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Progress in Wilderness Fire Science: Embracing Complexity

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Wilderness has played an invaluable role in the development of wildland fire science. Since Agee's review of the subject 15 years ago, tremendous progress has been made in the development of models and data, in understanding the complexity of wildland fire as a landscape process, and in appreciating the social factors that influence the use of wilderness fire. Regardless of all we have learned, though, the reality is that fire remains an extraordinarily complex process with variable effects that create essential heterogeneity in ecosystems. Whereas some may view this variability as a management impediment, for others it provides a path forward. As research has shown, embracing fire in all its complexity and expanding its use can help reduce fuels, restore resilient landscapes, and contain costs. Wilderness fire science will continue to play an important role in understanding opportunities for using fire, its role in ecosystems, its risks and benefits, and the influence of risk perception on decisionmaking.

Keywords: wilderness, wildland fire use, prescribed natural fire, risk

Wilderness holds unique scientific value as a reference or benchmark for change because researchers can study ecosystems that are less affected by modern human activities. Early observations of wilderness fire and its important role in sustaining ecosystems led directly to the Leopold Report (Leopold et al. 1963) and the Wilderness Act of 1964, both of which recognized the role of natural ecological processes, including fire, in shaping primitive wilderness landscapes. Shortly thereafter, new federal policies allowed the use of natural fires in wilderness. The earliest wilderness fire programs in the National Park Service began at Sequoia and Kings Canyon National Parks in 1968, at Yosemite National Park in 1972, at Saguaro National Monument in 1971, and at Yellowstone National Park in 1972. The US Department of Agriculture (USDA) Forest Service wilderness fire program was launched in the Selway-Bitterroot Wilderness in 1972. Slowly, other parks and wilderness areas adopted the practice of allowing some natural ignitions to burn with limited or no interference (e.g., Gila Wilderness in 1975, Scapegoat Wilderness in 1981, and Glacier National Park in 1994).

The terminology of wilderness fire has changed many times (Hunter et al. 2014). Originally referred to as "let burn," wilderness fire came to be known as "natural fire management" and, for more than a decade, as "prescribed natural fire." A federal policy review in 1995 emphasized the work done by fire and renamed it "wildland fire use for resource benefit," which in practical use was shortened to WFU, or simply "fire use" (Philpot et al. 1995). Although the practice of WFU was not limited to wilderness, the vast majority of these fires occurred in wilderness areas or national parks. In 2009, a change in federal fire policy guidance (Fire Executive Council 2009) eliminated WFU as a separate category of fire—any natural fire could be managed for multiple objectives, including ecological benefits. This change has spawned references to "AMR (appropriate management response) fires," "multiobjective fires," or simply "managed wildfire" to refer to any fire managed for its ecological benefits. Throughout this article, we use the term "wilderness fire" to emphasize its historical roots in wilderness, whether the fire occurs there or not. Furthermore, we present wilderness fire as essential for responsible land stewardship and as a sustainable strategy for achieving long-term land management objectives.

The *history* of wilderness fire can be found in several compilations and summaries (Lotan et al. 1985, Brown et al. 1995, van Wagtendonk 2007). In 1999, as part of a major conference on wilderness *science*, Agee (2000) reviewed the state of knowledge of wilderness fire and the progress since the first such review 15 years earlier (Kilgore 1986). In his survey, Agee covered the historical evolution of wilderness fire science, the impact of the Yellowstone fires of 1988,

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This article uses metric units; the applicable conversion factors are: meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi; hectares (ha): 1 ha = 2.47 ac.

the drivers of wilderness fires and fire regimes, the value and status of models, and the importance of monitoring.

In this article, we review progress in wilderness fire science in the 15 years since Agee's (2000) review. A state-of-knowledge review is timely and relevant as we celebrate 50 years of the Wilderness Act, and as the practice of wilderness fire appears poised to expand from wilderness to the broader landscape. We begin by examining recent progress and then look to the future and attempt to chart a direction for fire management that capitalizes on the lessons learned from the first 50 years of wilderness fire science. Most of the science we cite and the lessons we glean come from the western United States; this is a direct reflection of the historical geography of wilderness fire.

Recent Progress in Wilderness Fire Science

From Agee's (2000) review, we gleaned four general themes that captured the major research needs for wilderness fire science at that time: (1) the limitations of models and data availability; (2) the complexity of fire (especially recognition of patchiness and synergistic interactions); (3) the landscape context of wilderness and accounting for fire as a landscape process; and (4) the sociological and institutional barriers to expanded wilderness fire. Here, we review progress in each of these areas and attempt to capture lessons relevant to expanding the benefits of wilderness fire into the future.

Models, Tools, and Data

During the past 50 years, the improved ability to predict fire behavior and fire effects has been an important advance for wilderness fire science. At the time of Agee's review, models could predict tree mortality at the stand scale (e.g., Reinhardt et al. 1997). Individual-based gap models (e.g., Keane et al. 1990, Miller and Urban 1999), state-and-transition vegetation models (e.g., Arbaugh et al. 2000), and individual growth-and-yield models (e.g., Dixon 2002) were incorporating fire to allow the study of long-term successional dynamics, all at the stand scale. Still relatively new were models that could simulate landscape-scale fire-vegetation dynamics, and these varied in complexity (Keane et al. 1996, Mladenoff and He 1999, Roberts and Betz 1999, Kurz et al. 2000, Keane et al. 2002, Chew et al. 2004). Also new on the scene was FARSITE (Fire Area Simulator), a spatially and temporally explicit model of fire growth that could be used to predict spread of wilderness fires (Finney 1994). In noting the importance of these models, Agee (2000) lamented that the data required by these newer models were insufficient for most places. Since then, the availability of remotely sensed satellite data, particularly from Landsat, has led to the development of large-scale data sets; the spatial data that were once lacking now exist.

Vegetation and fuels data are critical inputs to fire growth modeling tools such as FARSITE. Their increased availability since 2000 is largely due to substantial investments in the LANDFIRE (Landscape Fire and Resource Management Planning Tools) project (Rollins and Frame 2006). LANDFIRE data include landscape-scale geospatial products describing vegetation, fuels, topography, and fire regimes at a 30-m resolution. Despite being criticized for inaccuracy and a simplistic characterization of vegetation condition (see, e.g., Aplet and Wilmer 2005, Krasnow et al. 2009), LANDFIRE data have the advantages of being consistently derived and readily available for download. In addition to being widely used for operational incident management (Ryan and Opperman 2013), the wall-to-wall coverage of these data greatly facilitates investigations at large landscape scales that are directly relevant to wilderness fire and its management (e.g., Black and Opperman 2005, Miller 2007, Keane and Karau 2010).

The Monitoring Trends in Burn Severity (MTBS) project[1] (Eidenshink et al. 2007) is a particularly valuable and recent contribution to wilderness fire science. Using Landsat data dating back to 1984, MTBS has quantified burn severity—a measure of ecological change—for all known fires larger than 405 ha. These data allow the study of variability and patchiness resulting from fires, and because these data are consistently produced, they are well-suited to broad geographic investigations (Dillon et al. 2011) (Figure 1). In addition, these data are superior to many fire perimeter data sets (e.g., Kolden and Weisberg 2007, Shapiro-Miller et al. 2007) and can be used to investigate influences on area burned, fire size, and fire spread (e.g., Haire et al. 2013, Morgan et al. 2014, Parks et al. 2015). As with LANDFIRE, MTBS data are readily accessible and available at a 30-m resolution. Like LANDFIRE, criticisms include the heavy reliance on remotely sensed data over field-based data. Nevertheless, MTBS has been a boon for fire research in wilderness, where field-based data collection is especially time-consuming and challenging.

Another new data resource for wilderness fire research is the Moderate Resolution Imaging Spectroradiometer (MODIS) fire detection points (NASAMCD14ML product, Collection 5, Version 1). These satellite data contain the date and location of actively burning pixels since 2000. Although they are at a coarse spatial resolution (pixel size of 0.25 km^2), they have a fine temporal resolution (two sensors, twice a day) and can be used to develop consistent spatiotemporal fire progression information that is often lacking for remote wilderness fires. Spatial interpolation methods can link 30-m pixels within a fire perimeter to an estimated day of

Management and Policy Implications

The past 50 years of wilderness fire science has shown the benefits that accrue from fires that burn on their own terms and under less-than-extreme conditions. Fuel loads are lower, fire behavior is moderated, fire sizes are limited, forest structural diversity and wildlife habitat are improved, and fuel breaks are created that can help in the management of today's long-duration fires. Although improvements in modeling and data have increased our ability to support decisionmaking and incident management, inadequate monitoring and poor reporting of management activities hinder wilderness fire research. To effectively justify and support wilderness fire, we will need to adapt existing tools and develop new approaches for evaluating the long-term risks and benefits of wilderness fire. Although current Federal Wildland Fire Policy (Philpot et al. 1995, Douglas et al. 2001) provides the rationale and flexibility to expand wilderness fire use, achieving its full potential will require bureau policies that overcome the numerous institutional barriers that continue to constrain decisionmakers. Incentives are needed to encourage fire use by managers who have received advanced training and employ skilled and well-staffed fire use management teams. Even with adequate policies, uncertainties and complexities associated with climate change and risks accompanying an expanding wildland-urban interface will continue to challenge this expansion.

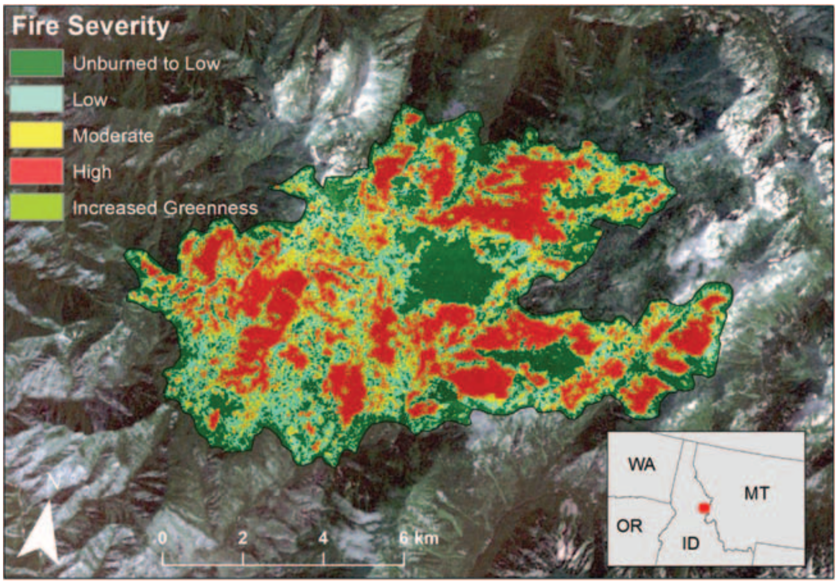

Figure 1. Remote sensing data derived from satellite imagery have greatly advanced our ability to conduct research on wilderness fires. Shown here are consistently derived and readily available data describing categories of burn severity as differences in the Normalized Burn Ratio index between prefire and postfire images. Data shown are from the MTBS[1] project for a fire in 1988 in the Selway-Bitterroot Wilderness.

burning and associated weather information (Parks 2014).

In 1999, the lack of good weather information was perceived as a barrier to accurate forecasting of fire behavior as well as to reconstruction of historical events (Agee 2000). Certainly, weather data have improved, both as a result of deploying more weather stations and improved modeling and interpolation, but it is not clear that our ability to forecast weather or future fire behavior has improved concomitantly. Improvements in weather forecasting would no doubt improve the confidence that managers will need to allow fires to burn, but limitations in predictive ability may not be the barrier to wilderness fire that it was once perceived to be. Today, approaches using historical weather to model probabilistic outcomes (e.g., Finney et al. 2011a, 2011b) may provide sufficient decision support for wilderness fire.

Researchers have been making better use of historical weather data to study the drivers of past fires and fire regimes. In particular, gridded weather and climate products derived from meteorological station data (e.g., Daly et al. 2000) have been crucial for investigating the geography of fire and the drivers of fire regimes. These data have been used to tease out the complex influence of climate on fire regimes from other biophysical variables (e.g., topography) and have recently highlighted the value of wilderness areas as natural benchmarks. For example, one recent study revealed patterns in anthropogenic influences on wildland fire probability corresponding with large wilderness areas in the western United States (Parisien et al. 2012), and another pointed to stronger fire-climate relationships in wilderness compared with those in human-dominated areas (Parks et al. 2014).

In addition to the increased availability of these landscape-scale data, new algorithms and platforms have operationalized the application of fire behavior models. FlamMap, for example, maps fire behavior characteristics at a landscape level, allowing spatial variability in fire behavior to be examined (Finney 2006). FARSITE, as previously mentioned, simulates spatially and temporally explicit fire growth as an expanding fire front (Finney 2004). Two other modeling tools, FSPro (Finney et al. 2011b) and FSim (Finney et al. 2011a), support fire incident management decisions and national fire management strategic planning and budgeting. Although not specifically geared to supporting decisions to allow fires to burn, these tools have been used in a few cases to justify and support wilderness fire. For example, FARSITE has been used to quantify the effectiveness of wildland fire as a fuel treatment (Cochrane et al. 2012) as well as the ecological restoration opportunities that are lost when fires are suppressed (Miller and Davis 2009, Miller 2012). FSim has been used to identify when and where ignitions starting in a wilderness setting are least likely to escape wilderness and affect the wildland-urban interface (WUI) (Scott et al. 2012, Barnett 2013) (Figure 2).

As the fire management community has embraced risk as a framework for making decisions (Wildland Fire Executive Council 2009), these new modeling platforms have found utility in fire risk analysis. Quantitative risk analysis approaches take advantage of fire behavior modeling tools to estimate likelihood, fire effects models to estimate susceptibility, and valuation techniques to estimate net value change (Finney 2005). In the wilderness context, however, this framework remains problematic for several reasons. One is that values related to wilderness character are difficult, if not impossible, to quantify. Another is that it is easier to quantify short-term risks than long-term consequences of management. Indeed, incorporating the long-term risks and future opportunity costs that accrue after suppression decisions has proven to be a nontrivial challenge (Houtman et al. 2013, Miller and Ager 2013).

Today, knowledge of fire behavior and fire effects continues to be hindered by a lack of monitoring information and a lack of accurate records. Monitoring of fire effects over time has been inconsistent. Although MTBS has helped enormously, it is a poor substitute for field-based fire effects monitoring such as that instituted by the National Park Service (National Park Service 2003). Inconsistent and poor reporting of fire management activities in wilderness, combined with the logistical challenges of working in remote settings where research activities must conform to wilderness character, leave wilderness underexploited as a natural laboratory. Continued suppression in most wilderness areas further compromises its value as a natural benchmark. Although wilderness designation has been used to infer the influence of wilderness fire management (Haire et al. 2013, Morgan et al. 2014), we still cannot answer how well we are managing fire as a natural process or the degree to which ecosystems have been affected by past suppression (Collins and Stephens 2007).

Complexity and Variability of Fire

A handful of early fire histories (Heinselman 1973, Habeck 1976, Kilgore and Taylor 1979) showed the important role that fire has played in a few high-profile wilderness ecosystems and served as the early

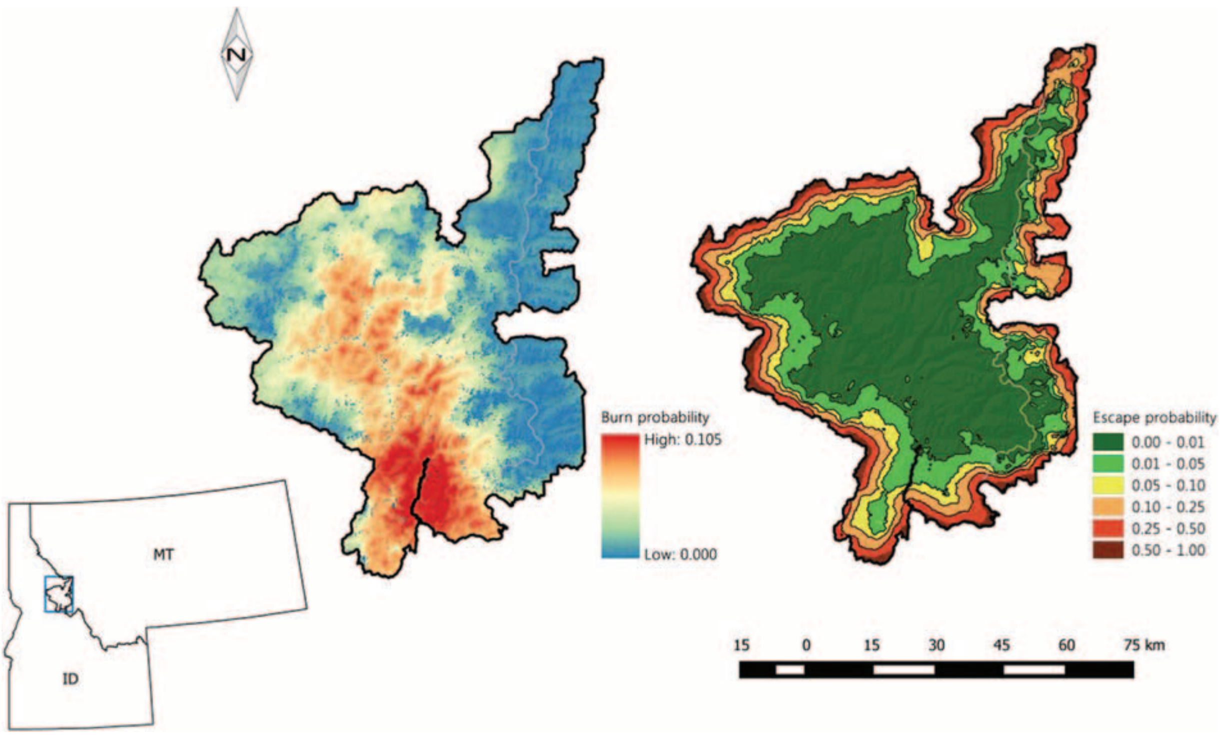

Figure 2. Fire behavior modeling tools can be adapted for spatial risk assessments and decision support for wilderness fires. These maps were developed for the Selway-Bitterroot Wilderness with model output from FSim, which generates perimeters for many thousands of simulated fires occurring under statistically generated weather streams (Finney et al. 2011b). On the left is a map of burn probability, or likelihood of fire, a key component of risk. The map on the right was derived from FSim output using methods from Barnett (2013) to depict the probability that ignitions will escape the wilderness. Fires that ignite in the large interior zone shown in dark green have little chance of spreading beyond the wilderness boundary. (Courtesy of Kevin Barnett.)

impetus for the wilderness fire program. Subsequent fire history studies have included a broader array of ecosystems and locations and shown how varied the role of fire can be, even within a single forest type (e.g., Beaty and Taylor 2001, Taylor and Skinner 2003, North et al. 2005, Collins and Stephens 2007, Scholl and Taylor 2010). We have learned that fire can function very differently due to specifics of regional climate, ignition availability, and local topography (Heyerdahl et al. 2001, Kellogg et al. 2008, Falk et al. 2011). All this variability can make it difficult to characterize the ecological role of fire.

Defining what we mean by a "characteristic fire regime," both as a description and a prescription, has become much more sophisticated but remains an intellectual challenge (Krebs et al. 2010). Through the 1980s, the mean or median value of fire frequency was commonly used to describe the role of fire. However, as Agee (2000) and others (e.g., Sugihara et al. 2006) have noted, the fire regime has multiple parameters, including frequency, intensity, seasonality, and extent. Although we now recognize the multiparameter nature of fire regimes, we still base classifications on frequency and severity (e.g., LANDFIRE); such discrete classifications no longer seem adequate to capture the wide ranging role of fire in ecosystems (Table 1).

At the time of Agee's writing, a multiparameter "historical range of variability" (HRV) of the ecological process of fire held promise as a guidepost to assist management (Morgan et al. 1994). The idea behind HRV was that the best models of sustainable ecosystems are the dynamic, disturbance-influenced ecosystems of the past. Sustaining ecosystems into the future requires sustaining ecological processes, such as natural disturbances, that governed those ecosystems historically (Aplet and Keeton 1999). In practice, applying the HRV concept has proven challenging. For example, Fire Regime Condition Class (FRCC) (Hann and Strohm 2003) was developed to describe ecosystem departure from a characteristic disturbance regime, but its characterization of "HRV" as a static distribution of vegetation structural stages fails to account for ecosystem dynamics, or even a range of historical conditions (Aplet and Wilmer 2005). Even if we were more successful in describing characteristic HRV, climate change, changing land use patterns, and restrictive air quality regulations have now drawn its utility into question.

The late 20th century saw the scale of ecological investigations evolve from the stand to the landscape. In 1985, at the time of Kilgore's state-of-knowledge review, fire ecology was focused on the stand scale. By the time of Agee's 2000 summary, researchers were studying fires at landscape scales. For example, large landscape-scale fire history studies in wilderness were increasing our understanding of the drivers of fire regimes (e.g., McKenzie et al. 2000, Heyerdahl et al. 2002, Rollins et al. 2002), and variability and patchiness had been accepted as core principles of landscape ecology (Turner 1989). As more fires have burned since then, inside and outside wilderness, the importance of variability and patchiness has become impossible to ignore. For example, before 2000, mixed-severity fire was recognized but typically regarded as an aberrant category of fire. With the increased prevalence of fires on the landscape, the evidence of a mixture of fire severities and patch sizes is everywhere.

Table 1. Comparison of the fire regime classification developed by the USDA Forest Service (Hardy et al. 1998) using only fire frequency and severity to the extended definition offered by Krebs et al. (2010).

USDA Forest Service fire regimes	Determinants of an extended definition of fire regimes
Fire Regime I: 0–35 yr frequency, low severity Fire Regime II: 0–35 yr frequency, stand replacement severity Fire Regime III: 35–100+ yr frequency, mixed severity Fire Regime IV: 35–100+ yr frequency, stand replacement severity Fire Regime V: 200+ yr. frequency, stand replacement severity	Factors affecting the condition of fires • Fuel characteristics (quantity, flammability, connectivity, compactness, classification . . .) • Meteorology (fire weather . . .) • Causes of fires (ignition sources . . .) • Anthropogenic conditions (fire policy and legislation, prescribed fire, burning motives and techniques . . .) • Synergisms (logging techniques, exceptional droughts . . .) Factors affecting when, where, and which fires burn • Temporal distribution (chronology, duration, fire-free interval, fire rotation, seasonality . . .) • Spatial distribution (extent, fire size, shape of fires, ignition points, area burned per decade . . .) • Fire characteristics (vegetation type, vegetation layer, fire behavior, intensity . . .) Factors affecting immediate effects • Ecological severity (mortality, depth of burn . . .) • Severity for society (costs, damage, victims . . .)

The USDA Forest Service system is useful in its simplicity but leaves out a number of factors responsible for the complexity of fire regimes.

Ecologists have long recognized the potential for fire to interact synergistically with other ecological disturbances (White and Pickett 1985), but as Agee (2000) noted, we lack the ability to quantify or predict these synergisms. Despite intensive study of some of the largest insect outbreaks ever observed over the past 15 years, not much has changed. As reviewed by Jenkins et al. (2014), we have seen increasing synergies and interacting effects with other disturbances (insects and disease) since 2000, especially as climate strongly mediates each of these processes. Our ability to predict these effects, however, remains elusive (Hicke et al. 2012).

Fire as a Landscape Process: Self-Limiting Effects and Resilience

Wilderness fires over recent decades have revealed important long-term landscape-scale effects and provided numerous anecdotal observations by managers that landscapes are less flammable after a fire, at least until vegetation regrows and fuels accumulate again. Ecological theory posits that this pattern-process dynamic confers ecosystem resilience to subsequent fires and other disturbances (Peterson 2002). A number of recent studies are providing support for landscape ecological theory and quantifying the self-limiting effects of fire in terms of the severity, extent, and occurrence of subsequent fires. Although these self-limiting effects are certainly not unique to wilderness, wilderness contains the majority of observations for studying and quantifying these effects.

The burned area created by a fire can temper the burn severity of a subsequent fire and help restore landscapes that are resilient to frequent, low-severity fires. Holden et al. (2010) studied areas burned twice by fire across a range of vegetation types in the Gila-Aldo Leopold Wilderness Complex in New Mexico and found that the second fire tended to burn at lower severity than the initial fire. Parks et al. (2014) confirmed this, finding substantially lower burn severity for previously burned areas in this same study area as well as for the Frank Church Wilderness in Idaho. In the Illilouette Creek basin of the Yosemite Wilderness, a mix of factors influenced the severity of reburns (van Wagtendonk et al. 2012), but reburn severity was consistently lower where fires had been allowed to burn in the past. The study also revealed emerging complexities: where fire severity was high, a vegetation type change often occurred that would perpetuate subsequent high-severity fires.

The burned area created by a fire can act as a fuelbreak that limits the progression, and therefore the extent, of subsequent fires. Results from four different wilderness areas (Gila-Aldo Leopold, Frank Church, Selway-Bitterroot, and Bob Marshall) show that previous fires limit the progression of subsequent fires but that this effect diminishes with time since the initial fire and with fire weather (Teske et al. 2012, Parks et al. 2015). In the Yosemite Wilderness, Collins et al. (2009) similarly found that the ability of burned areas to constrain the extent of subsequent fires depended on time since initial fire and fire weather. These studies provide valuable quantitative information for fire managers who are looking to opportunistically use these previously burned areas (also known as "burn scars") as fuel breaks in the safe and effective management of subsequent wilderness fires.

Fires can also reduce the ignitability of a landscape, whereby the resulting burned area is left with insufficient fuels to support the ignition of subsequent fires. Reduced fire occurrence lessens the need for initial attack resources and continued suppression operations, leading to cost savings and lower exposure to risk in subsequent years. Although not widely studied, this effect has been noted in several studies (Lutz et al. 2009, Scholl and Taylor 2010, Miller 2012) and recently quantified for four large study areas (Parks et al. 2015).

Mid- to lower elevation dry forests that historically experienced frequent fires have been particularly affected by fire exclusion (Noss et al. 2006). In some cases, it appears that natural fire can be reintroduced to these ecosystems after a long period of fire exclusion, even if fuels have accumulated to hazardous levels and vegetation structure has changed. A study in the Bob Marshall Wilderness in Montana recently showed that these unlogged, fire-excluded forests possess a "latent resilience" to reintroduced fires and suggested that a viable prescription for restoration may be simply to allow lightning-ignited fires to burn (Larson et al. 2013). A similar suggestion was made after a study comparing historical fire sizes and frequency with those observed in the modern fire use period (Collins and Stephens 2007). Despite initial concerns about potential mortality of large ponderosa pine (*Pinus ponderosa*) trees after fires in 2003 in the Bob Marshall Wilderness (Keane et al. 2006), researchers found less mortality than expected when they followed up 6 years later (Leirfallom and Keane 2011). This resistance of large fire-adapted trees has also been seen in the Southwest in the Gila and Saguaro wilderness areas. There, Holden et al. (2007) found that long fire-free intervals do indeed alter forest structure, but with repeated fires, small diameter trees can be killed without significantly affecting the density of the largest trees. Other work has shown that forest structure can be restored with fires that burn intensely enough to kill trees (Fulé and Laughlin 2007).

Social and Institutional Barriers to Wilderness Fire

Social science investigations related to fire tend to focus on the built environment where humans most frequently interact with and are affected by fire (McCaffrey et al. 2013). Only a few studies of wilderness visitors have examined human relations with fire in the wilderness context (Stankey 1976, McCool and Stankey 1986).

However, some very useful social science research has investigated the factors influencing the decision to suppress or allow a fire to burn. Surveys and interviews support the conventional wisdom that the location and timing of ignitions are important factors considered by managers when they assess the short-term risks of fire (Doane et al. 2006, Williamson 2007): ignitions closer to the wilderness boundary and early in the fire season are more likely to be suppressed. Lack of public support for wilderness fire is also cited by managers as an obstacle to allowing fire to burn, and whereas there does appear to be tension between the public's support for wilderness fire and community protection concerns (Winter 2003, Kneeshaw et al. 2004), trends in attitudes of wilderness visitors suggest increasing support for the use of fire in wilderness (Knotek 2006).

Research has also revealed the strong influence of factors internal to the federal agencies (Steelman and McCaffrey 2011). Decisions to allow fires to burn are subject to much higher levels of scrutiny than decisions to suppress, and a variety of institutional factors influence the use of fire in wilderness, including insufficient internal human resource capacity, lack of internal agency support, concerns about career advancement in the event of a negative outcome, and inadequate individual commitment to using natural fire (Doane et al. 2006, Williamson 2007, Black et al. 2008). The daunting implication of these constraints, barriers, and disincentives is that the success of a wilderness fire program may hinge on the beliefs, commitment, and risk aversion of an individual line officer.

Extending the Benefits of Wilderness Fire

Collectively, the foregoing suggests a need for an expansion of wilderness fire and the science to support decisions to use it. Where wilderness fire has been encouraged, research has demonstrated desirable results. Fuel loads are lower, fire behavior is moderated, fire sizes are limited, forest structural diversity and wildlife habitat are improved, and fuel breaks have been created that can help in the management of today's long-duration fires (e.g., Figure 3; Holden et al. 2007, Collins et al. 2009, Parks et al. 2014, 2015).

Figure 3. Ignited by lightning in the Selway-Bitterroot Wilderness, the 2013 Gold Pan fire approached the historic Magruder Ranger Station adjacent to the Wilderness. Despite burning under extremely dry conditions and growing to over 40,000 acres, fires from previous years had reduced fuel loads so that the Gold Pan fire did not pose a serious threat to the Ranger Station. (Photo by Steve McCool.)

The success of wilderness fire stands in stark contrast to the more typical response, where fire is suppressed unless it cannot be due to weather. Initial attack is successful 98% of the time; however, the 2% of ignitions escaping initial attack burn under the most extreme conditions, exhibit the most extreme fire behavior, and have the greatest ecological and economic impacts (Calkin et al. 2005). Under these conditions, fire behavior can be explosive, producing large patches of uncharacteristically severely burned vegetation (e.g., Graham 2003). The current situation, as aptly described by Forest Service Deputy Chief Jim Hubbard (pers. comm., Oct. 16, 2002) is one in which "we have two kinds of fire…the kind we put out and the kind we get out of the way of." Strategic fuels management coupled with a high initial attack success rate can perhaps exclude damaging effects of fire from human communities, but implementing fuels management at the scales that are necessary to be effective is infeasible (North et al. 2012, 2015). One way out of this untenable situation is to focus efforts on expanding a third kind of fire, wilderness fire: the kind we *could* put out because the weather is less than extreme, but we *choose* not to.

Climate change increases both the challenges and the importance of maintaining or restoring fire regimes. What has been considered extreme fire danger in the past will become more the norm by the middle of this century (Brown et al. 2004). Fire seasons will lengthen and involve more landscape area (Miller et al. 2011). In an attempt to avoid extreme fire behavior and adverse fire effects, managers may be increasingly inclined to suppress fires. However, wilderness fires have taught us that when fires are allowed to burn under less-than-extreme weather, they produce more heterogeneous and desirable conditions (Collins et al. 2009, Collins and Stephens 2010, Meyer 2015). Furthermore, ecosystems where fire has been allowed to occur naturally may be better prepared to cope with a changing climate (Allen et al. 2002). Forests whose tree densities have been reduced by previous fires may be less vulnerable to drought and insect attacks (Guarín and Taylor 2005, Fulé 2008), and the heterogeneity in forest structure and composition resulting from past fires may limit the extent of insect-caused mortality (Bentz et al. 2009).

As noted earlier, social science research has revealed a number of cultural and procedural obstacles to wilderness fire. Much of the wilderness fire management expertise that developed over the past 40 years has been lost due to retirement, and the staff that is now in charge may not be as experienced or comfortable with managing a fire that might burn for weeks or months. Whether training can fill this experience void remains to be seen (Kobziar et al. 2011). An expanding WUI will expose more people to fire. Concerns about damage to inholdings and infrastructure, and procedural requirements of smoke management remain serious disincentives. Concerns about decisionmaker liability and lack of professional incentives to promote fire can also be barriers to restoring and maintaining fire-resilient landscapes (Calkin et al. 2011, Steelman and McCaffrey 2011).

To capitalize on the benefits of wilderness fire, it will be necessary to look beyond the boundaries of wilderness and address concerns at the landscape scale. Arno and Brown (1989) proposed a three-zone fire management strategy, in which landscapes would be segregated into a wilderness fire zone, a residential zone (i.e., WUI), and a zone in between where fuels should be managed through forestry. Aplet and Wilmer (2010) expanded on this idea to argue for restoration forestry beyond the WUI and a dramatic expansion of the wilderness fire zone to include all areas sufficiently distant from communities that fire is not an immediate concern.

Extending the benefits of fire beyond wilderness is now well supported by federal fire policy, which states,

> Fire, as a critical natural process, will be integrated into land and resource management plans and activities on a landscape scale, and across agency boundaries. (Philpot et al. 1995, p. 5, Douglas et al. 2001, p. 23)

The 2009 *Guidance for implementation of Federal Wildland Fire Management Policy* allows that any fire "may be concurrently managed for one or more objectives and objectives can change as the fire spreads across the landscape" (Fire Executive Council 2009, p. 7) thus providing managers with more flexibility than ever to encourage fire where it is achieving objectives. Actually realizing the promise of federal policy, though, will require overcoming the previously described barriers. Among the changes needed are increased recognition of the importance of fire in land and resource management plans, new incentives and performance measures to encourage managers to use fire, enhanced training for fire managers in the use of fire and the establishment of highly trained and well-staffed fire use management teams, and incentives for air quality regulators to facilitate the use of fire to achieve ecosystem and long-term public health benefits. Furthermore, more research, especially social science research, is needed to determine how to overcome these barriers.

Risk Analysis: Framing a Wilderness Fire Research Agenda

The concept of risk has become central to fire management to the point that it now serves as a framework for a national cohesive strategy for fire management (Wildland Fire Executive Council 2014). Some of the earliest studies about wildland fire risk focused on how managers and homeowners perceive and assess risk (e.g., Gardner et al. 1987, Cortner et al. 1989). In recent years, we have seen an increasing sophistication in how fire risk is assessed (Miller and Ager 2013). Risk is understood to be composed of likelihood (or probability of occurrence), intensity, and effects, which can be positive or negative. As such, it is an expectation of loss or benefit (Finney 2005).

This conception of risk might provide a framework for realizing the benefits of expanded wilderness fire in the future. For example, managing fire in a landscape context requires understanding the likelihood of fire and its expected behavior across landscapes. Quantifying effects as positive or negative requires understanding the consequences of fire under different conditions, including less-than-extreme weather. And, expanding wilderness fire will require understanding and addressing perceptions of risk among managers and the public. We use this framework to offer the following research agenda for wilderness fire science:

1. *Use our understanding of the likelihood of fire and its expected behavior across large landscapes to identify opportunities for wilderness fire.* Risk analysis tools are commonly used to map where fire is likely to cause damage or harm and to quantify those damages. However, these same tools can be adapted for a different use: to identify where and when opportunities exist for wilderness fire. For example, existing risk analysis tools have recently been used to determine where ignition opportunities can be exploited (Scott et al. 2012, Barnett 2013). These approaches can generate maps that show "windows of opportunity" that can be used during the size-up of new incidents. Even a small wilderness area may have a short window of opportunity late in the fire season. Furthermore, these approaches could reveal where changes to landscapes from past fires present new opportunities for wilderness fire. For example, in Colorado, the 35,000-ha High Park Fire in 2012 may have created opportunities for wilderness fire in the 3,700-ha Cache La Poudre Wilderness, previously thought to be too small to manage fire. Where opportunities for wilderness fire are lacking, this information can help inform the ongoing unresolved debate about restoring natural fire regimes with prescribed fire in wilderness (Knotek et al. 2008).

2. *Study the effects of the "third kind of fire" that burns under less-than-extreme conditions.* The few fires that we choose *not* to put out and instead allow to burn for long durations can provide us with empirical data that are otherwise unavailable. As discussed earlier, we have made considerable progress in our understanding of fire as a landscape process, especially where we have had the opportunity to observe reburns and interacting fires. When fires burn under a wide variety of weather and landscape conditions, they are likely to have a wider range of ecological effects, and research suggests that these effects fall within the natural range of variation (Meyer 2015). Although this recent empirical work has yielded very valuable and useful information, more settings and more fires need to be examined. Although research often focuses on the conditions that drive rapid spread or extreme fire behavior, we can use fires that burn under more moderate conditions to learn what drives the quiescent periods during a long-duration fire. Similarly, patches of high-severity fire understandably garner a lot of attention, but the less severely burned or unburned patches are equally, if not more, important features to study as they potentially serve as refugia critical for postfire recovery (Kolden et al. 2012, Berry et al. 2015).

3. *Develop better methods for a full, balanced accounting of risks and benefits.* We have yet to populate a complete "balance sheet" for fire and are therefore unable to weigh the benefits and costs of wilderness fire against the benefits and costs of suppression. A full accounting of the risks and benefits would help ensure that every decision,

including those that defer risk into the future and forgo the potential benefits of wilderness fire, is justified. Conceptually, the risk framework can accommodate such a comprehensive and balanced accounting of fire. Practically, however, this remains a challenge. We need innovative econometric approaches that can quantify the long-term opportunity costs and benefits of management as well as the short-term ones.

4. *Investigate how people perceive and react to fire risk.* Embracing wilderness fire requires that we see beyond the present moment and choose to accept some level of risk now in favor of deferring that risk to the future. Unfortunately, we understand very little about how risk is perceived and used in making choices. Among managers, we need to understand a lot more about what motivates fire management decisions. Among members of the public, we need to understand how their perceptions and attitudes vary and what changes in conditions or policies affect those perceptions.

Conclusion

In the 15 years since Agee last summarized the state of wilderness fire science, much has changed while much remains the same. Agee exhorted scientists and managers to conceive of wilderness not as an island but as part of a linked landscape; today, we understand wilderness to be part of a larger landscape, which is affected by the process of fire. Agee also called on scientists to incorporate patchiness into models of fire behavior; current landscape fire models can reflect the heterogeneity of burning conditions and resultant patchiness that their antecedents could not. Indeed, the understanding of fire as a heterogeneous process at all scales is one of the great advancements of the past 15 years. Even so, fire management practices today do not appear to match our ecological understanding. Few managers are keen to manage long-duration fires that grow beyond jurisdictional boundaries, exhibit unprecedented fire behavior, or leave behind fire effects that span the entire spectrum of severities.

Since the establishment of the first wilderness fire programs, fire science has matured and has expanded in its study of fire behavior across variable landscapes and regions and the resulting variability in fire regimes. Consistent through this transition, though, was the belief that the role of science was to reduce uncertainty in our understanding of fire to improve the ability of managers to predict fire effects and fine-tune prescriptions. Reducing uncertainty would provide managers with the confidence they need to predict fire behavior and expand the use of wilderness fire. Although much has been learned about fire behavior and fire effects in the ensuing years, we may be no closer to the elusive predictions. Instead, it seems that the more we learn, the more complex the story becomes. All this complexity leaves us challenged to describe an appropriate fire regime for a particular wilderness or the likely ecosystem responses to fire. Fire science once focused on increasingly precise characterizations of fire return intervals and the tidy categorization of fire regimes, but we now understand fire to be highly variable in space and time, leaving the manager with a host of questions and imagined scenarios. Indeed, Agee (2000, p. 17) observed,

> Natural resources science often does not provide specific answers to operational problems. At best, it may provide limits or boundaries on uncertainty, or it may increase the uncertainty of the manager's domain. This may be very pleasing to a scientist, but it may leave the manager with a longer list of what might go wrong.

Uncertainty does present challenges to the manager who is looking for simple answers, but for others, it presents a path forward. If there is one thing we have come to appreciate in the past 15 years, it is that although there are characteristic patterns of fire effects for different vegetation types and biogeographical regions, fire and fire effects are highly heterogeneous (see, e.g., Romme 2005). Rather than trying to achieve greater control over fire or feeling bewildered by the physical complexity of fire, we might instead embrace the lessons of the first 50 years of wilderness fire: the imprecision of wilderness fire yields precisely the heterogeneity that is essential to ecosystem resilience. By accepting this imprecision, managers can promote the heterogeneity that will become increasingly important in an era of changing climate and increased fire activity.

Regardless of our current state of knowledge, decisions to allow fire will be made as they always have been— by individuals who believe it is the right thing to do for the resource. These decisions have taken a tremendous amount of courage, and wilderness fire science owes its success to those managers who have made these difficult calls (Agee 2000). As Miller (2014, p. 24) concluded recently:

> The past 50 years have shown that the decision to allow a fire to burn has always been a difficult one to make. As environmental and social trends complicate the context for wilderness fire management over the next 50 years, this decision will only get more difficult. The future of wilderness fire management programs may now depend on adding to the knowledge that has developed over the past 50 years with research as well as an unwavering commitment by individuals to managing this keystone natural process.

The success of wilderness fire and wilderness fire science depends on supporting and rewarding those managers who stand up and make the tough decisions. Science will play an important role in developing the tools to support those decisions, but science alone cannot solve the problem.

Endnote

1. For more information on the data from the MTBS project, please see www.mtbs.gov.

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