.

Fettig and McKelvey (2014) monitored the effects of fuel reduction treatments on levels of tree mortality at Blacks Mountain Experimental Forest in California over a 10-year period. Twelve experimental plots (ranging from 190 to 356 acres (76–142 ha)) were established to create two distinct forest structural types: midseral stage (with low structural diversity) and late-seral stage (with high structural diversity). Following harvesting, half of each plot was treated with prescribed fire.

A total of 16,473 trees (9 percent of all trees) died. Mortality was concentrated:

- On plots with high structural diversity (64 percent);
- On burned-split plots (61 percent);
- Within the two smallest diameter classes (87 percent); and
- During the second sample period (3 to 5 years after prescribed burns).

Most mortality was caused by bark beetles (65 percent), notably fir engraver *(Scolytus ventralis)* in white fir *(Abies concolor)* and mountain pine beetle, western pine beetle, and pine engraver *(Ips pini)* in ponderosa pine. The authors concluded that this level of tree mortality did not interfere with management objectives aimed at increasing overall forest resilience.

Similarly, Douglas-fir beetle, pine engraver, and western pine beetle caused some tree mortality following prescribed fires in western Montana. Mortality occurred shortly after prescribed fires, and unburned plots were unaffected. However, following a regional mountain pine beetle outbreak that started about 5 years after treatments were completed, 50 percent of ponderosa pines in control (untreated) plots and 39 percent in prescribe-burned plots were colonized

It is reasonable to assume that bark beetles and wildfires will increasingly interact to shape western forests.

and killed. Almost no trees were killed by mountain pine beetle in thinned plots and thinned-and-prescribe-burned plots (Hood and others 2016). Thinning treatments, with or without prescribed fire, dramatically increased tree growth rates and production of resin ducts (a measure of conifer defense against bark beetles) relative to the control and prescribed fire treatments.

In some cases, concerns about maintaining large-diameter trees following prescribed fire have been justified. For example, Fettig and McKelvey (2014) reported that most tree mortality (78 percent) in the largest diameter class occurred during the first 5 years after prescribed fire and that 66 percent was caused by bark beetles. Tree protection treatments (such as insecticides and semiochemicals) can be selectively used to protect individual trees from colonization by bark beetles (Fettig and Hilszczański 2015). Furthermore, methods such as raking litter and duff from the bases of large-diameter trees have been shown to reduce prescribed fire severity and levels of tree mortality (Fowler and others 2010; Hood 2010). Additional research is needed to determine under what conditions large-diameter trees are most susceptible to delayed mortality following prescribed fire and when tree protection treatments are warranted.

The limited number of studies on the effects of season of burn (spring versus fall) on levels of tree mortality caused by bark beetles show mixed results. Some studies show increases in certain bark beetle species following fall treatments (that is, when fuels are drier and burns are more intense); see, for example, Fettig and others (2010). Other studies show stronger effects following early-season burns (that is, when bark beetles are more active); see, for example, Schwilk and others (2006). More research is needed to fully define these relationships in different forest types.

Although most of the tree mortality caused by bark beetles following prescribed fire occurs during the first few years, this pattern might differ in adjacent untreated areas. The reason, in part, is that unburned areas do not benefit from the positive effects of prescribed fire (such as increased growing space due to reduced tree density), which affect tree vigor and susceptibility to colonization by bark beetles. Notable infestations in adjacent unburned areas are uncommon but can occur and should be watched for in case additional management is warranted to limit tree losses (Fettig and Hilszczański 2015).

MECHANICAL FUEL TREATMENTS

Factors such as stand density, host density, and average tree diameter are strong predictors of the severity of bark beetle infestations in the Western United States. High levels of beetle-caused tree mortality (for example, greater than 20 percent) should be expected following fuel reduction treatments that retain high residual stand densities, regardless of treatment effects. Although thinning has long been advocated as a measure to reduce beetle-caused tree mortality (Fettig and others 2007), thinning prescriptions for fuel reduction differ from prescriptions for reducing susceptibility to bark beetles. In the latter, crown or selection thinning (that is, removal of larger trees in the dominant and codominant crown classes) is typically required to achieve target threshold densities and residual tree spacing as well as significant reductions in the abundance of preferred hosts. Nevertheless, thinning from below (for fuels reduction) does release growing space, reducing a stand's susceptibility to bark beetles.

A common concern following mechanical fuel treatments is that bark beetles could breed in logging residues (chips and/or slash) and emerge to colonize residual trees. However, most studies indicate that this is uncommon (see, for example, Fettig and others 2006). Six and others (2002) showed that pine engravers are unable to colonize and reproduce in chips. Moreover, slash can be managed to minimize colonization of residual trees by bark beetles (DeGomez and others 2015).

EFFECTS OF WILDFIRES ON BARK BEETLES

Factors that influence tree mortality caused by bark beetles are the same after wildfires as after prescribed fires. Our distinction is based not on ignition type but largely on differences in fire intensity and fire severity: most wildfires are higher in intensity and severity than prescribed fires (though not always). Low-severity wildfires can induce tree defenses against bark beetles (Hood and others 2015). Resin-duct-related defenses take about 1 year after wildfire to form; during this time, fire-injured trees can be more susceptible to colonization by bark beetles, which might help explain some of the near-term increases in levels of beetle-caused tree mortality after some wildfires and prescribed fires (Hood and others 2015, 2016). The level of tree injury influences bark beetle attraction, with moderately injured trees being most susceptible to colonization by bark beetles (see, for example, Hood and Bentz 2007; Lerch and others 2016; and Powell and others 2012).

Firefighters should anticipate the potential for unusual fire behavior in beetle-affected forests and the unique suppression challenges that can result.

High-severity wildfires generally reduce susceptibility to bark beetles by killing large numbers of host trees. For example, research in subalpine forests in Colorado shows that spruce beetle outbreaks are reduced for decades after high-severity wildfires (Bebi and others 2003), the dominant fire regime in these forests. As with prescribed fires, bark beetles routinely cause additional levels of tree mortality after wildfires, but infestations in adjacent unburned areas are uncommon (Davis and others 2012; Lerch and others 2016; Powell and others 2012).

EFFECTS OF BARK BEETLE OUTBREAKS ON FUELS AND FIRE BEHAVIOR AND SEVERITY

Although fuel reduction treatments and wildfires can affect bark beetles, the reverse is also true: bark beetles can alter wildfire behavior by changing fuel conditions. Of the bark beetle–host systems to consider, the effects of mountain pine beetle in lodgepole pine *(Pinus contorta)* have been most intensively studied (table 1), and for good reason: mountain pine beetle alone is responsible for almost half of the total area affected by bark beetles in the Western United States. All other bark beetle–host systems have received less attention, some little or none (table 1).

Fire behavior in beetle-affected forests largely depends on the severity of the outbreak (the proportion of trees colonized and killed) and the amount of time since the outbreak occurred. Jenkins and others (2008, 2014) use the term "bark beetle rotation" to describe the period from the start of a bark beetle outbreak to the next outbreak within susceptible forests. In the "endemic phase," beetle-caused tree mortality is limited (for example, to less than 2 trees per acre per year) and generally isolated to stressed hosts. In the "epidemic phase," beetles colonize and kill large numbers of susceptible hosts. In the "post-epidemic phase," beetle populations subside and most beetle-killed trees fall to the forest floor. The endemic and post-epidemic phases can last for decades to centuries, whereas the epidemic phase usually lasts from 2 to 10 years.

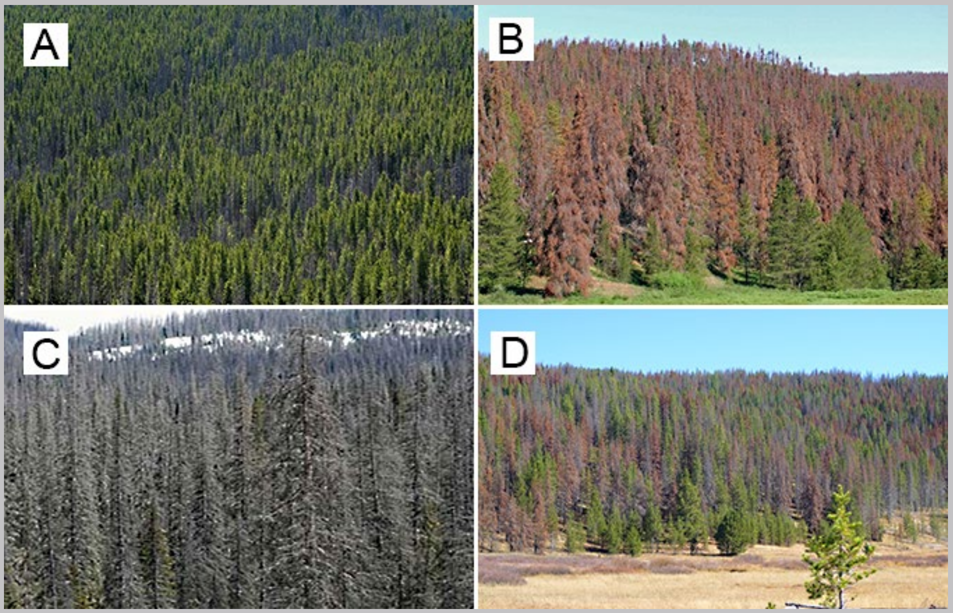

Figure 2—*Bark beetles can cause dramatic changes to forest canopies in coniferous forests. For example, during and after mountain pine beetle* (Dendroctonus ponderosae) *outbreaks, lodgepole pine* (Pinus contorta) *canopies transition from the green-infested stage (A) to the red stage (B) in about 1 to 3 years and then to the gray stage (C), which lasts from about 3 to 25 years following the outbreak. The likelihood of crown and spot fires is greater during the red stage and possibly reduced during the gray stage. Bark beetle activity frequently results in a mosaic of green, red, and gray trees (D) as trees are attacked and killed over several years (usually 2 to 6 years for mountain pine beetle), which can complicate fire behavior prediction in these forests. Photos: J. Runyon, USDA Forest Service.*

Recently attacked trees are referred to as "green-infested" (fig. 2A). As needles fade, trees enter the "yellow" stage. In the "red" stage, needles on beetle-killed trees turn red (fig. 2B). The final stage is the "gray" stage, when needles fall off the trees (fig. 2C). The timing of needle fade and color change varies considerably by tree species, bark beetle species, and geographic location. For example, in the mountain pine beetle–lodgepole pine system, the green-infested stage lasts for about 1 year; the yellow and red stages last for about 1 to 3 years; and the gray stage lasts for about 3 to 25 years (Klutsch and others 2009). It is important to note that, during an outbreak, trees are attacked and killed over several years, and cumulative levels of tree mortality vary considerably even within the same bark beetle–host system. Therefore, a forest often contains trees and stands in multiple stages and phases of a bark beetle rotation at the same time (fig. 2D).

Not surprisingly, beetle-induced changes to foliar moisture have the greatest effects on flammability.

CROWN AND CANOPY FUELS

Not surprisingly, beetle-induced changes to foliar moisture have the greatest effects on flammability. This is because water is a heat sink and moisture in plant tissues increases the amount of energy required for fuels to ignite and burn. Trees colonized and killed by bark beetles rapidly dry out and lose most of their water content by the first summer following attack as needles transition from green to red (fig. 2A, 2B). For example, the twigs and needles of lodgepole pine killed by mountain pine beetle lose 80 to 90 percent of their water content within 1 year of attack (Jolly and others 2012a; Page and others 2012). The loss of moisture increases flammability by shortening time to ignition, lowering temperature at ignition, and raising heat yields when burned (Jolly and others 2012a; Page and others 2012). Reduction in moisture content explains nearly 80 percent of the increase in needle flammability (Page and others 2012). Similar reductions in foliage moisture content and increases in flammability have been documented in Engelmann spruce *(Picea engelmannii)* killed by spruce beetle (Page and others 2014) and Douglas-fir killed by Douglas-fir beetle (Giunta 2016).

Figure 3—*Coarse woody fuel accumulations following a bark beetle outbreak in the Sierra Nevada in California. Based on a survey of 180 plots across 4 national forests, 31 percent of the dead trees fell to the forest floor within 4 years of being killed, which is much faster than reported elsewhere in the literature for other locations and bark beetle–host systems (Fettig and others 2019). Stephens and others (2018) concluded that a greater potential for "mass fires" exists for this region, driven by the amount, size, and continuity of dry combustible woody fuels, which could produce large, severe, and uncontrollable wildfires. Mass fires or "firestorms" (Finney and McAllister 2011) can occur when large areas burn simultaneously for long periods at high intensities, generating their own weather conditions. The science on mass fires (such as Countryman 1965) is limited and the risks are poorly understood. Photo: L. Mortenson, USDA Forest Service.*

Bark beetles alter foliage flammability in other ways as well. The proportions of fat, fiber, lignin and cellulose, starches, and sugars change in needles after beetle colonization, and each factor can affect flammability (Jolly and others 2012a; Page and others 2012, 2014). Conifers also contain large amounts of flammable terpenes. Beetle attack generally increases the emission of terpenes and terpene concentrations within needles (Giunta and others 2016; Page and others 2012, 2014), which can shorten time to ignition, lower temperature at ignition, and increase the maximum rate of mass loss (an indication of burning rate) (Page and others 2012, 2014). Moreover, the emission of terpene "clouds" from plants has been linked to eruptive fire behavior in Europe (Barboni and others 2011; Courty and others 2012) but has not yet been studied in the Western United States. Firefighters have reported observations that support the existence of terpene clouds in western forests during the epidemic phase; additional research is warranted on terpene clouds and their potential effects on fire behavior in the Western United States.

Outbreaks also alter canopy fuel arrangement (Hicke and others 2012; Jenkins and others 2008). As trees move from the red to the gray stage (fig. 2B, 2C), canopy fuels decrease. As dead trees deteriorate and fall to the forest floor (fig. 3), canopy bulk density and canopy cover decline over time. The decrease in canopy fuel continuity also reduces the sheltering effect of the forest, causing higher wind speeds near the ground (Hoffman and others 2015). Increased light and moisture availability resulting from mortality of dominant and codominant trees release smaller surviving trees that were unsuitable hosts for bark beetles, increasing ladder fuels during the post-epidemic phase.

LITTER, FINE FUELS, AND COARSE WOODY FUELS

Although dying and dead foliage is more flammable than live foliage, it remains in the canopy for only a short time (usually 3 years or less). The accumulation rate of canopy materials (foliage and twigs) on the forest floor can be of greater importance, influencing surface fuel loadings and associated fire hazards.

Stalling and others (2017) evaluated the effects of mountain pine beetle and Douglas-fir beetle outbreaks on fuel conditions in Montana and Idaho. Foliage deposition occurred mostly during the first 2 years of the epidemic phase. Unlike foliage, fine woody and nonwoody material tended to come down irregularly, deposited at essentially the same rate from year to year. Tree fall and accumulations of coarse woody surface fuels were limited over the 10-year period of study. These findings suggest that fire hazards in these forests were influenced less during the late epidemic and early post-epidemic phases than previously thought. Highly flammable dead foliage does not stay in the canopy for long, and accumulations of canopy materials on the forest floor do not exceed the annual rate of fuel decomposition (Stalling and others 2017).

Ultimately, all of the woody fuel from beetle-killed trees is transferred to the forest floor during the post-epidemic phase. This period varies considerably by site and tree species, among other factors, with half-lives (the time required for half of the dead trees to fall to the forest floor) ranging from years (such as for ponderosa pines killed by western pine beetle in the central and southern Sierra Nevada (fig. 3)) to decades (such as for lodgepole pines killed by mountain pine beetle in northeast Oregon (Harvey 1986)). Over time, medium and coarse woody fuels gradually accumulate, increasing fuel bed depth. For example, Jenkins and others (2014) reported that medium and coarse woody fuels increased by a factor of about 2.5 to 8 in forests of the Intermountain West following mountain pine beetle outbreaks 20 years earlier.

FIRE BEHAVIOR AND SEVERITY

Modeling fire behavior in beetle-affected forests is challenging, largely because fire behavior model assumptions are violated (Hood and others 2018b; Jenkins and others 2012, 2014; Page and others 2014). The limited ability to use empirical data to evaluate model predictions (Alexander and Cruz 2013a) has fed controversy over whether epidemic and/or post-epidemic phases have more fire behavior hazards than the endemic phase (Jolly and others 2012a; Simard and others 2011, 2012).

Physics-based models suggest that bark beetle outbreaks increase wildfire rates of spread, with spread rates peaking during the red stage. Rates of spread remain higher than in the endemic phase even though canopy fuels decrease (Hoffman and others 2015). In an experiment on needle flammability, red needles from beetle-attacked trees ignited faster than green needles, which could lead to increased crown fire potential (Jolly and others 2012b). However, it is unknown whether the increase in flammability scales up to entire canopies and results in higher intensity crown fires (Alexander and Cruz 2013b). After a crown fire begins, fire behavior in lodgepole pine forests under dry, windy conditions is likely to be similar, regardless of bark beetle activity (Schoennagel and others 2012). Under most circumstances, severe fire weather conditions trump beetle-induced changes in fuel conditions.

Figure 4—*Gray-stage coniferous forest following a bark beetle outbreak. Fire behavior in beetle-affected forests largely depends on the proportion of trees killed and the amount of time since the bark beetle outbreak (that is, the "bark beetle rotation"). In the gray stage, fire severity—and, presumably, the potential for heightened fire behavior—is reduced. However, high-severity crown fires have been reported in some gray-stage forests (Agne and others 2016), especially after significant accumulations of coarse woody fuels. The science on fire behavior in gray-stage forests is limited. Photo: S. Hood, USDA Forest Service.*

Using a physics-based model, Sieg and others (2017) found higher fire severity (that is, tree mortality) in ponderosa-pine-dominated forests during the red stage than in the endemic phase but unchanged or even lower fire severity during the gray stage. The observed increases in fire severity attributed to the bark beetle outbreak declined under high wind conditions (Sieg and others 2017).

Fire severity, measured as change in vegetation, decreased over time following mountain pine beetle outbreaks in Washington and Oregon (Meigs and others 2016). By contrast, Prichard and Kennedy (2014) reported higher fire severity during the red stage following mountain pine beetle outbreaks in Washington.

Harvey and others (2014) reported similar levels of fire severity in red-stage and gray-stage lodgepole pine forests following mountain pine beetle outbreaks in the Northern Rockies. They evaluated several metrics of fire severity and found that only extreme fire weather conditions increased fire severity in terms of deep charring (that is, charring into the wood along tree boles and into crowns, with less than 5 percent of branches remaining) (Harvey and others 2014).

After forests enter the gray stage, evidence suggests that fire severity—and, presumably, the potential for heightened fire behavior—diminish for some time (Hicke and others 2012) (fig. 4). However, more research is needed to fully understand the potential for crown fires in the gray stage.

Although bark beetle outbreaks can influence fire behavior and severity, they have little effect on the extent of the area burned (see, for example, Hart and others 2015) or the likelihood or frequency of wildfire occurrence (Bebi and others 2003; Meigs and others 2015).

The effects on fire behavior and severity have important implications for fire management and firefighter safety. For example, the likelihood of torching, crowning, and spotting can be greater in forests containing an abundance of red crowns (Schoennagel and others 2012; Jenkins and others 2014). Moreover, firefighters have observed "surprising" fire behavior in some forests during the epidemic and post-epidemic phases (Moriarty and others 2019; Page and others 2013). Rapid shifts from surface fires to crown fires pose safety risks to firefighters caused by increases in fireline intensities and spotting, which might necessitate larger safety zones (Butler and Cohen 1998). Snags are an important safety concern, particularly during the post-epidemic phase (fig. 3). Accordingly, firefighters should anticipate the potential for unusual fire behavior (even during the green-infested stage) in beetle-affected forests and the unique suppression challenges that can result (such as increased difficulties in fireline construction and establishment of access, egress, and escape routes).

Since 2000, about 25.5 million acres in the Western United States have been affected by mountain pine beetle.

LOOKING FORWARD

A key finding of the recently published U.S. Fourth National Climate Assessment is that it is "very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes" (Vose and others 2018). As such, it is reasonable to assume that bark beetles and wildfires will increasingly interact to shape western forests.

Recognizing this, the fire science and forest health communities have largely bridged cultural and communication divides (Jenkins and others 2009) and have strengthened relationships with managers in hopes of delivering science of utmost relevance to managers' concerns (Kocher and others 2012). A tremendous amount of knowledge has been developed on bark beetle and fire interactions in western coniferous forests in the last 15 years. Much of this information has been synthesized in notable publications (such as Hicke and others 2012; Jenkins and others 2008, 2012, 2014; Kane and others 2017; and Stephens and others 2018). We encourage the reader interested in delving deeper into this topic to consult these publications.

The scientific community now has a pretty solid understanding of the effects of fuel reduction treatments on bark beetles, which tend to lead to fairly consistent responses among different forest types in the Western United States. Nevertheless, knowledge gaps exist and need to be addressed. Many initial fears concerning long-term increases in levels of delayed tree mortality caused by bark beetles were unfounded. Accordingly, one might view the associated increases in tree mortality as "short-term losses" suffered for "long-term gains" (Fettig and McKelvey 2014). This is especially true when considering that rates of tree mortality caused by bark beetles are generally low (less than 5 percent) and concentrated in small-diameter trees (that is, ladder fuels) and in fire-intolerant tree species (such as white fir).

Although the scientific literature shows mixed results, most suggests that bark beetle outbreaks can significantly change fuel profiles and fire behavior and severity during the epidemic and post-epidemic phases. Nevertheless, discussions of the effects of bark beetle outbreaks on fuels and fire behavior get unnecessarily complex and occasionally contentious if they ignore:

- The amount of time that has occurred since the outbreak (that is, the bark beetle rotation);
- The type and severity of the outbreak (including such factors as whether small trees or big trees are killed and whether some trees or nearly all trees are killed);
- The dominant fire regime of the forest type;
- The spatial scale; and
- Limitations in the prediction of fire behavior in beetle-affected forests.

Furthermore, most studies are retrospective (rather than controlled experiments) and inherently have a lot of variability.

Given the implications for firefighter safety and fire suppression activities, work is needed to more accurately quantify relationships between bark beetle outbreaks and fire behavior and severity, especially in understudied forest types (table 1). Creating and maintaining forest structures that are more resilient to bark beetles and wildfires will go a long way toward addressing concerns regarding increases in fire behavior and severity following bark beetle outbreaks.

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LITERATURE CITED

Agee, J.K.; Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211: 83–96.

Agne, M.C.; Woolley, T.; Fitzgerald, S. 2016. Fire severity and cumulative disturbance effects in the post-mountain pine beetle lodgepole pine forests of the Pole Creek Fire. Forest Ecology and Management. 366: 73–86.

Alexander, M.E.; Cruz, M.G. 2013a. Limitations on the accuracy of model predictions of wildland fire behaviour: a state-of-the-knowledge overview. The Forestry Chronicle. 89: 372–383.

Alexander, M.E.; Cruz, M.G. 2013b. Assessing the effect of foliar moisture on the spread rate of crown fires. International Journal of Wildland Fire. 22: 415–427.

Barboni, T.; Cannac, M.; Leoni, E.; Chiaramonti, N. 2011. Emission of biogenic volatile organic compounds involved in eruptive fire: implications for the safety of firefighters. International Journal of Wildland Fire. 20: 152–161.

Bebi, P.; Kulakowski, D.; Veblen, T.T. 2003. Interactions between fire and spruce beetles in a subalpine Rocky Mountain forest landscape. Ecology. 84: 362–371.

Bentz, B.J.; Régnière, J.; Fettig, C.J. [and others]. 2010. Climate change and bark beetles of the Western United States and Canada: direct and indirect effects. Bioscience. 60: 602–613.

Butler, B.W.; Cohen, J.D. 1998. Firefighter safety zones: a theoretical model based on radiative heating. International Journal of Wildland Fire. 8: 73–77.

Countryman, C.M. 1965. Mass fire characteristics in large-scale tests. Fire Technology. 1: 303–317.

Courty, L.; Chetehouna, K.; Halter, F. [and others]. 2012. Flame speeds of α-pinene/air and limonene/air mixtures involved in accelerating forest fires. Combustion Science and Technology. 184: 1397–1411.

Davis, R.S.; Hood, S.; Bentz, B.J. 2012. Fire-injured ponderosa pine provide a pulsed resource for bark beetles. Canadian Journal of Forest Research. 42: 2022–2036.

DeGomez, T.; Fettig, C.J.; McMillin, J.D.; Anhold, J.A.; Hayes, C. 2015. Managing slash to minimize colonization of residual leave trees by *Ips* and other bark beetle species following thinning in southwestern ponderosa pine (revised 10/2014). AZ1449. Tucson, AZ: University of Arizona, College of Agriculture and Life Sciences Bulletin. 12 p.

Fettig, C.J.; McKelvey, S.R. 2014. Resiliency of an interior ponderosa pine forest to bark beetle infestations following fuel-reduction and forest-restoration treatments. Forests. 5: 153–176.

Fettig, C.J.; Hilszczański, J. 2015. Management strategies for bark beetles in conifer forests. In: Vega, F.E.; Hofstetter, R.W. eds. Bark beetles: biology and ecology of native and invasive species. London: Springer: 555–584.

Fettig, C.J.; McMillin, J.D.; Anhold, J.A. [and others]. 2006. The effects of mechanical fuel reduction treatments on the activity of bark beetles (Coleoptera: Scolytidae) infesting ponderosa pine. Forest Ecology and Management. 230: 55–68.

Fettig, C.J.; Klepzig, K.D.; Billings, R.F. [and others]. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. Forest Ecology and Management. 238: 24–53.

Fettig, C.J.; McKelvey, S.R.; Cluck, D.L. [and others]. 2010. Effects of prescribed fire and season of burn on direct and indirect levels of tree mortality in ponderosa and Jeffrey pine forests in California, USA. Forest Ecology and Management. 260: 207–218.

Fettig, C.J.; Mortenson, L.A.; Bulaon, B.M.; Foulk, P.B. 2019. Tree mortality following drought in the central and southern Sierra Nevada, California, U.S. Forest Ecology and Management. 432: 164–178.

Finney, M.A.; McAllister, S.S. 2011. A review of fire interactions and mass fires. Journal of Combustion. 2011: Article 548328. DOI: 10.1155/2011/548328.

Flannigan, M.D.; Amiro, B.D.; Logan, K.A. [and others]. 2006. Forest fires and climate change in the 21st century. Mitigation and Adaptation Strategies for Global Change. 11: 847–859.

Fowler, J.F.; Sieg, C.H.; Wadleigh, L.L. 2010. Effectiveness of litter removal to prevent cambial kill-caused mortality in northern Arizona ponderosa pine. Forest Science. 56: 166–171.

Giunta, A. 2016. Douglas-fir beetle mediated changes to fuel complexes, foliar moisture content, and terpenes in interior Douglas-fir forests of the central Rocky Mountains. Master's Thesis. Logan, UT: Utah State University. 161 p.

Giunta, A.D.; Runyon, J.B.; Jenkins, M.J.; Teich, M. 2016. Volatile and within-needle terpene changes to Douglas-fir trees associated with Douglas-fir beetle (Coleoptera: Curculionidae) attack. Environmental Entomology. 45: 920–929.

Hart, S.J.; Schoennagel, T.; Veblen, T.T.; Chapman, T.B. 2015. Area burned in the Western United States is unaffected by recent mountain pine beetle outbreaks. Proceedings of the National Academy of Sciences. 112: 4375–4380.

Harvey, B.J.; Donato, D.C.; Turner, M.G. 2014. Recent mountain pine beetle outbreaks, wildfire severity, and postfire tree regeneration in the U.S. Northern Rockies. Proceedings of the National Academy of Sciences. 111: 15120–15125.

Harvey, R.D. 1986. Deterioration of mountain pine beetle-killed lodgepole pine in northeast Oregon. Pap. R6–86–13. Portland, OR: USDA Forest Service. 10 p.

Hicke, J.A.; Johnson, M.C.; Hayes, J.L.; Preisler, H.K. 2012. Effects of bark beetle-caused tree mortality on wildfire. Forest Ecology and Management. 271: 81–90.

Hicke, J.A.; Meddens, A.J.H.; Kolden, C.A. 2016. Recent tree mortality in the Western United States from bark beetles and forest fires. Forest Science. 62: 141–153.

Hoffman, C.M.; Linn, R.; Parsons, R. [and others]. 2015. Modeling spatial and temporal dynamics of wind flow and potential fire behavior following a mountain pine beetle outbreak in a lodgepole pine forest. Agricultural and Forest Meteorology. 204: 79–93.

Hood, S.M. 2010. Mitigating old tree mortality in long-unburned, fire-dependent forests: a synthesis. Gen. Tech. Rep. RMRS–GTR–238. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 71 p.

Hood, S.M.; Bentz, B. 2007. Predicting post-fire Douglas-fir beetle attacks and tree mortality in the Northern Rocky Mountains. Canadian Journal of Forest Research. 37: 1058–1069.

Hood, S.; Sala, A.; Heyerdahl, E.K.; Boutin, M. 2015. Low-severity fire increases tree defense against bark beetle attacks. Ecology. 96: 1846–1855.

Hood, S.; Baker, S.; Sala, A. 2016. Fortifying the forest: thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience. Ecological Applications. 26: 1984–2000.

Hood, S.; Varner, M.; van Mantgem, P.; Cansler, C.A. 2018a. Fire and tree death: understanding and improving modeling of fire-induced tree mortality. Environmental Research Letters. 13: 113004.

Hood, S.; Keane, R.E.; Smith, H.Y. [and others]. 2018b. Conventional fire behavior modeling systems are inadequate for predicting fire behavior in bark beetle-impacted forests. In: Potter, K.; Conkling, B., eds. Forest health monitoring: national status, trends, and analysis 2017. Gen. Tech. Rep. SRS–GTR–233. Asheville, NC: USDA Forest Service, Southern Research Station: 167–176.

Jenkins, M.J.; Hebertson, E.; Page, W.; Jorgensen, W.P. 2008. Bark beetles, fuels, fires and implications for forest management in the Intermountain West. Forest Ecology and Management. 254: 16–34.

Jenkins, M.J.; Fettig, C.J.; Hebertson, E.G. 2009. Bark beetles, fuels and fire: a synthesis of our present understanding and implications for management. In: Rideout-Hanzak, S.; Oswald, B.P.; Beierle, M., comps. 4th Annual International Congress on Fire Ecology and Management: Fire as a Global

Process. Leavenworth, WA: The Association for Fire Ecology.

Jenkins, M.J.; Page, W.G.; Hebertson, E.G.; Alexander, M.E. 2012. Fuels and fire behavior dynamics in bark beetle-attacked forests in Western North America and implications for fire management. Forest Ecology and Management. 275: 23–34.

Jenkins, M.J.; Runyon, J.B.; Fettig, C.J. [and others]. 2014. Interactions among the mountain pine beetle, fires, and fuels. Forest Science. 60: 489–501.

Jolly, W.M.; Parsons, R.A.; Hadlow, A.M. [and others]. 2012a. 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.

Jolly, W.M.; Parsons, R.; Varner, J.M. [and others]. 2012b. Comment: Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecology. 93: 941–946.

Kane, J.M.; Varner, J.M.; Metz, M.R.; van Mantgem, P.J. 2017. Characterizing interactions between fire and other disturbances and their impacts on tree mortality in western U.S. forests. Forest Ecology and Management. 405: 188–199.

Kocher, S.D.; Toman, E.; Trainor, S.F. [and others]. 2012. How can we span the boundaries between wildland fire science and management in the United States? Journal of Forestry. 110: 421–428.

Kolb, T.E.; Fettig, C.J.; Ayres, M.P. [and others]. 2016. Observed and anticipated impacts of drought on forest insects and diseases in the United States. Forest Ecology and Management. 380: 321–334.

Klutsch, J.G.; Negron, J.F.; Costello, S.L. [and others]. 2009. Stand characteristics and downed woody debris accumulations associated with a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in Colorado. Forest Ecology and Management. 258: 641–649.

Lerch, A.P.; Pfammatter, J.A.; Bentz, B.J.; Raffa, K.F. 2016. Mountain pine beetle dynamics and reproductive success in post-fire lodgepole and ponderosa pine forests in northeastern Utah. Plos One 11: e0164738.

McIver, J., Stephens, S.; Agee, J. [and others]. 2013. Ecological effects of alternative fuel reduction treatments: highlights of the national fire and fire surrogate study (FFS). International Journal of Wildland Fire. 22: 63–82.

Meigs, G.W.; Campbell, J.L.; Zald, H.S.J. [and others]. 2015. Does wildfire likelihood increase following insect outbreaks in conifer forests? Ecosphere. 6: art118.

Meigs, G.W.; Zald, H.S.J.; Campbell, J.L. [and others]. 2016. Do insect outbreaks reduce the severity of subsequent forest fires? Environmental Research Letters. 11: 045008.

Moriarty, K.; Cheng, A.S.; Hoffman, C.M. [and others]. 2019. Firefighter observations of "surprising" fire behavior in mountain pine beetle-attacked lodgepole pine forests. Fire. 2: 34. DOI: 10.3390/fire2020034.

Morris, J.L.; Cottrell, S.; Fettig, C.J. [and others]. 2018. Bark beetles as agents of change in social-ecological systems. Frontiers in Ecology and the Environment. 16(S1): S34–S43.

Page, W.G.; Jenkins, M.J.; Runyon, J.B. 2012. Mountain pine beetle attack alters the chemistry and flammability of lodgepole pine foliage. Canadian Journal of Forest Research. 42: 1631–1647.

Page, W.G.; Alexander, M.E.; Jenkins, M.J. 2013. Wildfire's resistance to control in mountain pine beetle-attacked lodgepole pine forests. The Forestry Chronicle. 89: 783–794.

Page, W.G.; Jenkins, M.J.; Runyon, J.B. 2014. Spruce beetle-induced changes to Engelmann spruce foliage flammability. Forest Science. 60: 691–702.

Powell, E.N.; Townsend, P.A.; Raffa, K.F. 2012. Wildfire provides refuge from local extinction but is an unlikely driver of outbreaks by mountain pine beetle. Ecological Monographs. 82: 69–84.

Prichard, S.J.; Kennedy, M.C. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications. 24: 571–590.

Ritchie, M.W.; Skinner, C.N.; Hamilton, T.A. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. Forest Ecology and Management. 247: 200–208.

Schoennagel, T.; Veblen T.T.; Negron J.F.; Smith, J.M. 2012. Effects of mountain pine beetle on fuels and expected fire behavior in lodgepole pine forests, Colorado, USA. Plos One. 7(1): e30002.

Schwilk, D.W.; Knapp, E.E.; Ferrenberg, S.M. [and others]. 2006. Tree mortality from fire and bark beetles following early and late season prescribed fires in a Sierra Nevada mixed-conifer forest. Forest Ecology and Management. 232: 36–45.

Seybold, S.J.; Huber, D.P.W.; Lee, J.C.; Graves, A.D.; Bohlmann, J. 2006. Pine monoterpenes and pine bark beetles: a marriage of convenience for defense and chemical communication. Phytochemistry Reviews. 5: 143–178.

Sieg, C.H.; Linn, R.R.; Pimont, F. [and others]. 2017. Fires following bark beetles: factors controlling severity and disturbance interactions in ponderosa pine. Fire Ecology. 13: 1–23.

Simard, M.; Romme, W.H.; Griffin, J.M.; Turner, M.G. 2011. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecological Monographs. 81: 3–24.

Simard, M.; Romme, W.H.; Griffin, J.M.; Turner, M.G. 2012. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Reply. Ecology. 93: 946–950.

Six, D.L.; Vander Meer, M.; DeLuca, T.H.; Kolb, P. 2002. Pine engraver *(Ips pini)* colonization of logging residues created using alternative slash management systems in western Montana. Western Journal of Applied Forestry. 17: 96–100.

Stalling, C.; Keane, R.E.; Retzlaff, M. 2017. Surface fuel changes after severe disturbances in northern Rocky Mountain ecosystems. Forest Ecology and Management. 400: 38–47.

Stephens, S.L.; Moghaddas, J.J.; Edminister, C. [and others]. 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. [and others]. 2012. The effects of forest fuel-reduction treatments in the United States. Bioscience. 62: 549–560.

Stephens, S.L.; Collins, B.M.; Fettig, C.J. [and others]. 2018. Drought, tree mortality, and wildfire in forests adapted to frequent fire. Bioscience. 68: 77–88.

Vose, J.M.; Peterson, D.L.; Domke, G.M. [and others]. 2018. Forests. In: Reidmiller, D.R.; Avery, C.W.; Easterling, D.R. [and others], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II. Washington, DC: U.S. Global Change Research Program: 223–258.

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Atmospheric Turbulence in Wildland Fire Environments: Implications for Fire Behavior and Smoke Dispersion

Warren E. Heilman

The atmospheric environment surrounding wildland fires is often extremely turbulent, characterized by varying wind speeds and directions (that is, wind gusts and vortices) associated with the ambient atmosphere or with fire-induced perturbations of the atmosphere. These turbulent circulations can have direct and indirect impacts on how wildland fires spread across landscapes and how fire emissions are transported and dispersed away from combustion zones (Forthofer and Goodrick 2011; Heilman and others 2019).

Connections between fire behavior, smoke plume dynamics, and atmospheric turbulence have been established through numerous past observations of wildland fire events and through idealized and case study numerical model simulations of fire/atmosphere interactions (such as Clements and others 2008; Sun and others 2009; and Ward and Hardy 1991). However, gaps in our understanding of the typical characteristics of turbulence regimes surrounding wildland fires and the mechanisms by which they can influence fire behavior and smoke dispersion still exist.

Scientists are working to fill these gaps in understanding through new observational research, with the ultimate goal of providing the foundational science for developing new and improved operational predictive tools for fire behavior and smoke dispersion. This paper summarizes some of these research efforts and their key findings.

PRESCRIBED FIRE AND WILDFIRE TURBULENCE OBSERVATIONS

Over the past 10 to 15 years or so, many wildland fire experiments have been conducted in a variety of settings, with a special emphasis on measuring turbulent circulations within and near the fire environment. In February 2006, one of the first comprehensive studies of fire-induced turbulence regimes during a prescribed high-intensity heading (generally spreading in the direction of the ambient wind) grass fire was carried out at the Houston Coastal Center in Texas; it was known as the FireFlux I experiment (Clements and others 2007).

Then, in January 2013, a second prescribed heading grass fire experiment (FireFlux II) with enhanced atmospheric measurements was carried out at the same location, with the same emphasis on measuring fire-induced turbulence regimes (Clements and others 2019). Using onsite tower-based high-frequency (10- or 20-hertz) sonic anemometer and thermocouple measurements for both experiments, the spatial and temporal

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Warren Heilman is a research meteorologist for the Forest Service, Northern Research Station, Lansing, MI.

Figure 1—*Instrumented 30-meter (98-foot) mobile tower set up in the interior of a burn block in the New Jersey Pinelands National Reserve in 2011 to measure atmospheric turbulent circulations at multiple heights in the vicinity of a spreading prescribed fire beneath forest overstory vegetation. Photo: Nicholas Skowronski, USDA Forest Service.*

variations in the three-dimensional wind field and temperature field were examined as the grass fires spread through the monitoring networks. From these high-frequency measurements, new insight was gained into how heading grass fires can change the general properties of turbulent circulations typically found under no-fire conditions. For example, the measurements indicated that strong turbulent downdrafts (consistent with horizontal roll vortices; see Haines and others 1982) behind, just ahead, and downwind of advancing fire fronts can reach the surface and potentially contribute to the deposition of soot and embers.

Followup analyses of the FireFlux I data revealed that the energy of turbulent circulations (also known as turbulent kinetic energy) generated by and in the vicinity of heading grass fires can greatly exceed the typical energy of ambient (no-fire) near-surface atmospheric turbulent circulations over grasslands (Clements and others 2008). Furthermore, the energy of the horizontal versus vertical wind gusts/lulls within convective plumes above grassland fire fronts was found to be similar, in contrast to what is observed near the surface under no-fire conditions, where energy differences are typically much larger (that is, anisotropic turbulence).

The higher intensity FireFlux I grass fire experiment set the stage for a series of new lower intensity prescribed fire experiments conducted in forested (longleaf pine (*Pinus palustris* Mill.)) and nonforested (grass and shrub) ecosystems in Florida and Georgia during the autumn and winter seasons of 2008, 2011, and 2012. Collectively, this suite of experimental burns comprised the well-known Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE), which is fully described by Ottmar and others (2016). As in the FireFlux I and II experiments, a substantial component of the RxCADRE program was devoted to assessments of the atmospheric environment surrounding advancing fire fronts, including ambient and fire-induced turbulent circulations (Clements and others 2016). The RxCADRE onsite tower-based turbulence measurements revealed that even low-intensity surface fires beneath forest overstory vegetation can lead to fire/atmosphere interactions that generate turbulent circulations capable of perturbing fire fronts.

Concurrent with the RxCADRE program, the U.S. Joint Fire Science Program sponsored a series of low-intensity wildland fire experiments conducted in forested environments in New Jersey (pitch pine (*Pinus rigida* Mill.) and mixed oak (*Quercus* spp.)) and North Carolina (longleaf pine) to assess how forest overstory vegetation can affect turbulent circulations in the vicinity of fire fronts and local smoke dispersion (Strand and others 2013; Heilman and others 2013). Onsite tower-based measurements (see, for example, figure 1) of turbulent circulations and thermal conditions within and above forest overstory vegetation layers during the experiments provided a wealth of information about (1) the energetics of fire-induced turbulent circulations (such as updrafts, downdrafts, and inflow into the combustion zone) when forest overstory vegetation is present; (2) the potential effects that fire fronts underneath overstory vegetation can have on the skewness of horizontal and vertical turbulent velocity distributions (that is, the creation of non-Gaussian turbulence); and (3) the relative contributions that horizontal and vertical turbulent fluxes of heat and momentum can make to the total heat and momentum flux fields in the vicinity of fire fronts in forested environments.

Key findings from fire experiments suggest the following:

- Downdrafts associated with fire-induced turbulent eddies in the vicinity of fire fronts can bring cooler air from aloft deep into forest overstory layers and potentially affect fire spread and local smoke dispersion (Seto and others 2014; Heilman and others 2015).
- The energy of fire-induced turbulent eddies (turbulent kinetic energy) is likely to be at a maximum at or near the top of forest canopies instead of near the surface combustion zones, which implies more turbulent mixing of smoke as it exits the top of the canopy than near the surface (Heilman and others 2015).
- The horizontal turbulent mixing of smoke during low-intensity fires in forested environments tends to exceed vertical turbulent mixing, especially near the surface and near the canopy top (Heilman and others 2015, 2017).
- Both vertical wind shear and buoyancy contribute substantially to the production of turbulent eddies and the increase in turbulent kinetic energy during the passage of fire fronts in forested environments, whereas the diffusion of turbulent kinetic energy during periods of fire front passage tends to reduce energy levels above fire fronts (Heilman and others 2017).
- The presence of wildland fires in forested environments can result in highly skewed horizontal and vertical velocity distributions (that is, non-Gaussian turbulence regimes), which calls into question the use of smoke dispersion predictive tools that assume Gaussian turbulence fields (Heilman and others 2017).
- On average, horizontal turbulent heat fluxes tend to exceed vertical turbulent heat fluxes above and in the vicinity of surface fire fronts in forested environments, whereas vertical turbulent momentum fluxes tend to exceed horizontal turbulent momentum fluxes (Heilman and others 2019).

Forest Service scientists and external collaborators are conducting research to assess the mechanisms by which heat and momentum are vertically transported away from and into wildland fire fronts in forested and grassland environments by atmospheric turbulence. The vertical transport of warm/cool air and high/low-horizontal-momentum air away from and into combustion zones by turbulent eddies is accomplished through events called sweeps, ejections, outward interactions, and inward interactions (figs. 2, 3):

- ***Sweeps:***
  - Heat—Downward flux of cool air from above.
  - Momentum—Downward flux of high-horizontal-momentum air from above.
- ***Ejections:***
  - Heat—Upward flux of warm air from below.
  - Momentum—Upward flux of low-horizontal-momentum air from below.
- ***Outward Interactions:***
  - Heat—Upward flux of cool air from below.
  - Momentum—Upward flux of high-horizontal-momentum air from below.

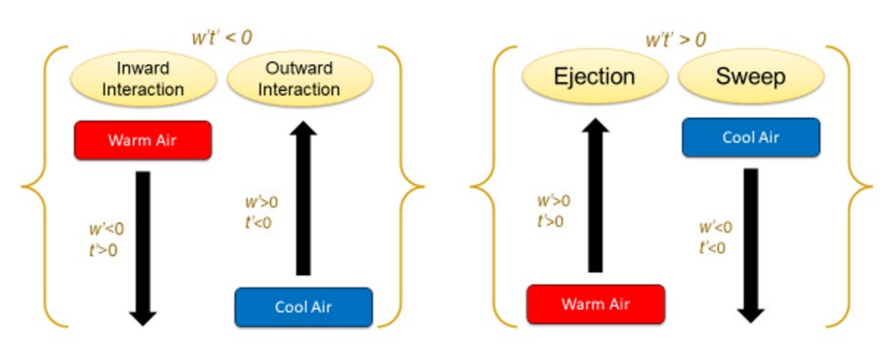

Figure 2—*Schematic of the contributions of sweep, ejection, outward interaction, and inward interaction events to vertical turbulent heat fluxes (w't'), where w' is a perturbation vertical velocity and t' is a perturbation temperature. Inward and outward interactions (left side of figure) result in negative heat fluxes (w't' < 0) caused by the downward transport (w' < 0) of warm air (t' > 0) from above (inward interaction) or the upward transport (w' > 0) of cool air (t' < 0) from below (outward interaction). Ejections and sweeps (right side of figure) result in positive heat fluxes (w't' > 0) caused by the upward transport (w' > 0) of warm air (t' > 0) from below (ejection) or the downward transport (w' < 0) of cool air (t' < 0) from above (sweep).*

Scientists are working to fill these gaps in understanding through new observational research.

- ***Inward Interactions:***
  - Heat—Downward flux of warm air from above.
  - Momentum—Downward flux of low-horizontal-momentum air from above.

Using data collected during some of the previously described wildland fire experiments (FireFlux I and II and the Joint Fire Science Program New Jersey burn experiments), scientists are investigating the typical frequencies of occurrence for the different types of events and their typical overall contributions to average heat and momentum fluxes near fire fronts in grassland and forested environments. Initial findings from this research suggest that, for turbulent heat fluxes, ejection events (upward fluxes of warm air from below) may be the most common type of event within near-surface atmospheric layers above grassland fire fronts, whereas sweep events (downward fluxes of cool air from above) may be the most frequent type of event above surface fire fronts in forested environments. For turbulent momentum fluxes, the initial analyses suggest that both sweeps (downward fluxes of high-horizontal-momentum air from above) and ejections (upward fluxes of low-horizontal-momentum air from below) are likely the most prevalent types of events above grassland fire fronts. Above surface fire fronts in forested environments, initial results suggest a very different momentum flux picture, with sweeps and outward interactions (upward fluxes of high-horizontal-momentum air from below) potentially being the most prevalent types of events. New wildland fire experiments currently underway, such as experiments funded by the U.S. Department of Defense's Strategic Environmental Research and Development Program in the New Jersey Pine Barrens (*https://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Resiliency/Air-Quality/RC-2641*), are providing critical observational datasets for further evaluating how sweeps, ejections, outward interactions, and inward interactions contribute to turbulent heat and momentum fluxes under different environmental and fire-intensity conditions.

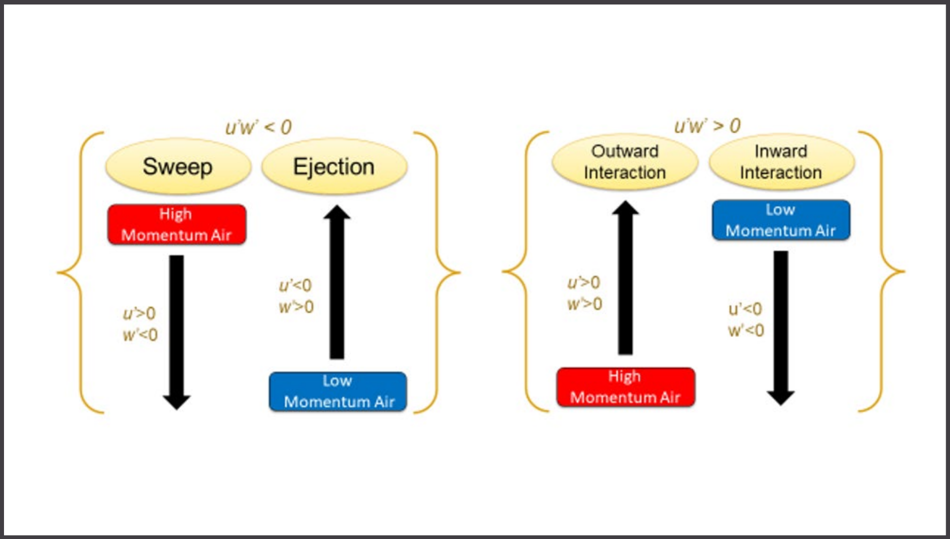

Figure 3—*Schematic of the contributions of sweep, ejection, outward interaction, and inward interaction events to vertical turbulent momentum fluxes (u'w'), where u' is a perturbation streamwise horizontal velocity and w' is a perturbation vertical velocity. Sweeps and ejections (left side of figure) result in negative momentum fluxes (u'w' < 0) caused by the downward transport (w' < 0) of high horizontal momentum air (u' > 0) from above (sweep) or the upward transport (w' > 0) of low horizontal momentum air (u' < 0) from below (ejection). Outward and inward interactions (right side of figure) result in positive momentum fluxes (u'w' > 0) caused by the upward transport (w' > 0) of high horizontal momentum air (u' > 0) from below (outward interaction) or the downward transport (w' < 0) of low horizontal momentum air (u' < 0) from above (inward interaction).*

In addition to wildland fire experiments in relatively flat terrain (discussed above), other recent experiments have assessed fire-induced turbulence regimes in areas of complex terrain. These experiments have expanded our understanding, based on earlier studies (as summarized in Werth and others (2011)), of potential fire/turbulence interactions in complex-terrain settings.

For example, Seto and Clements (2011) conducted a prescribed (heading) grass fire experiment in 2008 in complex terrain east of San José, CA. They used tower-based sonic anemometer and thermocouple instrumentation to measure terrain- and fire-induced turbulent circulations and temperature fluctuations as the fire spread through the burn block. The study was instrumental in showing how sea-breeze fronts, upvalley flows, and fires can interact to create near-surface turbulence regimes favorable for firewhirl formation.

Gaps in our understanding of the connections between atmospheric turbulence and wildland fires still exist.

Clements and Seto (2015) conducted another prescribed grass fire experiment (known as the Grass Fires on Slopes Experiment) in 2010, with a heading fire on a simple slope near Dublin, CA, under ambient cross-slope winds. Using monitoring technology similar to that used in their 2008 experiment, they found that fire-induced turbulent circulations can enhance the upslope spread of fires, even in the presence of moderate ambient cross-slope winds. They also found that the energy associated with fluctuations in horizontal velocities tended to exceed the energy associated with vertical velocity fluctuations just above fire fronts (that is, anisotropic turbulence), although the degree of anisotropy was less than what is typically observed under no-fire conditions. The anisotropy was most pronounced for low-frequency velocity fluctuations associated with large turbulent eddies (Seto and others 2013). These findings are consistent with other observations of turbulence anisotropy above fire fronts in forested environments, also described in Seto and others (2013) and in Heilman and others (2015, 2017).

A year later in 2011, Charland and Clements (2013) conducted a prescribed downslope surface backing fire experiment in an oak woodland located in a complex-terrain area east of San José, CA. Utilizing ground-based scanning Doppler lidar technology, they were able to identify windflow convergence zones associated with turbulent vortices/eddies within and downwind of the convective smoke plume generated by the fire. These types of vortices/eddies can affect the entrainment of ambient air into convective smoke plumes and the dispersion of fire emissions.

Although onsite or nearby measurements of turbulence regimes during wildfires are much more difficult to carry out than experimental fires (which are typically lower in intensity), some recent wildfire behavior observations and analyses (such as alpine bushfires in Australia in 2003) strongly suggest that ambient and fire-induced turbulence can contribute to the spread of fires over complex terrain in directions transverse to ambient wind directions, the development of spot fires through ember transport by turbulent eddies, and the generation of firewhirls (see, for example, Sharples 2009; and Sharples and others 2010, 2012). The connections between ambient and fire-induced turbulence and convective smoke plume behavior during wildfire events in complex-terrain regions have also been measured recently through remote sensing technology (such as Doppler lidar) as part of the Rapid Deployments to Wildfires Experiment (Clements and others 2018). For example, Lareau and Clements (2017) used a scanning Doppler lidar system during the 2014 El Portal Fire in California to measure turbulent circulations within and in the vicinity of the fire's convective plume. The measurements clearly highlighted the important role that turbulent eddies play in entraining ambient air into smoke plumes and increasing the radii of smoke plumes with height as they move upward.

Fire-induced turbulent circulations can enhance the upslope spread of fires, even with the presence of moderate ambient cross-slope winds.

RESEARCH GAPS AND OPPORTUNITIES

The onsite and remotely sensed measurements of atmospheric turbulence characteristics during wildland fire events carried out over the last 10 to 15 years have led to a much-improved understanding of how fires can interact with the atmosphere. Nevertheless, gaps in our understanding of the connections between atmospheric turbulence and wildland fires still exist. In particular, we don't fully understand how backing and heading fires with different intensities in grassland and forested environments actually respond to turbulent circulations associated with different turbulent eddy sizes.

New wildland fire experiments that incorporate high-frequency measurements of fire front behavior and spread, coupled with onsite or remotely sensed measurements of atmospheric turbulence-related variables at and near the fire front, are needed to close the knowledge gap. The suite of ongoing and planned wildland fire experiments for the Fire and Smoke Model Evaluation Experiment (FASMEE) (Potter and Clements 2017; Prichard and others 2019) offers an excellent opportunity to assess the direct and indirect connections between wildland fire behavior and turbulence. The knowledge gained from FASMEE and similar wildland fire experiments will be critical for the development of atmospheric turbulence parameterizations that more fully capture the effects of fire-induced turbulent circulations on fire spread and smoke transport in operational fire behavior and smoke dispersion modeling systems.

LITERATURE CITED

Charland, A.M.; Clements, C.B. 2013. Kinematic structure of a wildland fire plume observed by Doppler lidar. Journal of Geophysical Research: Atmospheres. 118: 1–13.

Clements, C.B.; Zhong, S.; Goodrick, S. [and others]. 2007. Observing the dynamics of wildland grass fires. Bulletin of the American Meteorological Society. 88: 1369–1382.

Clements, C.B.; Zhong, S.; Bian, X. [and others]. 2008. First observations of turbulence generated by grass fires. Journal of Geophysical Research. 113: D22102. *https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008JD010014*. (21 January 2020).

Clements, C.B.; Seto, D. 2015. Observations of fire-atmosphere interactions and near-surface heat transport on a slope. Boundary-Layer Meteorology. 154: 409–426.

Clements, C.B.; Lareau, N. P.; Seto, D. [and others]. 2016. Fire weather conditions and fire–atmosphere interactions observed during low-intensity prescribed fires – RxCADRE 2012. International Journal of Wildland Fire. 25: 90–101.

Clements, C.B.; Lareau, N.P.; Kingsmill, D.E. [and others]. 2018. The Rapid Deployments to Wildfires Experiment (RaDFIRE). Bulletin of the American Meteorological Society. 99: 2539–2559.

Clements, C.B.; Kochanski, A.K.; Seto, D. [and others]. 2019. The FireFlux II experiment: a model-guided field experiment to improve understanding of fire–atmosphere interactions and fire spread. International Journal of Wildland Fire. 28: 308–326.

Forthofer, J.M.; Goodrick, S.L. 2011. Review of vortices in wildland fire. Journal of Combustion. 2011: 984363. *https://doi.org/10.1155/2011/984363*. (21 January 2020).

Haines, D.A. 1982. Horizontal roll vortices and crown fires. Journal of Applied Meteorology. 21: 751–763.

Heilman, W.E.; Zhong, S.; Hom, J.L. [and others]. 2013. Development of modeling tools for predicting smoke dispersion from low-intensity fires. Final Report; U.S. Joint Fire Science Program; project 09–1–04–1. 61 p. *https://www.firescience.gov/projects/09-1-04-1/project/09-1-04-1_final_report.pdf*. (21 January 2020).

Heilman, W.E.; Clements, C.B.; Seto, D. [and others]. 2015. Observations of fire-induced turbulence regimes during low-intensity wildland fires in forested environments: implications for smoke dispersion. Atmospheric Science Letters. 16: 453–460.

Heilman, W.E.; Bian, X.; Clark, K.L. [and others]. 2017. Atmospheric turbulence observations in the vicinity of surface fires in forested environments. Journal of Applied Meteorology and Climatology. 56: 3133–3150.

Heilman, W.E.; Clements, C.B.; Zhong, S. [and others]. 2019. Atmospheric turbulence. In: Manzello, S., ed. Encyclopedia of wildfires and wildland-urban interface (WUI) fires. Basel, Switzerland: Springer Nature. https://doi.org/10.1007/978-3-319-51727-8. (21 January 2020).

Lareau, N.P.; Clements, C.B. 2017. The mean and turbulent properties of a wildfire convective plume. Journal of Applied Meteorology and Climatology. 56: 2289–2299.

Ottmar, R.D.; Hiers, J.K.; Butler, B.W. [and others]. 2016. Measurements, datasets and preliminary results from the RxCADRE project – 2008, 2011 and 2012. International Journal of Wildland Fire. 25: 1–9.

Potter, B.E.; Clements, C. 2017. Development of a comprehensive plume dynamics and meteorology study plan for FASMEE. Final report; U.S. Joint Fire Science Program; project 16–4–03–1. 9 p. https://www.firescience.gov/projects/16-4-03-1/project/16-4-03-1_final_report.pdf. (22 January 2020).

Prichard, S.; Larkin, N.; Ottmar, R. [and others]. 2019. The Fire and Smoke Model Evaluation Experiment—a plan for integrated, large fire–atmosphere field campaigns. Atmosphere. 10(2): 66. https://doi.org/10.3390/atmos10020066. (22 January 2020).

Seto, D.; Clements, C.B. 2011. Fire whirl evolution observed during a valley wind-sea breeze reversal. Journal of Combustion. Article ID 569475. DOI: 10.1155/2011/569475.

Seto, D.; Clements, C.B.; Heilman, W.E. 2013. Turbulence spectra measured during fire front passage. Agricultural and Forest Meteorology. 169: 195–210.

Seto, D.; Strand, T.M.; Clements, C.B. [and others]. 2014. Wind and plume thermodynamic structures during low-intensity subcanopy fires. Agricultural and Forest Meteorology. 198–199: 53–61.

Sharples, J.J. 2009. An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. International Journal of Wildland Fire. 18: 737–754.

Sharples, J.J.; McRae, R.H.D.; Weber, R.O. 2010. Wind characteristics over complex terrain with implications for bushfire risk management. Environmental Modelling and Software. 25: 1099–1120.

Sharples, J. J.; McRae, R.H.D.; Wilkes, S.R. 2012. Wind-terrain effects on the propagation of wildfires in rugged terrain: fire channeling. International Journal of Wildland Fire. 21: 282–296.

Strand, T.M.; Rorig, M.; Yedinak, K. [and others]. 2013. Sub-canopy transport and dispersion of smoke: a unique observation dataset and model evaluation. Final report; U.S. Joint Fire Science Program; project 09–1–04–2. 63 p. https://www.firescience.gov/projects/09-1-04-2/project/09-1-04-2_final_report.pdf. (21 January 2020).

Sun, R.; Krueger, S.K.; Jenkins, M.A. [and others]. 2009. The importance of fire–atmosphere coupling and boundary-layer turbulence to wildfire spread. International Journal of Wildland Fire. 18: 50–60.

Ward, D.E.; Hardy, C.C. 1991. Smoke emissions from wildland fires. Environment International. 17: 117–134.

Werth, P.A.; Potter, B.E.; Clements, C.B. [and others]. 2011. Synthesis of knowledge of extreme fire behavior: volume I for fire managers. Gen. Tech. Rep. PNW–GTR–854. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 144 p.

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Indigenous Fire Stewardship: Federal/Tribal Partnerships for Wildland Fire Research and Management

Frank Kanawha Lake

Over millennia, many indigenous and Tribal peoples in North America's fire-prone ecosystems developed sophisticated relationships with wildland fire that continue today. This article introduces philosophical, conceptual, and operational approaches to working with American Indians through research and management partnerships in the fields of wildland fire, forestry, and fuels, with applications to climate change and forest landscape restoration strategies (Mansourian and others 2019). Of central importance are respectful collaborative relationships among the various parties (Tribes, agencies, organizations, academics, and citizens) that seek to integrate both indigenous and Western knowledge systems into environmental stewardship practices.

There is a great degree of genetic, linguistic, and cultural diversity among the indigenous peoples of North America, who comprise numerous American Indian and Alaskan Native Tribes. Tribal cultures are as diverse as the fire-prone ecosystems across North America (Stewart 2002). The Tribes, clans, and other sociocultural institutions of indigenous communities are as varied as the habitats they live in. Just as there are different local habitats, so there are numerous cultural uses of the landscapes and species that comprise tribally valued resources, all of which are affected both spatially and temporally by fire in some manner.

For many Tribes who have lived and evolved with fire-prone ecosystems, aspects of their traditions, livelihoods, economies, and cultures evolved with and rely on fire-dependent species and fire-affected ecological processes. At this nexus of people and their environment is the genealogy of indigenous fire stewardship and how cultural burning practices formed. Analogous to fire-dependent species, many indigenous peoples and Tribal communities are fire-dependent cultures, having adapted to and been influenced or affected by the fire regimes of their landscapes (Lake 2018). Indigenous fire stewardship, derived from many types of knowledge systems, can be described as "the use of fire by various Indigenous, Aboriginal, and Tribal peoples to modify fire regimes, adapting and responding to climate and local environmental conditions to promote desired landscape, habitats, species and to increase the abundance of favored resources to sustain knowledge systems, ceremonial and subsistence practices, economies and livelihoods" (Lake and Christianson 2019). Central to indigenous fire stewardship is the cultural ability to mediate and reduce extreme natural fire events by adapting to changing climatic and environmental conditions. Fire-dependent cultures can be thought of as mutualistic with their fire-prone ecosystems (Lake 2018).

Indigenous knowledge can help identify trigger points, thresholds, and indicators for ecosystems, habitats, and resources of interest.

TYPES OF INDIGENOUS KNOWLEDGE

Indigenous knowledge, which reflects Tribal communities' metaphysical and biophysical understanding of their environment, encompasses traditional ecological knowledge, traditional fire knowledge, and traditional forest-related knowledge.

Frank K. Lake is a research ecologist for the Forest Service, Fire and Fuels Program, Pacific Southwest Research Station, Arcata, CA.

- ***Traditional ecological knowledge*** has been defined as a “cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with the environment … [it] is both cumulative and dynamic, building on experience and adapting to changes” (Berkes 1999).
- ***Traditional fire knowledge,*** as defined by Huffman (2013), is “fire-related knowledge, beliefs, and practices that have been developed and applied on specific landscapes for specific purposes by long time inhabitants.” Traditional fire knowledge encompasses over 69 distinct elements, as documented in a global synthesis of indigenous people and their relationships with fire. Included are elements of geology, topography, soils, vegetation, fuels, weather, fire behavior, and fire effects, along with fire operations, fire governance, and various social factors (Huffman 2013).
- ***Traditional forest-related knowledge*** is defined essentially as traditional ecological knowledge (Trosper and Parrotta 2012)

At the foundation of many indigenous creation teachings is the belief that humans are related to all aspects of their environment—that they have interrelationships with nature. This corresponds to the belief that fire is spirit, an element that is often revered and feared but is also essential to fire-prone ecosystems and fire-dependent species; fire is critical to the health of fire-dependent cultures. Many indigenous cultures consider their knowledge and use of fire a spiritual obligation, part of indigenous/Tribal land and resource stewardship practices (Eriksen and Hankins 2014; McKemey and others 2020). In many indigenous teachings, fire is “medicine” for people and land. With respect to prescribed fire or indigenous fire stewardship, not enough fire can make the land and people sick (unhealthy), and too much fire can be bad as well (akin to a catastrophic overdose). Central to indigenous fire stewardship is the sociocultural ability to influence, mediate, and reduce extreme natural fire events by adapting to changing climatic and environmental conditions (Lake and Christianson 2019).

At the foundation of many indigenous creation teachings is the belief that humans are related to all aspects of their environment.

For many Tribes, the cessation of indigenous fire stewardship and colonial government policies of fire suppression (which collectively resulted in fire exclusion) have degraded the land and many species used as valued resources. With increases in fuel loading, growing vegetation density and the resulting catastrophic fires are like an overdose of medicine. Additionally, among indigenous philosophies, if fire is medicine, then water is like the blood of land and people. Fire is connected to water at all scales, and water is sacred and one of the highest resource values (Hannibal 2014).

Indigenous knowledge guides fire stewardship in fire-prone ecosystems for fire-dependent species. Cultural burning is human services for ecosystems,* a tool for fulfilling spiritual obligations in Tribal belief systems and practices (Eriksen and Hankins 2014). The evolution of cultural fire regimes emerged from indigenous cultural adaptations to form fire-dependent cultures. The spatial and temporal extent of indigenous fire use varies by ecosystem and habitats and is linked to fire-affected resources of value. Philosophically, if fire is medicine, then indigenous fire stewardship and cultural burning are human services that meet obligations for metaphysical (spiritual) commitments. These human services achieve biophysical stewardship and environmental resource objectives and deliver a range of sociocultural values (Eriksen and Hankins 2015; Worl and Norgaard 2019).

Anyone considering collaboration with indigenous peoples and Tribal communities should know that indigenous fire stewardship is diverse, with a distribution of gender, age, and cultural responsibilities among individuals in a community. Members of indigenous communities hold various types of knowledge and practice various types of cultural burning, and it is important to ask what their particular responsibilities for and roles in fire use are. Differences in indigenous fire stewardship and cultural burning reflect roles based on spiritual/ceremonial, subsistence, utilitarian/domestic, and economic/security responsibilities and governance. Working with diverse indigenous communities (Nations-Tribes/villages), groups (clans/families), and leaders (governance/religious) means including a full range of indigenous knowledge systems (Eriksen and Hankins 2014, 2015).

Anyone seeking to understand the reasons for and objectives of indigenous fire stewardship and cultural burning should be aware that indigenous people might not disclose specifics due to their belief systems; to a desire for confidentiality; or to fear of inappropriate exploitation, adoption, or cooptation of practices by nonindigenous peoples. Indigenous knowledge, particularly related to indigenous fire stewardship, is a responsibility. Those seeking such knowledge should be clear as to their reasons for wanting it (the use it serves or the objective it achieves) and understand what commitments they make in exchange for acquiring the knowledge.

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*Bill Tripp. Karuk Tribe. Personal communication.

INDIGENOUS FIRE STEWARDSHIP AND CULTURAL FIRE REGIMES

Cultural fire regimes differ from natural fire regimes, and indigenous cultures have developed sophisticated burning practices (Huffman 2013; Lake and Christianson 2019). Pyrodiversity is augmented by cultural burning, which can become human services for fire-prone ecosystems. Indigenous fire stewardship created cultural fire regimes by influencing and diversifying the frequency, seasonality, extent, locality, intensity, and resultant severity of fires (Lake and others 2017; Lake and Christianson 2019; McKemey and others 2020). For example:

- **Frequency:** Indigenous peoples apply fire for specific resource values and objectives (fig. 1). Such applications of fire are often more frequent than natural ignitions with respect to particular resources and habitats.
- **Seasonality:** The timing of burning is often different from natural ignitions (that is, lightning) and more diverse within seasons, linked to plant and fungus phenology or breeding and migration times for animals (such as ungulates, birds, and fish).
- **Specificity:** Ignition strategies within different ecosystems and habitats are targeted toward various species used as resources.

The continuum from a natural fire regime (based on ignitions such as lightning) to a cultural fire regime (based on human fire use) depends on the extent and magnitude of indigenous fire stewardship (Lake and Christianson 2019). Often, the objectives of cultural burning are directly linked to responsibility for using different burning practices in response to topography, fuel loading, phenology, weather, and resource quality as well as cultural, spiritual, ceremonial, subsistence, utilitarian, and economic objectives (Eriksen and Hankins 2014, 2015; McKemey and others 2020). Documented reasons for American Indian fire use include but are not limited to hunting, crop management, pest management, range management, fireproofing, clearing areas for travel, clearing riparian areas, basket materials, and fuelwood (see Stewart 2002).

ROLE OF SCIENTIFIC RESEARCH AND INDIGENOUS KNOWLEDGE IN SUPPORTING WILDLAND FIRE MANAGEMENT

Indigenous science support for exploring management options builds on the foundation of indigenous knowledge and Tribal traditional ecological knowledge. Researchers can seek to understand indigenous science support needs, the research questions of interest, and the management challenges that Tribes and indigenous communities face. In developing research partnerships with indigenous communities, researchers should link multiple lines of evidence using various interdisciplinary methods to broaden the exploration of indigenous fire stewardship and cultural burning. Responding to policy directives and management needs, researchers can explore the treatment-based outcomes of traditional ecological knowledge and cultural practices as part of their experimental approach.

Including the elements of indigenous knowledge (traditional ecological knowledge, traditional fire knowledge, and traditional forest-related knowledge) can lead to a better understanding of the implications of frequency and/or seasonality for developing treatment prescriptions and discerning the effects of potential management strategies. Indigenous knowledge can help identify trigger points, thresholds, and indicators appropriate to the ecosystems, habitats, and resources of interest. Indigenous knowledge can reveal the metrics applicable at a particular scale or useful for exploring synergistic mechanisms or effects. In working cooperatively with Tribes and Tribal organizations, indigenous knowledge can guide land managers in the monitoring and adaptive management of habitats, species, and resource conditions and their desired quality or abundance based on their sociocultural uses. This can contribute to a better understanding of the implications of fire effects on the values associated with habitats, species, and resource conditions (Welch 2012).

Fire-dependent cultures can be thought of as mutualistic with their fire-prone ecosystems.


Figure 1—*A mixed-conifer/hardwood forest in the western Klamath Mountains, partially burned to improve subsistence resources of Tribal value affected by fire (mushrooms, huckleberries, and oak (acorn) food resources associated with a known cultural use site). Photo: Frank K. Lake, USDA Forest Service.*

In developing a research framework for incorporating indigenous knowledge, researchers would be well advised to consider the following questions:

- At what scale should forestry, fire, and climate effects be studied?
- At what scale should wildland fire and fuels reduction treatments be evaluated as management practices in relation to tribally valued resources and habitats?

- How should the scale or metrics that are most applicable be identified?
- What are the resources and habitats valued within a cultural ecosystem services framework?

Resources are broadly tangible and intangible elements of the environment: landscapes (areas), sites, objects, and states of mind. Natural and cultural resources are used to perpetuate Tribal customs, practices, and knowledge systems. Habitats are landscapes or places that support Tribal ceremonial and subsistence practices, which are often defined in biophysical or sociocultural terms as site characteristics for places that support—or potentially could support—single or multiple resources of Tribal value (fig. 1).

In upscaling and integrating research approaches to support strategies for collaborative restoration planning and implementation, researchers can draw on such interdisciplinary methods as paleoclimate and fire history (that is, lake sediment pollen/charcoal cores and tree age/fire scars) as well as ethnographic and oral-histories data (including historical maps and photos), taking into account past and present Tribal resource uses across a variety of habitats. For example, studies in the field of ethnobotany can focus on how indigenous fire stewardship and cultural burning (as well as wildland fire) promote species used for basketry and as foods (see Hummel and Lake 2014; Long and others 2016; Marks-Block and others 2019).

A research project—or, more likely, a program—can link individual plant traits as one organizational unit (such as an ethnobotany-food or basketry plant) that can be nested within plots (as a defined sampling area containing the plant's habitat or population). For example, forestry/vegetation plots, as a discrete sampling area, can be used to characterize habitat and resource quality, focusing on trees, fuels, and understory plant diversity. Cross-scale units of study, such as a 30-square-meter plot area, could then be studied using remote sensing (such as satellite imagery or aerial LiDAR) to reflect local interest (onsite resources or values associated with a particular habitat type) and scaled up to landscape conditions. The results could be combined with evaluations by managers and Tribal practitioners of existing conditions to determine how public and Tribal values would influence the development of prescriptions for various treatments (Lake 2013) and for assessment of those treatments and wildland fire effects.

Indigenous fire stewardship is inclusive of gender, age, and cultural responsibilities among individuals in a community.

Some commonly aligned public and Tribal values are reducing hazardous fuels and fire risk (for example, in the wildland–urban interface to protect life, property, and resources for increasing suppression action effectiveness) while also promoting the heterogeneity and resilience of the vegetation. Reduced fuel continuity increases human and wildlife access and mobility; retains larger and older fire-resistant trees; and promotes fire-adapted/drought-tolerant species associated with biodiversity that are used by Tribes as food, medicine, and materials (fig.2). It can also give wildland fire managers more options for suppression actions or to achieve resource objectives when and where desired. For example, managers might use such strategies as:

Figure 2—*Fire personnel on the Six Rivers National Forest in California conducting a prescribed cultural burn on a strategic ridge along a road to improve opportunities for future wildland fire response and Tribal gathering access. The understory contains a high density of beargrass (a tribally valued basketry resource requiring fire to promote desired leaf growth). Photo: Frank K. Lake, USDA Forest Service.*

- Promoting drought-tolerant fire-adapted species by removing undesired (fire-intolerant or diseased) trees through thinning from above, reducing crown area, reducing tree density, and creating openings or extending patch size for early-seral understory species;
- Manual thinning from below to reduce understory fuel continuity, including mastication on plantations and chainsaw cutting to reduce the density of small trees and shrubs as ladder fuels and to increase the height to live crown;
- Contributing to overall increased species heterogeneity while retaining certain trees (based on species preference as well as on size/diameter, height, crown positions/form, and vigor) and certain shrubs (used as food, basketry, and wildlife cover); and
- Placing piles and conducting seasonal burns to reintroduce fire after long periods of fire exclusion or to build upon recent fire effects.

Infused into the research study design would be sociocultural, ecological, and economic considerations of how multiple public and Tribal values can be simultaneously achieved.

CROSS-CULTURAL AND INTERDISCIPLINARY UNDERSTANDING AND COMMUNICATION

Researchers, managers, and practitioners who seek to work with indigenous communities on wildland fire management, fuels management, and forestry projects can take various partnership approaches. A crosswalk of variables of interest, metrics, and strategies or treatments that could be studied, monitored, and evaluated can help in exploring treatment-based outcomes for achieving desired resource conditions. Table 1 is a starting point for considering some of the main forestry and wildland fire variables and factors that could be aligned with management treatments in exploring research study design or management strategies. The goal is to understand how related factors or interest "variables" can be addressed through management.

ALIGNING COMMUNITIES' VALUES WITH RESEARCH AND MANAGEMENT STRATEGIES

Many forest landscape restoration strategies are designed to promote heterogeneity and resilience (see Hessburg and others 2015). At broader scales across planning units, land managers might consider strategically placed landscape area treatments (Finney 2001), which target about 20 to 30 percent of the planning area for a single treatment or combination of treatments. Working with Tribes and other entities to align values (such as through a "values overlay") can help managers identify the areas of highest priority for treatment with limited resources, such as roads, ridges, and the wildland–urban interface. By incorporating indigenous knowledge, the partners can learn about historical contexts that pertain to modern resource management objectives (figs. 2, 3; Harling and Tripp 2014).

Climate change vulnerability assessments and adaptation planning can help identify the threats, stressors, and other challenges to the local environment and to Tribal or community stewardship practices (Karuk Tribe 2019). Forest landscape restoration

Table 1—*Alignment of forestry and wildland fire variables with cultural and Tribal values and restoration treatments.*

Forestry/wildland fire management factor or interest	Forestry/fire variable/metric	Cultural/Tribal value linked to forestry/fire interest	Cultural variable or value	Restoration treatment that aligns management and tribal values
Forest and understory plant diversity	Species per acre; diversity index	Higher density of foods, material, medicinal plants	Increased seasonal use for multiple purposes	Thinning certain types of trees and shrubs; wildland fire
Tree diameter/size ranges	Diameter at breast height; basal area	Larger full crown; structurally diverse trees; fewer trees per acre	Older/mature forest with favored tree species	Thinning certain types of trees; wildland fire
Crown fire initiation; ladder fuels; canopy tree volume and density	Canopy base height; ground-to-crown height; torching index	Increased access, foraging, and viewing	Walking and searching quality; site quality for valued species	Limbing up large trees; removing small suppressed trees; removing selected trees; thinning from above
Brown's fuels transects; surface fuel loading	Tons per area by fuel size classes; fuelbed depth; duff/litter depth	Increased access, foraging, and viewing; percentage of duff for fungi and herbs	Walking, searching, and foraging quality	Removing surface fuels by manual or mechanical means or by wildland fire
Canopy cover/closure; sunlight	Density of tree crowns (bulk density); amount of sunlight on plot	Open or partial sunlight for fruiting and understory plants (shrubs, forbs, ferns, grasses)	Quality and quantity of fruit; light for understory plants	Manual or mechanical thinning of certain types of trees; single-tree treatments

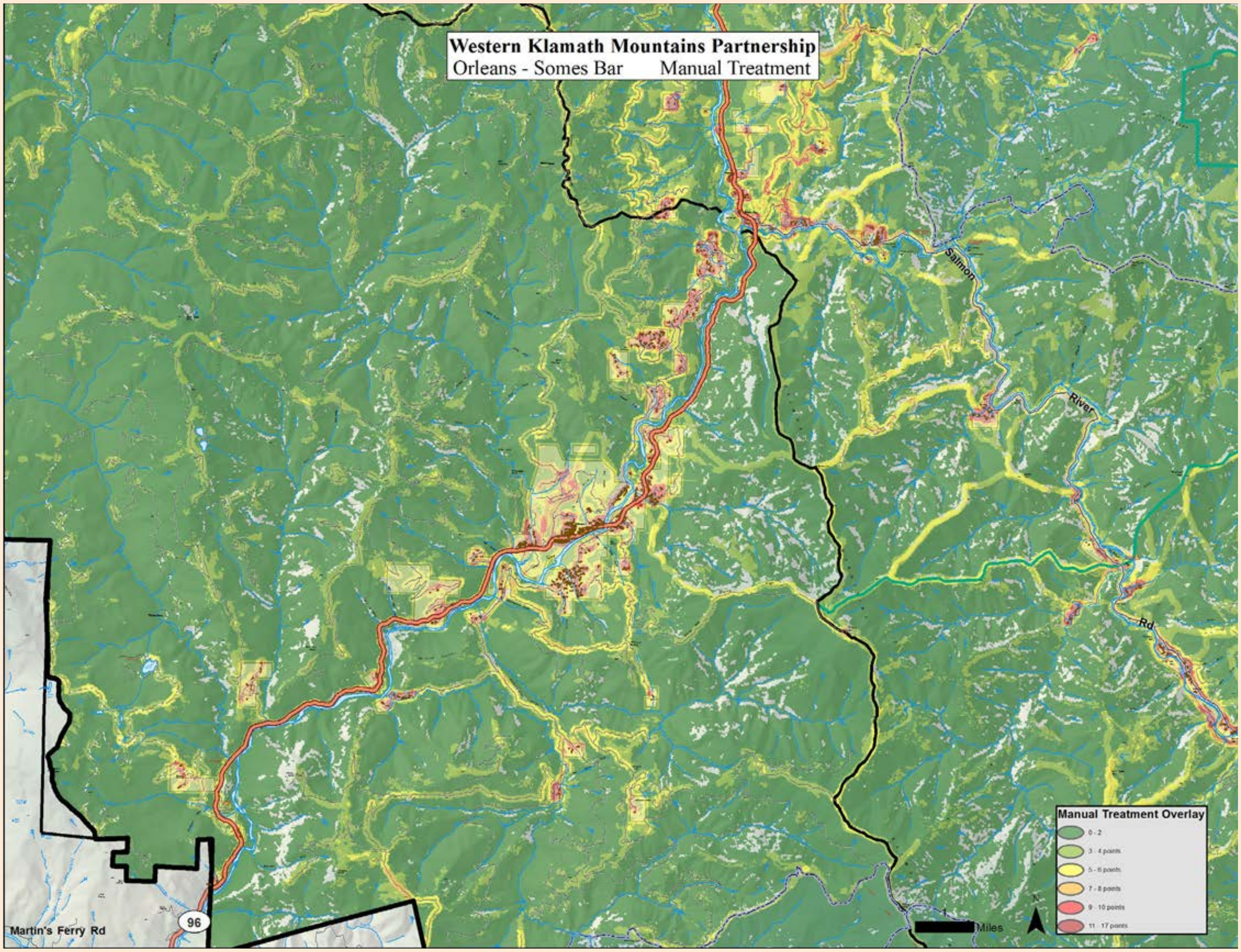


Figure 3—*Map of the area near Orleans/Somes Bar, CA, depicting the overlay assessment of values that represent zones of agreement for prioritizing treatments, from red (highest priority) to green (lowest priority). Source: Karuk Department of Natural Resources, Western Klamath Restoration Partnership.*

planning strategies could incorporate ecosystem services provided by fire-prone landscapes, taking natural and cultural resources of importance to the public and Tribal communities into account. Restoration partnerships can align research and management components by tiering to national and State policies, authorities, and regulatory initiatives (such as the National Cohesive Wildland Fire Management Strategy).

The Cohesive Strategy has three main components:

1. Resilient landscapes;
2. Fire-adapted communities (or, in a Tribal context, fire-dependent cultures); and
3. Wildland fire management responses.

Efforts to integrate research and management into the three components can link to Tribal and rural community values (fig. 2). This can be achieved by aligning multiple resource objectives with community values for the reintroduction of fire, taking an approach that supports Tribal ecocultural restoration or revitalization. Adaptive research and management can integrate shared values by collaboratively developing or selecting the metrics (what is measured as well as why and at what scale it is measured) and by incorporating agreed-upon indicators of success for strategies with treatments at different scales. Such treatments might be to improve the condition of resources of interest (such as the quality of habitat for threatened or endangered species), to increase the abundance of trees or shrubs used by

Establishing meaningful working relationships with indigenous communities and Tribes results from consultation, coordination, and communication for more successful collaboration.

In many indigenous teachings, fire is "medicine" for people and land.

Tribes for food and basketry, or to improve the composition and structure/fuel loading at the habitat or plot scale.

TRIBAL TRADITIONAL KNOWLEDGE AND FOCAL SPECIES AS INDICATORS

In connection with linking forest landscape restoration strategies with indigenous knowledge about fuels and wildland fire treatments, some Tribes use focal species to represent different habitat requirements across the landscape. Each species has components of its life history that make it vulnerable to or benefit from the effects of wildland fire (see Karuk 2019).

In northwestern California, for example, the Western Klamath Restoration Partnership adopted the Somes Bar Integrated Fire Management Project indicators. The Karuk Tribe selected Pacific giant salamander (for water); willow (for riverine/riparian habitats); Roosevelt elk (a seasonal elevational migrant); Pacific fisher (for old-growth forest with early-seral habitat); and northern spotted owl (for conservation/threatened and endangered species). Indigenous knowledge of these species' habitat requirements, combined with broader shared values representative of the overall restoration partnership, are integrated into the development of prescriptions for mechanical, manual, and fire-based treatments (Harling and Tripp 2014; Lake and others 2018). These focal species are also represented in research and monitoring approaches linking treatment units to habitats and the broader landscape regarding the reintroduction of fire (Karuk 2019).

WORKING WITH TRIBAL GOVERNMENTS AND INDIGENOUS COMMUNITY ORGANIZATIONS: WILDLAND FIRES

Establishing meaningful working relationships with indigenous communities and Tribes results from consultation, coordination, and communication for more successful collaboration. In several regions, the Forest Service has Government-to-Government agreements or memorandums of understanding (MOUs) between national forests and Tribes (see the sidebar for sample text from an MOU signed in 2019). These agreements are national to regional in scope (a national agreement template, for example, is the Master Cooperative Wildland Fire Management and Stafford Act Response Agreement).

Locally, fire and fuels management agreements or MOUs tiered to different authorities utilize designated Tribal representative and the Tribal heritage resources advisors or consultants who work with incident management teams (IMTs) on wildfires. These Tribal leaders and consultants work directly with incident leadership and fireline field resources, which can foster cooperative job training and wildland fire education for Tribal and non-Tribal fire personnel. This gives IMTs and field-going fire leadership (branch/division), type I and type II crews, and specialists such as archeologists, members of wildland fire use modules, fire behavior analysts, and GIS/planning consultants opportunities to work with local traditional knowledge. Such agreements, along with an understanding of Tribal values and interests, can help wildland fire managers protect or mitigate impacts to maintain archeological, cultural, and heritage resources (see Lake 2011).

Wildland fire affects more than archeological sites. The living cultural resource and habitat conditions are potentially affected by fire suppression strategies and actions and by the fire itself, both indirectly and directly (Welch 2012). When adequate consultation, coordination, and communication take place between Tribes and IMTs/fire personnel, wildland fire management activities can foster and support living cultural resources linked with traditional practices and desired fire effects from patches (as resource gathering areas) across the landscape (as multiple resource

MEMORANDUM OF UNDERSTANDING

Between The

KARUK TRIBE

And The

USDA, FOREST SERVICE

KLAMATH & SIX RIVERS NATIONAL FORESTS

And The

USDI, BUREAU OF INDIAN AFFAIRS

SACRAMENTO FIELD OFFICE

This MEMORANDUM OF UNDERSTANDING (MOU) is hereby made and entered into by and between the Karuk Tribe, hereinafter referred to as "Tribe," the United States Department of Agriculture (USDA), Forest Service, Klamath and Six Rivers National Forests, hereinafter referred to as the "U.S. Forest Service," and the United States Department of Interior (DOI), Bureau of Indian Affairs, Sacramento Field Office, hereinafter referred to as the "BIA."

Background: In 1994, a consultation protocol MOU was signed by the Karuk Tribe and Klamath National Forest as a framework for conducting Government to Government Consultation. This was a useful tool; however, it was quickly identified that existing protocols did not allow for timely Karuk consultation and coordination during wildland fire incidents.

The Karuk Tribe and Klamath National Forest then signed the inaugural Fire MOU 1996 to "establish and maintain a mutually beneficial strategy for incorporating Karuk gathering areas affected by fire at different seasons and frequencies) (Lake 2011; Lake and others 2017).

Across the United States, more consultation and coordination are needed with Tribes on fuels reduction treatments and wildland fire management. In northwestern California, fire management agreements/MOUs between the Karuk Tribe and the Six Rivers National Forest have improved working relationships through the use of Tribal elders (level II, nonfireline qualified) and heritage consultants (level I, fireline qualified) to share traditional knowledge and Tribal values regarding wildland fire management (Lake 2011). Coordinating resources for carrying out fire suppression strategies and for managing fires to achieve resource objectives has improved understanding of the effects of fire suppression and exclusion and of fuels management treatments on the condition of landscapes and species as well as on the quality of their cultural use. The agreements support the sharing of knowledge about values at risk, which can be used in the Wildland Fire Decision Support System and for local implementation of the Cohesive Strategy while increasing the pace and scale of desired burning and protecting cultural/heritage resources and Tribal values. Such Government-to-Government agreements/MOUs support knowledge exchange for linking traditional ecological knowledge to fire effects in relation to cultural resources and Tribal values (Lake 2007, 2013; Welch 2012).

DECOLONIZING WILDLAND FIRE MANAGEMENT AND RESEARCH

Decolonization of wildland fire management and research is an indigenous-led process together with partners (governments, organizations, academics, and private individuals). Most of the work has been conducted based on academic descriptions of decolonization processes in research related to nonfire disciplines. The key is to recognize and acknowledge the effects of colonization on indigenous lands and territories as well as the impacts on indigenous cultures and knowledge systems and on fire-prone ecosystems. The process builds understanding of the colonial factors that have contributed to erasing indigenous fire sovereignty and cultural fire regimes and of the factors that still affect indigenous communities (Eriksen and Hankins 2015; Norgaard 2019).

The main colonial factors have been—and still are—Federal and State fire policies to eliminate or limit indigenous burning and stewardship practices, ranging from actions by the first Spanish governor of Alta California to later State and Federal laws, such as the 1911 Weeks Act (Norgaard 2019). The factors include the effects of genocide and the forced removal and relocation of Tribes, followed by governmental, religious, and educational efforts to acculturate Tribal peoples, along with the passage of fire laws and legal sanctions that prosecute indigenous peoples for what Federal and State authorities consider to be illegal burning (such as cultural burning classified as arson and incendiarism). Examples include legal actions at the Federal and State levels against indigenous "arsonists" or fines and imprisonment of Tribal people for incendiarism when they were or are carrying out practices conforming to what they consider to be their precolonial retained rights to burn and a sociocultural responsibility (Norgaard 2019).

Decolonization of wildland fire management and research can take a multiscaled approach of collaborative governance that entails:

- Supporting indigenous sovereignty (self-governance) and decision-making authority (coleadership/oversight) through collaborative partnerships;
- Increasing and improving administrative and jurisdictional opportunities for indigenous fire stewardship through coleadership, shared decision making, and indigenous management of ancestral Tribal territories;

Of central importance are respectful collaborative relationships.

Cultural concerns into the existing incident management system used by the Forest Service for the management of wildfire." There have been four iterations of the MOU since 1996, one in May 2001, which included as new signatories, the Six Rivers and Shasta Trinity National Forests; one in April 2008, which included the Six Rivers but not the Shasta Trinity; and one in 2013, which tracks the 2008 version and expired in July of 2018.

These iterations mentioned above, coupled with the Karuk Tribe's active involvement with the Forests during management of wildland fire incidents, have helped raise awareness regarding the value of incorporating Karuk Traditional Ecological Knowledge into fire management strategies to better protect important tribal values; and have helped create the fifth iteration of this living document.

Title: Terms of Expedited Tribal Consultation During Wildland Fire Incidents

I. PURPOSE:

The purpose of this MOU is to document the cooperation between the parties concerning wildland fire incidents, providing clear direction to the Tribe, Forest Service and BIA regarding ordering and reimbursable expenditures protocols, as well as Roles & Responsibilities for personnel assigned to an incident. It further provides a communication structure, allowing for expedited consultation with the Tribe during ongoing incidents. It enables Tribal concerns to be considered while providing for safe, effective, and efficient wildland fire management activities on lands managed by the Forest Service. This instrument outlines a cooperative approach to addressing concerns in the area of mutual interest depicted in Attachment "A" "Karuk Aborignial Territory" in accordance with the following provisions

- Supporting funding for increased fiscal/budgetary appropriations and allocations to support indigenous fire stewardship;
- Planning at meaningful scales for cross-jurisdictional prioritization of and strategies for types of fuels and wildland fire management and research (Lake and others 2017; Karuk 2019); and
- Taking operational actions on the ground to carry out programs and projects with indigenous engagement, including consultation, coordination, and cooperation for improved collaboration.

These steps will lead to a healing process of reconciliation, repatriation, and restoration for indigenous communities. They can promote the recovery of indigenous burning practices, fire-adapted ecosystems and species, and cultural fire regimes to support Tribal fire-dependent cultures. This approach can be aligned with the broader public interest, wildland fire management opportunities, and governmental policies.

POTENTIAL FOR PARTNERSHIPS

Philosophical, conceptual, and operational approaches toward working with American Indians to form research and management partnerships in the fields of wildland fire, forestry, and fuels hold promise for applications to climate change and forest landscape restoration strategies. In many indigenous teachings, fire is "medicine" for people and land. Anyone who considers collaborating with indigenous peoples and Tribal communities should note that indigenous fire stewardship is both diverse and inclusive of gender, age, and cultural responsibilities among individuals. Different members of indigenous communities hold different types of knowledge and practice various types of cultural burning.

Some Tribes are using agreements/MOUs, joining collaborative groups, and developing research within management projects linked to forest landscape restoration strategies. Decolonization and restoration of indigenous fire stewardship can take a multiscaled approach of collaborative governance that involves supporting indigenous sovereignty (self-governance) and decision-making authority (coleadership/oversight) through partnerships. Working with Tribes as fire-dependent cultures in fire-prone ecosystems can assist society in learning to live with wildland fire, accomplish resource objectives, and promote socioecological resilience among communities and across landscapes.

LITERATURE CITED

Berkes, F. 2008. Sacred ecology. 2nd ed. New York: Routledge. 313 p.

Eriksen, C.; Hankins, D.L. 2014. The retention, revival, and subjugation of Indigenous fire knowledge through agency fire fighting in Eastern Australia and California. Society and Natural Resources. 27(12): 1288–1303.

Eriksen, C.; Hankins, D.L. 2015. Colonization and fire. Coles, A.; Gray, L.; Momsen, J., eds. The Routledge Handbook of Gender and Development, New York: Routledge: 129–137. Chap. 14.

Finney, M.A. 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science. 47(2): 219–228.

Hannibal, M.E. 2014. Lighting cultural fires: let it burn. Boom: A Journal of California. 4(3): 51–59. DOI: 10.1525/boom.2014.4.3.51.

Harling, W.; Tripp, B. 2014. Western Klamath Restoration Partnership: a plan for restoring fire adapted landscapes. Mid Klamath Watershed Council. 57 p. *https://www.karuk.us/images/docs/dnr/2014%20Western%20Klamath%20Restoration%20Partnership_Restoration%20Plan_DRAFT_FINA%20%20%20.pdf.* (31 March 2020).

Hessburg, P.F.; Churchill, D.J.; Larson, A.J. [and others]. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landscape Ecology. 30(10): 1805–1835.

Huffman, M.R. 2013. The many elements of traditional fire knowledge: synthesis, classification, and aids to cross-cultural problem solving in fire-dependent systems around the world. Ecology and Society. 18(4): 3.

Hummel, S.; Lake, F.K. 2014. Forest site classification for cultural plant harvest by Tribal weavers can inform management. Journal of Forestry. 113(1): 30–39.

Karuk Tribe 2019. Karuk Climate Adaptation Plan. Karuk Department of Natural Resources. 232 p. *https://www.karuk.us/index.php/departments/natural-resources/525-climate-adaptation.* (31 March 2020).

Lake, F.K. 2011. Working with American Indian Tribes on wildland fires: protecting cultural heritage sites in northwestern California. Fire Management Today. 71(3): 14–21.

Lake, F.K. 2013. Trails, fires and tribulations: Tribal resource management and research issues in Northern California. Occasion: Interdisciplinary Studies in the Humanities. 5. 22 p. *https://www.fs.fed.us/psw/publications/lake/psw_2013_lake005.pdf.* (16 January 2020).

Lake, F.K. 2018. Fire as medicine: fire-dependent cultures and re-empowering American Indian Tribes. Fire Adapted Communities Fire Learning Network. 13 September 2018. *https://fireadaptednetwork.org/fire-as-medicine-fire-dependent-cultures/.* (9 December 2019).

Lake, F.K.; Christianson, A.C. 2019. Indigenous fire stewardship. In: Manzello, S.L., ed. Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Basel, Switzerland: Springer Nature Switzerland AG. *https:doi.org/10.1007/978-3-319-51727-8_225-1.* (15 January 2020).

Lake, F.K.; Wright, V.; Morgan, P. [and others]. 2017. Returning fire to the land: celebrating traditional knowledge and fire. Journal of Forestry. 115(5): 343–353.

Lake, F.K.; Parrotta, J.; Giardina, C.P. [and others]. 2018. Integration of traditional and Western knowledge in forest landscape restoration. In: Mansourian, S.; Parrotta, J., eds. Forest landscape restoration: integrated approaches to support effective implementation. New York: Routledge: 198–226. Chap. 12.

Long, J.W.; Anderson, M.K.; Quinn-Davidson, L. [and others]. 2016. Restoring California black oak ecosystems to promote Tribal values and wildlife. Gen. Tech. Rep. PSW–GTR–252. Albany, CA: USDA Forest Service, Pacific Southwest Research Station. 110 p.

Mansourian, S.; Parrotta, J.; Balaji, P. [and others]. 2019. Putting the pieces together: integration for forest landscape restoration implementation. Land Degradation and Development. 49(2): 192–203. DOI: org/10.1002/ldr.3448.

Marks-Block, T.; Lake, F.K; Curran, L.M. 2019. Effects of understory fire management treatments on California hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. Forest Ecology and Management. 450: 117517.

McKemey, M.; Ens, E.; Rangers, Y.M. [and others]. 2020. Indigenous knowledge and seasonal calendar inform adaptive savanna burning in northern Australia. Sustainability. 12(3): 995. *https://doi.org/10.3390/su12030995.* (30 April 2020).

Norgaard, K.M. 2019. Salmon and acorns feed our people: colonialism, nature, and social action. New Brunswick, NJ: Rutgers University Press. 312 p.

Stewart, O.C. 2002. Forgotten fires: Native Americans and the transient wilderness. Norman, OK: University of Oklahoma Press. 352 p.

Trosper, R.L.; Parrotta, J.A. 2012. Introduction: the growing importance of traditional forest-related knowledge. In: Parrotta, J.A.; Trosper, R.L., eds. Traditional forest-related knowledge: sustaining communities, ecosystems and biocultural diversity. World Forest Series. Dordrecht, The Netherlands: Springer: 1–36. Chap. 1. Vol. 12.

Welch, J.R. 2012. Effects of fire on intangible cultural resources: moving toward a landscape approach. In: Ryan, K.C.; Jones, A.T.; Koerner, C.L.; Lee, K.M., tech. eds. Wildland fire in ecosystems: effects of fire on cultural resources and archaeology. Gen. Tech. Rep. RMRS–GTR–42–vol. 3. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station: 157–170. Chap. 8.

Worl, S.; Norgaard, K.M. 2019. What Western States can learn from Native American wildfire management strategies. GreeenBiz. 1 November 2019. *https://www.greenbiz.com/article/what-western-states-can-learn-native-american-wildfire-management-strategies.* (31 January 2020).

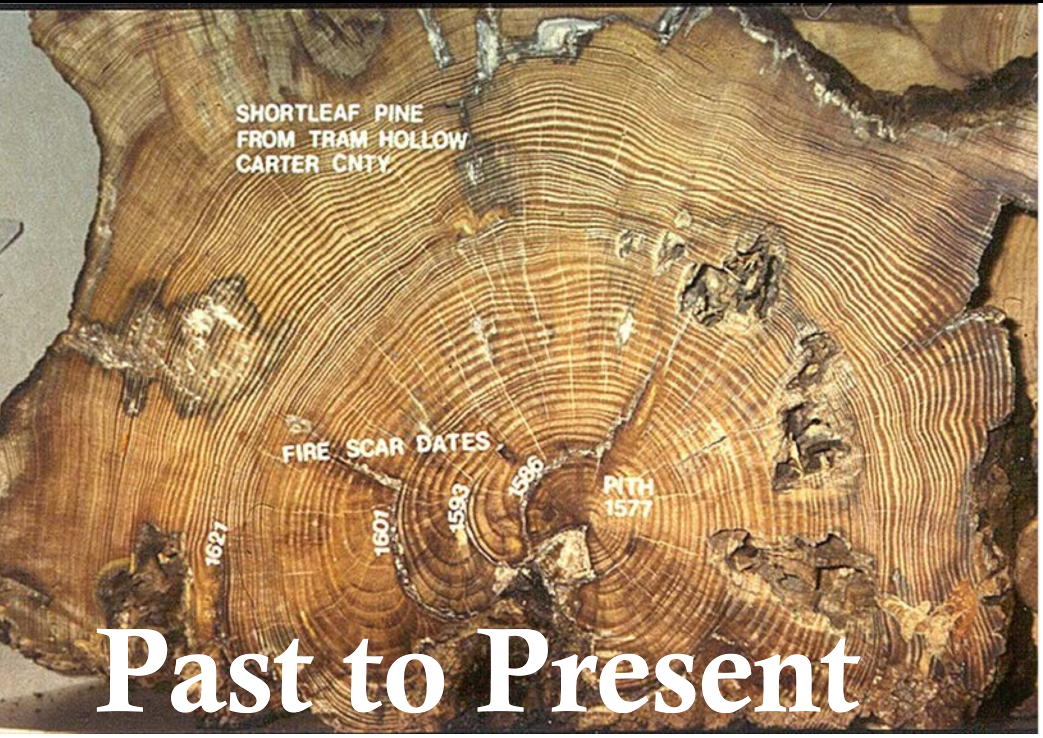
SUGGESTED RESEARCH EXAMPLES

Hummel, S.; Lake, F.K. 2014. Forest site classification for cultural plant harvest by Tribal weavers can inform management. Journal of Forestry. 113(1): 30–39.

Hummel, S.; Lake, F.; Watts, A. 2015. Using forest knowledge: how silviculture can benefit from ecological knowledge systems about beargrass harvesting sites. Gen. Tech. Rep. PNW–GTR–912. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. 9 p.

Long, J.W.; Anderson, M.K.; Quinn-Davidson, L. [and others]. 2016. Restoring California black oak ecosystems to promote Tribal values and wildlife. Gen. Tech. Rep. PSW–GTR–252. Albany, CA: USDA Forest Service, Pacific Southwest Research Station. 110 p.

Marks-Block, T.; Lake, F.K; Curran, L.M. 2019. Effects of understory fire management treatments on California hazelnut, an ecocultural resource of the Karuk and Yurok Indians in the Pacific Northwest. Forest Ecology and Management. 450: 117517.



Section of a shortleaf pine from the Missouri Ozark region that was cut in the early 1900s. Fire scars from when the tree was young date to the late 1500s. Shortleaf pine is considered fire adapted based on many characteristics, including a unique ability to resprout following topkill when small. Photo: Michael Stambaugh.

Past to Present Human Influences on Fire Regimes: Lessons Learned From Missouri

Michael C. Stambaugh and Daniel C. Dey

Fire regimes are defined by the frequency, severity, intensity, seasonality, type, and extent of wildland fire on the landscape. These characteristics are often described at time scales spanning decades to centuries and spatial scales covering sites to regions (Parisien and Moritz 2009). Fire regimes are primarily affected by climate, topography, and ignitions, but humans have shown their ability to overwhelm the relative importance of each of these factors, not only in the past but also in the present.

HUMAN IMPACTS ON FIRE REGIMES

Fire suppression since the early 20th century is an example of the potential for humans to alter fire regimes at a continental scale. In the fire suppression era of the 20th century, regional differences in the type of fire activity, such as prescribed fire or arson, illuminated cultural and land use differences. The role of human influences on fire regimes prior to the era of fire suppression is less well understood, but evidence exists. In recent years, an emerging theme of fire research has been historical human influences, traditional ecological knowledge, and social sciences (Roos and others 2014; Senos and others 2006; Taylor and others 2016).

> **One of the most studied regions in the world for fire regimes and human/fire associations is in the Ozarks of southeastern Missouri.**

Apart from the Southeastern United States, humans are thought to be the primary ignition source for fire regimes in the Eastern United States (east of the Great Plains). Early documents contain numerous examples and fire uses by American Indians and early settlers from Europe. Many of the historical purposes for burning continue to be relevant, although some are not. For this reason, it is important to consider the purpose for burning when interpreting historical fire regimes and not assume associations between fire regimes and vegetation without careful attention to fire ecology.

Many proxy fire data are available for understanding historical fire regimes and the potential for human influences. These data exist at a range of overlapping scales. Charcoal and pollen provide centuries to millennia of records about climate, vegetation, fire, and human influences. The long charcoal records,

Michael Stambaugh is an associate research professor, School of Natural Resources, University of Missouri, Columbia, MO; and Daniel Dey is a research forester and project leader for the Forest Service, Northern Research Station, Columbia, MO.

For at least 500 years, Native American as well as European cultural groups used fire to manage the land for benefits and survival.

often dated with decadal accuracy, inform more precise fire scar records that often span centuries and can be pinpointed by year and precise location. Fire scar records inform documents such as early surveys and journals, which often contain highly descriptive accounts. Finally, modern experiments and records of fire events provide observable data about fires and their environmental contexts. Each of these types of data about fire events influences modern management and policymaking.

OZARK FIRE REGIMES

One of the most studied regions in the world for fire regimes and human/fire associations is in the Ozarks of southeastern Missouri. The region is an ancient eroded mountain dome containing some of the oldest rocks in North America. Here exists a wealth of human/fire information from a range of sources, including:

- Charcoal in sediments (Nanavati and Grimm 2019);
- Fire scars on trees (Stambaugh and Guyette 2008);
- Early surveyor notes (Hanberry and others 2014);
- Cultural fire histories (Guyette and others 2002);
- Fire incident reports;
- Prescribed fire experiments (Dey and Hartmann 2005; Knapp and others 2015);
- Remote sensing and landscape models (Yang and others 2008); and
- Large-scale ecosystem restoration projects (Thompson and others 2018).

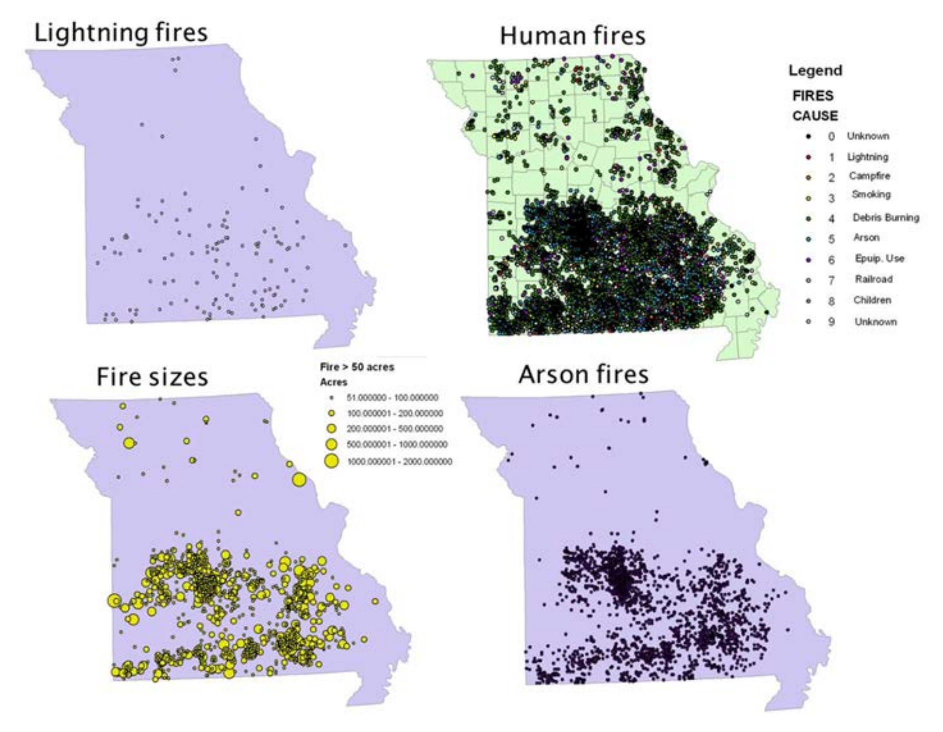
Each of these information sources serves to improve our understanding of fire regimes, fire effects, fire management, and the changing role of humans.

Charcoal records going back for 2,000 years show a constant fire presence. Shortleaf pine, a fire-adapted resprouter, has been present the entire time but declined to about 10 percent of its range before European settlement due to logging and fire suppression. A major feature of the charcoal and fire scar records is a rise in fire activity from about 1600 to 1850 associated with populations of American Indians in the region. Fire scars reflect changes in the frequency and spatial extent of fire with changes in human populations and cultures. Fires were generally frequent, low-severity, and dormant-season events. Extensive historical fire years in Missouri coincided with those in Arkansas and Oklahoma, leading to estimates of millions of acres burned during extreme drought years.

The spatial pattern of historical fires in the Ozarks related to the spatial pattern of vegetation. Historical fire frequency gradients aligned with species composition and structures (Batek and others 1999). When the Ozarks were first surveyed in the mid-1800s, surveyors often found no trees to mark section corners due to the open conditions. Most of Missouri was in open woodland conditions, not dense forests. Many of these areas have transitioned to dense forests only in the last century; accordingly, many dense forests still have a legacy of sun-loving prairie flora in the soil seedbank and root bank.

HUMAN FIRE USE IN THE OZARKS

A distinct characteristic of fire regimes in the Ozarks is strong evidence for fire attribution to humans. For at least 500 years, American Indian as well as European cultural groups used fire to manage the land for benefits and survival. A clear progression of anthropogenic fire regime stages occurred through time, repeated in regions around the globe.



Fire occurrences in Missouri from 1986 to 2003 based on rural fire department records and the National Fire Occurrence Database. The Ozark region generally covers the bottom half of the State, outlined by the dense pattern of human fires.

Fire suppression since the early 20th century is an example of the potential for humans to alter fire regimes at a continental scale.

Although the 20th century was primarily a period of fire suppression, in recent decades, humans rekindled fire management through prescribed burning. In Missouri and other parts of the Ozarks, 100,000 to 300,000 acres (40,000–120,000 ha) of forests are burned annually to manage the land for fire-dependent communities of plants and animals. The use of prescribed fire is an extension of centuries of anthropogenic fire regimes.

In the 21st century, the focus of management has been on ecological restoration for ecosystem health, economic benefits, biodiversity, and wildlife habitat. Recent land management has increasingly become for multiple uses compared to past management, which focused on single natural resource values (such as timber or game species).

LITERATURE CITED

Batek, M.J.; Rebertus, A.J.; Schroeder, W.A. [and others]. 1999. Reconstruction of early nineteenth-century vegetation and fire regimes in the Missouri Ozarks. Journal of Biogeography. 26: 397–412.

Dey, D.C.; Hartman, G. 2005. Returning fire to Ozark Highland forest ecosystems: effects on advance regeneration. Forest Ecology and Management. 217: 37–53.

Guyette, R.P.; Muzika, R.M.; Dey, D.C. 2002. Dynamics of an anthropogenic fire regime. Ecosystems. 5: 472–486.

Hanberry, B.B.; Jones-Farrand, D.T.; Kabrick, J.M. 2014. Historical open forest ecosystems in the Missouri Ozarks: reconstruction and restoration targets. Ecological Restoration. 32: 407–416.

Knapp, B.O.; Stephan, K.; Hubbart, J.A. 2015. Structure and composition of an oak-hickory forest after over 60 years of repeated prescribed burning in Missouri, U.S.A. Forest Ecology and Management. 344: 95–109.

Nanavati, W.P.; Grimm, E.C. 2019. Humans, fire, and ecology in the southern Missouri Ozarks, USA. The Holocene. 30(1): 125–135.

Parisien, M.-A.; Moritz, M.A. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecological Monographs 79: 127–154.

Roos, C.I.; Bowman, D.M.J.S.; Balch, J.K. [and others]. 2014. Pyrogeography, historical ecology, and the human dimensions of fire regimes. Journal of Biogeography. 41: 833–836.

Senos, R.; Lake, F.K.; Turner, N.; Martinez, D. 2006. Traditional ecological knowledge and restoration practice. In: Apostol, D.; Sinclair, M., eds. Restoring the Pacific Northwest: the art and science of ecological restoration in Cascadia. Washington, DC: Island Press: 393–426.

Stambaugh, M.C.; Guyette, R.P. 2008. Predicting spatio-temporal variability in fire return intervals using a topographic roughness index. Forest Ecology and Management. 254: 463–473.

Taylor, A.H.; Trouet, V.; Skinner, C.N.; Stephens, S. 2016. Socioecological transitions trigger fire regime shifts and modulate fire–climate interactions in the Sierra Nevada, USA, 1600–2015 CE. Proceedings of the National Academy of Sciences USA. 113: 13684–13689.

Thompson, F.R., III; Hanberry, B; Shifley, S.R.; Davidson, B.K. 2018. Restoration of pine-oak woodlands in Missouri. The Wildlife Professional. July/August: 56–60.

Yang, J.; He, H.S.; Shifley, S.R. 2008. Spatial controls of occurrence and spread of wildfires in the Missouri Ozark Highlands. Ecological Applications. 18: 1212–1225.

Coproducing Science on Prescribed Fire, Thinning, and Vegetation Dynamics on a National Forest in Alabama

Callie Schweitzer and Daniel Dey

Southeastern forests are no strangers to fire. Historically, frequent fire was prevalent across the landscape (Guyette and others 2012; Lafon and others 2017). Today, however, wildfire affects southeastern upland hardwood forests only to a limited extent due to effective fire suppression. (An exception of note was in 2016, when the Great Smoky Mountains National Park experienced a 17,000-acre wildfire near Gatlinburg, TN, killing 14 people and causing $500 million in damage.) Most fires are quickly suppressed; human-ignited wildfires are normally small in area, driven by climate, terrain, and vegetation.

Callie Schweitzer is a research forester for the Forest Service, Southern Research Station, Huntsville, AL; and Daniel Dey is a research forester and project leader for the Forest Service, Northern Research Station, Columbia, MO.

This loss of fire from the southern region is a relatively recent phenomenon, beginning in about the 1950s. It has resulted in forest changes that are not always considered desirable due to loss of native biodiversity, decline in quality of wildlife habitat, and escalating problems in regenerating oak and pine species.

FIRE USE IN SOUTHEASTERN HARDWOODS

It is an understatement to declare that the type of fire, fire behavior, and response of vegetation after fire in southeastern upland hardwood forests differ from fire and vegetation dynamics in western mixed-conifer and southeastern pine forests. Upland hardwood forest managers throughout the Southeastern United States, including those on the

William B. Bankhead National Forest (BNF) in north-central Alabama, are increasingly interested in the use of fire for a variety of management goals. In terms of planning, prescription, and implementation, however, they are challenged on how to use fire as a forest management tool to obtain desired future forest conditions. Strategies, approaches, methods, and tools in fire management from other regions and forest types are not necessarily directly applicable to upland southern hardwood forests. The role of prescribed fire in upland hardwood forests is understudied relative to other regions. Prescribed fire in upland hardwood forests is being used and examined for its ability to achieve three main objectives: fuel reduction, ecosystem restoration, and sustaining oak forests.

Prescribed fire in hardwood systems is often used in some "restoration" capacity because of wildfire's demise in the Nation's forest and grassland systems due to the success of the national Smokey Bear campaign in preventing forest fires and, by extension, in validating fire exclusion. The suppression of wildland fire across the Nation resulted in the loss of a fundamental forest process, a type of disturbance that needs to be restored to counter the loss of native biodiversity, the degradation of wildlife habitat, the failure of desired tree species to regenerate, the decline in forest and landscape resilience, and the unique role of fire in catalyzing the disruption of forest processes. Understanding the feedback system of fire, whereby vegetation influences flammability and fire effects and fire effects influence future vegetation, is paramount in using fire in a restoration capacity (Mitchell and others 2009; Tiribelli and others 2018).

Managers are using prescribed fire in upland hardwood or mixed hardwood/pine systems to move the stands towards some specific species composition and structure. A common goal is to create conditions conducive to recruiting oak (*Quercus* spp.) into more competitive understory positions, with heightened probabilities to dominate in future stands (Arthur and others 2015; Brose and others 2013; Hutchinson and others 2012; McEwan and others 2011; Schweitzer and others 2016). Currently, the predominate use of prescribed fires in the Southeastern United States is for site preparation and for postplanting competition control of oaks and other hardwoods in the management of loblolly (*Pinus taeda*), shortleaf (*P. echinata*), and longleaf pine (*P. palustris*) forests (Hiers and others 2014). Fire also contributes to the restoration of native grasses and forbs in these systems as well as in oak woodlands.

The oak-fire hypothesis proposes that prescribed fire in upland hardwoods can be used to promote species such as oaks over other hardwood species (Arthur and others 2012). However, questions abound regarding this hypothesis and what it means for practical on-the-ground management incorporating prescribed fire, especially given that the genus *Quercus* contains species with disparate responses to fire regimes. The partnership of research and management is foundational to identifying research problems in forestry and to developing practical science-based solutions to problems of high priority to forest managers.

Many managers in the Southeast use prescribed fire in either pine or hardwood systems as a part of integrated management plans. In this article, we discuss a project involving researchers and managers in examining the use of fire as a management tool on the BNF, a good example of coproduced science. We also provide some summary observations from this large-scale, long-term study, after years of research and management related to fire and fuels on the BNF, about restoring fire as a process and changing the reproduction cohort.

Restoring the historic disturbance regime, which included fire, is paramount to successful restoration of healthy and resilient hardwood forests.

COPRODUCTION OF SCIENCE

Administrative constraints, social influences on management decisions, and imperfect transfer of knowledge from researchers to forest managers limit the adoption of prescribed fire in southeastern upland hardwood forests. The authors were fortunate to partner with the BNF, located in north-central Alabama, at the nexus of a newly approved forest plan and the need for study of active management, including prescribed fire (Schweitzer and others 2008). While developing the forest plan, scientists and managers exchanged ideas; engaged in discussions; held field exploration events; and copresented to the public the ideas, current state of knowledge, and potential researchable questions in the proposed management program.

Researchers worked with the BNF staff to design a large-scale, long-term study aligned with the treatments approved through the Forest Health and Restoration Project (USDA Forest Service 2003, 2004). The northern portion of the BNF was designated for upland hardwood, hardwood/pine, or oak woodlands restoration. It covers approximately 110,000 acres (44,000 ha), of which 1,898 acres (759 ha) were included in our study. In essence, we used the Forest Health and Restoration Project's parameters of thinning (with a residual basal area ranging from 75 to 50 square feet per acre) and prescribed fire (with a return interval ranging from 3 to 9 years) to plan and implement a study with a randomized complete block design with a 3-by-3 factorial treatment arrangement and four replications of each treatment (see Schweitzer and others (2016) for study details). We are using these tools to move mixed pine/hardwood forests towards forests that are more hardwood dominated.

Stands were delineated by BNF staff, and reconnaissance visits with staff and researchers allowed selection of stands that met pretreatment criteria for study in that stands had similar disturbance histories and species compositions. A significant amount of coordination and communication among managers and researchers allowed not only the successful implementation of this study but also continued research over 16 years.

Each year, the BNF prescribe-burns between 18,000 and 22,000 acres (7,200–8,800 ha) of its 157,000 acres (62,800 ha) that are outside wilderness areas by burning nearly every day that meets exacting prescription parameters, from November through May. Maintaining any specific burn block on an exact schedule is exceptionally difficult.* Much commendation is to be given to Kerry Clark, the fire management officer on the BNF, who has been instrumental in implementing a total of 86 prescribed burns on schedule since 2006. While management and research is done at the stand level, prescribed fire is done at the landscape scale, and burn sizes ranged from 150 to 3,000 acres (60–1,200 ha). The "research burns" were embedded within a larger burn plan on the BNF; accordingly, although we reported results at a stand level, we must keep in mind the broader impacts occurring at the landscape scale.

Our study on the BNF is a true Forest Service partnership between the National Forest System and Research and Development. The BNF held all responsibility for treatment implementation, and researchers held all responsibility for completing the research. For example, we installed fire temperature monitoring equipment prior to each burn, which required flexibility and responsiveness to complete installation in the morning before each fire. Understanding by all parties allowed for acceptance of no burn situations after equipment installation and altering of initial ignition sites to allow for installation completion.

Typical dormant season fire on the Bankhead National Forest in Alabama. Photo: Callie Schweitzer, USDA Forest Service.

PRESCRIBED FIRE AND FUELS IN HARDWOODS

Southeastern pine forests have long been managed using prescribed fire. In these systems, intensive management in silviculture prescriptions includes, for example, a stand that is removed in a single harvest, which is followed by site preparation done mechanically with drum rollers and choppers, chemically with herbicides, or through prescribed fire. At times, more than one of these practices is used. Once the site is clear, pine seedlings (*Pinus taeda, P. echinata,* or *P. palustris*) are planted at given spaces; the pine quickly obtains some height growth, and prescribed fire is used to reduce any competition, which consists of volunteer herbaceous vegetation and hardwoods.

> **We are using thinning and burning tools to move mixed pine/hardwood forests towards forests that are more hardwood dominated.**

Because the pines have amplified growth compared to the volunteer hardwood stems in these stands, the larger stemmed pines are relatively unaffected by the dormant-season fires that top-kill small woody stems and reduce any accumulated surface fuels. Pines are more fire resistant than hardwoods due to early thick bark production, and shortleaf and longleaf pine are especially fire adapted. Most understory hardwood stems will sprout following a single fire, and additional fires will be needed to control hardwood competition. Maximum fire temperatures are higher under pines than under oaks, and those higher temperatures differentially contribute to oak attrition (Williamson and Black 1981). It takes multiple fires to remove the hardwoods, until eventually the pines have a sufficient early height growth advantage over the hardwood sprouts and other competing stems that fire is no longer needed. Depending on site conditions and landowner objectives, additional fires may be used as a tending treatment to clear out the underbrush during midrotation.

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* Scott, A. 2020. Personal communication, 28 January. District ranger, William B. Bankhead National Forest, 1070 AL 33, Double Springs, AL 35553; *Andy.scott@usda.gov*; 205-489-5111.

Although the intensive silviculture used to manage pine plantations has been well established by researchers and managers over the years and significant advances have been made in longleaf pine management, the ecology and role of fire in pine plantations is not transferable to hardwood systems. Prescribed fire in southeastern hardwood forests is nascent in its use by managers; moreover, the potential for use throughout the southeastern hardwood region is substantial, and our need for research is great.

Most prescribed fires are executed during the dormant season of January, February, and March, based on experience, resource allocation commitments, and burning priorities in different forest types as well as on meeting many burn parameter prescriptions to manage fire behavior, fire effects, and smoke dispersion. Collectively, managers and researchers desire an improved understanding of the ability of treatments to reduce fuel hazards, provide ecological benefits, and validate fire behavior and effects models.

Researchers lack site-specific data related to fuel loading in upland hardwood or hardwood/pine forests in the Southeast, although load inputs and consumption algorithms are paramount to the accuracy of many fire effects models. Because we were interested in stand-level fuel dynamics and the surface fuel components most closely related to the vegetation response, we quantified these surface fuels by collecting fuel samples immediately before and immediately after prescribed fire in replicated treatment stands on the BNF. Five burns at 3-year return intervals have been conducted; for most treatments, we collected surface fuels and duff. For control stands (no thinning and no burning), we collected fuels only at the same time as preburn data collection. Stands were thinned once, either to a residual basal area of 75 square feet per acre (light thin) or 50 square feet per acre (heavy thin). Surface fuel samples were processed in the laboratory, sorted by component, and dried to get load weight. Components included 10-hour fuels, 1-hour fuels, duff, leaves/needles, fruit, and bark.

Thinning initially increased the loading of fine fuels, duff, and bark (fig. 1), but that increase was not evident 3 years after the first prescribed fire. Most components decreased slightly after each fire, and the overall trend of forest floor fuels was decline, including in the control stands. Fruit loading during this time was the most variable (fig. 1), with hardwood masting and fire-induced cone drop from pines contributing much to this. Unfortunately, we did not sort the fruits by species, so these are only inferences based on field observations.

Fire and thinning on the BNF were done as intermediate stand disturbances. The distribution, type, and amount of fuels we examined were consistent, over time,

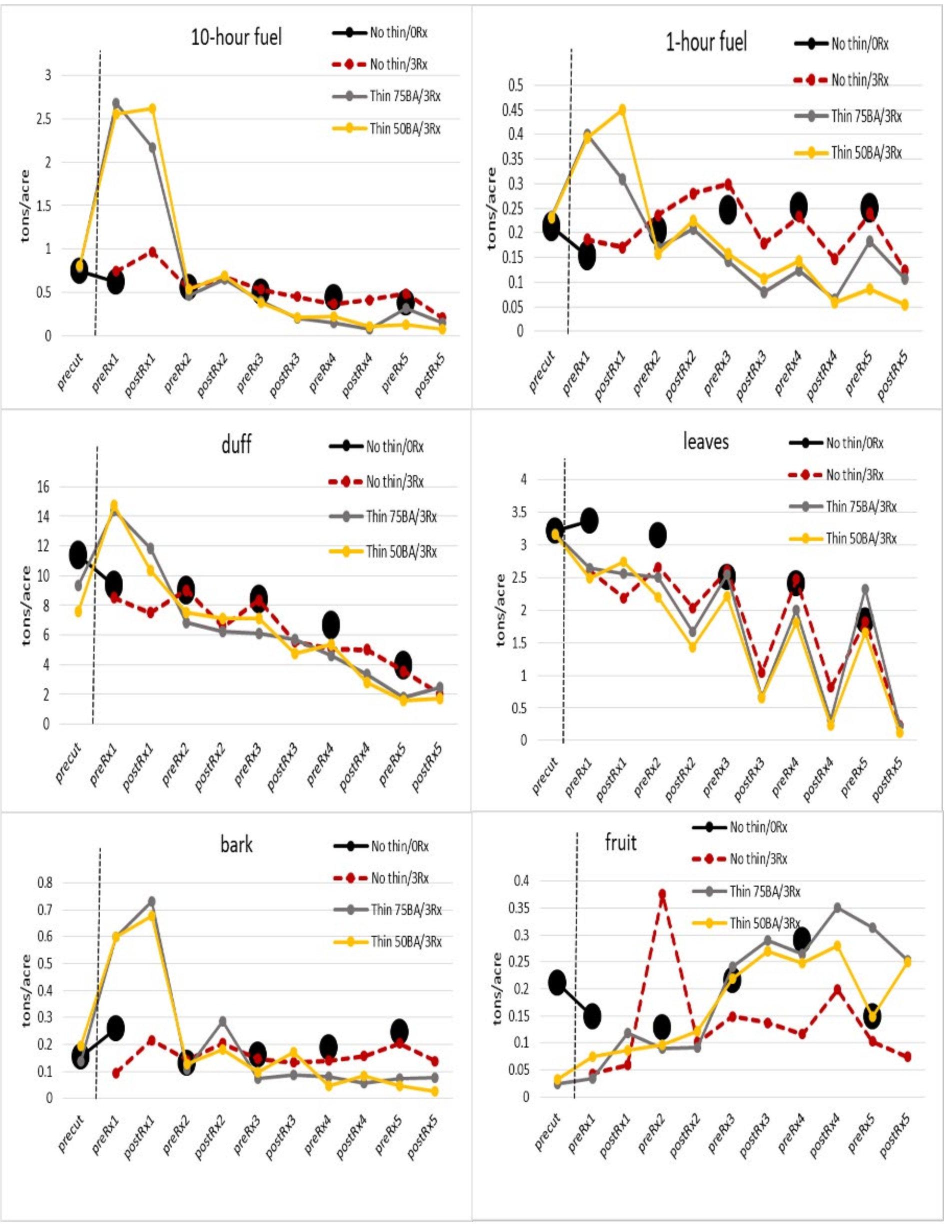

Figure 1—*Fuel loading from oven-dried field samples collected prior to and immediately after prescribed burns on the Bankhead National Forest in Alabama. All burns were conducted in the dormant season and were on a 3-year return interval. Treatments were: no thin/0Rx = control (no thin and no burns); no thin/3Rx = no thin and three burns; thin 75 BA/3Rx = thin to a residual basal area of 75 square feet per acre and three burns; thin 50 BA/3Rx= thin to a residual basal area of 50 square feet per acre and three burns. The dashed line indicates the time of the thinning. The control data, represented by a point, were collected only prior to scheduled burns on the other treatments, and point size is for demonstration purposes only. The timelag between pre- and postdata collection for a given fire is 1 to 3 months; the time lag between fires is 3 years.*

with those of natural decomposition processes, as demonstrated by the control (Graham and McCarthy 2006). Although the data were collected neither to quantify all fuels nor to model fire behavior, we have an opportunity to make some general inferences.

Estimates of fuel loading and consumption lack validation in upland hardwoods and mixed pine/hardwood systems, and there are no published data on fuel loads and consumption for the BNF. If models are being used to make management decisions, such as burning acreage and timing allowable given compliance with air quality standards, then we need parameter validation with local fuel loading and cover type.

For southeastern hardwoods, the testing of inputs is limited. Prichard and others (2014) found that the First Order Fire Effects Model (FOFEM) predictions for woody fuel, litter, and duff consumption should be improved for hardwood forests in Kentucky and Virginia. Reid and others (2012) found that FOFEM default litter fuel loads in oldfield pine communities were less than observed loads and that duff loads were greater than observed. In mixed oak/pine stands in Arkansas, Daniels and others (2016) used default preburn fuel loads and found FOFEM litter and duff estimates to be greater than field estimates.

Our study on the BNF is a true Forest Service partnership between the National Forest System and Research and Development.

In general, our measured consumption of 33 percent for litter was low compared to other reported values for mixed hardwoods, although ranges are reported from 50 to 93 percent across sites (Clinton and others 1998; Prichard and others 2014; Reid and others 2012; Scholl and Waldrop 1999; Sullivan and others 2003). We did not consider impacts on larger fuels, but we plan to correlate fuel loading by components to estimate values obtained through field transects (Brown 1974), a more commonly applied technique for estimating fuels than fine fuel collection.

RESTORING THE PROCESS OF FIRE IN HARDWOODS

Managing hardwood systems is nothing like managing southern pines. For one, our southeastern hardwood stands may have 40 species in dominant or codominant positions, with 5 to 20 of commercial or wildlife value. The lack of fire and other disturbances in hardwoods has resulted in stand compositional and structural changes, often referred to as mesophication (Nowacki and Adams 2008). In essence, the lack of disturbance has altered the understory environment; without disturbance and the resultant increase in light penetration through the canopy, the understory is no longer subjected to periodic xeric conditions, which contributes to a change in the regeneration cohort from oak dominance to dominance by red maple (*Acer rubrum*) or other less xeric and less fire-tolerant species. Restoring the historic disturbance regime, which included fire, is paramount to successful restoration of healthy and resilient hardwood forests. Restoring the process of fire will require managers to develop a prescribed fire regime in which the process outcomes meet the goals of creating the environment needed to move our stands towards desired future composition. After 86 prescribed fires, the BNF has successfully restored fire to these systems.

Many managers in the Southeast use prescribed fire in either pine or hardwood systems as a part of integrated management plans.

Prescribed burning was conducted during the dormant season (January through March) using backing fires and strip head fires to ensure that only surface fire occurred. Immediately prior to each fire, we installed six to eight HOBO data recorders (HOBO U12 Series Dataloggers from Onset Computer Corporation in Cape Cod, MA) connected to a temperature probe (an HOBO TCP6-K12 Probe Thermocouple Sensor from the same corporation) at each vegetation sampling plot (30 to 48 probes per stand). Installation was based on the design of Iverson and others (2004). Ignition type included hand strip firing at approximately 26-foot (8-m) intervals and aerial ignition for six fires; all others were ignited by hand strip firing along ridgetops, allowing the fire to burn downslope. All study burns were included as part of a larger target burn area on the BNF, and burn areas ranged from 150 to 3,000 acres (60–1,200 ha). Absolute maximum fire temperatures ranged from 2 °F (on January 27, 2007) to 575.4 °F (on March 16, 2013). On average, the maximum temperature was 203.9 °F (with a standard deviation of 145.1 °F) for the first burn, 253.8 °F (with a standard deviation of 130.3 °F) for the second burn, and 407.1 °F (with a standard deviation of 165.4 °F) for the third burn.

CHANGING THE REPRODUCTION COHORT

Almost all hardwoods will sprout if their aboveground growth is removed, and sprouting in seedlings promotes their survival under a variety of stressful conditions. Thus, most hardwood seedlings, when subjected to a fire that removes their aboveground portion, will sprout. Both time and temperature influence this response; in general, the thermal death point for mesophytic plants lies between 122 °F and 131 °F (Hare 1961). The premise used to support prescribed fire is that juvenile oaks are more tolerant to fire due to their physiological propensities: they store carbohydrates belowground as a priority over aboveground growth, and the area around the root collar has an abundance of dormant buds that are often located in the soil, where they are better insulated from fires (Tredici 2001). Single fires do not often turn the competitive tables in oaks' favor, but frequent fires eventually increase oaks' ability to dominate over other reproduction.

Fire behavior greatly influences any resulting sprouting response: hotter, slower moving fires with longer residence time have a greater effect in killing juvenile hardwoods. Prescribed fires in hardwood systems are mostly during the dormant season; they have slow spread rates and somewhat cooler temperatures. However, the minimal thermal death temperature was met on all prescribed fires under study on the BNF. Some involved with restoration in these systems have suggested burning during different seasons to alter fire behavior (to have hotter fires, for example); however, prescription parameters and resource limitations, as well as a lack of sufficient scientific studies detailing vegetation response in hardwood systems, make the possibility of implementing their recommendations tenuous.

The Nation's ability to sustain southeastern oak systems faces enormous challenges (Clark and Schweitzer 2019). Oak reproduction is advance-growth dependent, with greater densities and larger seedlings resulting in the highest probabilities of oak recruiting into larger size classes. Oak reproduction comes from new germinates (acorns) and sprouts from both seedlings and larger trees. Because forest overstories remain dominated by oak, acorn production and germination are not a challenge. The challenge is creating the conditions that encourage small advance-reproduction stems to grow into larger size classes without stimulating competition from the surrounding woody vegetation. Can managers use fire to get oaks through this bottleneck by changing understory conditions? Using fire to manipulate the understory in hardwood systems, with the goal of enhancing oak recruitment into larger size classes, has been reported with disparate results (Arthur and others 2015; Brose and others 2013; Hutchinson and others 2012; McEwan and others 2011).

We have reported on the initial results of reproduction and stand dynamics on the BNF (Schweitzer and others 2008, Schweitzer and Wang 2013, Schweitzer and others 2016; Schweitzer and others 2019). As we continue with these studies, we have noticed an interesting response with regard to sprouting and competition between oak and red maple, the major competitor to oak on the BNF. We examined stands that were thinned or not and had three dormant-season fires at a 3-year return interval and a control with no thinning and no fire. After three prescribed fires, midstory stem density was reduced and overstory mortality was not affected. The reproduction was dominated by sprouts (see Schweitzer and others 2016). The number of clumps, defined as a seedling sprout assemblage with two or more stems, increased over time in all stands, but this increase was three to four times greater in stands that had three fires compared to the controls (fig. 2). There were more seedling sprouts in all treatments, with red maple densities greater than oak densities in all prescribed fire treatments (fig. 2); moreover, the red maple sprouts shielded from fire were in the largest size class for red maple sprouts under the thinning-and-three-fires prescription (fig. 2).

As we continue to burn these stands, we are observing that red maple seedling sprouts are dominating the regeneration cohort. Moreover, many of the red maple clumps have 10 to 15 sprouts, with subsequent fires affecting only the outermost sprouts, which serve as sentinels, protecting the innermost sprouts. The reproduction "fire trap" for red maple may be defeated by this unique sprouting defense, while smaller and less sprout-dense oak continue to be completely top-killed. Red maple is obtaining a competitive advantage over oak in that the unburned protected sprouts are gaining more height growth over the oak sprouts.

As part of the study, we will continue to burn these stands; however, if the management goal is to regenerate oak on these sites, we would suggest removing fire and treating the clumps of red maple sprouts with herbicide. The open midstory

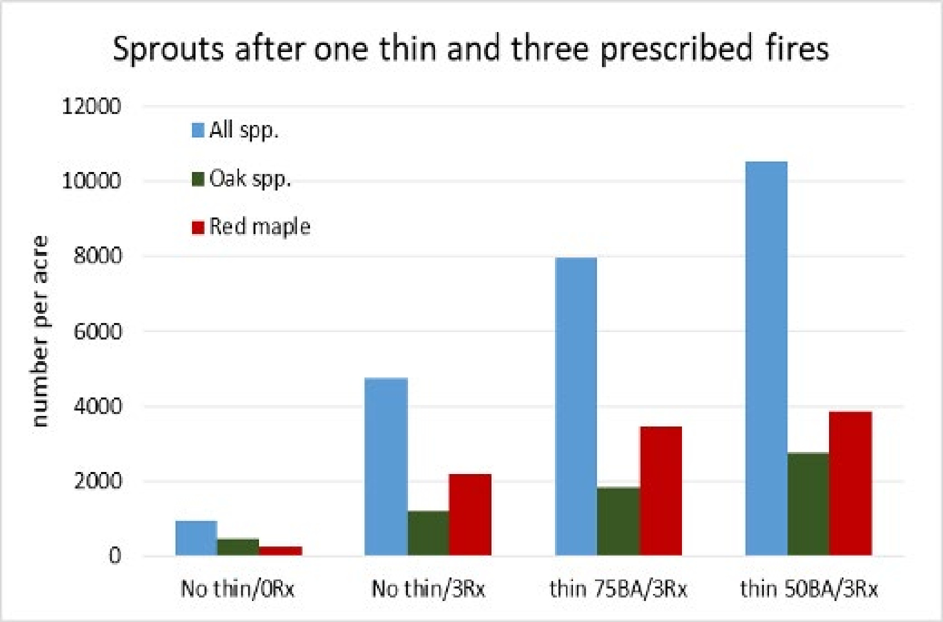

Figure 2—*Reproduction vegetation structures for woody species after one thinning and three prescribed burns on the Bankhead National Forest in Alabama. Reproduction tallied was all stems from 0 to 4.5 feet (0–1.4 m) tall and up to 1.5 inches (3.8 cm) in diameter at breast height. Clumps were enumerated as a reproductive structure with two or more stems, and sprouts were counted as those stems. All burns were conducted in the dormant season and were on a 3-year return interval. Treatments were: no thin/0Rx = control (no thin and no burns); no thin/3Rx = no thin and three burns; thin 75 BA/3Rx = thin to a residual basal area of 75 square feet per acre and three burns; and thin 50 BA/3Rx = thin to a residual basal area of 50 square feet per acre and three burns.*

conditions should enhance recruitment of oak into larger size classes, at which time the overstory can be removed. Alternative fire regimes need to be tested, including hotter fires, more frequent fires, and growing-season fires. Benefit and cost analysis also needs to be made for restoration scenarios using prescribed fire in combination with other management practices and schedules that meet specific management challenges, such as competition from red maple sprouts.

Stand development processes, especially the recruitment stage for oak, must be incorporated into silvicultural prescriptions. Interactions between fire and the resulting species composition and structure are governing intermediate stand development on the BNF, such as the prolific sprouting of red maple. Legacies of past fire suppression and the status of contemporary forests may have increased the density of fire-intolerant hardwood structures, such as fecund sprouting stocks of red maple.

Some have postulated that the leaves of mesic species such as red maple are not as flammable as those of oaks, which also drives the fuel ecology (Nowacki and Abrams 2008). The density of red maple in the understory has increased, potentially altering the concentration of red maple leaf litter. At the same time, our fire temperatures have increased with subsequent burns. This disparity in the vegetation/fuel feedback system is intriguing. Low to moderate fuel loads in these systems will limit the potential for catastrophic wildfires, but restoring fire to these systems is fundamental to restoration goals.

While we did not discuss the effects that fire may be having on residual tree quality, mortality, and timber value (Schweitzer and others 2019; Dey and others 2020, in this issue), the complex feedback between fire, fuels, and vegetation and the long-term rotation length in these systems must be considered (Dey and Schweitzer 2018). Without fire, these forests are moving away from a predominately oak composition; but how to favor oak is not exactly known in terms of the prescriptions that are most effective and efficient, both ecologically and economically. Fire does have a role to play in the restoration and sustainability of southeastern oak forests.

Red maple clumps and sprouts after three prescribed fires on the Bankhead National Forest in Alabama. Photo: Callie Schweitzer, USDA Forest Service.

Red maple sprouts with dead "sentinels" (the outermost sprouts, killed by prescribed fire) and live stems on the Bankhead National Forest in Alabama. Photo: Callie Schweitzer, USDA Forest Service.

COPRODUCING NEEDED SCIENCE

This study exemplifies the ability of managers and researchers to design and implement long-term, stand-level studies to answer questions germane to forest types and restoration goals in forest management plans. Under tight operational tempos, we succeeded in carrying out treatments and collecting data. Meeting specific management goals while relying on prescribed fire can be tenuous, but it can be done.

Researchers and managers have much to learn about fire behavior in southeastern hardwood systems as well as about assessing response under conditions of variable habitat and structural complexity. Managers should consider alternatives to prescribed fire because natural and anthropomorphic restrictions seem to be limiting the number of days on which they can burn. They also must consider the consequences of not reaching desired

Along the way, we demonstrated that coproducing science isn't really that daunting.

outcomes with the fire tool.

We used the template of this study to add to existing research, such as research on the response of the herbaceous community (Barefoot and others 2019; Willison and others 2018); on herpetofauna (Sutton and others 2017); and on birds (Wick and others 2013). These other studies responded to a need by the BNF to establish desired future conditions for multiple uses, goods, and services. Studies at this scale, both spatially and temporally, are essential in producing the science most needed by managers.

At a broad scale, land managers have increased the heterogeneity of forest structure and fuels across thousands of acres. Repeated fires are changing the composition of midstory and understory species. Although it is a mantra among researchers, we do need more data to move our understanding forward. Few replicated studies exist at this scale that are examining stand-level responses to repeated fires.

The response of the red maple clumps, with their protective sentinels, will be tested on future fires. At some point, fire will have to be removed from these stands to allow the reproduction cohort to develop. At that time, our understanding of the fuels and the feedback regulating vegetation dynamics will be more complete. To date, researchers and managers together have accomplished the objectives put forth in the forest plan: we have introduced disturbances that are moving these stands towards upland hardwood dominance; we have influenced surface fuels and reduced hazardous fuel conditions; and we have restored the process of fire to these systems. And along the way, we demonstrated that coproducing science isn't really that daunting.

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LITERATURE CITED

Arthur, M.A.; Alexander, H.D.; Dey, D.C. [and others]. 2012. Refining the oak-fire hypothesis for management of oak-dominated forests of the Eastern United States. Journal of Forestry. 110: 257–266.

Arthur, M.A.; Blankenship, B.A.; Schorgendorfer, A. 2015. Changes in stand structure and tree vigor with repeated prescribed fire in an Appalachian hardwood forest. Forest Ecology and Management. 340: 46–61.

Barefoot, C.; Willson, K.; Hart, J. [and others]. 2019. Effects of thinning and prescribed fire frequency on ground flora in mixed *Pinus*-hardwood stands. Forest Ecology and Management. 432: 729–740.

Brose, P.H.; Dey, D.C.; Phillips, R.J.; Waldrop, T.A. 2013. A meta-analysis of the fire-oak hypothesis: Does prescribed burning promote oak reproduction in eastern North America? Forest Science. 59: 322–334.

Brown, J.K. 1974. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT–GTR–16. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Clark, S.; Schweitzer, C. 2019. Oak symposium: sustaining oak forests in the 21st century through science-based management. e-Gen. Tech. Rep. SRS–GTR–237. Asheville, NC: USDA Forest Service, Southern Research Station. 192 p.

Clinton, B.D.; Vose, J.M.; Swank, W.T. [and others]. 1998. Fuel consumption and fire characteristics during understory burning in a mixed white pine-hardwood stand in the Southern Appalachians. Res. Pap. SRS–RP–12. Asheville, NC: USDA Forest Service, Southern Research Station. 8 p.

Daniels, V.L.; Perry, R.W.; Koerth, N.E.; Guldin, J.M. 2016. Evaluation of FOFEM fuel loads and consumption estimates in pine-oak forests and woodlands of the Ouachita Mountains in Arkansas, USA. Forest Science. 62: 307–315.

Dey, D.C.; Schweitzer, C.J. 2018. A review of the dynamics of prescribed fire, tree mortality, and injury in managing oak natural communities to minimize economic loss in North America. Forests. 9: 461. DOI: 10.3390/f9080461.

Dey, D.C.; Stambaugh, M.; Schweitzer, C. 2020. Learning to live with fire: managing the impacts of prescribed burning on eastern hardwood value. Fire Management Today. 78(3): 51–59.

Graham, J.B.; McCarthy, B.C. 2006. Forest floor fuel dynamics in mixed-oak forests of south-eastern Ohio. International Journal of Wildland Fire. 15: 479–488.

Guyette, R.P.; Stambaugh, M.C.; Dey, D.C. [and others]. 2012. Predicting fire frequency with chemistry and climate. Ecosystems. 15(2): 322–335.

Hare, R.C. 1961. Heat effects on living plants. Occasional Pap. 183. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station. 32 p.

Hiers, J.K.; Walters, J.R.; Mitchell, R.J. [and others]. 2014. Ecological value of retaining pyrophytic oaks in longleaf pine ecosystems. Journal of Wildlife Management. 78: 1–11.

Hutchinson, T.F.; Yaussy, D.A.; Long, R.P. [and others]. 2012. Long-term (13-year) effects of repeated prescribed fires on stand structure and tree regeneration in mixed-oak forests. Forest Ecology and Management. 286: 87–100.

Iverson, L.R.; Yaussy, D.A.; J. Rebbeck, J. [and others]. 2004. A comparison of thermocouples and temperature paints to monitor spatial and temporal characteristics of landscape-scale prescribed fires. International Journal of Wildland Fire. 13: 311–322.

Lafon, G.W.; Naito, A.T.; Grissino-Mayer, H.D. [and others]. 2017. Fire history of the Appalachian region: a review and synthesis. Gen. Tech. Rep. SRS–GTR–219. Asheville, NC: USDA Forest Service, Southern

Fire does have a role to play in the restoration and sustainability of southeastern oak forests.

Research Station. 108 p.

McEwan, R.W.; Dyer, J.M.; Pederson, N. 2011. Multiple interacting ecosystem drivers: toward an encompassing hypothesis of oak forest dynamics across eastern North America. Ecography. 34: 244–256.

Mitchell, R.J.; Hiers, J.K.; O'Brien, J.; Starr, G. 2009. Ecological forestry in the Southeast: understanding the ecology of fuels. Journal of Forestry. 107: 391–397.

Nowacki, G.J.; Abrams, M.D. 2008. The demise of fire and the mesophication of forests in the Eastern United States. BioScience. 58: 123–138.

Prichard, S.J.; Karau, E.C.; Ottmar, R.D. [and others]. 2014. Evaluation of the CONSUME and FOFEM fuel consumption models in pine and mixed hardwood forests of the Eastern United States. Canadian Journal of Forest Research. 44: 784–795.

Reid, A.M.; Robertson, K.M.; Hmielowski, T.L. 2012. Predicting litter and live herb fuel consumption during prescribed fires in native and old-field upland pine communities of the Southeastern United States. Canadian Journal of Forest Research. 42: 1611–1622.

Scholl, E.R.; Waldrop, T.A. 1999. Photos for estimating fuel loadings before and after prescribed burning in the Upper Coastal Plain of the Southeast. Gen. Tech. Rep. SRS–GTR–26. Asheville, NC: USDA Forest Service, Southern Research Station. 29 p.

Schweitzer, C.J.; Wang, Y. 2013. Overstory tree status following thinning and burning treatments in mixed pine-hardwood stands on the William B. Bankhead National Forest, Alabama. In: Guldin, J.M., ed. Proceedings of the 15th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS–GTR–175. Asheville, NC: USDA Forest Service, Southern Research Station: 57–63.

Schweitzer, C.J.; Clark, S.L.; Gaines, P. [and others]. 2008. Integrating land and resource management plans and applied large-scale research on two national forests. In: Deal, R.L., tech. ed. Integrated restoration of forested ecosystems to achieve multiresource benefits. Gen. Tech. Rep. PNW–GTR–733. Portland, OR: USDA Forest Service, Pacific Northwest Experiment Station: 127–134.

Schweitzer, C.J.; Dey, D.C.; Wang, Y. 2016. Hardwood-pine mixedwoods stand dynamics following thinning and prescribed burning. Fire Ecology. 12: 85–104.

Schweitzer, C.J.; Dey, D.; Wang, Y. 2018. Overstory tree mortality and wounding after thinning and prescribed fire in mixed pine-hardwood stands. In: Kirschman, J.E.; Johnsen K., comps. Proceedings of the 19th Biennial Southern Silviculture Research Conference. e-Gen. Tech. Rep. SRS–GTR–234. Asheville, NC: USDA Forest Service, Southern Research Station: 337–346.

Schweitzer, C.J.; Dey, D.C.; Wang, Y. 2019. White oak *(Quercus alba)* response to thinning and prescribed fire in northcentral Alabama mixed pine–hardwood systems. Forest Science. 65: 758–766.

Sullivan, B.T.; Fettig, C.J.; Otrosina, W.J. [and others]. 2003. Association between severity of prescribed burns and subsequent activity of conifer-infesting beetles in stands of longleaf pine. Forest Ecology and Management. 185: 327–340.

Sutton, W.; Wang, Y.; McClure, C; Schweitzer, C. 2017. Spatial ecology and multi-scale habitat selection of the copperhead (*Agkistrodon contortrix*) in a managed forest landscape. Forest Ecology and Management. 391: 469–481.

Tiribelli, F.; Kitzberger, T.; Morales, J.M. 2018. Changes in vegetation structure and fuel characteristics along post-fire succession promote alternative stable states and positive fire-vegetation feedbacks. Journal of Vegetation Science. 29: 147–156.

Tredici, P.D. 2001. Sprouting in temperate trees: a morphological and ecological review. The Botanical Review. 67: 121–140.

USDA Forest Service. 2003. Final environmental impact statement, forest health and restoration project. Management Bulletin R8–MB 110B. Atlanta, GA: USDA Forest Service, Southern Region. 352 p.

USDA Forest Service. 2004. Revised land and resource management plan: National Forests in Alabama. Management Bulletin R8–MB 112A. Atlanta, GA: USDA Forest Service, Southern Region. 330 p.

Wick, J.; Wang, Y.; Schweitzer, C. 2013. Immediate effect of burning and logging treatments on the avian community at Bankhead National Forest of northern Alabama. In: Guldin, J.M., ed. Proceedings of the 15th Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS–GTR–175. Asheville, NC: USDA Forest Service, Southern Research Station: 33–37.

Williamson, G.B.; Black, E.M. 1981. High temperatures of forest fires under pines as a selective advantage over oaks. Nature. 293: 643–644.

Willson, K.; Barefoot, C.; Hart, J. [and others]. 2018. Temporal patterns of ground flora response to fire in thinned *Pinus-Quercus* stands. Canadian Journal of Forest Research. 48: 1–13.

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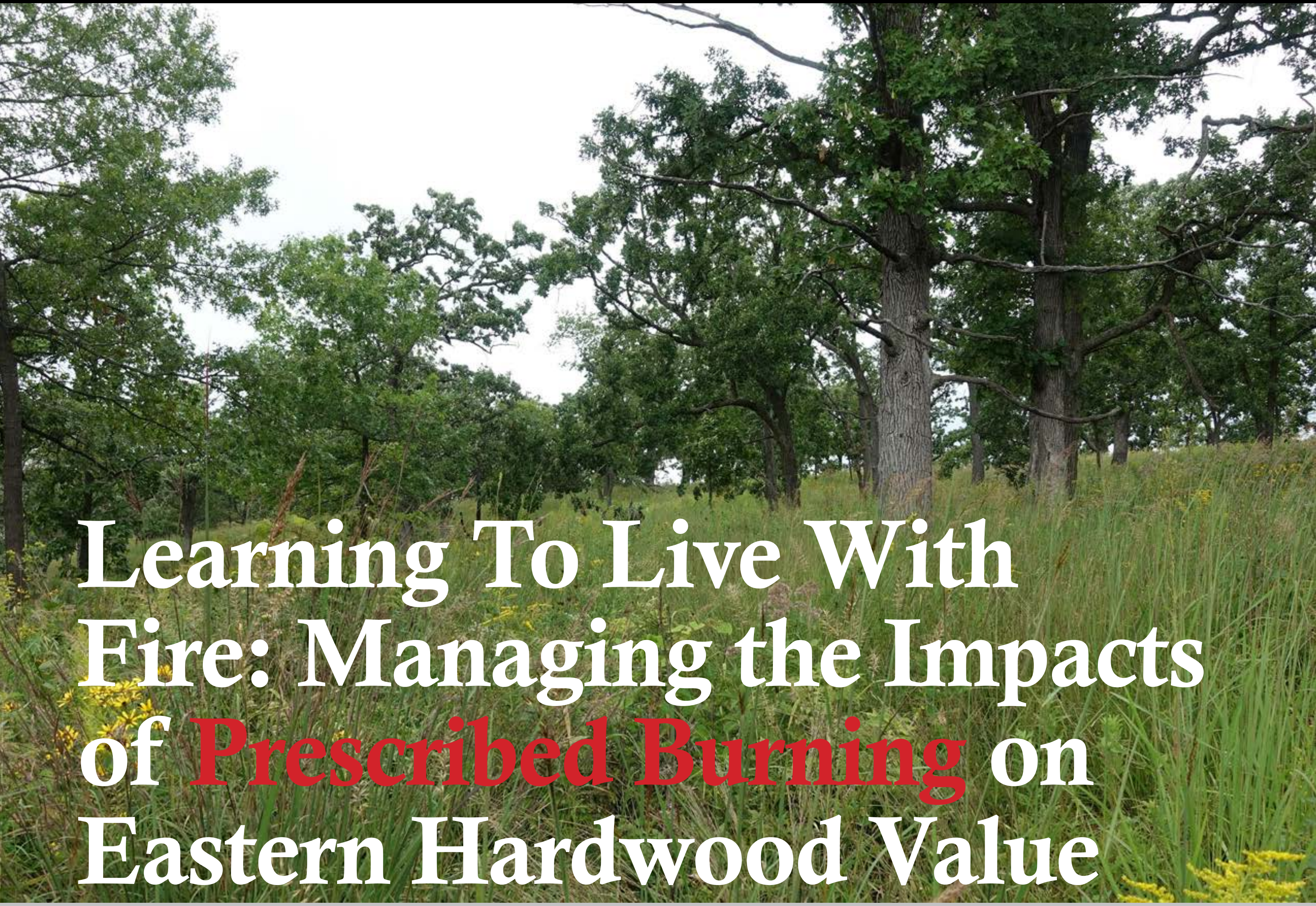


Learning To Live With Fire: Managing the Impacts of Prescribed Burning on Eastern Hardwood Value

Daniel C. Dey, Michael C. Stambaugh, and Callie J. Schweitzer

Oak savanna in southern Wisconsin. Photo: Dan Dey, USDA Forest Service, Northern Research Station.

Oak (*Quercus*) is a fire-adapted genus that has assumed dominance in forests, woodlands, and savannas over thousands of years during periods of frequent fire in North America (fig. 1). Fire has played an important and sustaining role in regeneration, competitive dynamics, rise to overstory dominance, and ecosystem structure and function in oak-dominated ecosystems.

Oak and pine *(Pinus)* were highly sought-after timber species during the initial logging boom of the late 19th and early 20th centuries, prized for their high quality and the diversity of forest products made from them during a period of frequent and mixed-severity fire regimes. It is somewhat ironic then, but understandable, that fire would come to be viewed as a negative, destructive force in American forestry, in part due to the catastrophic fires that burned over millions of acres and took thousands of lives.

Fires such as the Miramichi in Maine (1825), Peshtigo in Wisconsin (1871), and Hinckley in Minnesota (1894), along with the Big Blowup in the Northern Rockies (1910), all contributed to the national sentiment that fire must be controlled and eliminated from our forests and grasslands. The four Chiefs of the Forest Service who served after Gifford Pinchot from 1910 to 1939 all saw fireline action on the complex of fires that raged during the Big Blowup. They saw firsthand the devastation of timber and land wrought by wildfire. Consequently, early Forest Service policies and goals were to defeat fire and remove it from the landscape. By 1935, the formal policy was to suppress all fires by 10 a.m. on the day following their initial report.

An indirect influence on U.S. fire policy was the schooling that Gifford Pinchot and many other early leaders in American forestry received. Their formal training in forestry was in Germany and France, where intensive forest management for timber growth and yield left little room for fire in forestry. The ecological role of fire and the benefits of frequent light burning

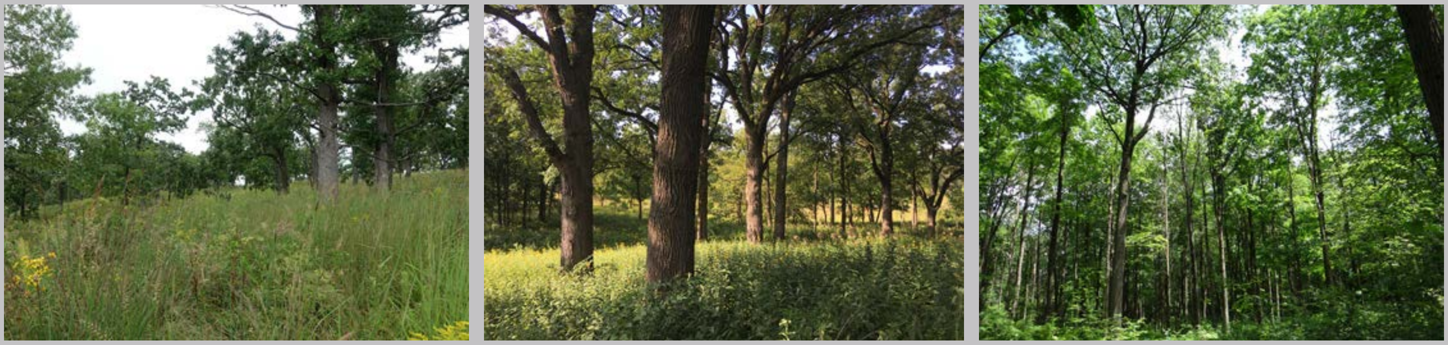


Figure 1—*Oak savannas (left, southern Wisconsin), woodlands (center, northern Illinois), and forests (Pennsylvania, right) were dominant oak ecosystems throughout the Eastern United States. Landscapes were diverse mosaics of these vegetation types, depending largely on the fire regime, topography, and human land use. Photos: Dan Dey, USDA Forest Service, Northern Research Station.*

were debated in the early 20th century, but the case for waging all-out war on wildland fire won out.

During the initial timber boom in the Eastern United States, entire regions were logged over within a short period of time in an era of exploitation from the mid-19th to early 20th centuries. Frequent to annual wildfires were ignited by settlers to promote browse and forage for open-woods grazing, to convert forests to agriculture, and for other reasons. These fires burned through logging slash, often under high-fire-danger weather conditions, severely scarring surviving trees.

Over the decades, substantial amounts of decay developed in the lower boles of the wounded trees, causing high amounts of volume, quality, and value loss due to decay and lumber grade defects. Estimates that half of the standing live timber was cull were common throughout the eastern hardwood region (Burns 1955; Gustafson 1944; Hepting 1937; Kaufert 1933). It is then understandable why foresters were taught about the destructiveness of fire in forests. Fire was relegated to accomplishing singular and very specific tasks, such as consuming logging slash and preparing sites for planting or natural regeneration. Under more sustainable forest management and fire suppression practices since the mid-20th century, merchantable volume, quality, and value increased in eastern hardwood forests by the early 21st century (Oswalt and others 2019).

Prescribed fires in eastern hardwood forests generally result in a low level of overstory mortality (less than 5 percent loss of basal area).

Barriers to expanding the use of prescribed fire limit the treatment of a vast portion of the Nation’s forests.

For the better part of the 20th century, fire was an enemy to be defeated, and our ability to do so increased as national and State forestry agencies were established with a primary mission of fire suppression. Our ability to suppress fires was greatly advanced by the men returning home from World War II and the ready availability of military heavy equipment and aircraft. At about the same time (in 1944), Smokey Bear began delivering his message against human-caused forest fires, a successful advertising campaign that helped to shape public opinion regarding wildland fire.

RETHINKING OUR RELATIONSHIP WITH FIRE

In the past 30 years, we have witnessed the increase in frequency, size, and severity of megafires (wildfires 100,000 acres (40,000 ha) or more in size), especially in the Western United States. Many of the underlying factors arise from decades of widespread fire suppression, which set the stage for megafires in an era of increasing drought frequency and severity, higher seasonal and annual temperatures, and prolonged fire seasons. Initial regional exploitative logging, followed by declining levels of active management, have resulted in homogeneous landscapes that are vulnerable to widespread mortality from insects and diseases as well as megafires.

Decades of fire exclusion across the country have resulted in landscapes characterized by unprecedentedly high levels of forest density and fuel loading and complex vertical tree canopy and fuel structure. These changes in fuel conditions have resulted in forests with low resistance and resilience to disturbances; fires of higher intensity, size, and severity; and increased chances of crown fires. In the aftermath of megafires, catastrophic floods and debris flows degrade waterways, riparian resources, and lowland communities. Megafires inhibit forest regeneration over large areas for prolonged periods or even cause vegetation type conversions from forests to grasslands or shrublands.

More recently, we have been seeing the ecological impacts of fire exclusion in the loss of native biodiversity, landscape diversity, prairies, savannas, and woodlands. We are also seeing the disruption of ecosystem processes such as regeneration. Such disruptions inhibit sustainability and promote the transition toward novel forest composition and structure, which in many ways are less desirable for human well-being.

In the 1990s, the idea of an appropriate management response to fire suppression began to replace the 10 A.M. Policy, and it was formally adopted in 2008. In 2014, the National Cohesive Wildland Fire Management Strategy was finalized, presenting a new vision for national fire policy (WFLC 2014): "To safely and effectively extinguish fire, when needed; use fire where allowable; manage our natural resources; and, as a Nation, live with wildland fire." From 1947 to 2001, Smokey Bear went from saying "Only you can prevent forest fires" to "Only you can prevent wildfires." Room has been made in forest and wildland fire management for prescribed fire and managed wildfires.

The need to restore fire in fire-dependent forests and grasslands is great over substantial portions of the United States.

PRESCRIBED FIRE IN THE UNITED STATES

By the end of the 20th century, the negative ecological consequences of all-out fire suppression were beginning to be recognized in terms of:

- The loss of key wildlife habitat, landscape diversity, and native biodiversity;
- Increasing forest regeneration problems in fire-dependent systems;
- Increasing fuel loading and hazardous fuel conditions as forests became denser and structurally complex,
- Woody encroachment in grassland and shrubland ecosystems; and
- Widespread forest health outbreaks, resulting in catastrophic tree mortality over millions of acres.

The need to restore fire in fire-dependent forests and grasslands was great over substantial portions of the United States. In addition, using prescribed fire or managed wildfire to reduce the occurrence of high-severity wildfires that threaten communities was an increasingly important strategy in managing landscapes and regions.

From 1998 to 2015, approximately 2.2 million acres (0.9 million ha) per year were prescribe-burned on average by Federal, State, and other forest (including range) landowners (Melvin 2018; NIFC 2020). Since 2016, the area of forests and rangelands burned under prescription has increased, rising to 8.8 million acres (3.5 million ha) in 2018 (Melvin 2018). Most (70–80 percent) of the prescribed fires occur in the Southeastern United States, and most of those are to manage southern pine forests, plantations, and woodlands (Kolden 2019; Melvin 2018; Schweitzer and Dey 2020, in this issue).

This level of prescribed burning is only half or less of what it should be to manage fuels and reduce the risk of high-severity fires on national forest lands and other lands across the Nation (Kolden 2019; North and others 2012, Vaillant and Reinhardt 2017). The need for prescribed fire is even greater when one considers the potential for it to restore ecosystem processes important to increasing the regeneration potential of desired tree species such as oaks and pines; providing for landscape diversity and resilience; and restoring long-lost native woodland, savanna, and grassland habitats important to native wildlife, plant species, and other biodiversity of conservation concern.

Leenhouts (1998) estimated that 86 to 212 million acres (34–85 million ha) burned per year in the conterminous United States before the industrial period (about 200 to 500 years ago) but that only 12 to 17 million acres (5–7 million ha) burn per year now. He estimated that 44 to 106 million acres (18–42 million ha) of fire-deficient forests and grasslands are in need of burning each year to restore ecosystem form and function.

RELUCTANCE TO USE PRESCRIBED FIRE

Many historically fire-dependent, frequent-fire ecosystems in the United States are now more dense with vegetation and have higher fuel loading than ever before. Combinations of forest thinning and repeated prescribed fire have been shown to be effective in ameliorating future wildfire behavior and severity; restoring historic open forest structure and fire regimes; increasing native floral diversity; improving habitat conditions for many wildlife species; returning critical ecosystem processes and function; and avoiding the environmental degradation that follows catastrophic, high-severity megafires (Fontaine and Kennedy 2012; Fulé and others 2012; Kalies and Yocom Kent 2016; McIver and others 2013; Schwilk and others 2009; Stephens and others 2012).

However, barriers to expanding the use of prescribed fire limit the treatment of a vast portion of the Nation's forests, even though they are fire deficient and hence of low resilience to future perturbations, contributing to catastrophic forest mortality and wildfires. Calkin and others (2015), Melvin (2018), and Schultz and others (2019) have identified barriers to the increased use of managed wildfires and prescribed fires, such as:

- Agency capacity to manage fires,
- Unfavorable weather,
- Smoke-related air quality concerns,
- Agency policies and rewards that act as disincentives to managers and negatively alter their perception of personal risk to do anything other than suppress fires, and
- A disconnect between fire and forest management.

A specific additional barrier to the use of prescribed fire in eastern hardwood forests is manager and landowner concern about negative fire effects on timber volume, quality, and value.

In the hardwood forest products industry, the quality of trees, logs, and lumber is paramount in importance in determining their value. For example, the 2018 (fourth-quarter) price differential for Kentucky white oak *(Quercus alba)* sawlogs by quality class per thousand board feet (MBF) was (University of Kentucky, n.d.):

Figure 2—*Prescribed fires are often conducted in the dormant season (September to April) in eastern hardwood ecosystems. They are typically low to moderate in intensity and severity. Backing and flanking fires (top) are commonly set to establish safe control lines. Then strip head fires or gridded spot fires (center and bottom) are lit to burn out the core of the unit. A wide array of ignition strategies and methods can be used to keep fires in prescription and meet management objectives. Controlling fire temperature and duration are key to minimizing damage to valuable timber and overstory trees. Photos: Dan Dey, USDA Forest Service, Northern Research Station.*

High quality	$1,238
Medium quality	$743
Low quality	$320

High-quality white oak stave logs used in the spirits barrel industry were valued at $1,363 per MBF.

Lumber prices in Indiana for 2018 reflect the value difference by quality (Settle and Gonso 2018). FAS (Firsts and Seconds) and Premium white oak lumber brought $1,675 per MBF, compared to $1,030 and $570 per MBF for no. 1C and no. 2A lumber, respectively.

Fire injuries to tree boles can lead to volume loss through wood decay and quality grade reductions caused by mineral stain, shakes, and checks, which have a very real impact on agency and landowner financial returns. No wonder that foresters and landowners are hesitant to set fire to their woods.

PRESCRIBED FIRE DAMAGE TO TREES: OVERSTORY MORTALITY

Prescribed fire is normally conducted in a way and under conditions that result in low to moderate fire behavior and severity (fig. 2). Although it is possible to kill large overstory trees with prescribed fire, using fire to manage the overstory is not normally an objective of the burn. Reductions in overstory density are often better achieved through commercial thinning or timber harvesting, which are more efficient and effective than fire in managing overstory density and spatial arrangement. In addition, revenues from commercial sales can be used to offset the other costs of restoration and management.

Fire is good for managing seedlings and saplings, shrubs, herbaceous plants, and surface fuels. Prescribed fires in eastern hardwood forests generally result in a low level of overstory mortality (less than 5 percent loss of basal area) (fig. 1) (Hutchinson and others 2005; Kinkead and others 2017; Regelbrugge and Smith 1994; Smith and Sutherland 2006). Oaks have a number of fire adaptations that aid in their persistence and dominance in frequent fire regimes (fig. 3), including:

- High ability to resprout as seedlings and saplings after fire kills the shoot;
- Rapid diameter growth and wound closure as sprouts arise from well-developed root systems;
- Ability to compartmentalize fire injury, especially in white oak species; and
- Development of thick bark in maturing trees.

PRESCRIBED FIRE DAMAGE TO TREES: RESISTANCE TO STEM INJURY

Prescribed fire is quite capable of wounding trees, even large overstory trees (fig. 3). Tree injury usually occurs at the base of the tree when fire kills cambial tissue. This may lead to an open wound that permits fungal and bacterial infections to enter the tree bole. With time, wood decay may advance, causing volume loss. The injury and infection also commonly cause mineral stain, checks, shakes, and other grade defects in the tree that reduce its forest product value.

Basal wounds that affect the lowest part (butt log) of the tree are significant because most of the tree's volume is in the butt log; the potential for having the highest grade and value forest products, such as stave and veneer logs, is therefore in the butt log. There is much at risk when a tree is injured at the base by fire or mechanical means. A more thorough review of prescribed fire effects on tree mortality, injury, and economic loss is presented by Dey and Schweitzer (2018) and Wiedenbeck and Smith (2019).

The amount of tree wounding by fire depends on several factors:

- Fire temperature and duration of heating;
- Tree characteristics such as species, tree diameter, bark thickness, and physiological activity; and
- Ambient environmental conditions, including air temperature.

Of course, higher fire temperatures of longer duration are increasingly capable of killing cambium tissue. Trees vary in their ability to resist cambial injury, based primarily on bark thickness. Bark is a good insulator of the cambium from the heat of fire, and bark thickness increases with increasing tree diameter. As bark increases in thickness, there is an exponential degree of protection of the cambium from high fire temperatures (Hare 1965; Pausas 2015; Vines 1968). Bark accumulates at different rates, with increasing diameter growth, depending on the species.

In general, upland species have thicker bark than bottomland species for similar-sized trees in eastern North America (Sutherland and Smith 2000). Bark thickness is greatest in white oak group species (*Quercus* section *Quercus*) followed by the red oak group species (*Quercus* section *Lobatae*). Resistance to scarring decreases in upland oaks, from post oak (*Q. stellata* Wangenh.) and bur oak (*Q. macrocarpa* Michx.), to white oak (*Q. alba* L.), to black oak (*Q. velutina* Lam.), to southern red oak (*Q. falcata* Michx.), to scarlet oak (*Q. coccinea* Muenchh.) (Hengst and Dawson 1994; Kinkead and others 2017; Scowcroft 1966; Stevenson and others 2008). Species with inherently thinner bark include American beech (*Fagus grandifolia* Ehrh.), flowering dogwood (*Cornus florida* L.), black cherry (Prunus serotina Ehrh.), maples (*Acer* spp.), and hickories (*Carya* spp.).

The rate of bark thickening during growth is important because faster growth rates allow trees to earlier reach critical thresholds of thickness that are associated with protection of the cambium and survival. Eastern cottonwood (*Populus deltoides* Bart. ex Marsh.) and yellow-poplar (*Liriodendron tulipifera* L.) are both thin-barked, fire-sensitive species when trees are small and young, but they have rapid rates of bark growth and are considered resistant to fire scarring as large, mature trees (Hengst and Dawson 1994; Wiedenbeck and Schuler 2014). In contrast, silver maple (*A. saccharinum* L.) has a slow rate of bark growth all its life and is vulnerable to fire injury even when it is a large tree. Species that have smooth bark texture, such as water oak, are more vulnerable to fire injury to the cambium than are deeply fissured, rough-textured species such as chestnut oak (*Q. montana* L.) and bur oak. The bark of southern yellow pines confers a high degree of resistance to fire scarring (Kinkead and others 2017; Stevenson and others 2008). Once a tree is scarred by a fire, it is more vulnerable to additional scarring in future fires because the bark is thin on the callus wood forming over the original scar.

Figure 3—*Post, chinkapin, black, and white oaks resprout (top left) in a frequently burned oak/pine woodland in the Missouri Ozarks. Oaks are known for their ability to resprout after a shoot is lost to fire. White oak species are especially able to compartmentalize injuries to the bole (top right) and contain the spread of fungi and bacteria that otherwise would cause wood decay and mineral stain, lowering the volume and value of the wood. This white oak was injured by fire when young and small in diameter but was able to contain the damage in the core of the bole and produce clear wood afterwards; red oak species are more susceptible to decay. Thick bark develops on a bur oak (bottom left) as it grows in diameter; typical of many oak species, the thickness of the bark helps to protect the cambium from fire injury, but scarlet and pin oaks have thinner bark and less resistance to fire injury. Trees capable of rapid diameter growth (bottom right) following fire injury are able to quickly cover over open wounds and minimize fungal infections that lead to rot. However, the bark on the woundwood is thinner and susceptible to injury in future fires. Photos: Tree cross section photo by Michael Stambaugh, University of Missouri, The School of Natural Resources; all others by Dan Dey, USDA Forest Service, Northern Research Station.*

PRESCRIBED FIRE DAMAGE TO TREES: RESPONSE TO STEM INJURY AND DECAY

Trees have several defense mechanisms to inhibit decay, including rapid diameter growth, compartmentalization, and heartwood resistance. Open wounds are susceptible to fungal and bacterial infection that leads to internal decay, and the faster a tree is able to close over wounds, the lower the probability that decay will occur (fig. 4). Diameter growth rates vary by species, site productivity, tree vigor and health, and stand density/competition. Larger wounds prolong the time a wound is exposed to infection.

Trees have several defense mechanisms to inhibit decay, including rapid diameter growth, compartmentalization, and heartwood resistance.

If fire is applied judiciously and in a manner to minimize scarring of the bole, then value loss can be managed.


Figure 4—*Small oaks that are dominant on productive sites can grow rapidly enough in diameter to close small fire injuries in a few years (top left). More severely damaged small trees that have slower growth potential or are repeatedly wounded by fire can develop large catfaces that serve as entry points for wood-decaying fungi (top right). Because such trees may persist in forests for decades, substantial decay can develop. Concentrations of large fuels against the boles of trees, even mature thick-barked oaks, can cause severe fire injuries (bottom left). These wounds develop into large catfaces (bottom right), increasing the likelihood of repeated fire injuries and serving as entry points for fungi that cause advanced decay in the butt log. Photos: Dan Dey, USDA Forest Service, Northern Research Station.*

For example, Stambaugh and others (2017) observed that fire scars in mature white oak averaged 3.5 inches (8.9 cm) in width and took, on average, 10 years to close in a Missouri oak woodland managed by prescribed burning; but larger scars (9 inches (23 cm) wide) took up to 24 years to close. Mature trees in the Central Hardwood Region that were scarred in logging operations took 10 to 13 years for 59 percent to 76 percent, respectively, of the trees to close wounds (Smith and others 1994; Jensen and Kabrick 2014). Decay progresses more rapidly in red oak species and sugar maple (*Acer saccharum* Marsh.) (Forest Products Laboratory 1967; Hesterberg 1957).

Fire frequency has an effect on potential scar sizes, with percent of trees scarred and scar size lower in annual than in periodic fire regimes (that is, with fires every 4 to 5 years) (Knapp and others 2017; Scowcroft 1966, Stambaugh and others 2014). Periodic fires can retard wound closure by repeatedly wounding the thinner barked woundwood. Prescriptions to promote oak or pine regeneration or to restore oak/pine woodlands and savannas often combine overstory thinning and prescribed fire. Burning in such stands with slash increases not only the percentage of trees scarred but also the average scar size in oaks (Kinkead and others 2017).

Compartmentalization is a process by which a tree establishes a defensive barrier around an injury, thus limiting the spread of fungi and bacteria throughout the bole (fig. 5) (Smith 2015). The ability to compartmentalize wounds varies by species; for example, the birches (*Betula* spp.) are less effective at it than maples and oaks (Sutherland and Smith 2000). Oak species, especially those in the white oak group, have an unusual ability to rapidly compartmentalize fire injuries (Smith and Sutherland 1999; Sutherland and Smith 2000). Resistance to the spread and development of decay in the heartwood varies by species. Species of the white oak group, black locust (*Robinia pseudoacacia* L.), catalpa (*Catalpa* spp.), black cherry, eastern redcedar (*Juniperus virginiana* L.), and cypress (*Taxodium* spp.) have heartwood that ranges from resistant to very resistant to decay (Forest Products Laboratory 1967). Red oak group species, hickories, maples, sweetgum (*Liquidambar styraciflua* L.), yellow-poplar, birches, eastern cottonwood, and American beech have only slight to no resistance to heartwood decay.

Figure 5—*This mature white oak was wounded by fire in a northern Missouri woodland but was able to compartmentalize the fire injury, close over the open wound, and thereby minimize wood loss to decay. Some mineral stain has formed in reaction to the injury and infection, which degrades lumber value. Since fire injuries occur on the large end of the butt log, any damage remains outside of the scaling cylinder for a time and hence has minimal impact on log and lumber value. Harvesting injured trees within 5 to 10 years after injury also minimizes volume and value loss. Photo: Dan Dey, USDA Forest Service, Northern Research Station.*

TREE AND STAND VOLUME, GRADE, AND VALUE LOSS

In individual tree assessments of fire damage and loss, Marschall and others (2014) reported an increase in both value and volume loss to decay and a decrease in lumber grade in Missouri Ozark black oak, northern red oak (*Q. rubra* L.), and scarlet oak butt logs with increasing prescribed fire severity and initial fire scar size as represented by scar height and scar depth (fig. 6). Most of the devaluation in the butt log resulted from declines in lumber grade and not from volume loss. However, they found that scaled volume loss averaged only 4 percent and value loss averaged 10 percent after 14 years from fire injury. They concluded that, where less than 20 percent of the bole circumference was scarred and scar heights were less than 20 inches (51 cm), the value loss would be insignificant within 15 years of scarring; they found that harvesting the most severely injured trees within 5 years limits value loss.

In other studies, Loomis (1974) also reported that value and volume loss increased with increasing fire scar size (wound width and length), time since wounding, and tree diameter at the time of scarring. Similar evidence of the extent of fire injury was noted by Smith and Sutherland (1999), who measured scorch height on oak boles and found that it was generally less than 40 inches (102 cm) after low-intensity prescribed fires in Ohio. They observed that most wounds occurred near the ground and were covered by intact bark, were small in size, and were rapidly and effectively compartmentalized within 2 years of the fire. Wiedenbeck and Schuler (2014) reported fire-related decreases in lumber quality that ranged from 7 percent in yellow-poplar to 12–13 percent in red and white oak and 16 percent in red maple (*Acer rubrum* L.) 5 to 8 years after two prescribed fires in West Virginia oak/mixed hardwood stands.

At the stand level, anywhere from 30 to 67 percent of trees can be scarred by fire in upland oak forests that are subjected to repeated prescribed fires over several decades (Knapp and others 2017; Mann and others 2020; Stevenson and others 2008; Stanis and others 2019). Stanis and others (2019) reported minor losses in volume and tree grade for a mix of

Figure 6—*Decay and stain associated with a fire-scarred red oak in Missouri, defects in the wood that developed within 15 years of the fire injury. Photo: Dan Dey, USDA Forest Service, Northern Research Station.*

hardwood species that had experienced one to more than four prescribed fires over a 25-year period in southern Indiana. They found that relative volume of the butt log decreased by less than 2.5 percent where there were three fires or less and averaged 6 percent in trees that were burned four times or more. Only 3.3 percent of the trees showed a decrease in tree grade overall, but 7 percent of the trees burned four times or more had a decrease in grade. Grade change was least in white oak.

On four national forests in the Central Hardwood Region, Mann and others (2020) evaluated the loss in butt log volume and value at the stand level in forests that received one to four or more prescribed fires over a 25-year period. About one-third of the trees were scarred and 6.6 percent had a decline in tree grade. They found that the relative volume of the butt log decreased by 1 to 2 percent on the Hoosier, Wayne, and Daniel Boone National Forests and by 10 percent on the Mark Twain National Forest. Volume loss varied by species or species group, with red oaks (13 percent) and sugar maple (10 percent) losing the most compared to white oaks (2 percent). Loss was significantly greater in trees that experienced four or more burns. Relative value loss in the butt log ranged from 1 to 3 percent on the three more easterly national forests to 15 percent on the Mark Twain National Forest. White oaks and yellow-poplar had the least loss in value (4.5 percent) compared to sugar maple (10 percent) and red oaks (13 percent).

Losses from wildfires are substantially greater than from prescribed fires. For example, Reeves and Stringer (2011) estimated that timber value loss averaged 47 percent, including cull volume, mortality, and changes in species and size classes in Kentucky hardwood forests. In contrast, overstory mortality is low in most prescribed burns, and value loss is predominately limited to changes in tree, log, and lumber grade.

However, Knapp and others (2017) demonstrated the importance of fire-induced shifts in species composition from higher to lesser valued species over time. They concluded that the greater loss in stand value in a Missouri Ozark oak forest was due to changes in species composition from white oak to post oak after 60 years of prescribed fire. Thus, losses due to wood decay can be minimized if fire intensity and duration are low, fires are ignited in a way that limits scarring, scarred trees are harvested before decay advances into the log scaling cylinder, and forests are managed to prevent shifts in composition to lower valued species.

PROMISING RESULTS

An increasing number of goals and objectives, including reducing wildfire risk and severity as well as ecosystem restoration, require forest managers to incorporate prescribed fire into the management system and at the landscape level. There are many reasons why managers are reluctant to apply prescribed fire and manage wildfire on large acreages. However, the current level of prescribed burning is orders of magnitudes below what is needed or possible.

Recent research on the effects of fire on hardwoods has begun to shed light on a concern about timber loss from fire due to scarring and subsequent decay. Many forest managers fear a corresponding loss of grade as well as timber volume and value in the highly profitable fine hardwoods. Early results are very promising, showing less than 5 to 10 percent loss of volume or value, depending on the circumstances in the short term.

If fire is applied judiciously and in a manner to minimize scarring of the bole, then value loss can be managed through periodic harvesting of wounded trees before decay and loss of grade advance into the scaling cylinder. Much more research and application of prescribed fire is needed to fine-tune its use in eastern hardwood forests. By quantifying the loss in volume and value of fire-injured timber, managers can make better decisions about balancing the benefits of prescribed fire against the potential costs. The actual loss so far has been shown to be in line with other traditional costs of forest management. And the costs may be seen as entirely acceptable when the ecological gains are considered.

LITERATURE CITED

Burns, P.Y. 1955. Fire scars and decay in Missouri oaks. Columbia, MO: University of Missouri, College of Agriculture, Agriculture Experiment Station. 8 p.

Calkin, D.E.; Thompson, M.P.; Finney, M.A. 2015. Negative consequences of positive feedbacks in United States wildfire management. Forest Ecosystems. 2: 9. DOI: 10.1186/s40663-015-0033-8.

Dey, D.C.; Schweitzer, C.J. 2018. A review on the dynamics of prescribed fire, tree mortality, and injury in managing oak natural communities to minimize economic loss in North America. Forests. 9(8): 461. 22 p. DOI: 10.3390/f9080461.

Fontaine, J.B.; Kennedy, P.L. 2012. Meta-analysis of avian and small-mammal response to fire severity and fire surrogate treatments in U.S. fire-prone forests. Ecological Applications. 22(5): 1547–1561.

Forest Products Laboratory. 1967. Comparative decay resistance of heartwood of native species. Res. Note FPL–0153. Madison, WI: USDA Forest Service, Forest Products Laboratory. 2 p.

Fulé, P.Z.; Crouse, J.E.; Roccaforte, J.P.; Kalies, E.L. 2012. Do thinning and/or burning treatments in Western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? Forest Ecology and Management. 269: 6–81.

Gustafson, R.O. 1944. Cull as determined from basal wounds in Kentucky highlands timber. Journal of Forestry. 42: 181–184.

Hare, R.C. 1965. The contribution of bark to fire resistance of southern trees. Journal of Forestry. 63: 248–251.

Hengst, G.E.; Dawson, J.O. 1994. Bark properties and fire resistance of selected tree species from the Central Hardwood Region of North America. Canadian Journal of Forest Research. 24: 688–696.

Hepting, G.H. 1937. Decay in merchantable oak, yellow poplar, and basswood in the Appalachian Region. Washington, DC: USDA Forest Service. 30 p.

Hesterberg, G.A. 1957. Deterioration of sugar maple following logging damage. St. Paul, MN: USDA Forest Service, Lake States Forest Experiment Station. 58 p.

Hutchinson, T.F.; Sutherland, E.K.; Yaussy, D.A. 2005. Effects of repeated prescribed fires on the structure, composition, and regeneration of mixed-oak forests in Ohio. Forest Ecology and Management. 218: 210–228.

Jensen, R.G.; Kabrick, J.M. 2014. Following the fate of harvest damaged trees 13 years after harvests. In: Groninger, J.W.; Holzmueller, E.J.; Nielsen, C.K.; Dey, D.C., eds. Proceedings, 19th Central Hardwood Forest Conference. Gen. Tech. Rep. NRS–P–142. Newtown Square, PA: USDA Forest Service, Northern Research Station: 199–200.

Kalies, E.L.; Yocom Kent, L.L. 2016. Tamm review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecology and Management. 375: 84–95.

Kaufert, F.H. 1933. Fire and decay injury in the southern bottomland hardwoods. Journal of Forestry. 31: 64–67.

Kinkead, C.S.; Stambaugh, M.C.; Kabrick, J.M. 2017. Mortality, scarring, and growth in an oak woodland following prescribed fire and commercial thinning in the Ozark Highlands. Forest Ecology and Management. 403: 12–26.

Knapp, B.O.; Marschall, J.M.; Stambaugh, M.C. 2017. Effects of long-term prescribed burning on timber value in hardwood forests of the Missouri Ozarks. In: Kabrick, J.M.; Dey, D.C.; Knapp, B.O. [and others], eds. Proceedings of the 20th Central Hardwood Forest Conference. Gen. Tech. Rep. NRS–P–167. Newtown Square, PA: USDA Forest Service, Northern Research Station: 304–313.

Kolden, C.A. 2019. We're not doing enough prescribed fire in the Western United States to mitigate wildfire risk. Fire. 2(2): 30. DOI: 10.3390/fire2020030.

Leenhouts, B. 1998. Assessment of biomass burning in the conterminous United States. Conservation Ecology. 2(1): 1. Available from the Internet. URL: *http://www.consecol.org/vol2/iss1/art1/.* (6 February 2020).

Loomis, R.M. 1974. Predicting the losses in sawtimber volume and quality from fires in oak-hickory forests. Res. Pap. NC–104. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station. 6 p.

Mann, D.P.; Wiedenbeck, J.K.; Dey, D.C.; Saunders, M.R. 2020. Evaluating economic impacts of prescribed fire in the Central Hardwood Region. Journal of Forestry. DOI: 10.1093/jofore/fvaa004.

Marschall, J.M.; Guyette, R.P.; Stambaugh, M.C.; Stevenson, A.P. 2014. Fire damage effects on red oak timber product value. Forest Ecology and Management. 320: 182–189.

McIver, J.D.; Stephens, S.L.; Agee, J.K. [and others]. 2013. Ecological effects of alternative fuel-reduction treatments: highlights of the National Fire and Fire Surrogate study (FFS). International Journal of Wildland Fire. 22: 63–82.

Melvin, M. 2018. 2018 national prescribed fire use survey report. Tech. Rep. 03–18. Coalition of Prescribed Fire Councils, Inc. 23 p. *https://www.stateforesters.org/wp-content/uploads/2018/12/2018-Prescribed-Fire-Use-Survey-Report-1.pdf.* (6 February 2020).

NIFC (National Interagency Fire Center). 2020. Prescribed fires and acres by agency, 1998–2018. *https://www.nifc.gov/fireInfo/fireInfo_stats_prescribed.html.* (25 January 2020).

North, M.; Collins, B.M.; Stephens, S.L. 2012. Using fire to increase the scale, benefits, and future maintenance of fuels treatments. Journal of Forestry. 110(7): 392-401.

Oswalt, S.N.; Smith, W.; Miles, P.D.; Pugh, S.A., coords. 2019. Forest Resources of the United States, 2017: a technical document supporting the Forest Service 2020 RPA Assessment. Gen. Tech. Rep. WO-97. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 223 p. https://doi.org/10.2737/WO-GTR-97

Pausas, J.G. 2015. Bark thickness and fire regime. Functional Ecology. 29: 315–327.

Reeves, C.; Stringer, J. 2011. Wildland fires' long-term costs to Kentucky's woodlands. Kentucky Woodlands Magazine. 6(3): 6–7.

Regelbrugge, J.C.; Smith, D.W. 1994. Postfire tree mortality in relation to wildfire severity in mixed oak forests in the Blue Ridge of Virginia. Northern Journal of Applied Forestry. 11: 90–97.

Schultz, C.A.; Thompson, M.A.; McCaffrey, S.M. 2019. Forest Service fire management and the elusiveness of change. Fire Ecology. 15:13 doi:10.1186/s42408-019-0028-x

Schweitzer, C.; Dey, D. 2020. Coproducing science on prescribed fire, thinning, and vegetation dynamics on a national forest in Alabama. Fire Management Today. 78(3): 42–50.

Schwilk, D.W.; Keeley, J.E.; Knapp, E.E. [and others]. 2009. The national fire and fire surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecological Applications. 19(2): 285–304.

Scowcroft, P.G. 1966. The effects of fire on the hardwood forests of the Missouri Ozarks. Columbia, MO: University of Missouri. Master's thesis. *https://www.researchgate.net/publication/36026587_The_effects_of_fire_on_the_hardwood_forests_of_the_Missouri_Ozarks_microform.* (29 July 2018).

Settle, J; Gonso, C. 2018. 2018 Indiana forest products price report and trend analysis. Indianapolis, IN: Indiana Division of Forestry, Department of Natural Resources. 27 p. *https://www.in.gov/dnr/forestry/files/fo-spring_2018_Timber_Price_Report.pdf.* (26 January 2020).

Smith, H.C.; Miller, G.W.; Schuler, T.M. 1994. Closure of logging wounds after 10 years. Res. Pap. NE–692. Radnor, PA: USDA Forest Service, Northeast Forest Experiment Station. 6 p.

Smith, K.T. 2015. Compartmentalization, resource allocation, and wood quality. Current Forestry Reports. 1(1): 8–15.

Smith, K.T.; Sutherland, E.K. 1999. Fire scar formation and compartmentalization in oak. Canadian Journal of Forest Research. 29: 166–171.

Smith, K.T.; Sutherland, E.K. 2006. Resistance of eastern hardwood stems to fire injury and damage. In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers. Newtown Square, PA: USDA Forest Service, Northern Research Station: 210–217.

Stambaugh, M.C.; Marschall, J.M.; Guyette, R.P. 2014. Linking fire history to successional change of xeric oak woodlands. Forest Ecology and Management. 320: 83–95.

Stambaugh, M.C.; Smith, K.T.; Dey, D.C. 2017. Fire scar growth and closure rates in white oak *(Quercus alba)* and the implications for prescribed burning. Forest Ecology and Management. 391: 396–403.

Stanis, S.; Wiedenbeck, J.; Saunders, M.R. 2019. Effect of prescribed fire on timber volume and grade in the Hoosier National Forest. Forest Science. 65(6): 714–724.

Stephens, S.L.; McIver, J.D.; Boerner, R.E.J. [and others]. 2012. The effects of forest fuel-reduction treatments in the United States. BioScience. 62(6): 549–560.

Stevenson, A.P.; Muzika, R-M; Guyette, R.P. 2008. Fire scars and tree vigor following prescribed fires in Missouri Ozark upland forests. In: Jacobs, D.F.; Michler, C.H., eds. Proceedings, 16th Central Hardwood Forest Conference. Gen. Tech. Rep. NRS–P–24. Newtown Square, PA: USDA Forest Service, Northern Research Station: 525–534.

Sutherland, E.K.; Smith, K.T. 2000. Resistance is not futile: the response of hardwoods to fire-caused wounding. In: ; Yaussy, D.A., ed. Workshop on fire, people, and the Central Hardwoods landscape. Newtown Square, PA: USDA Forest Service, Northeastern Research Station: 111–115.

University of Kentucky. [N.d.]. Delivered timber prices. Lexington, KY: College of Agriculture, Food and Environment, Department of Forestry and Natural Resources. *http://forestry.ca.uky.edu/delivered-timber-prices.* (26 January 2020).

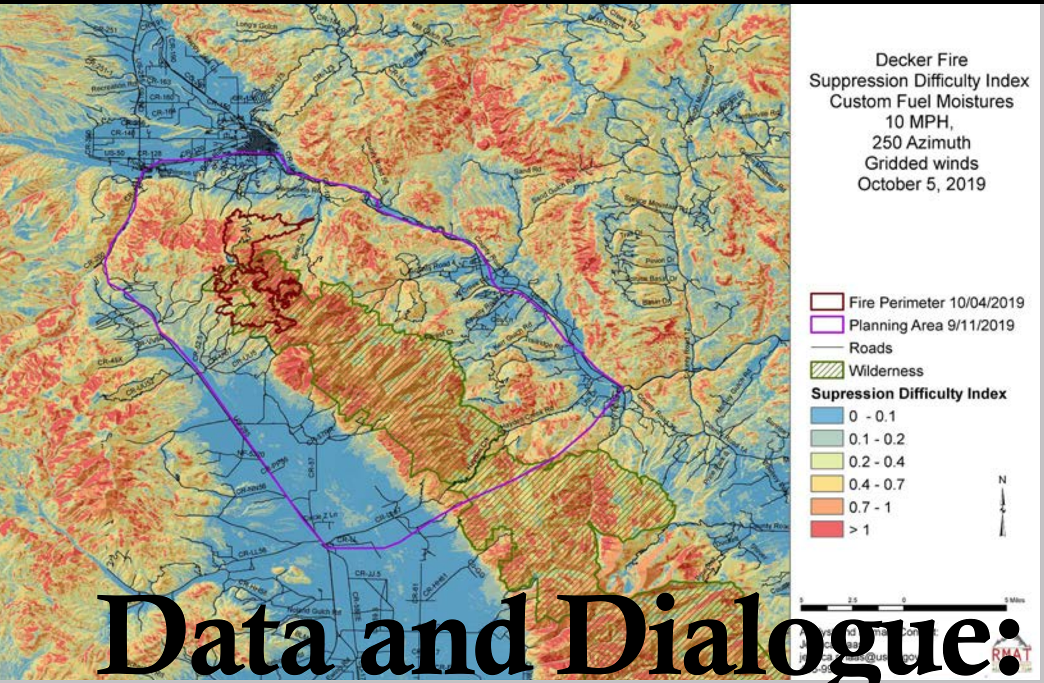
Vaillant, N.M.; Reinhardt, E.D. 2017. An evaluation of the Forest Service hazardous fuels treatment program—are we treating enough to promote resiliency or reduce hazard? Journal of Forestry. 115(4): 300–308.

Vines, R.G. 1968. Heat transfer through bark, and the resistance of trees to fire. Australian Journal of Botany. 16: 499–514.

Wiedenbeck, J.K.; Schuler, T.M. 2014. Effects of prescribed fire on the wood quality and marketability of four hardwood species in the central Appalachian region. In: Groninger, J.W.; Holzmueller, E.J.; Nielsen, C.K.; Dey, D.C., eds. Proceedings of the 19th Central Hardwood Forest Conference. Newtown Square, PA: USDA Forest Service, Northern Research Station: 202–212.

Wiedenbeck, J.; Smith, K.T. 2019. Hardwood management, tree wound response, and wood product value. The Forestry Chronicle. 94(3): 292–306.

WFLC (Wildland Fire Leadership Council). 2014. The national strategy: the final phase in the development of the National Cohesive Wildland Fire Management Strategy. Washington, DC: U.S. Department of the Interior. 93 p. *https://www.forestsandrangelands.gov/documents/strategy/strategy/CSPhaseIIINationalStrategyApr2014.pdf.* (6 February 2020).



Suppression difficulty index map, one of the risk management assessment tools used on the Decker Fire in fall 2019 in Colorado.

Data and Dialogue: Assessing Forest Service Risk Management Assistance

Chad Kooistra and Courtney Schultz

With an increase in wildland fire frequency, size, intensity, duration, and complexity, managing wildland fire has become increasingly challenging for the Forest Service and its cooperators. In 2016, Forest Service wildland fire leaders adopted an approach to help resolve ongoing concerns about protecting firefighter safety and values at risk while improving decision-making accountability, both internally and to Congress. The resulting risk management assistance (RMA) teams were tasked with supporting line officers through refined risk analytics and in-depth discussions to improve the quality of decision making and transparency on large wildfires.

> **Our goal was to help the Forest Service understand the efficacy of risk management assistance and options for expanding its use.**

Chad Kooistra is a research associate and Courtney Schultz is an associate professor and director of the Public Lands Policy Group, Forest and Rangeland Stewardship Department, Colorado State University, Fort Collins, CO.

FOREST SERVICE RISK MANAGEMENT ASSISTANCE

The RMA teams consisted of experienced line officers, fire operations experts, researchers, and risk management specialists. The teams began traveling to fire events in 2017, but they were not meant to be a permanent structure. A long-term goal has been to explore decision support needs, apply emerging research tools, support ongoing learning through feedback, and institutionalize RMA best practices and tools so that line officers and their teams can use them on fire events throughout the agency. RMA support was provided exclusively through in-person teams in 2017 and through a combination of in-person teams and remote or virtual assistance in 2018.

One change initiated in 2019—and anticipated for the future—was to make RMA support primarily virtual; in fact, the "T" was dropped from the initial acronym (RMAT, for risk management assistance team) because teams no longer responded in person. The range of available RMA products (see the sidebar) reflects their overarching intent:

- To enhance decision making;
- To improve accountability and resource use; and
- To provide up-to-date information and predictions about the characteristics of a fire, forest and weather conditions, and other management considerations (see the RMA website at *https://wfmrda.nwcg.gov/RMAT.html* for more information about products and for examples).

Recognizing that feedback is an essential component of organizational learning, RMA leaders regularly evaluated their success in postevent summaries and internal discussions. They also requested a third-party assessment of RMA after its first 2 years to gain additional insights.

In response, our team from Colorado State University independently assessed RMA results in the summer and fall of 2019. Our goal was to help the Forest Service

RMA Products Offered in 2019*

INCIDENT TIMELINE

Helps track and justify key decisions and resource use throughout a fire event. Sample information includes fire size, cost/expenditures, number of personnel, percent containment, directed strategy, relative risk assessment, assigned incident management team, structures threatened/destroyed, and decision status.

RESOURCE TIMELINE

Similar to the incident timeline but displays the specific type of resources (such as camp crews, dozers, masticator, helicopters, and water tanker) by date. It also includes fire size, cost to date, number of personnel, and percent containment.

MANAGEMENT DIRECTION ALIGNMENT TABLE

Helps decision makers ensure that incident objectives, Wildland Fire Decision Support System course of action, leader's intent, and the incident action plan align with the unit's land and resource management plan. Sample categories include general fire management, safety/risk management, cultural resources, infrastructure/private property, smoke, silviculture/vegetation ecology, wildlife/fisheries, soils, range, wilderness, and watershed.

COURSE OF ACTION/ TRADEOFF ANALYSIS EXERCISE

Helps decision makers systematically consider different strategies based on ratings of risk to firefighters, public safety, and other values potentially affected by the fire. The worksheet gives a framework for considering the different risk tradeoffs across a fire for the set of values identified by decision makers across different potential strategies.

AVIATION USE SUMMARY

Helps decision makers quantify and track aviation use on a fire. It spatially tracks

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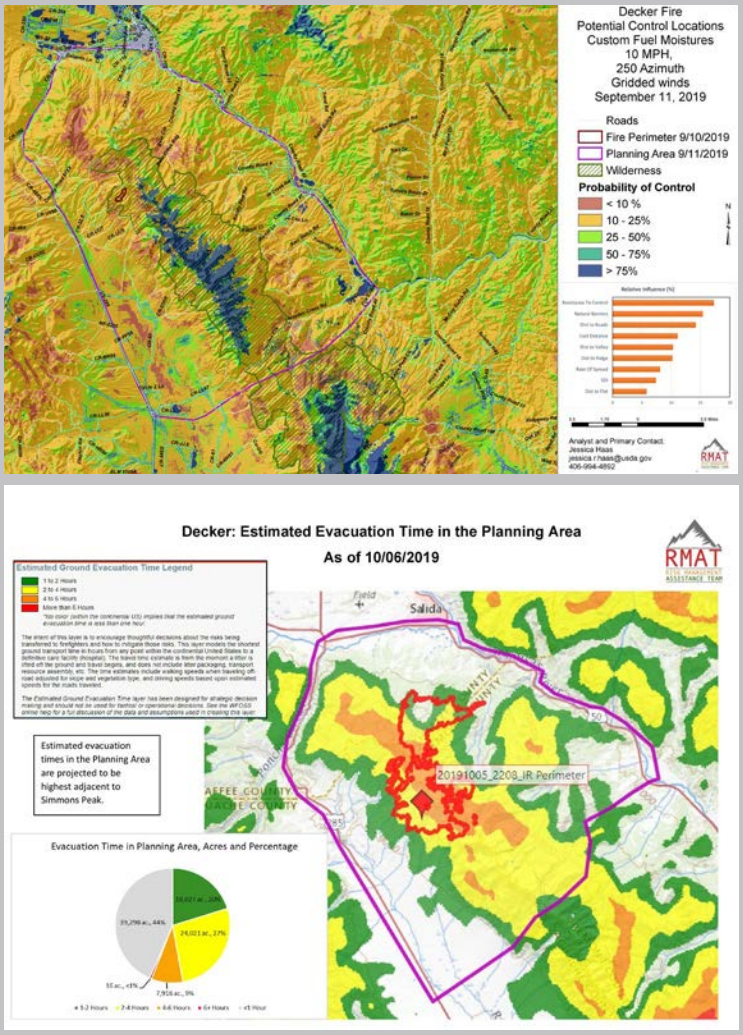
*Adapted from https://wfmrda.nwcg.gov/RMAT.html.



Potential control locations map (left) and ground evacuation map (right), one of the risk management assessment tools used on the Decker Fire in fall 2019 in Colorado.

understand the efficacy of the RMA approach and options for expanding the use of RMA concepts going forward. This article presents the main findings from our assessment, including specific findings about RMA and general findings regarding risk-informed decision making on wildland fire events (see Schultz and others (2020) for more detailed findings).

INTERVIEWS WITH RMA DELIVERERS AND RECEIVERS

We started by reviewing background information on RMA and conducting preliminary informational interviews with RMA team members to help design our study. We then conducted 33 semistructured and confidential phone interviews in the summer of 2019 with both RMA "deliverers" (RMA team members who delivered products and support) and "receivers" (fire managers who received the support during an incident in 2017 or 2018). Receivers included line officers/agency administrators on fire incidents and a smaller number of analysts, incident commanders, operations chiefs, and other agency personnel.

Overall, we conducted 42 interviews averaging about 1 hour each. Our research team recorded, transcribed, and analyzed the confidential interviews using social science analysis techniques to identify key themes.

In the fall of 2019, we decided that a case study of RMA support on a recent fire would provide updated insights.

the use of different types of aircraft, including helicopters, large airtankers, and scoopers. The information displayed can track the use of retardant and help guide subsequent analysis of the associated environmental impacts.

SUPPRESSION DIFFICULTY INDEX (SDI) MAP

Displays how complex wildfire-related operations may be based on factors such as modeled fire behavior, responder mobility, available fuel breaks, and time to create line. Higher values on the SDI scale indicate more hazardous situations or areas.

POTENTIAL CONTROL LOCATION MAP

Shows the likelihood of fire stopping in a given area based on historical fire perimeters and other model drivers (such as fuel transitions, road networks, rate of spread, and suppression difficulty). Higher probabilities indicate better containment opportunities under current fire conditions.

SEASON-ENDING ANALYSIS

Describes the probability of a season-ending event, such as pulses of rain or snow, lower temperatures, and higher relative humidity.

SNAG HAZARD MAP

Estimates and displays the relative hazard from dead standing trees across the landscape using a mathematical relationship between Forest Inventory Analysis plot data and landscape characteristics.

GROUND EVACUATION MAP

Gives travel time estimates from different locations in the proximity of a fire to the nearest care facility, accounting for considerations such as road availability or conditions, slope, vegetation type, and driving speeds.

EXCEED PROBABILITY CURVES

Uses information from regional quantitative wildfire risk assessments and fire spread probability outputs to estimate the distribution of potential outcomes for highly valued resources and assets within a given timeframe.

We chose the Decker Fire in Colorado in fall 2019. We interviewed decision makers and the RMA delivery team, for a total of nine interviews related to the Decker Fire.

Below, we first present our main findings, followed by highlights from RMA on the Decker Fire. Then we discuss recommendations for future RMA efforts and for risk-informed decision making throughout the agency.

KEY FINDINGS

PERCEIVED VALUE OF RMA

People who received RMA support generally agreed that RMA products and specialists spurred valuable discussion about strategic alternatives for incident response and deliberation about risk-informed decision making among local political leaders, partners, and agency and fire management personnel. The discussions allowed for more structured and coordinated decisions. RMA offered evidence to support line officers' decisions, often providing validation for what already had been decided and, in most cases, increasing a line officer's confidence in those decisions.

As one line officer stated, "RMAT gives you a high degree of confidence that your decisions are sound. When you reach a decision, you are confident it's the right one given the circumstances."

We also heard that RMA provided tools to enhance transparency and accountability regarding decision-making rationale and procedures for resource use. The tradeoff analysis exercise in particular was called a useful tool and opportunity for considering different perspectives that may have been missed without a formal conversation. The exercise offered a structured format for discussing values at risk (such as firefighter safety, infrastructure, and water quality) across the landscape and how different fire management strategies might affect those values.

In general, we heard a need for a more comprehensive and common understanding of risk.

Interviewees consistently noted that one outcome of these discussions was clear, transparent communication about decision-making rationale among line officers when communicating with fire staff, partners, cooperators, and the public. Some said that this allowed line officers who were new to communities to include cooperators, partners, and local officials in conversations and to build trust with them.

As one deliverer stated, "[RMA] gave [agency administrators] a lot of scientific data, and it provided them with concrete data to show partners and stakeholders why decisions were made."

FACTORS THAT AFFECTED RMA IMPLEMENTATION

We asked RMA deliverers and receivers about the factors that affected decision makers' receptivity to RMA during a fire. Line officers, agency administrators, and fire staff who were familiar with RMA, whether through preseason exposure or by engaging with it on a previous fire, were more comfortable with and open to RMA processes and tools than those who were unfamiliar with RMA.

For instance, some line officers expressed a feeling of being second guessed when RMA teams showed up on a fire offering additional insights and analysis. However, such feelings were less common if the line officer was aware of the intent of RMA to provide additional support, as opposed to challenging decisions or providing another layer of oversight.

Line officers and fire staff also received RMA support more positively when RMA teams arrived prior to key decision points. Some said that when the RMA team arrived, decision makers had to spend valuable time with the team repeating prior discussions in order to get the team up to speed. They suggested that receiving RMA support prior to or during Wildland Fire Decision Support System (WFDSS) decision inputs would be more efficient than getting support after decisions are entered in the WFDSS.

Interviewees said that line officer personality, such as being open to mentoring and incorporating scientific analysis, also affected receptivity to RMA. Years of fire experience did not necessarily relate to RMA receptivity, although most interviewees perceived RMA as more beneficial for line officers with less fire experience. Local agency leaders clearly played an important role in communicating the benefits of RMA support, encouraging requests for RMA support and integrating RMA support with other information and decisions.

Any set of analytical tools carries a degree of uncertainty. A few fire staff expressed concerns about the reliability of some of the RMA products, such as an evacuation map suggesting a potential evacuation route on a washed-out road that was impassable. Others found the tradeoff analysis exercise to be subjective and redundant with other risk assessment processes.

The early timing of risk management assistance support on the Decker Fire improved the ability to more effectively integrate it into other processes and decision points.

People generally agreed, however, that any of these types of information and processes need to be complemented with both local knowledge and experiential knowledge in incident management. One suggestion was that local and regional fire staff, who have local knowledge and relationships, obtain more knowledge of RMA tools and approaches; this would require increased education, training, and capacity among local and regional staff for implementing RMA approaches.

Integrating any decision support system such as RMA requires balancing existing organizational structures, processes, and experiences against the increased use of analytics. As a recent article in *Harvard Business Review* emphasized, "Investments in analytics can be useless, even harmful, unless employees can incorporate that data into complex decision making" (Shah and others 2012).

BROADER CHALLENGES AND CONSIDERATIONS

We also sought to understand broader challenges and considerations regarding Forest Service fire management and the implications for RMA. In general, we heard a need for a more comprehensive and common understanding of risk among RMA deliverers, line officers, and fire staff, both within the agency and among partners.

The concept of operational risk is ingrained in firefighters' everyday practice from the first day on the job. Firefighters draw on their experience and training to help them mitigate risk. Over the past decade, improved analytical tools, such as the WFDSS, potential operational delineations, and now RMA, have supplemented experience and training in making risk-informed fire response decisions. The intent of such analytical tools is to move beyond mitigating operational risk into the realm of strategic risk management.

Interviewees said that aligning a broader understanding of risk management with on-the-ground decision making requires leaders and staff to step back in order to discuss the bigger picture of risk-informed decision making and how it plays out for different kinds of decisions and decision makers, essentially moving from operational to strategic risk management. As one RMA deliverer explained, there is a need for "a deeper, basic understanding of what risk really is and what [risk-informed] decision making might look like." A lack of alignment between how agency leaders and fire personnel perceive risk and approach risk management is a potential barrier to applying new tools and information.

Some people we spoke to thought that RMA has helped develop a common understanding and approach to assessing risk and informing decisions across all spectrums of risk (such as risk to firefighters, individual and organizational risk, short-term and long-term risk, and so forth). In discussing risk, several informants referred to the Forest Service's four-level risk diagram (enterprise, strategic, operational, and real-time risk management). One line officer pointed out how "RMAT helps people understand those various levels of risk. If applied well and communicated well to firefighters, you can connect those levels of risk to firefighters." The RMA process can be an important opportunity to create shared understanding about risk management among different personnel and across various situations.

Interviewees also discussed tensions connected to the notion of risk sharing in relation to roles and responsibilities in wildland fire management across the agency. Firefighters risk their own safety and lives on the ground. Line officers we spoke to universally took responsibility for decision making and outcomes on a fire because they often represent the agency in public, especially after a fire event. They agreed that RMA was only "providing support [because] you can't really share responsibility."

However, one deliverer explained that the agency as a whole bears responsibility for decisions by training and equipping line officers to make good decisions: "You happen to have delegated responsibilities. But at the end of the day, we are all responsible as an organization. We're all in the same boat." Nevertheless, interviewees generally thought that there is not a broad sense of shared risk across the hierarchy of the agency. Ultimately, RMA can help improve and support decision-making processes, but discussions about decision-making responsibility highlight the need to evaluate how and where organizational culture affects responsibility and risk sharing and where decision support tools fit into the complex relationship between organizational culture, decision making, and risk sharing.

Several line officers noted differing opinions in the community as to acceptable levels of risk to firefighters in protecting homes or other values.

Smoke from the Decker Fire in fall 2019, seen from Poncha Pass near Salida, CO. Photo: Chad Kooistra.

Aggressiveness in attacking a fire varies among firefighters, depending on the agency; on the team; and on condition-dependent factors such as weather, fire behavior, and fire history, among other considerations. One line officer questioned how to legitimately assess risk before ordering firefighters to engage a fire, citing such cultural factors as "the intense fear of humiliation and ridicule if we don't fulfill a mission [and] the biased can-do reaction [of firefighters]." Although interviewees noted disagreement about acceptable levels of risk, they agreed that firefighter safety is their top priority.

Broader debates about the values at risk and the responsibility for them are intertwined with diverging perspectives on the role of fire on the landscape. Interviewees said that there is a bias on incidents towards aggressive fire response rather than accepting the need and taking responsibility for a variety of fire management decisions. Agency personnel have disparate perceptions of fire's role on the landscape, interpretations of how to integrate fire as a resource management tool, and perspectives on how to consider a wide range of response options. As one deliverer said:

> We are very well split in the agency. Some fire folks see themselves as a fire organization, meaning they do suppression. They go every time the fire bell rings. They're in for war. … Then there's another group of people in the fire organization that see themselves as resource managers, in a way, and their job, it's an art. How much fire do you introduce in order to make a sustainable ecosystem? It's a lot different.

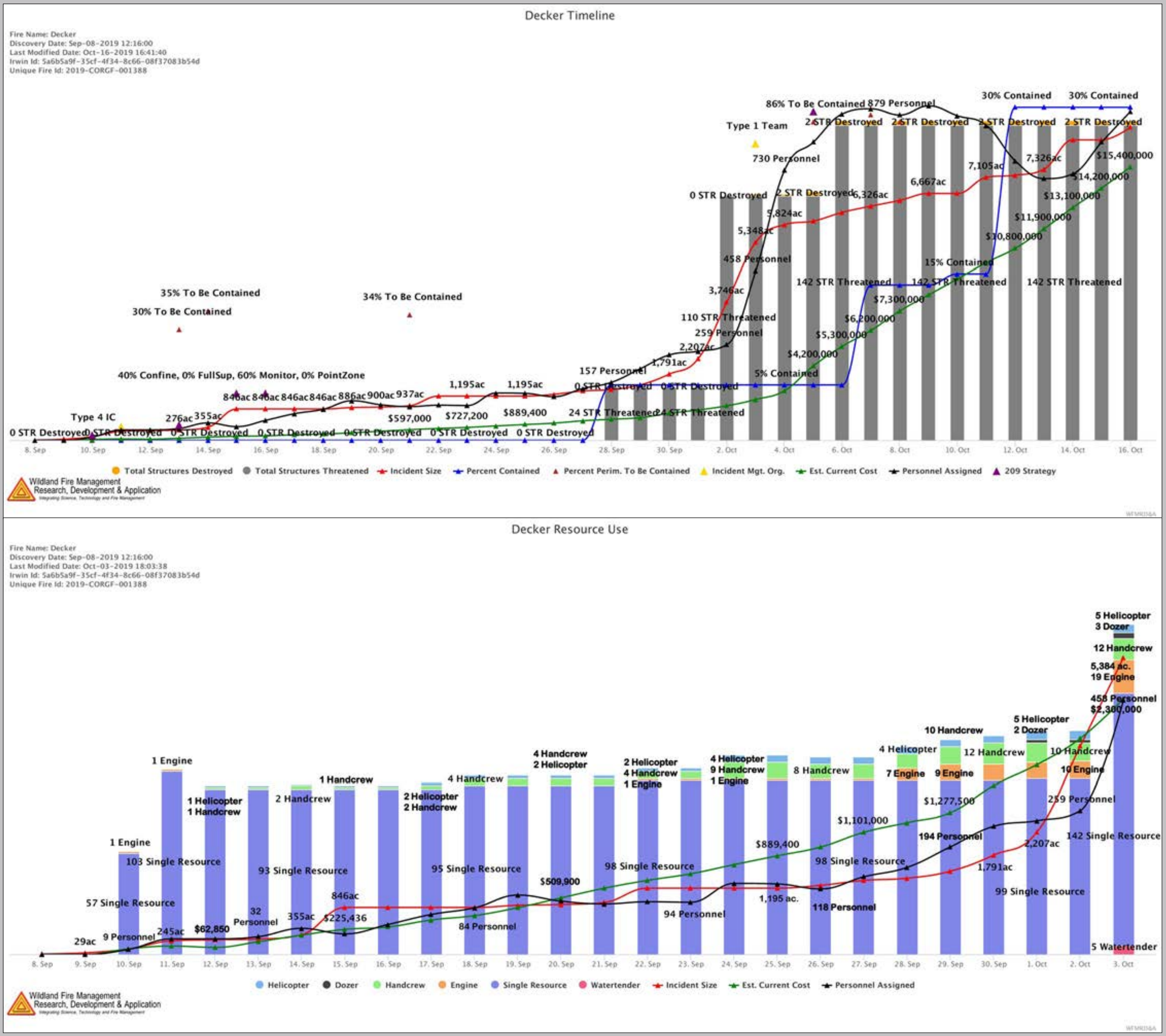
The ability to consider a variety of management response options also depends on local social and political pressure and local relationships. Local biophysical conditions, fire history, and social and political pressure can leave agency administrators with limited space to consider anything other than aggressive attack, according to some line officers. Such broader considerations will be important for the Forest Service to continue grappling with as new challenges related to fire management emerge and efforts such as RMA are made.

Partners, cooperators, agency administrators, and fire management team leaders review conditions and strategies during an evening briefing on the Decker Fire in fall 2019. Photo: Chad Kooistra.

2019 DECKER FIRE CASE STUDY

Leaders of the RMA effort sought to enhance the efficacy of RMA support during the 2019 fire season. One event in particular exemplified how RMA can succeed in the future.

Lightning ignited the Decker Fire in September 2019 in the Sangre de Cristo Wilderness in southern Colorado. The fire burned approximately 9,000 acres (3,600 ha) until the area received a significant snowfall 7 weeks after ignition. RMA support was requested and provided within the first 4 days of ignition and several times later during the fire.



Incident timeline (top) and resource timeline (bottom) from the Decker Fire in fall 2019, some of the risk management assessment tools used on the fire.

One person noted, "When I think back to all these different RMA fires, I like this [approach used on the Decker Fire] because it was used by multiple people at multiple times throughout the whole life cycle of the fire. This is the ideal example of how this could work on other fires."

Several line officers connected with the Decker Fire had extensive background in RMA and initiated early discussions about requesting RMA support. Agency administrators for the Decker Fire initially selected a strategy other than aggressive suppression due to the remoteness of the fire and predictions about growth. They requested RMA support within 2 days after ignition because they recognized the potential complexity of the fire. It was burning in an area surrounded by dense beetle-killed trees, abundant snags, and steep terrain, with the potential to move towards communities if weather patterns and fire behavior aligned. Line officers understood the potential for a complex and long-term event and wanted RMA support to help them thoroughly consider their short- and long-term options.

This type of leadership commitment, background knowledge, and training is essential for successfully integrating new systems and analytics into the fire management decision-making process.

Interviewees viewed the timing of initial RMA support on the Decker Fire as ideal because the support was available before major decisions were made. The early timing of RMA support also improved the ability to more effectively integrate RMA into other processes and decision points. As one person noted, "[RMA support] also really helped formulate some of the WFDSS decision making and objectives. It was really interesting because [the tradeoff analysis] also helped facilitate WFDSS, and WFDSS helped facilitate the tradeoff analysis."

Line officers and fire staff on the Decker Fire consistently mentioned the value of the tradeoff analysis exercise. They conducted three different tradeoff analysis exercises during the Decker Fire. Participants said that they walked away with the clearest understanding they had ever had of what the fire management team needed to do to succeed in a manner consistent with the agency administrator's strategy. For example, one participant told us the following:

> We thought that would be useful, and it was, for a sitdown with the type 3 team that we ordered and the agency administrators to really home in on what the values at risk were. … They changed their decision during the course of the risk assessment and the tradeoff analysis. They all had a mental outcome in mind, and then, when they went through the risk assessment and the tradeoff analysis, that actually changed.

Participants said that the tradeoff analysis exercises also created a structured opportunity to consider perspectives across different agencies and jurisdictions. Decision makers discussed and prioritized values at risk on two national forests, Bureau of Land Management (BLM) districts, and other lands and aligned the strategic approach accordingly. BLM partners identified important values at risk, such as impacts on sage grouse habitat, cultural considerations, and the effects of road closures on the hunting community. Recognizing these issues helped the team formulate decisions and consistently communicate the rationale for these decisions to the public and various stakeholder groups.

Risk management assessment teams consisted of experienced line officers, fire operations experts, researchers, and risk management specialists.

Those discussions also led to more efficient transitions between the multiple management teams throughout the fire because teams did not need to engage in that entire process to get the necessary information. The suite of RMA products was included in the packet of information provided to incoming teams and helped facilitate transitions between management teams.

As one member of an incident management team stated, "[The tradeoff analysis exercise] was fantastic. Because of the stuff that [an agency staff member] preloaded … instead of us getting up to speed in the first 3 to 4 days, we [were] up to speed in the first day or two."

Those involved with the Decker Fire were optimistic about the prospect of RMA remote support, especially with the availability of virtual, real-time assistance and well-trained local staff to interpret information and facilitate discussions. For instance, since RMA no longer includes in-person teams who can facilitate the tradeoff analysis exercise, participants recognized that designating a local expert to facilitate the process was ideal. Local agency staff familiar with RMA products and risk-informed decision-making principles systematically guided the team through the mechanics of the exercise, such as when and how to weigh different values and assign categories of risk. Having this type of local expertise across the agency—or at least having immediate access to trained experts—will be necessary for accurately interpreting other RMA analytics as well.

Agency administrators, line officers, and RMA deliverers said that multiple requests for RMA support throughout the duration of the Decker Fire improved the ability to integrate RMA products into key decisions by providing up-to-date and relevant information as fire conditions changed. At times, RMA deliverers also proactively provided additional information or suggested types of information that might be helpful. This kind of back-and-forth dialogue worked well for receivers and deliverers.

Interviewees pointed to a need for a stronger agencywide commitment to and leadership for risk-informed decision making.

Participants also said that RMA products from the Decker Fire will have utility after the fire for assessing fire impacts and shaping future planning efforts. Several interviewees pointed out how RMA risk assessment information could help the postfire burned area emergency response teams decide where to focus their efforts. Someone also discussed plans to use RMA products from the Decker Fire in future planning meetings on fuels mitigation to allow for fire to promote resource benefits. As one person said, "[RMA products] can be utilized in prescribed fire planning, treatment, public outreach, and communication." Such considerations could help the Forest Service communicate and embrace RMA approaches across the agency in the future.

RECOMMENDATIONS FOR RMA

A key question in our work was how to diffuse RMA principles throughout the Forest Service. Interviewees offered several observations and suggestions.

First, they pointed to a need for a stronger agencywide commitment to and leadership for risk-informed decision making. RMA deliverers in particular maintained that the approach was unlikely to succeed without communication from agency leaders about the importance of using improved analytics for decision making and a corresponding national commitment. Multiple interviewees added that RMA principles may not be widely adopted without performance measures, incentives, and rewards for line officers, along with clear communication to line officers about expectations.

The agency can help resolve broader risk-related issues through clearer leadership direction, incentives, and expectations to:

- Utilize strategic risk management approaches;
- Empower line officers to play the central role in decision making on fire incidents; and
- Employ a range of fire response tactics that might be desirable, depending on conditions and values at risk.

Second, increasing awareness of RMA and enhancing accessibility of the corresponding analytical tools are important next steps. Many interviewees mentioned a need to spread knowledge about RMA, noting that many line officers and fire staff remain unaware of the process for requesting RMA support and the range of RMA products available.

Continuing to diffuse knowledge of risk management principles among agency leaders, staff, and line officers through training and clear expectations would improve the effectiveness of future RMA implementation. Embedding RMA skills and tools at the region, forest, and district level would improve capacity to deliver RMA and minimize any resistance to accepting outside support. Preseason integration, exploration, and training in RMA principles may increase RMA incorporation into bigger picture discussions about risk management. Pursuing more interagency dialogue around risk-informed decision making will also encourage consistent approaches across agencies and enhance the range of application for efforts such as RMA.

Risk management assistance supported line officer decisions, often providing validation for what already had been decided.

Third, carefully developing and articulating the wider potential benefits and uses of RMA products can make RMA a prominent component of strategic wildland fire management, integrating it into preseason, fire season, and postseason tools and systems (Stratton 2020). Line officers, agency administrators, and fire managers said that RMA should be better integrated into existing decision-making systems and products so it can be used more broadly and efficiently.

Some interviewees wanted the ability to request RMA products and support directly through WFDSS or other easily accessible interfaces or websites. As one line officer said, "The game changer [would be] if those RMA products are integrated into WFDSS. So that when you bring in a fire, you have a point of ignition, you drop it in, [and] it starts to build the RMA products."

We heard that developing certain RMA products in advance, such as information about snag hazards and potential control locations, and having that information readily available before the fire season would allow RMA analytics to be immediately available when a fire starts or for prescribed fire planning efforts. These types of RMA analytics and processes, along with the discussions around them, would also align particularly well with ongoing efforts to engage partners in collaborative planning efforts such as potential operational delineations, where analytics and experience are combined with diverse stakeholder inputs to improve the efficacy of planning and incident response.

POTENTIAL ROLE IN THE FUTURE

The growing complexity of fire management requires new approaches, roles, and mindsets, which will take time to establish. RMA can serve an important role across the Forest Service. Successfully integrating support systems such as RMA requires giving clear leadership direction, communicating consistently about RMA and giving it widespread exposure, and carefully articulating expectations for planning and decision making among the different roles in the agency. Regularly monitoring how different forms of support are being perceived and applied across the agency and partners will help agency leaders evaluate the effectiveness of RMA and similar analytics in expanding the decision space in an increasingly complex wildland fire system.

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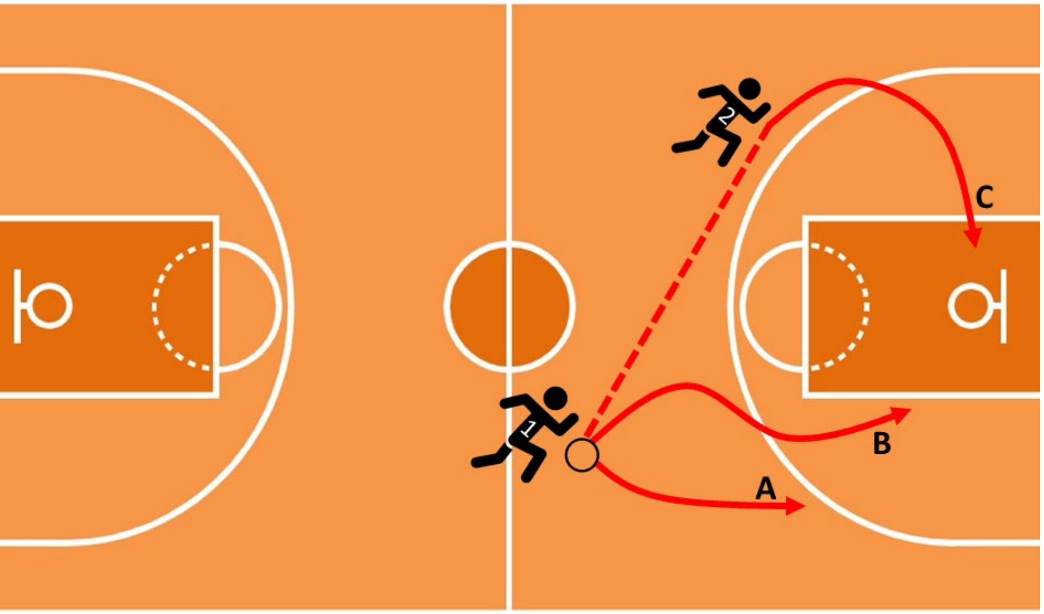
LITERATURE CITED

Schultz, C.; Kooistra, C.; Miller, L.; Ferguson, M. 2020. Findings from a third-party assessment of the U.S. Forest Service's Risk Management Assistance Teams. Pub. Lands Policy Gp. Pract. Pap. 04. Fort Collins, CO: Colorado State University. 36 p. *https://sites.warnercnr.colostate.edu/courtneyschultz/practitioner-papers/.* (18 February 2020).

Shah, S.; Horne, A.; Capellá, J. 2012. Good data won't guarantee good decision. Harvard Business Review. April. *https://hbr.org/2012/04/good-data-wont-guarantee-good-decisions.* (18 February 2020).

Stratton, R.D. 2020. The path to strategic wildland fire management planning. Wildfire. 29(1): 24–31.



Moneyball for Fire

Nicholas F. McCarthy, Matthew P. Thompson, and David E. Calkin

During wildfire incidents, decision making can be complex. Uncertainty, time pressures, and the need to balance tradeoffs across many dimensions (such as fire impacts, suppression expenditures, and public and responder safety) call for structured and timely decision support.

At the Forest Service, risk management is a required core competency for fire managers. As a set of coordinated activities to direct and control an organization with regard to risk, risk management has become somewhat of an organizing framework for the agency. Applications of risk management range from programmatic budgeting to fire prevention; fuel reduction; community planning; and broader topics such as performance, communication, and governance.

However, the great complexity of the decisions required in wildfire response means that decision support can be particularly lacking in the risk management domain. As a result, decision makers typically rely far more on expert judgment and experience than on the use of analytics.

MONEYBALL ANALOGY

When it comes to expert judgment, the current state of risk management in wildfire response shows a striking parallel to the sports analytics revolution illustrated by *Moneyball: The Art of Winning an Unfair Game,* a book about baseball that was made into a popular film. As a character in the film puts it:

> You don't put a team together with a computer, Billy. Baseball isn't just numbers—it's not science. If it was, then anybody could do what we're doing, but they can't because they don't know what we know. They don't have our experience and they don't have our intuition.

If we replace baseball with fire in this statement, the sentiment can seem familiar. However, the wildland fire science community knows that fire-related science and tools have limits. The science and numbers of analytics for risk management are a complement for wildland fire management, not a substitute.

A central thesis of recent research by the Forest Service's Wildfire Risk Management Science Team is that a stronger emphasis on data-driven decisions and analytics will accelerate the Forest Service's journey toward improved and empowered wildland fire response decision making and risk management. As this article shows, the power of analytics in fire lies in picking out patterns in data that humans (whether scientists or practitioners) can miss, whether because of the massive size of the data or because of its complexity.

In a companion piece in this issue of *Fire Management Today,* Kooistra and Schultz (2020) demonstrate data-driven risk management in action through risk management assistance (RMA) teams, with a case study from the 2019 Decker Fire. Here, we discuss related principles and insights by drawing from the analytics literature relevant to wildland fire management and emergency response. We argue for a new model, which we colloquially refer to as "Moneyball for fire," based on making more data-driven decisions in fire management, inspired by the innovative use of advanced data analytics in professional baseball and other sports.

Embracing analytics would help fire management organizations redeem some of their core risk management responsibilities.

Nicholas McCarthy is a postdoctoral fellow in the Forest and Rangeland Stewardship Department, Colorado State University, based at the Forest Service's Rocky Mountain Research Station, Missoula, MT; and Matthew Thompson is a research forester and Dave Calkin is a supervisory research forester for the Forest Service, Rocky Mountain Research Station, Missoula, MT.

The improvements in sports analytics started from the ability to conduct more complex analyses of recorded performance data. Real-time tracking in sports evolved from these earlier successes, which opened the door for more analysis, insight, and innovation, fundamentally transforming the games in unexpected ways (see, for example, a presentation on basketball at *https://tinyurl.com/r522jk3*).

Although organizations like the Forest Service collect considerable data related to wildfires, robust data on fire response and suppression resource performance is still lacking. Accordingly, the Moneyball analogy is not necessarily about making real-time adjustments in fighting fire or even about game strategy. Instead, the improvement we hope to see in performance will come from preparations made based on investments in real-time monitoring, analysis, and learning. Ultimately, these preparations will lead to a better informational basis for operations ranging from strategic planning to real-time decision making in emergency response.

WHY ANALYTICS?

In business, analytics aims to improve operations and decision making by using information, quantitative analysis, and technology (see the sidebar). In general, data-driven decisions tend to be better ones, and organizations with stronger analytics capabilities tend to outperform their counterparts. Analytics can improve decision making, measure performance, and even measure improvements in performance that come through analytics-based management. Real-time analytics now exist for a range of time-sensitive applications, including financial-market trading, military operations, smart electrical grids, intelligent transportation systems, and (of most relevance here) emergency response.

Wildland fire managers already feel the hunger for new technology, and new technologies drive modern analytics. In particular, advances in computer science allow for analyzing large, dynamic datasets in real time. However, like other fire-related technological advances, new technologies in analytics can fail to have an impact unless deployed within an effective organizational framework. Key to successful analytics are:

- Clear goals,
- Focused problems to solve,
- High-quality data from multiple sources,
- Multidisciplinary analytics teams,
- Accessible analytics systems,
- Data translators, and
- Collaborative decision-making processes.

Kooistra and Schultz (2020, in this issue) and Stratton (2020) use practical examples of analytics to show the techniques involved in rolling out the RMA program.

Table 1 shows the nine components (strategic, technical, and managerial) of an analytics management framework, which can also be thought of as an iterative cycle. The framework shows the required core elements of a successful analytics program and emphasizes the broader connections to people, processes, and even culture. It also shows how data informs insight and then value.

Translating analytics insight into action for fire management requires more than simply setting up data collection systems connected to a team of data analysts. Instead, embracing analytics may require a broader "data-driven cultural change" based on the creation of an analytics strategy, strong senior management support, and careful change management initiatives. In effect, the value of data analytics comes not only from the enabling technology but also from the organizational shifts in behavior and from enhanced capabilities for strategic insight and performance measurement.

Underpinning this shift is an acknowledgment—typical of data-driven organizations (see the sidebar)—that analytics is needed *in addition* to expert judgment and experience. It is worth stressing that the right technology is but one aspect of a successful analytics initiative; the right focus, the right people, and the right culture are also essential.

Benefits From Analytics

WHAT IS ANALYTICS?

Analytics is the extensive use of data, statistical and quantitative analysis, explanatory and predictive models, and fact-based management to drive decisions and actions.

HOW DOES USING ANALYTICS IMPROVE PERFORMANCE?

Data → Insight → Value

WHAT ARE THE MAIN PRINCIPLES OF ANALYTICS?

- Treating fact-based decision making not only as a best practice but also as a part of organizational culture.
- Recognizing the value of analytics and making its development and maintenance a primary focus.
- Applying sophisticated information systems and rigorous analysis to a range of functions.
- Considering analytics to be important enough to be managed at the enterprise level.
- Avidly consuming data and seizing every opportunity to generate information.
- Emphasizing the importance of analytics internally.
- Making quantitative capabilities part of the organization's story.
- Creating a workforce with strong analytical skills and considering it a key to organizational success.

HOW DO DATA-DRIVEN ORGANIZATIONS ACT DIFFERENTLY?

- The first question a data-driven organization asks itself is not, "What do we think?" but rather, "What do we know?"
- Decision makers move away from acting solely on hunches and instinct as well as from citing data to support decisions already made.

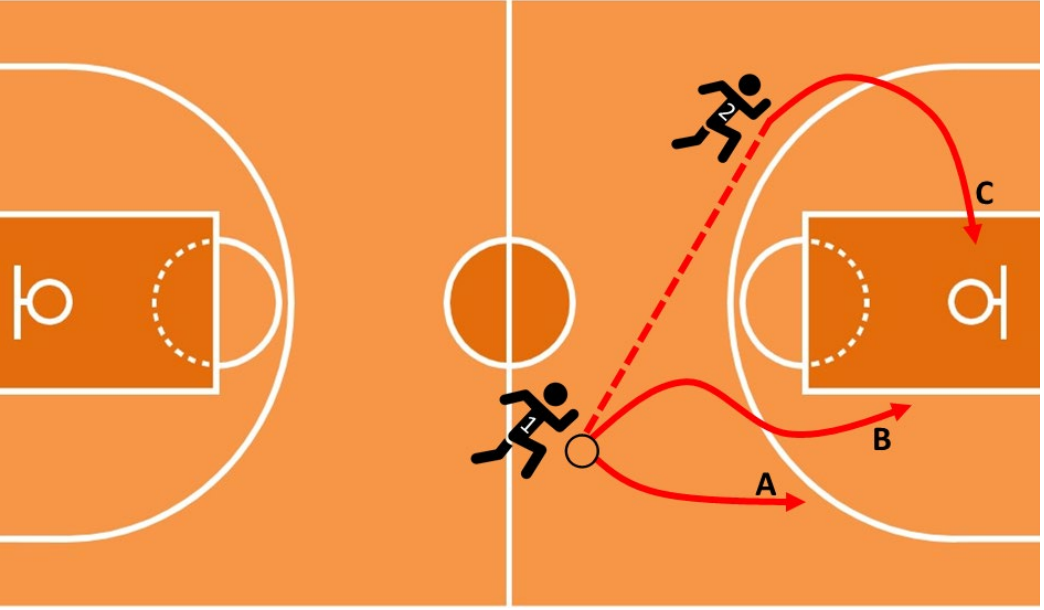


Figure 1—*A basketball scenario. Player 1 must decide between one of three options (A, B, and C): shooting for three, driving for the basket, and passing to player 2.*

Perhaps the most important caveat is that better data won't necessarily lead to better decisions (Shah and others 2012). Research has shown that "unquestioning empiricists" who trust numbers over judgment may be no better than "visceral decision makers" who go exclusively with their gut.

Accordingly, fire management agencies should foster "informed skeptics" who have strong analytic skills but can balance judgment against analysis in decision making. Human judgment therefore remains front and center in the context of embracing analytics to improve decision making. In many practical senses, the "informed skeptics" already exist and strike the right balance, but there is still a long road ahead to formalize, train, mentor, and support a broader culture of "informed skepticism" in fire management.

Table 1—*Analytics management framework.*

Strategic	**Organizational goal**	Prioritize goal(s) of the organization
	Problem	Define specific problem(s) that align with organizational goal(s)
	Data	Identify the data needed to solve key problems
Technical	**People**	Employ people to direct and manage analytics work
	Process	Capture, manage, model, analyze, and visualize data
	Technology	Adopt technologies to enable analytics work
Managerial	**Communication**	Translate analytical insights into actionable recommendations for key stakeholders
	Decision making	Use analytics insights in the decision-making process
	Iteration	Track results and improve upon the decision

Source: Shields (2019).

> **Risk management has become somewhat of an organizing framework for the Forest Service.**

SHOOTING FOR THREE

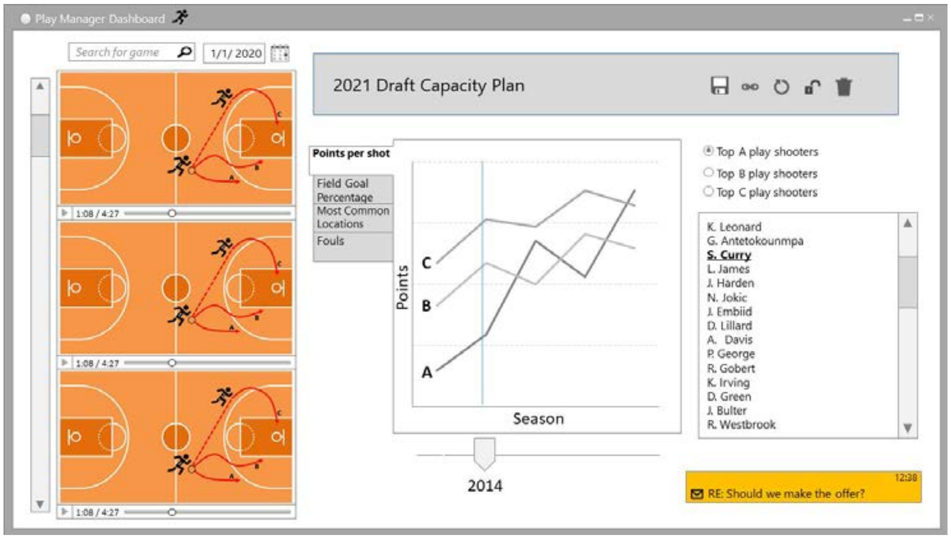
For a good example, let's look at basketball (fig. 1). Player 1, coming down the court, must decide between option A (shoot for three), option B (drive to shoot from the key), or option C (pass to player 2). The time-pressured decision is up to the player based on tactics and training. Even the coach setting strategy for the game can't make or change this decision, and it's not the time for an analyst to second-guess the decision.

So how can we use analytics to set the situation up for success? The decision point is time pressured; it's not the time for a change in strategy.

Figure 2 shows a hypothetical dashboard for building a team. We're interested in how this play and hundreds like it boil down to total points scored and ultimately to games won. By collecting the data and analyzing the player movement over hundreds of games and how those plays convert to points, the sport of basketball found a new way to build teams. The analytics are used to see how best to invest in the tactics through training, game strategy, and player choice.

An important point is that, in the context of analytics, the value is not in collecting the data from individual plays and games in order to criticize individual players for their tactical decisions. It's the patterns we cannot see in individual plays and games that show the strengths and weaknesses. Figure 3 shows how the patterns can inform strategy.

Extending the analogy, the analytics still have a use on game day. In this case, it's the coach who needs to be the "informed skeptic" by using the right bits of information—taking uncertainty into account—to arm players with the right tactics. The coach is responsible for choosing the right information, how to communicate it, and how to adapt it to



● Top A play shooters
○ Top B play shooters
○ Top C play shooters

12:38
RE: Should we make the offer?

Figure 2—*A hypothetical analytics dashboard analyzing the type of play in figure 1.*

this week's opposing side. The success of the analytics relies on the coach to put it into practice. Above all, success is in the interest of everyone: the players, coach, analyst, and manager.

In the case of increasingly destructive wildfires, rising suppression costs, and growing fire season severity, new avenues are needed to meet fire management objectives. If games are fires and the coaches are wildfire response managers, the same analytics in tactics and strategy still apply. Fire managers must understand the trends in their strengths and weaknesses as well as in risks and opportunities for success. To get there, they must focus on what the "players" are doing, not just on the fire.

RISK MANAGEMENT AND ANALYTICS IN WILDFIRE RESPONSE

With the case for analytics made, how does it relate to risk management?

We believe that embracing analytics would help fire management organizations redeem some of their core risk management responsibilities, such as generating better information to support risk-informed decisions and continually improving. For an example of how the Wildfire Risk Management Science Team is applying analytics to support strategic planning on the National Forest System, see the sidebar.

In effect, the goal is to see fire managers assume the role of the "informed skeptic" by:

- Developing a fluency with uncertainty and probability,
- Emphasizing structured decision making,
- Making a commitment to generate and use the best available information, and
- Monitoring and iteratively improving these core competencies over time.

Establishing the use of analytics in risk management cannot be achieved exclusively within the halls of research. It requires an emphasis on people and culture by fire management organizations. We propose three steps to contextualize and distill the pathway to successful application of analytics in wildland fire management:

1. Researchers and analysts providing more and better operationally relevant information on the safety and effectiveness of suppression strategies and tactics;
2. Fire managers using the information formally and transparently in their decision-making processes; and
3. Specialists comprehensively tracking decisions and actions in relation to strategic objectives of wildfire response as well as fire outcomes.

In practical terms, executing these steps requires developing a comprehensive roadmap to enhance analytics while allowing room for innovation, new ideas, and operational compromise. Analytics also has foundational data needs, many of which can be met by obtaining information from fire crews. Beyond this foundational information, however, there is a broader horizon for data

Figure 3—*Game day analytics: a conceptual figure of how analytics can support shooting in basketball, highlighting the best places to shoot from for the coach to tell players.*

capture that could capitalize on advanced technologies such as:

- Smartphone integration,
- Digital and dynamic incident action plans,
- Location-enabled digital radios,
- Smart dashboard cameras,
- Machine-to-machine communications,
- Next-generation computer-aided dispatch,
- Natural language processing, and
- “Gamification” of learning in time and strategy management.

Barriers exist to all of this. Organizations will face issues of data governance, liability, privacy, and security, leading to data policy questions, such as which data to make available, to whom, through what channels, and for what purposes. Limited abilities to effectively manage and standardize the complex data streams collected from various sources decrease the utility and increase the cost of data capture. These are all important issues that can be resolved by establishing feedback loops from data collection to the “informed skeptics” who are analytics users. In this way, the value proposition of data collection is shared and the design of the analytics is iterative.

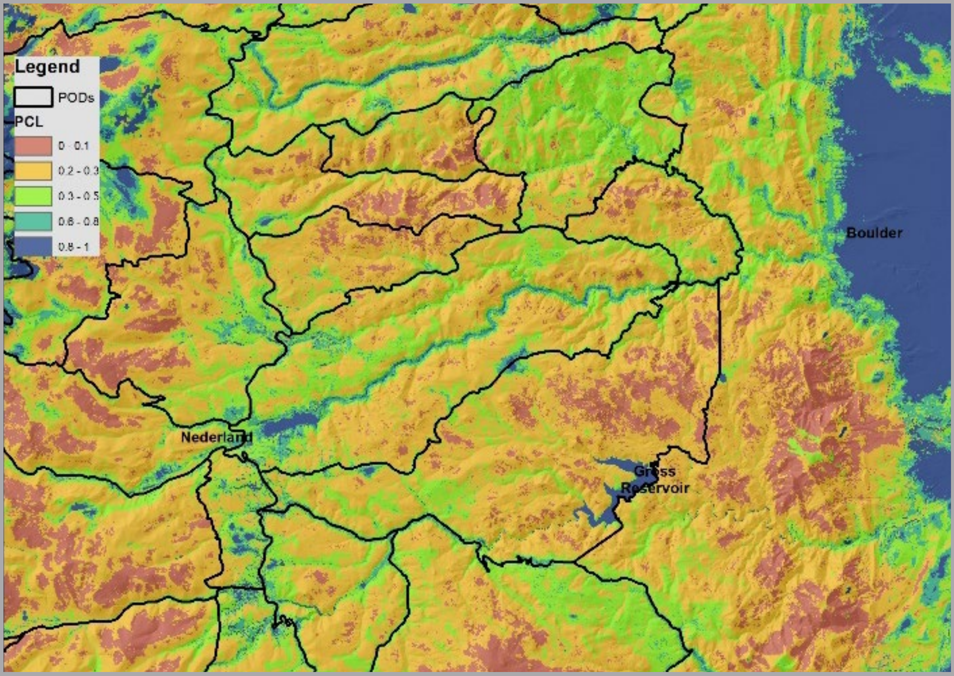
Organizations with stronger analytics capabilities tend to outperform their counterparts.

THE ROAD AHEAD: ANALYTICS NEEDS MANAGERS

We see a future with increased automation and prescriptive analytics recommendations, yet fire management will always be a question of human judgment. Every fire event has unique circumstances and potentially unresolvable uncertainties, hence the focus on decision makers; analytics that

Analytics Complements Expertise: An Example

The two figures below tell a story of advanced analytics supporting expert judgment in fire risk management planning.



On the top is a map of the Front Range of Colorado. The colors show the output of a machine learning model that predicts potential locations for controlling a wildfire (potential control locations, or PCLs), from red/orange for low potential to green/blue for high potential. The model has looked at all previous fire perimeters and picked up the landscape characteristics that usually lead to successful firelines. In this case, the model was trained by Ben Gannon for the Colorado Forest Restoration Institute in support of the Arapaho–Roosevelt and Pike–San Isabel National Forests.

The black lines on the map, however, were not created by the model. They show potential operational delineations (PODs) identified by the fire managers from the two forests. The image on the bottom shows the PCL product being used in workshops to complement local expertise and to support identification of PODs. The product is widely used to support both POD development and incident management through risk management assessment.

Fire management agencies should foster "informed skeptics" who have strong analytic skills but can balance judgment against analysis in decision making.

focuses entirely on what *should* happen is impractical.

This is the point we made through the basketball analogy (figs. 1–3). In analytics, many but not all aspects of expert judgment and organizational wisdom may be closely related to measurable and predictable metrics of performance and risk. Embracing analytics could help to correct an overreliance on expert judgment in making decisions.

A number of hurdles remain: increasing investment in data capture and analysis technology, dealing with data privacy and security issues, and developing better models and decision support tools. However, the bigger challenges may well be in catalyzing organizational and cultural change. Effectuating a data-driven cultural change is a known barrier to widespread adoption of analytics in other fields, including sports.

Using another sports analogy, researchers and analysts must demonstrate to fire managers in advance that enhanced monitoring and data collection (that is, descriptive analytics) are more closely related to watching the film after the game than to Monday morning quarterbacking. Demonstrating the value of predictive and prescriptive analytics to managers will be a challenge for the fire science community. At a critical point, however, better outcomes in terms of operational safety, efficiency, and effectiveness will help to justify the adoption of analytics.

The translation of scientific ideas and insights into practice can be essential for improving decision quality and cultivating stronger risk management processes. Despite the challenges, we see many opportunities for the use of analytics in fire. Similar cycles of the analytics strategy could be pursued for mopup, aviation, burnout operations, and structure protection. Developing core competencies in "informed skeptics" with analytics and cultivating a "Moneyball for fire" paradigm may help fire management organizations on their risk management journey.

LITERATURE CITED

Kooistra, C.; Schultz, C. 2020. Enhanced analytics to support decision making on wildfires: assessing risk management assistance at the Forest Service. Fire Management Today. 78(3): 60–67.

Shah, S.; Horne, A.; Capellá, J. 2012. Good data won't guarantee good decisions. Harvard Business Review. 90(4). *https://hbr.org/2012/04/good-data-wont-guarantee-good-decisions.* (20 February 2020).

Shields, B. 2019. Analytics management: business lessons from the sports data revolution. MIT Sloan School of Management, March 19–20, 2019

Stratton, R. 2020. The path to strategic wildland fire management planning. Wildfire. 29(1): 24–31. *https://www.iawfonline.org/wp-content/uploads/2020/01/Wildfire-2020-01-Strategic-fire-management-Stratton.pdf.* (20 February 2020).

ADDITIONAL READING

Dunn, C.J.; O'Connor, C.D.; Abrams, J. [and others]. 2020. Wildfire risk science facilitates adaptation of fire-prone social-ecological systems to the new fire reality. Environmental Research Letters. DOI: 10.1088/1748-9326/ab6498.

LaValle, S.; Lesser, E.; Shockley, R. [and others]. 2011. Big data, analytics and the path from insights to value. MIT Sloan Management Review. 52(2): 21–31.

McAfee, A.; Brynjolfsson, E.; Davenport, T.H. [and others]. 2012. Big data: the management revolution. Harvard Business Review. 90(10): 60–68.

O'Connor, C.D.; Calkin, D.E. 2019. Engaging the fire before it starts: a case study from the 2017 Pinal Fire (Arizona). Wildfire. 28 (1): 14–18.

Plucinski, M.P. 2019. Fighting flames and forging firelines: wildfire suppression effectiveness at the fire edge. Current Forestry Reports. 5(1): 1–19.

Plucinski, M.P. 2019. Contain and control: wildfire suppression effectiveness at incidents and across landscapes. Current Forestry Reports. 5(1): 20–40.

Thompson, M.P.; Wei, Y.; Calkin, D.E. [and others]. 2019. Risk management and analytics in wildfire response. Current Forestry Reports. 5(4): 226–239.

Vidgen, R.; Shaw, S.; Grant, D.B. 2017. Management challenges in creating value from business analytics. European Journal of Operational Research. 261(2): 626–639.

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Fire Management today

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