JFSP Final Report

Quantifying the effectiveness and longevity of wildland fire as a fuel treatment

Project 12-1-03-19

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October 1, 2015

Abstract

This project addressed JFSP project announcement FA-RFA-12-0001, task statement #3 “Fuel treatment effectiveness.” The project quantified the effectiveness of wildland fire as a fuel treatment, as well as the longevity of this effect. The project was divided into three distinct parts, each representing different aspects of fire’s role as a fuel treatment. Specifically, we quantified the ability of fire to limit the occurrence (Objective 1), progression (or extent) (Objective 2), and severity (Objective 3) of subsequent fires. We evaluated hundreds of wildland fire treatments from multiple study areas that spanned a wide range of environmental conditions and represent a diversity of vegetation types. Geospatial fire atlases spanning 1972-2012 were developed and included both fire perimeters and satellite-inferred fire severity. For objectives 1 and 2 (occurrence and progression), four large areas were analyzed. For objective 3 (severity), data from two large study areas were analyzed. Results provide land managers with quantitative information about fire’s ability to reduce future fire occurrence, progression/extent, and severity. This information is critically necessary for formulating an appropriate management response to wildland fire events, especially as recent changes in policy and climate will likely result in landscapes with more fire and repeated burns.

Background and Purpose

Wildland fires are not commonly thought of as a fuel treatment; however, because fire consumes fuel and alters vegetation structure, they have great potential to serve as fuel treatments in much the same way as more traditional means (e.g., mechanical or prescribed fire). As an example, some fire managers opportunistically use previously burned areas (aka “fire scars”) as fuel breaks in the management of subsequent fires (C. Farris, pers. comm.). Currently, wildland fires treat substantially more area on our public lands (6.8 million acres of wildland fire/year, 10-year avg.) (NIFC 2010) than traditional mechanical and prescribed fire treatment strategies combined (4 million acres/year, 15-year avg) (USDA Forest Service 2003b). The land area treated by wildland fire is expected to increase along with increases in fire frequency associated with climate warming (Krawchuk et al. 2009) and recent revisions to federal fire policy that allow the management of fire for multiple objectives.

To exploit a previously burned area as a fuel treatment, managers need to anticipate how effectively it may limit the occurrence, spread, and behavior of subsequent wildland fire. Unfortunately, observations of how wildland fires interact with burned areas are largely anecdotal and can vary widely (S. Hoyt, pers. comm.). In some cases, burned areas may appear to affect the progression and ultimate extent of a wildland fire. In other cases, burned areas appear to affect the fire behavior and severity without affecting a wildland fire’s extent. Drawing conclusions about the treatment effect from a previous fire based on such anecdotal observations is very difficult because other factors such as topography can influence fire spread and behavior, as can management actions such as backfiring. Furthermore, any treatment effect is likely to diminish over time as vegetation re-grows and fuels re-accumulate in the burned area, with recovery rates differing by ecosystem type and treatment severity (Keeley et al. 2008, Freeman and Kobziar 2011). Another complicating factor is that extreme fire weather may override the effect of a previously burned area as a fuel treatment (Moritz 2003). Managers weighing the long term consequences of a fire against the short term risks and costs need better scientifically robust information to anticipate the ability of a previously burned area to function as a fuel treatment.

The purpose of fuel treatments is to alter fuel conditions so that future wildland fires are less difficult, disruptive, and destructive (Reinhardt et al. 2008). Therefore, fuel treatments are usually considered effective if they limit extreme fire behavior. Wildland fire, however, can function as a fuel treatment in a few different ways. First, a fire may limit the occurrence of subsequent fires; that is, the consumption of flammable fuels by the wildland fire may leave the resulting burned area with insufficient fuels to support an ignition. Second, the burned area created by a wildland fire may act as a fuel break that limits the progression, and therefore the extent or size, of subsequent fires. Third, in instances when the wildland fire treatment does not limit the extent of a subsequent fire, the burned area created by a wildland fire treatment may temper or moderate the fire severity of a subsequent fire. These three ways to measure fuel treatment effectiveness (occurrence, extent, and severity) have important and different implications for management. Reduced wildland 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. The fuel break effect can help to limit the extent of subsequent fires and may help incident managers more safely and effectively manage wildland fire for multiple objectives. Lastly, areas that reburn with reduced severity may require less post-fire rehabilitation and in some cases may even serve to restore landscapes that are resilient to frequent, low-severity wildland fires.

Even for the more traditional fuel treatment strategies (mechanical and prescribed fire), quantifying treatment effectiveness has been difficult because it is relatively rare for fires to actually spread into a treatment (Omi and Martinson 2002, Rhodes and Baker 2008). In recent years, steady increases in implementation of treatments and area burned have provided new opportunities to empirically quantify fuel treatment effectiveness (Safford et al. 2009, Wimberly et al. 2009, Hudak et al. 2010). In spite of these increased opportunities, very few studies have explicitly examined wildland fire as a fuel treatment, making this line of research both timely and novel.

Prior to the study conducted here, only a handful of studies had investigated the degree to which wildland fire acts as effective fuel treatments in limiting the occurrence, size, and/or severity of subsequent fires. Krawchuk et al. (2006) implicitly tested and confirmed that recently burned landscapes experienced fewer fire initiations in the mixed-wood boreal forest, Canada. Collins et al. (2009) studied an upper mixed-conifer forest in the Sierra Nevada, California and found that wildland fire affected the size and severity of subsequent fires. This treatment effect was evident when the time between the fires was short (<9 years). The treatment effect was diminished, however, when fire weather conditions for the second fire were extreme. Holden et al. (2010)

studied fire severity across a range of vegetation types on the Gila National Forest in New Mexico and found that, in areas burned twice by wildland fire, the second fire tended to burn at lower severity than the initial fire. Finally, recent JFSP-funded work by Cochrane et al. (2013) shows that wildland fire limits the severity of subsequent fires. These studies complement simulation modeling experiments that have illustrated the effectiveness of wildland fire as a fuel treatment, whereby the number of subsequent ignitions, and the potential severity and extent of future fire events were reduced (Miller and Davis 2009, Davis et al. 2010).

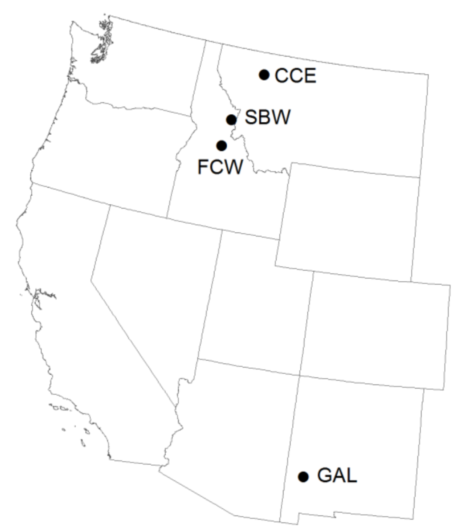
Although previous case studies have added to our knowledge of wildland fire as a fuel treatment, they provided insufficient information for determining if, and for how long, a given wildland fire or previously burned area might serve as an effective fuel treatment. Further, none of the studies examined all three ways that wildland fire can function as a treatment (i.e., limiting the occurrence, extent, and severity of subsequent fires). While a few studies found a threshold in the number of years for which the treatment effect persisted, none except Collins et al. (2009) had quantified the decay rate or produced a function to describe decreasing effectiveness over time. With one exception (Cochrane et al. 2013), the studies were limited in geographic scope and diversity of ecosystem types, and thus, in their generalizability. Finally, the data and statistical approaches used by these studies varied considerably, making synthetic comparisons among them problematic.

The study conducted here considerably advances our knowledge about the effectiveness and longevity of wildland fire as a fuel treatment. It provides information that can be applied widely across a diversity of geographic locations and ecosystem types, and should prove highly valuable to incident managers and would help managers and planners weigh the long term consequences of decisions and strategies over time.

Study Description and Location

We conducted our investigations within four study areas composed entirely of federally protected areas (wilderness and national park) in the western United States (Fig. 1), thereby limiting potential confounding effects of land management activities that are more common outside such areas (Parks et al. 2014b). The FCW (Frank Church – River of No Return Wilderness) study area is in central Idaho. The adjacent SBW (Selway-Bitterroot Wilderness) study area is in western Montana and north-central Idaho. The CCE (Crown of the Continent Ecosystem) study area comprises Glacier National Park and the Great Bear, Bob Marshall, and Scapegoat wilderness areas. Finally, the GAL study area incorporates the Gila and Aldo Leopold

Figure 1. Locations of the four study areas in the western US.



Wilderness Areas in western New Mexico. We evaluated objectives 1 and 2 (fire occurrence and progression/size) in all four study areas; objective 3 (fire severity) was evaluated only in FCW and GAL. All four study areas have experienced substantial fire activity in recent decades, thus providing sufficient data with which to evaluate the effectiveness of wildland fire as a fuel treatment. Some, but not all, fires were managed as natural events for their resource benefits.

FCW (Frank Church – River of No Return Wilderness)

The FCW (9777 km^2) is located in central Idaho and is the second largest wilderness area in the contiguous US. Elevations in FCW range from 600 to 3136 m and topographic features include river breaks, deep canyons, mountains, and glaciated basins (USDA Forest Service 2003a). Park-like groves of ponderosa pine occupy south and west slopes below 1500 m (Barrett 1988). Denser ponderosa pine and Douglas-fir forests occupy north and east aspects, up to elevations of ~2100 m. Still higher, the vegetation transitions to grand fir, lodgepole pine, and Englemann spruce. At the highest elevations, subalpine fir, whitebark pine, and alpine environments predominate (Barrett 1988, Finklin 1988). FCW has a mainly mixed-severity fire regime where low-elevation, open ponderosa pine forests typically experience frequent, low-intensity fires, and, generally, fire frequency decreases and severity increases with increasing elevation, moisture, and tree density (Crane and Fischer 1986).

SBW (Selway-Bitterroot Wilderness)

The SBW (5471 km^2) is located on the border of north-central Idaho and western Montana and is the third-largest wilderness area in the contiguous US and. Elevations range from 430-3070 m. Pacific maritime forests occur below ~1500m in the west and northwest portions of the study area and are composed of western hemlock, western red cedar, western white pine, and Douglas-fir (Rollins et al. 2002). Ponderosa pine is common at lower elevations in other portions of the study area, particularly on dry south-facing slopes (Brown 1994). As elevation increases, Douglas-fir and grand fir are prominent on mesic sites and ponderosa pine, Douglas-fir, and western larch are common on drier sites. The subalpine forests of the higher elevations (> ~2500 m) are composed of a collection of Engelmann spruce, whitebark pine, lodgepole pine, subalpine fir, and alpine larch (Rollins et al. 2002). At the highest elevations, alpine environments (i.e., barren or snow/ice) are common. The area experiences a mixed severity fire regime: many fires are nonlethal surface fires but under suitable weather and fuel conditions, lethal surface fires and even stand replacing crown fires occur.

CCE (Crown of the Continent Ecosystem)

The CCE is the largest (10,331 km^2) of the four study areas and straddles the east and west slopes of the continental divide in northwest Montana. Elevations range from 950 m to over 3100 m. In this rugged study area, alpine glacial canyons and cirques drain into major river valleys (Barrett et al. 1991, Keane et al. 1994). Ponderosa pine, lodgepole pine, Douglas fir, western larch are the dominant tree species at low-elevations (< ~1500 m) (Arno 1980, Keane et al. 2006). Western hemlock and western red cedar also occur in low-elevation (< 1500 m) mesic environments. As elevation increases the dominant species become lodgepole pine, subalpine fir, and Engelmann spruce. Whitebark pine and alpine larch are present near treeline (1800-2300 m elevation, depending on latitude); alpine environments are common above this elevation. Areas of ponderosa pine and mixed-conifer forest in CCE were historically maintained by low- and mixed-severity regimes (Keane et al. 2006). However, with the exception of alpine environments, most of the study area is characterized by a mixed- to high-severity fire regime (Arno et al. 2000).

GAL (Gila and Aldo Leopold Wilderness)
The GAL (3087 km^2) is located in west-central New Mexico. Elevations range from 1462 to 3314 m and the topography is diverse, composed of mountains, broad valleys, steep canyons, and extensive mesas. At the lowest elevations, the vegetation is desert scrub and grasslands. As elevation increases, it transitions to piñon-oak-juniper woodland, and then to ponderosa pine woodland and forest. The highest elevations are composed of Douglas-fir, Engelmann spruce, white fir, subalpine fir, southwestern white pine, and aspen forests (Rollins et al. 2002). Fires in GAL are generally frequent and low-severity surface fires, but fire severity tends to increase with elevation (Swetnam and Dieterich 1985) and varies with aspect, incident radiation and topographic position (Holden et al. 2009).

Key Findings:

1. Wildland fire acts as a fuel treatment. Three treatment effects are evident: wildland fire limits 1) the occurrence of subsequent fires, 2) the progression/extent of subsequent fires, and 3) the severity of subsequent fire. The treatment longevity varies by effect and study area.

The results of our study clearly indicate that wildland fire acts as a fuel treatment by limiting subsequent fire occurrence, progression/extent, and severity. Overall, the “treatment longevity,” defined as the length of time (in in years) until fire no longer acts as a fuel treatment, is shorter in the warm and dry study area in New Mexico (GAL) and is longer in the cooler and wetter study areas of the middle and northern Rocky Mountains (FCW, SBW, and CCE) (Table 1). The specific details of each treatment effect are available in Parks et al. (in press) (fire occurrence), Parks et al. (2015) (fire progression/extent), and Parks et al. (2014a) (fire severity).

Table 1. Length of time (number of years) wildland fire acts as a fuel treatment for three treatment effects. Note that there is some degree of uncertainty in these estimates.

Treatment effect	FCW	SBW	CCE	GAL
Fire occurrence (obj. 1)	>25	21	24	9
Fire progression/size (obj. 2)	16	18	15	6
Fire severity (obj. 3)	>20	na	na	>20

2. Wildland fire limits subsequent fire occurrence.

We used failure time analysis (also called survival analysis) to evaluate the time between an initial wildland fire and a subsequent fire occurrence, which we defined as an ignition that resulted in a fire ≥20 ha (50 acres). We also used a parallel analysis to generate a null model using randomly placed ignitions; the null model represents no effect of previous fire on subsequent fire occurrences. Comparisons between the observed and null models allow a formal evaluation of the effect of previous burned areas on subsequent fire occurrences. One of these evaluations is termed the "hazard ratio," which quantifies the strength of the treatment effect as a function of time since fire.

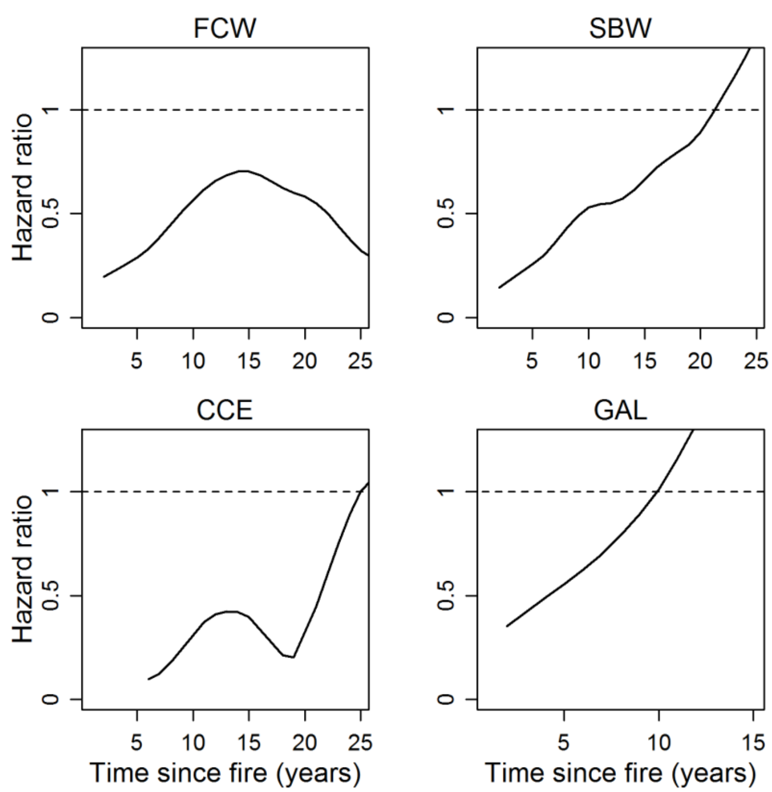


Figure 2. These hazard ratio plots depict the strength of the treatment effect. For example, a hazard ratio of 0.5 at time interval *t* indicates fires are half as likely to ignite within the perimeter of a fire *t* years post-fire compared to that expected by chance. A hazard ratio of 1.0 (dashed line) indicates that wildland fire no longer influences subsequent fire occurrence.

Analysis of the hazard ratio indicates that wildland fire limits subsequent fire occurrence in all four study areas (Fig. 2). This treatment effect varied in longevity among study areas, persisting for nine years in the warm/dry study area in the southwestern US and over 20 years in the cooler/wetter study areas in the northern Rocky Mountains (Table 1, Fig. 2). Such differences likely reflect differences in productivity and fire regime characteristics among study areas and ecosystems (Cleveland et al. 1999, Rollins et al. 2002). In GAL, for example, the relatively short longevity of the effect is consistent with the dominant vegetation (ponderosa pine forest with a grassy surface fuel understory) and fire regime (primarily low-severity surface fires) (Swetnam and Dieterich 1985). In this ecosystem, fine fuels such as grasses and surface litter (i.e., pine needles) recover quickly after fire, thereby quickly re-setting the stage for the occurrence of subsequent wildland fire. In FCW, SBW, and CCE, however, fire conducive conditions are less frequent, and as such, when fire does occur, it is less influenced by herbaceous fuels than it is by the ladder and canopy fuels that develop during the relatively long fire-free intervals (Schoennagel et al. 2004). Complete details on this component of the study are available in Parks et al. (in press).

3. Previous wildland fires limit fire progression

We analyzed fire perimeter data and created an objective and consistently applied rule-set to define whether or not burned areas acted as a barrier to fire progression, thereby either "limiting" or "not limiting" subsequent fire extent (Fig. 3). We analyzed these data using a logistic regression model (the binary response variable is either 0 [not limiting] or 1 [limiting]) with time-since-fire as the independent variable. The results can be summarized as the probability of wildland fire limiting subsequent fire progression as a function of time since fire.

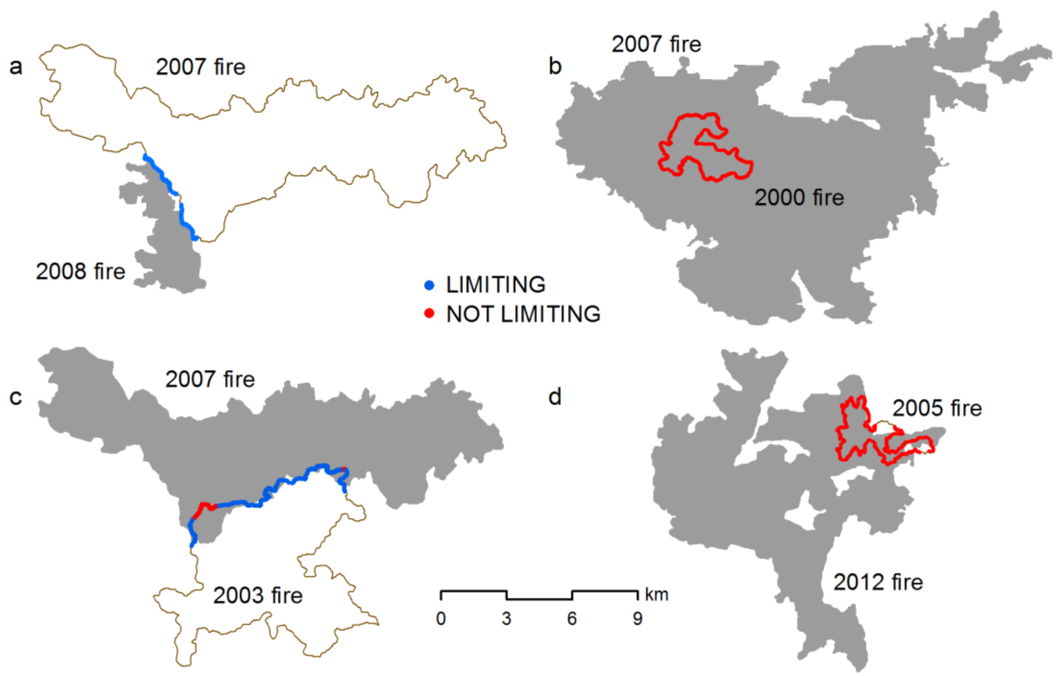


Figure 3. Examples from SBW depicting how pixels were defined as LIMITING or NOT LIMITING. In all examples, the initial wildland fire has a blue (LIMITING), red (NOT LIMITING), or brown (not analyzed) perimeter and the subsequent fire is solid gray. In panel (a), a 2007 fire interacts with a subsequent 2008 fire. Blue pixels are those defined as LIMITING and are ≤ 375 m (as measured outwards) or ≤ 750 m (as measured inwards) from the subsequent fire perimeter. Those pixels that do not interact with a subsequent fire (brown line) are excluded from the analyses. In panel (b), all pixels from the 2000 fire are NOT LIMITING since the 2007 fire burned over the entire 2000 fire and are > 750 m from the 2007 fire perimeter boundary (as measured inwards). In panel (c), some portions of the 2008 fire infiltrate the 2007 fire beyond 750 m; such pixels are defined NOT LIMITING. In panel (d), a large proportion of the perimeter of the 2005 fire is proximal to the perimeter of the 2012 fire. However, since > 35% of the 2005 fire overlaps with the 2012 fire, all proximal pixels are labeled NOT LIMITING (see Parks et a. [2015] for further details).

Results indicate that wildland fire does limit subsequent fire progression/extent. This treatment effect, however, decays over time; wildland fires no longer limit subsequent fire progression 6-18 years after a fire, depending on study area (Table 1, Fig. 4). Complete details on this component of the study are available in Parks et al. (2015).

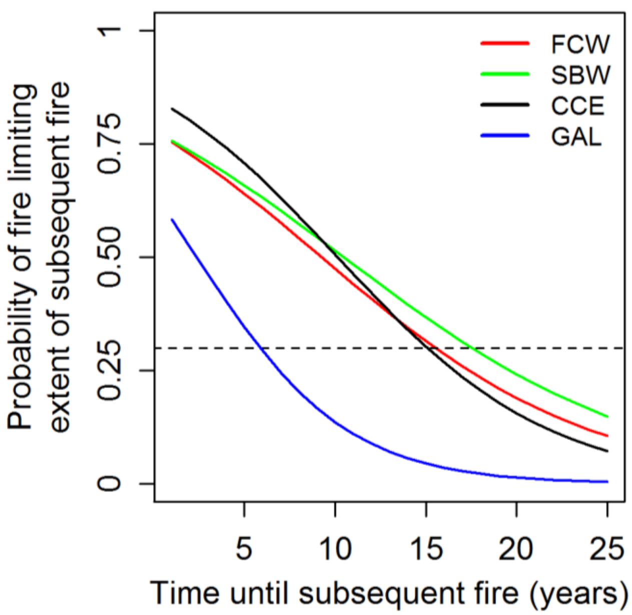


Figure 4. Probability of wildland fire limiting the progression/extent (obj. 2) of subsequent fire for each study area. The horizontal dashed line represents a threshold (0.30 probability) at which we assumed wildland fire no longer acts as an effective fuel break.

4. Previous fires moderate severity of subsequent wildland fires

We compared fire severity in areas that recently burned (i.e., a reburn) to fire severity in areas that had not recently burned (no reburn) in GAL and FCW. Fire severity was measured as the delta normalized burn ratio (dNBR; Key and Benson, 2006), an index that differences pre- and post-fire Landsat satellite imagery. In both study areas, mean and median dNBR were substantially lower in reburn pixels than in no-reburn pixels. In GAL, mean and median dNBR for reburn pixels were 89 and 68, respectively, compared to mean and median values of 213 and 178 for no-reburn pixels. In FCW, mean and median dNBR for reburn pixels were 158 and 112, respectively, compared to mean and median values of 339 and 272 for no-reburn pixels. A Kolmogorov–Smirnov test revealed that the dNBR frequency distributions of reburn and no-reburn pixels were significantly different in both study areas ($P < 0.001$).

We also evaluated how reburn severity (as measured by dNBR) varies as a function of time-since-fire and severity of previous fire. Results show that dNBR tends to increase with time since previous fire and that the treatment effect is still evident at ~20 between wildland fire events. Results also indicate that fire severity generally increases with severity of previous wildland fire. Complete details on this component of the study are available in Parks et al. (2014a).

5. The ability of wildland fire to act as a fuel treatment diminishes with time-since-fire.

For all three treatment effects (occurrence, progression/extent, and severity), the effect is generally strongest immediately after fire and diminishes as time-since-fire increases (e.g., Fig 2 and 4). The longevity of the fuel treatment effect varies among our study areas, and in general is shorter in our Southwest study area (GAL) than in our northern Rockies study areas (FCW, SBW, CCE) (Table 1). Simply put, as the fire-free interval increases, the ability of wildland fire to act as a fuel treatment diminishes. As such, it is very important to recognize that burned areas do not act as a fuel treatment in perpetuity.

6. Under extreme weather conditions, the ability of wildland fire to act as a fuel treatment is reduced.

We were able to evaluate the influence of extreme weather for only one of the treatment effects (fire progression/extent; obj. 2). The ability of wildland fire to limit subsequent fire progression/extent weakens with increasing fire-conducive weather conditions (as represented by ERC) in all study areas (Fig. 5). More details are available in Parks et al. (2015).

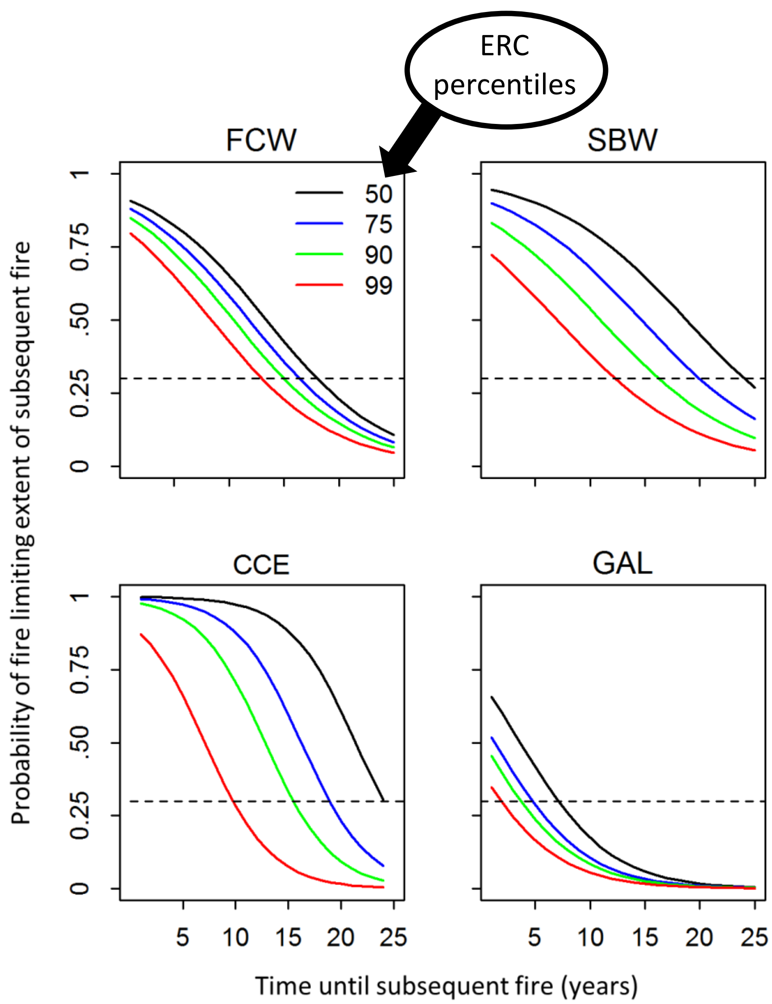


Figure 5. Response curves depicting how the probability of fire limiting the progression/extent of subsequent fire varies by ERC percentile. All ERC percentiles are study area specific and determined using ERC values occurring within the fire season; we defined the fire season as the beginning and ending date that encompassed 95% of the MODIS fire detections (USDA Forest Service 2013) for each study area. The horizontal dashed line represents the threshold (0.30 probability) at which wildland fire no longer acts as an effective fuel break.

7. The data from the Monitoring Trends in Burn Severity project (MTBS) were highly valuable but required correction and were augmented to include smaller fires and fires that occurred between 1972 and 1984.

We heavily relied on perimeter and burn severity data from the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink et al. 2007), which has mapped the perimeter and severity of fires ≥ 400 ha in the western US since 1984. In fact, for the fire severity treatment effect of the study (obj. 3), we relied entirely on MTBS data. However, for the fire occurrence and progression/extent treatment effects, we augmented the MTBS dataset and mapped smaller fires (≥ 20 ha), as well as earlier fires occurring since 1972. This provided us with a longer fire record and more fires. We used the entire record of Landsat data, including the multi-spectral scanner (MSS), thematic mapper (TM), enhanced thematic mapper plus (ETM+), and operational land imager (OLI) sensors to do this. During this process, we encountered some MTBS mapping inaccuracies which we corrected by cross checking with a variety of supplementary data sources. Methods are fully described in Parks et al. (2015). Across the four study areas, we were able to add almost 600 fires to the dataset we obtained from MTBS. These data are now available for download to support future research investigations (see Deliverables table for URL addresses).

Management Implications

Many landscapes, particularly in the western US, have experienced substantial fire activity in recent decades. Such landscapes potentially provide more opportunities and options for managing fires for ecological benefit and for restoring landscape resilience. The findings of this study add to and complement a growing body of knowledge that can provide tremendous decision support to fire managers. Knowing that fire occurrence (this study and Krawchuk et al. 2006), fire progression/extent (this study and Collins et al. 2009), and fire severity (this study and Miller and Safford 2012) are limited by previous wildland fire should provide greater flexibility and confidence in managing fire with beneficial outcomes and in a manner in which resilient landscapes can be better realized. For example, the findings of this study will help fire managers assess whether a previous wildland fire will act as a fuel treatment based its age, ecosystem type, and expected weather.

More broadly, however, by providing quantitative information about future reductions fire occurrence, progression/extent, and severity, the results of this study results provide land managers a longer timeframe in which to view the benefits and costs of an individual fire. The results of this study show that, under suitable fuels and weather conditions, there may be substantial long-term benefits resulting from a wildland fire that is managed for resource benefit as opposed to a one that is suppressed. In fact, our results suggest that, in the presence of recent previous wildland fire, suppressing a fire presents a *lost opportunity* to restore resilience, especially during non-extreme weather conditions. In landscapes that have experienced substantial fire over the last few decades, future wildland fire will inevitably interact with previous fires. Based on the results of this study, those previous fires (and all future fires) will serve as a fuel treatment.

Relationship to recent findings

Theory suggests that in landscapes with an active fire regime, landscape pattern is shaped by fire, but fire is also shaped by landscape pattern (Peterson 2002). This pattern-process feedback is a fundamental concept in disturbance ecology and can lead to self-regulating systems (Turner 1989, Agee 1999), underscoring the importance of wildland fire in creating and maintaining resilient landscapes (McKenzie et al. 2011). We refer the pattern-process feedback and self-regulation as the "treatment effect" of wildland fire. Our findings clearly indicate that wildland fire acts as a fuel treatment in our four western US study areas, thereby confirming and validating self-regulation theory in landscapes with active fire regimes.

In terms of the ability of wildland fire to limit subsequent *fire occurrence* (obj. 1), our findings are coherent with earlier JFSP funded work (JFSP 04-2-1-110) demonstrated through a simulation study several anecdotes of the limitation of future ignitions (Davis et al. 2010). Studies using empirical data have also demonstrated that wildland fire regulates the occurrence of subsequent fires (Krawchuk et al. 2006, Penman et al. 2013).

In terms of the ability of wildland fire to limit subsequent *fire progression/extent* (obj. 2), our findings are similar to those of Collins et al. (2009), who found also that wildland fire limits subsequent fire size. However, our results differ from those of Teske et al. (2012), who examined three of the same study areas we did (FCW, SBW, and CCE) and found that wildland fire limited the spread of subsequent fires in only one of them (FCW). The likely explanation for the lack of agreement involves methodological differences; Teske et al. (2012) did not include a statistical evaluation of time between fires in their analyses, and in not doing so, may have muted the statistical signal of fire as a fuel break.

In terms of the ability of wildland fire to limit subsequent *fire severity* (obj. 3), our findings are consistent with Arkle et al. (2012), who found that fire severity was lower in areas that were treated by prescribed burns compared to untreated areas. These results are also consistent with Miller et al. (2012), who found that there was proportionally less high severity fire in reburn compared to no-reburn. Several studies have found that areas that previously burned at high severity were more likely to burn at high severity during subsequent wildland fires (Thompson et al. 2007, Collins et al. 2009, Holden et al. 2010, van Wagtendonk et al. 2012). We also found that severity generally increases with the severity of previous fire. Fire severity increased with vegetation greenness, measured as NDVI, in both study areas. This follows other studies that have found more vegetation generally corresponds to higher fire severity (Cocke et al. 2005, Arkle et al. 2012). This highlights the importance of biomass productivity, but also the influence of topographic variables, on fire severity. For example, the increase in severity with elevation in FCW is likely explained by a combination of enhanced productivity (due to increased moisture) and increasing fuel load (due to reduced fire frequency) with elevation; Dillon et al. (2011) also found that elevation was a major influence in explaining high-severity fire in the northern Rocky Mountain, USA and suggested it was due to increased biomass in upper elevations.

Although wildland fire clearly acts as a fuel treatment, the strength of effect decays with time between fires, and as such, there is a time at which the treatment effect is no longer detectible (Table 1). This decay is apparent for all three treatment effects and is consistent with other studies that also found that the strength of regulatory feedbacks between wildland fires decreases as the fire-free interval increases (Collins et al. 2009, Bradstock et al. 2010, van Wagtendonk et al. 2012, Penman et al. 2013)

The ability of wildland fire to act as a fuel treatment weakens as weather becomes more fire-conducive (Fig. 3). This was also noted by Collins et al. (2009) and supports the assertion that the importance of fuels diminishes during extreme weather events (Bessie and Johnson 1995, Price and Bradstock 2011). Nevertheless, our results indicate that fuels, or lack thereof post-fire, strongly limit fire spread in the northern study areas in the years immediately following fire even under extreme weather conditions. Conversely, in GAL, which is generally comprised of dry conifer forest, fire limits subsequent fire spread for a only very short period of time (two years) under extreme weather conditions; a study by Price and Bradstock (2010) revealed similar findings in a dry forest in Australia.

Future work needed

Pertaining to the wildland fires limiting subsequent *fire occurrence*, further research is necessary to better identify the longevity of the effect, as there is some degree of uncertainty in our estimates (Table 1). More data (i.e., more fire seasons or a longer fire record) will likely be necessary to reduce uncertainty. Also, we did not evaluate the influence of weather even though fires are more likely ignite and spread during hot, dry, and/or windy conditions (Chang et al. 2013, Sedano and Randerson 2014). Given that other aspects of self-regulation weaken under extreme weather conditions (e.g., Collins et al. 2009), we would expect the longevity and strength of wildland fire's regulating effect on subsequent fire occurrence to be reduced during extreme weather. However, a formal evaluation of the effect of weather on wildland fire's capacity to regulate subsequent fire occurrence is necessary.

Pertaining to wildland fire limiting subsequent *fire progression/extent*, we did not account for fine scale weather events (e.g. rain, shifting winds, and diurnal fluctuations in humidity), topographic features (e.g., valley bottoms and ridges), or natural fuel breaks (e.g., lakes and alpine areas) that might limit the spread and size of fires. Future investigations should work toward quantifying the relative importance of these and other factors (e.g., roads). Furthermore, we did not account for direction of fire spread (e.g., heading vs. flanking), a factor that surely affects the ability of wildland fire to limit subsequent fire progression given that a heading fire has higher intensity and spread rate than a flanking or backing fire (Finney 2005).

Pertaining to wildland fire limiting subsequent *fire severity*, more work is necessary to incorporate valid and meaningful ecological measures of severity. We used a satellite-inferred metric of severity (dNBR) (Key and Benson 2006) because it has a fairly long temporal record (since 1984) and its spatial extent covers our study areas (and the globe). However, fire severity is the result of many complex physical and ecological factors that are difficult to represent with simplistic measures such as dNBR.

Lastly, our study was conducted in protected areas where roads and forest management do not have a strong influence on wildland fire. Although suppression does occur in our study areas, it occurs less often than in more managed lands and may sometimes be less effective due to the remoteness of these areas. As such, past wildland fire may be even more effective as a fuel treatment in more managed landscapes where the effect of roads and forest thinning can be leveraged in suppression activities. A formal evaluation of wildland fire as a fuel treatment in more managed landscapes would likely prove useful to managers.

Deliverables Crosswalk

Deliverable Type (See Format Overview, Section VIII)	**Description**	**Status**
Datasets	High quality *fire history* (polygons) and *fire severity* (raster datasets) atlas for each study area, spanning 1972-2012. All fires ≥ 20 ha (50 acres) are included. Emails describing these data and data availability were sent to individuals who are potentially interested (including GIS coordinators in each management unit). Data were archived according to the Data Management Plan. FCW: http://www.fs.usda.gov/rds/archive/Product/RDS-2015-0021 SBW: http://www.fs.usda.gov/rds/archive/Product/RDS-2015-0024 CCE: http://www.fs.usda.gov/rds/archive/Product/RDS-2015-0022 GAL: http://www.fs.usda.gov/rds/archive/Product/RDS-2015-0023	Completed
Refereed publication	Parks SA, Miller C, Nelson CR, Holden ZA (2014) Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. *Ecosystems*. 17:29-42. link	Completed
Refereed publication	Parks SA, Holsinger L, Miller C, Nelson CR (2015) Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. *Ecological Applications*. 25: 1478-1492. link	Completed
Refereed publication	Parks SA, Miller C, Holsinger L, Baggett S, Bird B (in press). Wildland fire limits subsequent fire occurrence. *International Journal of Wildland Fire.*	Completed
Refereed publication	Holsinger L, Parks SA, Miller C (in prep). Barriers to wildland fire spread: the role of fuel, weather, and topography	In preparation
Training session	Northern Rockies Fire Science Network and the Southwest Fire Science Consortium Webinar January 21, 2015. Title: The ability of wildland fire to act as a fuel treatment. Online at:	Completed

	http://nrfirescience.org/event/ability-wildland fire-act-fuel-treatment	
Training session	Presentation to Forest Service Northern Region fire management officer meeting, Missoula, MT, November 2014. Title: Quantifying the ability of wildland fire to act as a fuel treatment	Completed
Training session	Presentation to the local chapter of the Society of American Foresters monthly meeting, Missoula, MT, September 2014. Title: Quantifying the ability of wildland fire to act as a fuel treatment	Completed
Training session	Presentation at the Fire Lab weekly seminar, Missoula, MT, April 2014. Title: Wildland fire as a fuel treatment	Completed
Training material	"Research Brief" summarizing findings of project. To be distributed by the NR Fire Science Network and the SW Fire Science Consortium. Title: Quantifying the effectiveness and longevity of wildland fire to act as a fuel treatment.	In preparation
Ph.D. dissertation	Sean Parks received his Ph.D from the College of Forestry and Conservation, University of Montana, in May 2014. Dissertation title: Quantifying the Influence of Past Wildland fires on the Severity and Size of Subsequent Wildland fires	Completed
Conference presentation	Parks SA, Holsinger L, Miller C (2015) Resistance to reburn: factors contributing to reduced probability of burning in recently burned areas. To be presented (oral) at the 6th Fire Ecology and Management Congress, San Antonio, TX.	To be completed in 11/2015
Conference presentation	Holsinger LM, Parks, SA, Miller C (2015) Barriers to wildland fire spread: the role of fuels, weather, and topography. To be presented (poster) at the 6th Fire Ecology and Management Congress, San Antonio, TX.	To be completed in 11/2015
Conference presentation	Parks SA, Miller C, Holsinger LM (2015) Quantifying negative feedbacks between wildland fire and subsequent fire occurrence. Presented (oral) at the International Association for Landscape Ecology World Congress, Portland, OR.	Completed
Conference presentation	Holsinger LM, Parks SA, Carol C (2015) Barriers to the spread of wildland fire: quantifying the role of past fire disturbance and topography. Presented (oral) at the International Association for Landscape Ecology World Congress, Portland, OR.	Completed
Conference presentation	Miller C, Parks SA, Holsinger LM (2015) Wildland fires limit the occurrence, severity, and size of subsequent fire. Presented (oral) at the George Wright Society Biennial Conference, Oakland, CA.	Completed
Conference presentation	Parks SA, Miller C, Holsinger L (2014) Wildland fires limit the occurrence, severity, and size of subsequent fires. Presented (oral) at the National Wilderness Conference, Albuquerque, NM.	Completed
Conference presentation	Parks SA, Miller C, Holden Z, Abatzoglou J (2012) Previous wildland fires mediate burn severity of subsequent wildland fires. Presented (oral) at the 27th Annual Landscape Ecology Symposium, Newport Rhode Island.	Completed
Progress reports	Annual progress updates in 2013, 2014, final report	Completed

Literature Cited

Agee, J. K. 1999. Fire effects on landscape fragmentation in interior west forests. Page 323 *in* J. A. Rochelle, L. A. Lehmann, and J. Wisniewski, editors. Forest fragmentation: Wildlife and management implications. Koninklijke Brill NV, Leiden, The Netherlands.

Arkle, R. S., D. S. Pilliod, and J. L. Welty. 2012. Pattern and process of prescribed fires influence effectiveness at reducing wildfire severity in dry coniferous forests. Forest Ecology and Management **276**:174-184.

Arno, S. F. 1980. Forest fire history in the northern Rockies. Journal of Forestry **78**:460-465.

Barrett, S. W., S. F. Arno, and C. H. Key. 1991. Fire regimes of western larch – lodgepole pine forests in Glacier National Park, Montana. Canadian Journal of Forest Research **21**:1711-1720.

Bessie, W. C. and E. A. Johnson. 1995. The Relative Importance of Fuels and Weather on Fire Behavior in Subalpine Forests. Ecology **76**:747-762.

Bradstock, R. A., K. A. Hammill, L. Collins, and O. Price. 2010. Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. Landscape Ecology **25**:607-619.

Brown, D. G. 1994. Predicting vegetation types at treeline using topography and biophysical disturbance variables. Journal of Vegetation Science **5**: 641-656.

Chang, Y., Z. L. Zhu, R. C. Bu, H. W. Chen, Y. T. Feng, Y. H. Li, Y. M. Hu, and Z. C. Wang. 2013. Predicting fire occurrence patterns with logistic regression in Heilongjiang Province, China. Landscape Ecology **28**:1989-2004.

Cleveland, C. C., A. R. Townsend, D. S. Schimel, H. Fisher, R. W. Howarth, L. O. Hedin, S. S. Perakis, E. F. Latty, J. C. Von Fischer, A. Elseroad, and M. F. Wasson. 1999. Global patterns of terrestrial biological nitrogen (N-2) fixation in natural ecosystems. Global Biogeochemical Cycles **13**:623-645.

Cocke, A. E., P. Z. Fule, and J. E. Crouse. 2005. Comparison of burn severity assessments using Differenced Normalized Burn Ratio and ground data. International Journal of Wildland Fire **14**:189-198.

Collins, B. M., J. D. Miller, A. E. Thode, M. Kelly, J. W. van Wagtendonk, and S. L. Stephens. 2009. Interactions Among Wildland Fires in a Long-Established Sierra Nevada Natural Fire Area. Ecosystems **12**:114-128.

Davis, B. H., C. Miller, and S. A. Parks. 2010. Retrospective fire modeling: Quantifying the impacts of fire suppression. Page 40. USDA Forest Service, RMRS-GTR-236WWW, Fort Collins, CO.

Dillon, G. K., Z. A. Holden, P. Morgan, M. A. Crimmins, E. K. Heyerdahl, and C. H. Luce. 2011. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. Ecosphere **2**:art130.

Finney, M. A. 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management **211**:97-108.

Freeman, J. E. and L. N. Kobziar. 2011. Tracking postfire successional trajectories in a plant community adapted to high-severity fire. Ecological Applications **21**:61-74.

Holden, Z. A., P. Morgan, and J. S. Evans. 2009. A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. Forest Ecology and Management **258**:2399-2406.

Holden, Z. A., P. Morgan, and A. T. Hudak. 2010. Burn severity of areas reburned by wildfires in the Gila National Forest, New Mexico, USA. Fire Ecology **6**:77-85.

Hudak, A. T., T. B. Jain, P. Morgan, and J. T. Clark. 2010. Remote sensing of WUI fuel treatment effectiveness following the 2007 wildfires in central Idaho. Pages 302-312 *in* 3rd Fire Behavior and Fuels Conference. International Association of Wildland Fire., Spokane, WA.
Keane, R. E., S. Arno, and L. J. Dickinson. 2006. The Complexity of Managing Fire-dependent Ecosystems in Wilderness: Relict Ponderosa Pine in the Bob Marshall Wilderness. Ecological Restoration **24**:71-78.
Keane, R. E., P. Morgan, and J. P. Menakis. 1994. Landscape assessment of the decline of whitebark-pine (pinus-albicaulis) in the Bob Marshall Wilderness Complex, Montana, USA. Northwest Science **68**:213-229.
Keeley, J. E., T. Brennan, and A. H. Pfaff. 2008. Fire severity and ecosytem responses following crown fires in California shrublands. Ecological Applications **18**:1530-1546.
Key, C. H. and N. C. Benson. 2006. Landscape assessment (LA). Page 55 *in* D. Lutes, R. E. Keane, J. F. Caratti, C. H. Key, N. C. Benson, S. Sutherland, and L. Gangi, editors. FIREMON: Fire effects monitoring and inventory system. RMRS-GTR-164, Fort Collins, CO.
Krawchuk, M. A., S. G. Cumming, M. D. Flannigan, and R. W. Wein. 2006. Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. Ecology **87**:458-468.
Krawchuk, M. A., M. A. Moritz, M.-A. Parisien, J. Van Dorn, and K. Hayhoe. 2009. Global pyrogeography: the current and future distribution of wildfire. Plos One **4**:e5102.
McKenzie, D., C. Miller, and D. A. Falk. 2011. Toward a Theory of Landscape Fire. Pages 3-25 *in* D. McKenzie, C. Miller, and D. A. Falk, editors. The Landscape Ecology of Fire. Springer Netherlands.
Miller, C. and B. H. Davis. 2009. Quantifying the consequences of fire suppression in two California national parks. The George Wright Forum **26**:76-88.
Miller, J. D. and H. Safford. 2012. Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. Fire Ecology **8**:41-57.
Moritz, M. A. 2003. Spatiotemporal analysis of controls on shrubland fire regimes: Age dependency and fire hazard. Ecology **84**:351-361.
NIFC. 2010. National Interagency Fire Center Statistics. Available at: http://www.nifc.gov/fireInfo/fireInfo_statistics.html.
Omi, P. N. and E. J. Martinson. 2002. Final report: Effect of fuels treatment in wildfire severity, submitted to the Joint Fire Science Program Governing Board.
Parks, S. A., L. M. Holsinger, C. Miller, and C. R. Nelson. 2015. Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. Ecological Applications.
Parks, S. A., C. Miller, L. M. Holsinger, L. S. Baggett, and B. J. Bird. in press. Wildland fire limits subsequent fire occurrence. International Journal of Wildland Fire.
Parks, S. A., C. Miller, C. R. Nelson, and Z. A. Holden. 2014a. Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. Ecosystems **17**:29-42.
Parks, S. A., M.-A. Parisien, C. Miller, and S. Z. Dobrowski. 2014b. Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture. Plos One **9**:e99699.

Penman, T., R. Bradstock, and O. Price. 2013. Modelling the determinants of ignition in the Sydney Basin, Australia: implications for future management. International Journal of Wildland Fire **22**:469-478.

Peterson, G. D. 2002. Contagious disturbance, ecological memory, and the emergence of landscape pattern. Ecosystems **5**:329-338.

Price, O. F. and R. A. Bradstock. 2010. The effect of fuel age on the spread of fire in sclerophyll forest in the Sydney region of Australia. International Journal of Wildland Fire **19**:35-45.

Price, O. F. and R. A. Bradstock. 2011. Quantifying the influence of fuel age and weather on the annual extent of unplanned fires in the Sydney region of Australia. International Journal of Wildland Fire **20**:142-151.

Reinhardt, E. D., R. E. Keane, D. E. Calkin, and J. D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management **256**:1997-2006.

Rhodes, J. J. and W. L. Baker. 2008. Fire Probability, Fuel Treatment Effectiveness and Ecological Tradeoffs in Western U.S. Public Forests. The Open Forest Science Journal **1**:1-7.

Rollins, M. G., P. Morgan, and T. Swetnam. 2002. Landscape-scale controls over 20(th) century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecology **17**:539-557.

Safford, H. D., D. A. Schmidt, and C. H. Carlson. 2009. Effects of fuel treatments on fire severity in an area of wildland-urban interface, Angora Fire, Lake Tahoe Basin, California. Forest Ecology and Management **258**:773-787.

Schoennagel, T., T. T. Veblen, and W. H. Romme. 2004. The interaction of fire, fuels, and climate across rocky mountain forests. Bioscience **54**:661-676.

Sedano, F. and J. T. Randerson. 2014. Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems. Biogeosciences **11**:3739-3755.

Swetnam, T. W. and J. H. Dieterich. 1985. Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. Pages 390-397 *in* J. E. Lotan, B. M. Kilgore, W. C. Fischer, and R. W. Mutch, editors. Proceedings - symposium and workshop on wilderness fire. USDA Forest Service, Ogden, UT.

Thompson, J. R., T. A. Spies, and L. M. Ganio. 2007. Reburn severity in managed and unmanaged vegetation in a large wildfire. Proceedings of the National Academy of Sciences **104**:10743-10748.

Turner, M. G. 1989. Landscape Ecology - The Effect of Pattern On Process. Annual Review of Ecology and Systematics **20**:171-197.

USDA Forest Service. 2003a. The Frank Church-River of No Return wilderness management plan.

USDA Forest Service. 2003b. Healthy Forest Initiative: Fuels accomplishments. Available at: http://www.fs.fed.us/projects/hfi/May-2003/hfi-fuels-treatment-graphs.shtml.

USDA Forest Service. 2013. MODIS Fire detection GIS data. available at: http://activefiremaps.fs.fed.us/gisdata.php.

van Wagtendonk, J. W., K. A. van Wagtendonk, and A. E. Thode. 2012. Factors Associated with the Severity of Intersecting Fires in Yosemite National Park, California, USA. Fire Ecology **8**:11-31.

Wimberly, M. C., M. A. Cochrane, A. D. Baer, and K. Pabst. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications **19**:1377-1384.