Ecological Restoration Institute
Working Paper No. 27

27

Fuel Treatment Longevity

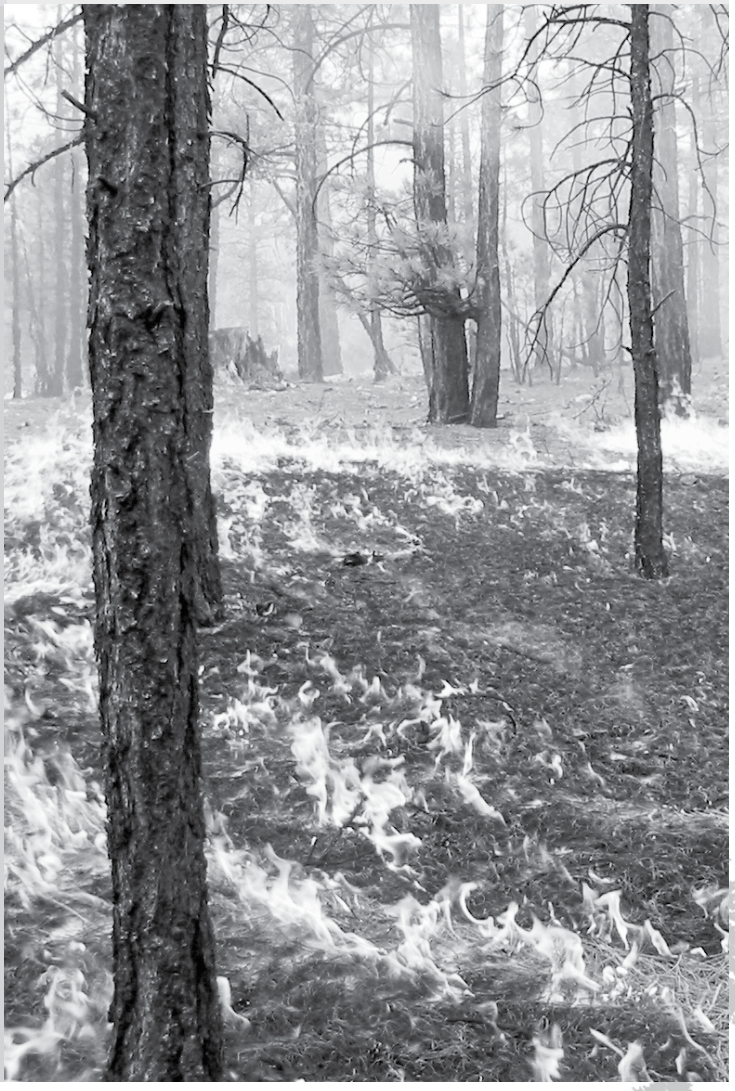
October 2013

SOUTHWEST FIRE SCIENCE CONSORTIUM

NORTHERN ARIZONA UNIVERSITY

Ecological Restoration Institute

JOINT FIRE SCIENCE PROGRAM



Working Papers in Intermountain West Frequent-fire Forest Restoration

Ecological restoration is a practice that seeks to heal degraded ecosystems by reestablishing native species, structural characteristics, and ecological processes. The Society for Ecological Restoration International defines ecological restoration as "an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability.…Restoration attempts to return an ecosystem to its historic trajectory" (Society for Ecological Restoration International Science & Policy Working Group 2004).

Most frequent-fire forests throughout the Intermountain West have been degraded during the last 150 years. Many of these forests are now dominated by unnaturally dense thickets of small trees, and lack their once diverse understory of grasses, sedges, and forbs. Forests in this condition are highly susceptible to damaging, stand-replacing fires and increased insect and disease epidemics. Restoration of these forests centers on reintroducing frequent, low-severity surface fires—often after thinning dense stands—and reestablishing productive understory plant communities.

The Ecological Restoration Institute at Northern Arizona University is a pioneer in researching, implementing, and monitoring ecological restoration of frequent-fire forests of the Intermountain West. By allowing natural processes, such as low-severity fire, to resume self-sustaining patterns, we hope to reestablish healthy forests that provide ecosystem services, wildlife habitat, and recreational opportunities.

The ERI Working Papers series presents findings and management recommendations from research and observations by the ERI and its partner organizations. While the ERI staff recognizes that every restoration project needs to be site specific, we feel that the information provided in the Working Papers may help restoration practitioners elsewhere.

This publication would not have been possible without funding from the USDA Forest Service and the Southwest Fire Science Consortium. The views and conclusions contained in this document are those of the author(s) and should not be interpreted as representing the opinions or policies of the United States Government. Mention of trade names or commercial products does not constitute their endorsement by the United States Government or the ERI.

Cover Photo: *Research shows that treating forested areas with prescribed ground-level fire, as seen in this photo, is effective in raising canopy base height if it scorches the lower branches. However, such fires can also result in increased fuel loads by killing small trees and causing lower branches and needles to fall to the surface. As a result, it may be necessary to reburn an area to maintain the effectiveness of the treatment. Researchers generally consider thinning followed by prescribed fire to be the most effective fuel treatment.* Photo courtesy of the Ecological Restoration Institute

Introduction

Dry forests of the western United States have been altered by long-term fire exclusion, resulting in a more dense forest structure and an increased risk of crown fire. Recently, thinning and prescribed fire treatments have been implemented in these forests for two main reasons: ecological restoration and fire hazard reduction. Ecological restoration is a holistic endeavor that focuses on restoring ecological patterns, processes, and functions. Ecological restoration goals often include restoring the process of fire to forested ecosystems and changing forest structure to fall within the historical range of variability as indicated by reference information. While fire hazard reduction is often a goal or an outcome of ecological restoration, not all treatments specifically designed to reduce fuels also restore ecosystem patterns, processes, and functions (Reinhardt et al. 2008). Fire hazard reduction treatments are designed specifically to reduce fire intensity, reduce fire severity, and increase the ability of firefighters to control wildfires (Table 1).

Fuel treatments are common and are generally regarded as beneficial for reducing fire behavior, as well as for ecological reasons such as increasing understory diversity and reducing competition among trees for nutrients and water. What remains unclear is how long such fuel treatments are effective in reducing undesirable fire behavior. This working paper addresses the following management questions regarding fuel treatment longevity: What factors influence fuel treatment longevity? How long will fuel treatments last before sites need to be retreated? Do some types of treatments last longer than others?

Table 1. Goals, effects, and advantages of different fire hazard reduction treatments (modified from Agee and Skinner 2005).

Goal	Effect	Advantage
Reduce surface fuels	Reduces potential flame length, reduces fire intensity/severity	Easier to control wildfires, less torching
Increase height to live crown	Requires longer flame length to begin torching	Less torching
Decrease crown density	Makes tree-to-tree crown fire less likely	Reduces crown fire potential
Keep big trees of resistant species	Less mortality with same fire intensity	Generally restores historic structure

Evaluating the longevity of fuel treatments

There are several ways to evaluate fuel treatment effectiveness: observations, case studies, mathematical models, and empirical studies (Carey and Schumann 2003). Within these four categories, there are several methods that can be used to evaluate the effectiveness of fuel treatments both immediately after treatment and over time (Table 2).

The immediate effectiveness of a fuel treatment can be evaluated by measuring the reduction in fuels that the treatment causes. For example, prescribed fire objectives usually include information about how much fuel of different size classes must be removed to reach desired fuel loads. Fuel treatments are deemed effective if they meet those fuel reduction objectives. Another way to judge the effectiveness of a fuel treatment is to run fire simulation models with fuel loads from before and after the treatment to determine how much the fuel treatment changed the potential fire behavior (Fernandes and Botelho 2003). Both of these methods can also be used to evaluate effectiveness of fuel treatments over time, although most modeling studies do not incorporate treatment longevity into their fire behavior modeling because assumptions have to be made about regeneration rates, mortality, growth, climate, and other variables that are difficult to predict accurately. Another method to evaluate fuel treatment effectiveness over time is to quantify wildfire effects in treated and untreated areas, and determine the age of treatments in which wildfire severity is effectively reduced (Fernandes and Botelho 2003).

Table 2. Methods to evaluate fuel treatment effectiveness, immediately after treatment or over time (based on ideas from Omi and Martinson 2002, Fernandes and Botelho 2003).

In the absence of wildfire	Post-wildfire
Fire hazard ratings	Anecdotal observations of fire behavior
Fuel inventory	Remote sensing of fire size and location
Fire behavior model predictions	Remote sensing of fire severity
Estimates by experts	Field measurements of fire severity (e.g., tree mortality, scorch height, tree crown damage, or soil damage)

Multiple factors influence fuel treatment longevity

Fuel treatment longevity depends on a multitude of factors (see Figure 1), including:

- Treatment design
- Treatment outcome
- Site-specific characteristics
- Stand-specific characteristics
- Fuel accumulation
- Climate

Treatment design factors influencing fuel treatment longevity

Fuel strata targeted

According to Stephens et al. (2012), surface fuels (e.g., grass, litter, coarse woody debris) may be the most important fuels to treat because a reduction in surface fuels helps reduce fireline intensity and gives fire fighters a better chance of managing fire. However, fuel treatments can target other fuels besides surface fuels, including trees and tree limbs to increase height-to- live crown and removing whole trees to decrease crown density. There may be tradeoffs between these different types of fuel treatments. For example, thinning to reduce crown fire hazard may result in increased rates of fire spread by allowing higher wind speeds under the canopy, more sunlight to reach the surface, and more understory vegetation growth (Reinhardt et al. 2008).

Fuel treatment longevity may vary widely depending on which fuel stratum is targeted. Vaillant et al. (2009) studied plots in 14 national forests in California in mixed-conifer, yellow pine, and red fir forests that were treated with either prescribed fire or mechanical thinning. They found that live surface fuels equaled or exceeded initial loadings within eight years after the treatments in almost all cases, but canopy base height remained higher than initial measurements for up to ten years post-treatment. Chiono et al. (2012) studied fuel treatments from 2 to 15 years old in mixed conifer and drier pine-dominated sites in northeastern California. Overstory characteristics in treated areas, including stand density, basal area and species composition, were still significantly different from untreated control areas even 8 to 15 years after treatment. However, other fuel categories, including shrub cover and seedling density, were so variable that the researchers were not able to see a pattern in those fuel loads over time after a treatment.

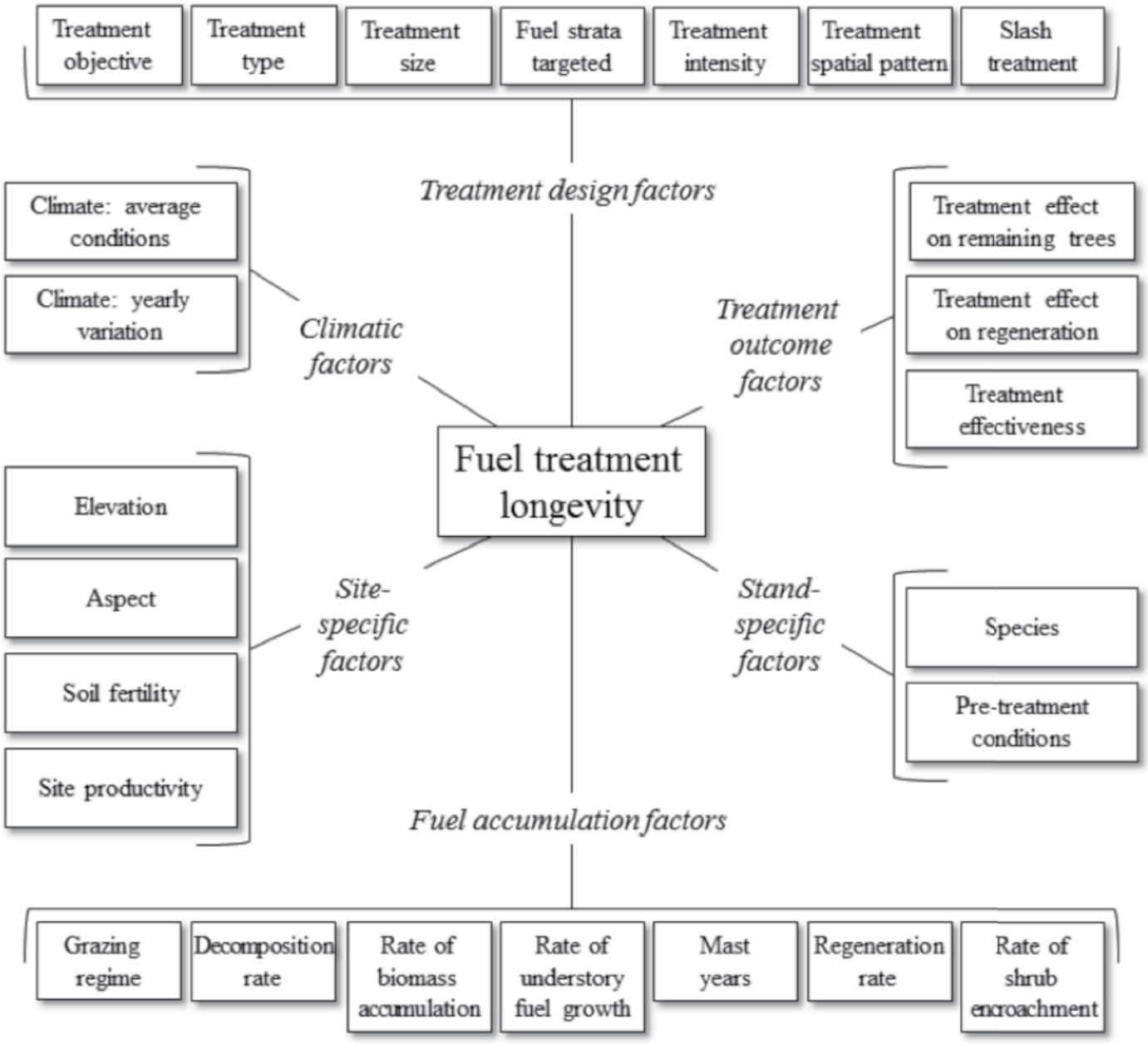
Box 1: When are prescribed fires most effective as a fuel treatment?

Land managers must wait until enough surface fuels have accumulated to allow another fire to burn and spread, but not so long that a prescribed fire will no longer meet management objectives (Stephens etal. 2012). For example, Battaglia et al. (2008) found that if managers waited more than about ten years to re-apply fire in the Black Hills of South Dakota, they would not be able to reduce sapling density using prescribed fire alone.

Fuel treatment type

Depending on management objectives and a site's proximity to human development, land managers may choose to use mechanical thinning, prescribed fire, or combinations of those methods to reduce fuels. In a study in a Sierra Nevada mixed-conifer forest, Stephens and colleagues (2012) compared fuel loads one year and seven years after fuel treatments. The treatments consisted of mechanical only, mechanical plus fire, fire only, and an untreated control. The team measured overstory and understory vegetation along with fuels. They modeled potential fire behavior with the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS), focusing on the outputs "total flame length" and "torching probability." The mechanical-only treatment did not change flame length and torching probability one year after treatment, while the two treatments using fire significantly reduced flame length and torching probability after that first year. However, after seven years there were no differences between the

Figure 1. Factors affecting fuel treatment longevity.



mechanical-only, mechanical plus fire, and fire-only treatments—all significantly reduced flame lengths and torching probabilities. The team concluded that an ideal treatment might consist of a mechanical thinning with a prescribed fire two to four years later because tree mortality from prescribed fire would be low in a thinned forest and surface fuel consumption would be high. These results, the researchers suggested, would lead to increased fuel treatment longevity.

Fulé et al. (2012) carried out a systematic review of fuel treatments in ponderosa and Jeffrey pine-dominated forests in the western United States. The authors found that thinning and burning treatments, on average, tended to be more effective than either thinning or burning treatments alone in reducing surface fuels and stand densities, while increasing crowning and torching indices. However, the results were highly mixed among individual studies, and the researchers did not include an analysis of fuel treatment effectiveness over time. Reinhardt et al. (2010) modeled forest structure and potential tree mortality following wildfire in stands of ponderosa pine and lodgepole pine in Montana that were subjected to various simulated treatments. Similar to Fulé et al. (2012), they found that thinning (commercial) followed by prescribed burning tended to be more effective than other treatment types in positively altering a suite of fire potential variables, including crowning index, torching index, potential mortality as a percentage of basal area, canopy base height, and canopy bulk density. This was the case in both lodgepole and ponderosa pine forests. Again, however, the results were highly variable and site-dependent.

Prescribed fire is effective in raising canopy base height if it scorches lower branches in a stand. However, it can also result in increased fuel loads by killing small trees and causing lower branches and needles to fall to the surface (Agee and Skinner 2005, Reinhardt et al. 2008). Because of this effect, it may be necessary to reburn an area to increase treatment longevity and maintain the effectiveness of the treatment (Stephens et al. 2012). In a management-focused report on "lessons learned" from prescribed burning in mixed-conifer and ponderosa pine forests in northern California, McCandliss reports that once an initial prescribed fire has been completed, it is scheduled for reentry in three to five years in order to kill newly-regenerated shrubs and consume the fuel created by the first burn. "It is clearly a waste of time, money, and effort to burn once and not come back to reburn at an appropriate interval" (McCandliss 2002).

Treatment size

Treatment size can make a difference in fuel treatment longevity because small treatments may be less effective at reducing potential extreme fire behavior across a landscape. "If fuel treatments are small and scattered, or a long time has elapsed since treatment (generally 10 to 15 years or more), they will be less effective in fragmenting the landscape fuel loads, and their efficacy at the stand level can be overwhelmed by intense fires burning in adjacent areas" (Agee and Skinner 2005, pp. 92-93). In a study in ponderosa pine forests after the Rodeo-Chediski Fire in Arizona, researchers found that treatment longevity increased with treatment size; they also noted that lower fire severity was associated with repeated fuel treatments (Finney et al. 2005).

Other treatment design factors that may influence the longevity of fuel treatments include:

- the original fuel treatment goals and objectives
- intensity of the treatment (Sackett and Hasse 1998)
- slash treatment (Weatherspoon and Skinner 1996)
- spatial pattern of the treatment (Finney et al. 2007).

Fuel accumulation factors influencing fuel treatment longevity

Site productivity strongly affects how long a fuel treatment will last. As Reinhardt and others (2008) write, "Tree crowns will eventually expand to fill canopy voids created by the treatment, tree regeneration will eventually lower canopy base height, and undergrowth will respond to increased light and water to achieve greater cover and height. More importantly, intact tree canopies will continue to drop leaf, cone, and woody litter at a rate that is dictated by ecosystem productivity and stand composition" (p. 2002). As an example, Stephens et al. (2012) noted that fuels accumulated faster in the Sierra Nevada than in the Rocky Mountains, because of higher productivity of Sierra Nevada forests. Many of the factors that influence productivity and fuel accumulation rates cannot be disentangled.

Rate of biomass accumulation

In northern California, Keifer et al. (2006) found that after a prescribed burn in ponderosa pine forests, surface fuels rebounded to 84% of pre-fire levels within ten years. They speculated that the rapid buildup of surface fuels may have been due to the high number of small trees killed in the prescribed fire or, perhaps, litterfall exceeded decomposition rates. In this same study, surface fuels were similar to untreated areas 31 years after a prescribed fire in ponderosa pine. In mixed conifer stands, surface fuels reached 66-83% of pre-fire levels within ten years. The authors recommend that to keep surface fuels below pre-fire levels, mixed conifer stands should be retreated every ten years (Keifer et al. 2006). Further, retreating with prescribed fire would be cheaper and result in less ground disturbance than repeated thinning treatments.

Surface fuel loads are notoriously difficult to predict because variability is very high across a landscape and even within a stand. Reinhardt et al. (2010) quoted Brown and See (1981), who analyzed fuel data from thousands of plots in the Rocky Mountains and found that "very little of the observed variation in loading was explained by any of the factors" such as stand age, aspect, slope, elevation, habitat type, and cover type. Therefore, it is very difficult to predict how fast surface fuels will accumulate after a fuel treatment.

Other fuel accumulation factors that affect fuel treatment longevity include:

- decomposition rates
- rates of understory plant growth
- mast years and regeneration rates
- rates of shrub encroachment
- level of animal grazing.

Treatment outcomes and fuel treatment longevity

Treatment effectiveness

The first treatment outcome factor that can influence fuel treatment longevity is the effectiveness of the treatment itself (i.e., prescription implementation). For example, land managers may want to kill tree seedlings and small trees with a prescribed fire, but if the fire is not hot enough, those goals will not be met and the effectiveness of the fuel treatment will not last long, if it is effective at all.

Vegetation responses to treatment

Mature vegetation on a site may respond positively or negatively to a fuel reduction treatment. A positive response would result if a treatment opened up growing space and allowed vegetation to grow at a faster rate, while a treatment that damages the remaining vegetation would result in a negative response. For example, Peterson et al. (1994) studied the effects of burning on tree growth and fuels in ponderosa pine forests in northern Arizona at seven different annual intervals. They found that burning at four- and six-year intervals did not negatively affect tree growth and these intervals were also the most effective in terms of fuel consumption. Burning at shorter and longer intervals resulted in less complete fuel consumption and had a negative impact on tree growth.

Regeneration responses to treatment

Regeneration rates influence fuel treatment longevity because saplings can become ladder fuels in a stand. According to Bailey and Covington (2002), "tree regeneration rates are regulated by the presence of sufficient seed-producing adults, periodicity of their cone/seed crops, predation on cones/ seeds, seed viability rates, seedbed conditions and germinant survival, and early seedling growth relative to microclimate, fire and competitive stresses" (p. 272). Similarly, Puhlick et al. (2012) showed that elevation, precipitation, temperature, seed tree presence, overstory basal area, understory species, and soil parameters can be important factors for ponderosa pine regeneration in the Southwest.

Although prescribed fire can kill seedlings, fuel treatments can also increase seedling density by opening the canopy and enhancing the seedbed for species such as ponderosa pine. In northern Arizona, higher-intensity treatments were found to have twice the number of ponderosa pine seedlings as low-intensity restoration treatments (Bailey and Covington 2002). Other researchers have found more seedlings germinated in burned treatments than in unburned treatments (Sackett and Haase 1998). Fajardo et al. (2007) noted that regeneration rates for Douglas-fir and ponderosa pine in Montana were higher ten years after cut-and-burn and cut-only treatments than they were in control plots. In ponderosa pine-Gambel oak forests on the South Rim of the Grand Canyon, Fulé et al. (2005) monitored the results five years after areas were treated with thinning and prescribed burning (full restoration), minimal thinning around old trees and prescribed burning (minimum restoration), and burning alone. They found relatively high rates of oak regeneration in all treatments, especially in full restoration and burn plots, and relatively low rates of ponderosa pine regeneration in all treatments, although burn plots exhibited higher pine regeneration than the others. The researchers noted that results were likely affected by pre-existing site differences and a drought as well as treatment effects.

In the Black Hills, Battaglia et al. (2008) found that ponderosa pine seedlings germinated, grew, and contributed to ladder fuels within 10 to 20 years after treatment. However, if a prescribed fire was applied within ten years after the first treatment, it would significantly reduce seedling density and prolong the effectiveness of the original treatment. Palmer (2012) used FVS to simulate ponderosa pine forest dynamics for a 50-year period at Grand Canyon National Park. She found that if regeneration rates were low (16.2 trees/ acre for ponderosa pine), burning every eight years was an effective way to keep tree density at desired levels while, when regeneration was high (162 trees/acre for ponderosa pine), eight-year intervals were not enough.

Other factors

Three additional groups of factors affect fuel treatment longevity. The first group, stand-specific factors, includes the species composition of the treated forest and pre-treatment conditions. The third group are climatic factors because both average climatic conditions and yearly variations in weather can play a role in how long fuel treatments last.

Post-wildfire evidence of fuel treatment longevity

Research studies of areas burned by wildfires provide another means of assessing the longevity of fuel treatments. Pollet and Omi (2002), for example, evaluated the fire severity of four wildfires in western ponderosa pine-dominated forests treated from 4 to 11 years before the wildfire. Treatments include thinning, prescribed fire, and thinning and burning. All four wildfires had a higher crown scorch percentage and fire severity rating in untreated stands compared to treated stands. This suggests that fuel treatment effectiveness lasted at least 11 years in the study sites. Similarly, Safford et al. (2012) found no difference between one- to nine-year-old treatments (mostly thinning-and-burning treatments) in their effect on fire severity and tree survival in 12 wildfires in yellow pine and mixed-conifer forests in California. This suggests that fuel treatments in those areas were effective for at least nine years.

Agee and Skinner (2005) report that under less extreme conditions during the 2002 Hayman Fire in Colorado, fuel treatments such as prescribed fire altered fire severity, except where treatments were small (less than ~250 acres) or where treatments were more than 10–15 years old. This suggests that 10-15 years is how long fuel treatments may be effective in the eastern Rocky Mountains in Colorado. In Yosemite National Park, managers and researchers have observed that most wildfires stop at old fire boundaries that are 15 years old or less (van Wagtendonk 1995, cited by Agee and Skinner 2005). Collins et al. (2009) also examined fire perimeters in mixed-conifer forest in Yosemite National Park and found that the probability of a wildfire burning into an area that had burned within the previous nine years was extremely low. Omi and Martinson (2007) reported that treatments were effective in reducing the wildfire severity of five fires in mixed-conifer forests in Washington, Oregon, California, Arizona, and Colorado for up to ten years, and were not effective in treatments older than that.

Finney and others (2005) analyzed remote sensing data after the Rodeo-Chediski Fire in Arizona to compare fire severity in areas of ponderosa pine forest that had been treated with prescribed fire and areas that had been untreated. They found that treated areas burned less severely than untreated areas, although severity increased with the age of the treatments. For instance, treatments less than two years old experienced lower fire severity than two- to three-year-old treatments, which did better than treatments more than four years old. However, fire severity in treatments up to nine years old was lower than in untreated areas. These results imply that although fuel treatment effectiveness declines over time, treatments in this area were noticeable up to nine years after treatments. In the same area, Strom (2005) found that areas treated with prescribed fire more than 11 years before the Rodeo-Chediski Fire were indistinguishable from untreated areas; treatments up to 11 years old made a difference in fire severity.

Finally, in a meta-analysis, Omi and Martinson (2010) found that fuel treatment effectiveness lasted about ten years, although longevity depended on ecosystem productivity. They write, "Fuel treatment effectiveness ultimately depends on the cumulative impact of a treatment regime applied across landscapes and maintained through time" (p. 9). There is clearly a wide range of fuel treatment effectiveness across the western United States.

Box 2: Can historical fire frequency be used as a benchmark for how frequently fuels should be treated?

Researchers and land managers know that in many dry western forests, surface fires or mixed-severity fires were historically frequent. Frequent, low-intensity surface fires kept surface fuels, ladder fuels, and canopy fuels from increasing to the point that crown fire could be carried across large landscapes. For instance, Harold Weaver (1951) reported, "The data indicate that in earlier days fires occurred just as frequently as fuel accumulated in sufficient quantity on the forest floor, when weather conditions were favorable, and when some natural or human agency caused them to start" (p. 94).

Where available, using historical fire frequency as a benchmark may give land managers a ballpark idea of how often fuel treatments need to be repeated. For example, some of the earliest reports about how often fuel treatments should be repeated in the Southwest came from Harold Biswell. He reported that on the Fort Apache Reservation in Arizona, the historical fire interval was six to seven years, and prescribed burns were effective in reducing wildfire hazard for five to seven years (Biswell et al. 1973). Researchers in recent years have suggested that using historical fire frequency as a benchmark for fuel treatment longevity is reasonable (Safford et al. 2012). However, it should be noted that there is a difference between how long it takes fuels to build up to a level that will support surface fire and how long managers can wait between fuel treatments before they are faced with fire behavior problems.

Using local data to schedule fuel treatments

There is no substitute for local knowledge, data, observations, and monitoring given the numerous factors that affect fuel treatment longevity and the variation that can occur across landscapes. As Reinhardt et al. (2010) point out, "The outcomes of treatments varied between stands, indicating that cookbook, one size-fits-all fuel treatment prescriptions are likely to be unsatisfactory" (p. 40).

Land managers may choose to use local data in models in order to schedule fuel treatments. For example, the Fire and Fuels Extension to the Forest Vegetation Simulator can be used to predict vegetation development over time. If managers have designated target fuel loads below which fire hazard is deemed acceptable, they can use this software to help schedule fuel treatments that will keep fuel loads below those target levels (Peterson et al. 2005). Land managers may also find useful a method developed by Keyes and O'Hara (2002) for developing silvicultural prescriptions. It is based on the BEHAVE surface fire model and modified versions of the Van Wagner crown ignition and crown fire spread equations.

Whether land managers are concerned about surface fuels or canopy fuels, crowning index or rate of spread, fire-induced tree mortality or soil damage, there is an appropriate metric they can use to determine whether the forest in a given location has moved out of prescription and is in need of further treatment. Although there is no single metric that will work for all areas and objectives, managers can use the metric(s) that work the best for their needs and closely monitor those variables. Researchers have identified potential thresholds of fuel levels that are unacceptable for particular situations. For example, crown bulk density above 0.1 kg/ha may be used as a threshold because research indicates that active crowning may occur above that threshold during extreme fire conditions (Agee 1996, cited by Omi and Martinson 2002). Height-to-live crown is also strongly associated with fire severity (Omi and Martinson 2002) and may serve as a metric when developing treatment schedules. Seedling density is another potentially useful metric because it has been suggested that to avoid the development of dense ladder fuels, regeneration densities should not exceed 500 stems per hectare or about 200 stems per acre (Battaglia et al. 2008).

Climate and drought

Climate change and drought are critical considerations for future forest management, including fuel treatments (Diggins et al. 2010). Many factors that affect fuel treatment longevity are likely to be affected by climate change, including the rate of fuel buildup, regeneration rates, and decomposition rates. In addition, fuel treatments that were once effective in a past climate may no longer be effective if fire seasons become longer, droughts more extensive, or other climate-driven changes to the fire regime occur. Finally, although fuel treatment effectiveness and longevity are uncertain given a changing climate, they may become even more important, to give native species and ecosystems the best possible chance to persist.

Future research needs

Several gaps in knowledge can be identified. One research need is better information about fuel buildup over time, in different forest types, after different fuel treatments, and in different climate regimes. Another need is more systematic studies of wildfire behavior in treated and untreated areas. Although we spend millions of dollars a year on fuel treatments and they are a high priority for policy-makers, managers, and the general public, we have surprisingly little information about their effectiveness over time.

Summary

- Fuel treatment longevity depends on a multitude of factors, including site- and stand-specific factors, treatment design and treatment outcome factors, climatic factors, and fuel accumulation factors.
- In studies of wildfire severity, treatments ranging in age from 2 to 15 years were effective in changing fire outcomes across the western United States.
- Although the evidence is limited, thinning and prescribed burning may be the most effective treatment combination.
- There is no "one-size-fits-all" number for fuel treatment longevity; local monitoring is essential.
- Climate change may impact fuel treatment longevity, but also may make fuel treatments even more essential in the future.
- Research needs include information about fuel accumulation rates in different forest types, after different fuel treatments, and in different climate regimes. Systematic studies of wildfire behavior in treated and untreated areas are also a high priority.

References

Agee, J.K. 1996. The influence of forest structure on fire behavior. Pages 52-68 *in* J. Sherlock. (chair). Proceedings of the 17th Annual Forest and Vegetation Management Conference. Redding, CA.

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

Bailey, J.D. and W.W. Covington. 2002. Evaluating ponderosa pine regeneration rates following ecological restoration treatments in northern Arizona, USA. *Forest Ecology and Management* 155:271-278.

Battaglia, M.A., F.W. Smith and W.D. Shepperd. 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? *Forest Ecology and Management* 256:2029-2038.

Biswell, H.H., H.R. Kallander, R. Komarek, R.J. Vogl, and H. Weaver. 1973. Ponderosa fire management: A task force evaluation of controlled burning in ponderosa pine forest of central Arizona. *Tall Timbers Research Station Miscellaneous Publication* 2:1-49.

Brown, J.K. and T.E. See. 1981. Downed dead woody fuel and biomass in the northern Rocky Mountains. General Technical Report INT-117. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Carey, H. and M. Schumann. 2003. Modifying wildfire behavior – the effectiveness of fuel treatments. *National Community Forestry Center Southwest Region Working Paper #2*. Santa Fe, NM.

Chiono, L.A., K.L. O'Hara, M.J. De Lasaux, G.A. Nader, and S.L. Stephens. 2012. Development of vegetation and surface fuels following fire hazard reduction treatment. *Forests* 3:700-722.

Collins, B.M., J.D. Miller, A.E. Thode, M. Kelly, J.W. van Wagtendonk, S.L. Stephens. 2009. Interactions among wildland fires in a long-established Sierra Nevada natural fire area. *Ecosystems* 12(1):114-128.

Diggins, C., P.Z. Fulé, J.P. Kaye, and W.W. Covington. 2010. Future climate affects management strategies for maintaining forest restoration treatments. *International Journal of Wildland Fire* 19:903-913.

Fajardo, A., J.M. Graham, J.M. Goodburn, and C.E. Fiedler. 2007. Ten-year responses of ponderosa pine growth, vigor, and recruitment to restoration treatments in the Bitterroot Mountains, Montana, USA. *Forest Ecology and Management* 243:50-60.

Fernandes, P.M. and H.S. Botelho. 2003. A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* 12:117-128.

Finney, M.A., C.W. McHugh, and I.C. Grenfell. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research* 35:1714-1722.

Finney, M.A., R.C. Seli, C.W. McHugh, A.A. Ager, B. Bahro and J.K. Agee. 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. *International Journal of Wildland Fire* 16: 712-727.

Fulé, P.Z., D.C. Laughlin, and W.W. Covington. 2005. Pine-oak forest dynamics five years after ecological restoration treatments, Arizona, USA. *Forest Ecology and Management* 218:129-145.

Fulé, P.Z., J.E. Crouse, J.P. Roccaforte, and E.L. Kalies. 2012. Do thinning and/or burning treatments in western USA ponderosa or Jeffrey pine-dominated forests help restore natural fire behavior? *Forest Ecology and Management* 269:68-81.

Keifer, M., J.W. van Wagtendonk, and M. Buhler. 2006. Long-term surface fuel accumulation in burned and unburned mixed-conifer forests of the central and southern Sierra Nevada, CA (USA). *Fire Ecology* 2(1):53-72.

Keyes, C.R. and K.L. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. *Western Journal of Applied Forestry* 17(12):101-109.

McCandliss, D.S. 2002. Prescribed burning in the Kings River Ecosystems Project Area: lessons learned. In: Proceedings of a Symposium on the Kings River Sustainable Forest Ecosystems Project: Progress and current status. USDA Forest Service General Technical Report PSW-GTR-183:37-46, Albany, CA.

Omi, P.N. and E.J. Martinson. 2002. Effect of fuels treatment on wildfire severity. Final report to the Joint Fire Science Program Governing Board. Colorado State University, Fort Collins.

___. 2007. Tested by fire: what happens when wildfires meet fuel treatments? *Joint Fire Science Program Fire Science Brief* 1:1-6.

___. 2010. Effectiveness of fuel treatments for mitigating wildfire severity: A manager-focused review and synthesis - Final Report to the Joint Fire Science Program. JFSP Project No. 08-2-1-09.

Palmer, K.E. 2012. Modeling long-term changes to the ponderosa pine forests of Grand Canyon National Park. M.S. Thesis. School of Forestry, Northern Arizona University, Flagstaff, AZ.

Peterson, D.L., S.S. Sackett, L.J. Robinson, and S.M. Haase. 1994. The effects of repeated prescribed burning on *Pinus ponderosa* growth. *International Journal of Wildland Fire* 4(4):239-247.

Peterson, D.L., M.C. Johnson, J.K. Agee, T.B. Jain, D. McKenzie, and E.D. Reinhardt. 2005. Forest structure and fire hazard in dry forests of the western United States. USDA Forest Service General Technical Report PNW-GTR-628, Portland, OR.

Pollet, J. and P.N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* 11:1-10.

Puhlick, J.J., D.C. Laughlin, and M.M. Moore. 2012. Factors influencing ponderosa pine regeneration in the southwestern USA. *Forest Ecology and Management* 264:10-19.

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.

Reinhardt, E.D., L. Holsinger, and R. Keane. 2010. Effects of biomass removal treatments on stand-level fire characteristics in major forest types of the northern Rocky Mountains. *Western Journal of Applied Forestry* 25(1):34-41.

Sackett, S.S. and S.M. Haase. 1998. Two case histories for using prescribed fire to restore ponderosa pine ecosystems in northern Arizona. Pages 380-389 *in* Fire in ecosystem management: shifting the paradigm from suppression to prescription. Proceedings of the 20th Tall Timbers Fire Ecology Conference, May 7-10, 1996, Boise, ID. Tall Timbers Research Station, Tallahassee, FL.

Safford, H.D., J.T. Stevens, K. Merriam, M.D. Meyer, A.M. Latimer. 2012. Fuel treatment effectiveness in California yellow pine and mixed conifer forests. *Forest Ecology and Management* 274:17-28.

Stephens, S.L., B.M. Collins, and G. Roller. 2012. Fuel treatment longevity in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* 285:204-212.

Strom, B. 2005. Pre-fire treatment effects and post-fire forest dynamics on the Rodeo-Chediski burn area, Arizona. M.S. Thesis, School of Forestry, Northern Arizona University, Flagstaff, AZ.

Vaillant, N., E. Noonan-Wright, S. Dailey, C. Ewell, and A. Reiner. 2009. Effectiveness and longevity of fuel treatments in coniferous forests across California. Final Report to the Joint Fire Science Program, Project ID 09-1-01-1.

van Wagtendonk, J.W. 1995. Large fires in wilderness areas. Pages 113-116 in Proceedings of a Symposium on Fire in Wilderness and Park Management. USDA Forest Service General Technical Report INT-GTR-320, Ogden, UT.

Weatherspoon, C.P. and C.N. Skinner. 1996. Landscape-level strategies for forest fuel management. Pages 1471-1492 in Sierra Nevada Ecosystem Project: Final Report to Congress. Vol. II. Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. Centers for Water and Wildland Resources, University of California, Davis.

Weaver, H. 1951. Fire as an ecological factor in the southwestern ponderosa pine forests. *Journal of Forestry* 49(2):93-98.

Working Papers in Intermountain West Frequent-fire Forest Restoration

Author: Larissa Yocom
Reviewers: Pete Fulé, David Huffman, Andrea Thode
Series Editor: Dave Egan

For more information about forest restoration,
contact the ERI at 928-523-7182 or **eri.nau.edu**

Northern Arizona University is an Equal Opportunity/Affirmative Action Institution
NAU Printing Services/74375/300/02-13

NORTHERN ARIZONA UNIVERSITY

Ecological Restoration Institute
P.O. Box 15017
Flagstaff, AZ 86011-5017
eri.nau.edu