The Effects of Forest Fuel-Reduction Treatments in the United States

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The current conditions of many seasonally dry forests in the western and southern United States, especially those that once experienced low- to moderate-intensity fire regimes, leave them uncharacteristically susceptible to high-severity wildfire. Both prescribed fire and its mechanical surrogates are generally successful in meeting short-term fuel-reduction objectives such that treated stands are more resilient to high-intensity wildfire. Most available evidence suggests that these objectives are typically accomplished with few unintended consequences, since most ecosystem components (vegetation, soils, wildlife, bark beetles, carbon sequestration) exhibit very subtle effects or no measurable effects at all. Although mechanical treatments do not serve as complete surrogates for fire, their application can help mitigate costs and liability in some areas. Desired treatment effects on fire hazards are transient, which indicates that after fuel-reduction management starts, managers need to be persistent with repeated treatment, especially in the faster-growing forests in the southern United States.

Keywords: fire surrogates, wildfire, fire ecology, forest management, forest conservation

For several millennia, frequent, low- to moderate-intensity wildfire has sculpted seasonally dry forests in the southern, eastern, and western United States. Low- to moderate-intensity fires reduced the quantity and continuity of fuels and discouraged the establishment of fire-intolerant species (Agee and Skinner 2005). Yet fire suppression, the preferential harvest of large-diameter trees, and land conversion over the past 150 years have changed fuel conditions over millions of hectares (ha) of forests (Stephens and Ruth 2005) such that recent wildfires have tended to be larger and more severe, and this trend may continue in some forests as climates continue to warm (McKenzie et al. 2004). Given this scenario, it is easy to see why tools such as prescribed-fire and *mechanical* (i.e., manual removal; e.g., thinning) fuel treatments are increasingly used by managers in an effort to change the only factors in the fire behavior formula they can: the quantity and continuity of fuel.

There is increased recognition that most low- to moderate-intensity fire regimes in US forests included some patchy high-severity fire (Hessburg et al. 2007, Beaty and Taylor 2008, Perry et al. 2011). Fire is an inherently complex landscape process, both within individual fires and among multiple fires over time. This complexity is driven by heterogeneity in vegetation and fuel, topography, and local weather for individual fires and by variability in the timing, effects, and extents of multiple fires (Collins and Stephens 2010). Patchy, high-severity fire provides opportunities for early seral habitat development and the production of deadwood resources from tree mortality that are important to many wildlife species (Hutto 2008, Kennedy and Fontaine 2009). As such, forest fuel treatments should not attempt to eliminate all high-severity fire, but most patches should be relatively small, as is the case in upper mixed-conifer forests in the Sierra Nevada, where the median high-severity patch size was approximately 2 ha (Collins and Stephens 2010). Current wildfire high-severity patch sizes and areas in many forests that once burned frequently with low- to moderate-intensity fire regimes are well outside historical conditions and this may increase as climates continue to warm (Miller et al. 2009).

As a fuel-reduction practice, prescribed fire (figure 1) is an attractive alternative to large, high-intensity wildfires, because it is thought to best emulate the natural process that it is designed to replace (Schwilk et al. 2009). However, forest managers have been so substantially constrained by social, economic, and administrative issues that prescribed-fire use is low, especially in the western United States. Therefore, fuel-reduction surrogates, such as forest thinning and mastication (figure 1), have become more attractive, especially when forest managers can use such treatments to accomplish

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Figure 1. Examples of fire and fire-surrogate treatments applied in order to reduce fire hazards in mixed-conifer forests in the central Sierra Nevada, California. (a) Mechanical fuel treatment using a rotary masticator mounted on an excavator. (b) Prescribed fire at night. Photographs: Jason Moghaddas.

stand-structure goals similar to those obtained by prescribed fire. Until recently, however, we knew little about the possible unintended consequences that might arise from widespread application of fire-surrogate treatments in seasonally dry forests.

The principle question addressed in this article is misleadingly simple: What components or processes are changed or lost, and with what effects, if fire surrogates such as cuttings and mechanical fuel treatments are used instead of fire or in combination with fire? To answer this challenging question, in this article, we summarize diverse research (including the national Fire and Fire Surrogate [FFS] Study and the broader literature) related to fuel treatments from multiple perspectives, including fuels and potential fire behavior, vegetation, soils, wildlife, bark beetles, carbon sequestration, and costs and utilization. This information is targeted toward scientists, policymakers, and managers of forests that were once dominated by frequent, low- to moderate-intensity fire regimes.

Fuels, fire behavior, and wildfire surrogates

A brief introduction of wildland fuels and their characteristics is necessary to understand the factors and processes important to achieving reductions in wildfire severity through the application of fuel-reduction treatments (Stephens and Ruth 2005). Wildland fuels can be classified into four groups: ground, surface, ladder, and crown; each of these has a different potential to influence fire behavior. *Ground fuels* include the duff (the O_i soil horizon) on the soil surface and generally do not contribute to wildfire spread or intensity. *Surface fuels* include all dead and down woody materials, litter, grasses, other herbaceous plant materials, and short shrubs, which are often the most hazardous fuels in many forests. This is particularly true in seasonally dry forests, where vegetative species composition, density, and structure have been influenced by decades of fire suppression and harvesting (Fulé et al. 2001, Agee and Skinner 2005). *Ladder fuels* are small trees or tall shrubs that provide vertical continuity from surface fuels to the crowns of tall trees and are generally the second-most-hazardous fuel component. *Crown fuels* are those in the overstory and are a small component of fire hazards in these forests (Stephens et al. 2009).

The potential for *passive crown fires* (initiated by the torching of a small group of trees) is reduced most efficiently by the reduction of surface fuels followed by a reduction of ladder fuels. Reducing surface fuels by prescribed fire is a very effective treatment for reducing the potential for passive crown fires. The potential for *active crown fires* (fire spreading in crown and surface fuels simultaneously) is reduced most effectively by a combination of mechanical and prescribed-fire treatments, because these treatments can target ladder and surface fuels and intermediate-size trees. However, prescribed fire alone can greatly increase the wind speed needed to initiate a passive crown fire, which effectively reduces stand vulnerability to torching and the transition to active crown fire (Stephens et al. 2009). This result is not only supported by modeling of fire behavior but by empirical studies of wildfires burning through treated stands (Ritchie et al. 2007).

The results of mechanical treatments alone are mixed regarding their ability to reduce potential fire severity (Agee and Skinner 2005, Stephens et al. 2009). In this regard, whole-tree-removal systems are one of the most effective mechanical systems and may be preferred where wood-chip or biomass markets are available. Where trees are too small (less than 20 centimeters [cm] in diameter) for sawn products and cannot be economically chipped and transported to a processing facility, subsidizing treatment or hauling costs should be considered if the corresponding decrease in fire hazard warrants the additional expenditure. Whole-tree-removal systems are also advantageous when forest managers plan to apply prescribed burns after harvesting, because this creates minimal logging debris, and therefore, only surface fuels existing prior to treatment need to be consumed.

An important difference between prescribed-fire treatments and combined mechanical and prescribed-fire treatments is the amount of residual dead material left standing after treatment, which is higher after prescribed-fire treatments (Stephens et al. 2009). This material, killed by the fire, will eventually fall to the ground and can exacerbate fire effects when the site burns again. Although the addition of this woody material may increase wildlife habitat value or may stabilize erosive soils, it will increase future surface-fuel loads and shorten the longevity of the fuel treatment. We expect that several fire-only treatments (two or three during a 10–20-year period) would be needed to achieve the management objective of reducing potential fire behavior and effects in the forests studied.

In many forest ecosystems, logistical constraints restrict fire prescriptions to cooler and milder conditions than those under which wildfires historically occurred (Fulé et al. 2004). Burning in the spring results in the fewest significant changes to stand and fuel structures, and spring burning results in greater retention of large woody debris, which could be desirable in some cases, including the retention of microhabitat features required by many wildlife species (Knapp et al. 2009, Fettig et al. 2010). Our analysis supports the assertion that a lack of treatment or passive management (Stephens and Ruth 2005) perpetuates the potential for extensive high fire severity in forests that once burned frequently with low- to moderate-intensity fire regimes. Retaining larger dominant and codominant trees in the residual stands also increases a forest's resistance to fire (Agee and Skinner 2005). Conversely, thinning from above, or overstory removal of dominant and codominant trees, decreases fire resistance (Stephens and Moghaddas 2005).

The net treatment costs and reduction in fire risk are critical considerations when determining the feasibility of any fuel treatment (Hartsough et al. 2008). The effectiveness of mechanical thinning for reducing passive and active crown fire potential is largely dependent on the type of harvest system used—particularly, whether the harvest system leaves logging debris within treated stands. Creating forest structures that can reduce fire severity at the landscape level may decrease the need for an aggressive suppression response and could eventually reduce the costs of fire suppression.

Vegetation

One of the primary concerns with prescribed fire as a management tool is its application outside of the historical fire season (Knapp et al. 2009). It is reasonable to assume that the seasonality of fire might interact with vegetative species' phenologies, but experimental results have been mixed. Early-growing-season burns occur at the beginning of the annual growth period, when plants are most susceptible to heat damage and when carbohydrate reserves are at their lowest levels. Burns implemented during the growing season may result in greater tree mortality than those implemented during the dormant season and may also cause greater damage to fine roots, particularly in old growth stands of ponderosa pine (*Pinus ponderosa*; Swezy and Agee 1991). Conversely, late-growing-season or dormant-season prescribed fires are likely to be of greater intensity and to entail greater fuel consumption and have been reported by some authors to result in greater amounts of tree mortality than early-season prescribed fires (e.g., Thies et al. 2005). Comparing early- and late-season prescribed fires, Schwilk and colleagues (2006) reported that the levels of tree mortality were related to fire intensity rather than to seasonality and tree phenology in California mixed-conifer forests. In eastern hardwood and southeastern pine forests, growing-season fires were the historical norm, but dormant-season burns have been used successfully (Glitzenstein et al. 1995, Brose and Van Lear 1998).

Mechanical fuel treatments can be successful surrogates for fire in modifying forest structure but are variable in their effects on understory plant communities because of large differences among treatments and the variation in understory vegetation composition and productivity among forest types. Although most studies of mechanical fuel treatments have been focused on their efficacy for reducing crown-fire hazard, in several recent investigations, the impacts of such treatments on plant communities have been measured (e.g., the FFS Study; Schwilk et al. 2009).

The mechanical fuel treatments implemented as part of the FFS Study proved more variable in their effects on understory vegetation than on stand structure (Schwilk et al. 2009). Mechanical treatments can vary widely, but there are several general ways in which mechanical fuel treatments may not act as surrogates for fire. Such treatments may disturb or add to organic material on the forest floor and may lack the heat required to kill fire-sensitive tree and shrub species or to cue seed germination in some fire-dependent species. Harvesting equipment may result in damage to nontarget species. However, mechanical fuel treatments, like fire, open the canopy and provide increased light to the understory and decreased competition among overstory trees. Therefore, a general pattern observed following mechanical fuel treatments is an increase in understory production and diversity similar to that seen following low- to moderate-intensity fire (Bartuszevige and Kennedy 2009).

Increases in understory vegetation richness tend to be greatest in closed-canopy forests that have the lowest understory component prior to treatment. In more open forests, the effects on understory species composition may take years to emerge, even when understory production increases rapidly following treatment (Laughlin et al. 2004). Both prescribed-fire and mechanical fuel treatments can increase the abundance of exotic species, and this increase is generally greatest with combined mechanical and prescribed-fire treatments (e.g., Bartuszevige and Kennedy 2009, Schwilk et al. 2009). Tree seedling recruitment is particularly sensitive to variation in mechanical treatment techniques, potentially as a result of variation in soil disturbance, compaction, and the amount of bare soil exposure (Schwilk et al. 2009), or this sensitivity to treatment may represent large, natural interannual variation in recruitment (League and Veblen 2006). Mechanical fuel treatments alone fail to mimic fire in systems containing species with fire-cued recruitment. This failure, combined with the increase in surface woody material common to many mechanical treatments, may explain a lack of shrub recruitment following mechanical treatments (e.g., Perchemlides et al. 2008). Across ecosystems in which such treatments are most commonly used (i.e., forests that historically experienced low- to moderate-intensity fire regimes), fire-surrogate treatments have not been shown to produce dramatic negative impacts on plant communities (table 1). There has been increased interest, however, in the application of both prescribed-fire and mechanical fuel treatments in communities that historically experienced infrequent crown fire, such as subalpine forests or shrublands. In these crown-fire systems, the lessons learned concerning vegetative responses from other forest types may be misleading (Schoennagel et al. 2004). Fire treatments have been successfully used in Florida scrub communities that contain fire-dependent species (Menges et al. 2006), but in shrub communities with many species sensitive to immaturity risk, frequent fire or mechanical disturbance can result in ecosystem degradation and local extirpation (Keeley 2002).

Soil properties

The literature indicates that the FFS Study is the most comprehensive study conducted on the effects of fuels treatments on soils, and we therefore rely most heavily on that study in this synthesis. The soils underlying the 12-site FFS Study network were very diverse and included six soil orders and more than 50 named soil series. Across their network, pretreatment soils varied in pH from less than 4 to more than 7 and exhibited ranges of 2 times in bulk density, 4 times in soil organic carbon content, 10 times in total inorganic nitrogen, and 200–1000 times in extractable base cations, such as calcium and potassium (Boerner et al. 2009).

Fuel-reduction treatments that include prescribed fire, alone or in combination with mechanical treatments, generally result in short-term losses of forest-floor organic layers, resulting in greater mineral soil exposure (figure 2; Boerner et al. 2009). Although considerable mineral soil exposure may be observed in skid trails and other areas of intensive vehicle activity during mechanical treatments, such treatments typically had an impact on less than 2% of the forest floor, and therefore had little effect on soil exposure. In the FFS Study, increases in mineral soil exposure persisted through later years (to the second or fourth year, depending on the site) only after the prescribed-fire-only treatment.

Soil bulk density (as a measure of soil compaction) was not affected significantly by any of the fuel-reduction treatments at the FFS Study–network scale, a result that is consistent with other studies (e.g., Moehring et al. 1966). Stand-replacing wildfires can result in considerable erosion because of processes that result from mineral soil exposure and, in some ecosystems, the development of hydrophobicity (e.g., overland flow, slope failure), and such impacts may be exacerbated by logging (Ice et al. 2004). However, the effects on soil physical properties regarding fire severity and harvest levels that characterize typical fuel-reduction treatments are relatively modest, and therefore, the potential for significant erosion or other hydrological impacts is small.

There was considerable within- and among-site variability in soil pH both before and after treatment in the FFS Study. Despite this variability, at the network scale, soil pH was significantly higher in soils of the combined mechanical and fire treatment than in untreated control soils during the first posttreatment year but not during the later sampling year (figure 2). Neither prescribed fire alone nor the mechanical treatment alone had a significant effect on soil pH at the FFS Study–network scale during either sampling year (figure 2). Within- and among-site variability in extractable base cation content was even more variable than was soil pH, with the result that there were no significant network-scale effects of the manipulative treatments on either extractable calcium or extractable potassium (Boerner et al. 2009).

Table 1. Prescribed-fire and mechanical fuel treatment use across several US forest types.

		Risks of prescribed fire		Risk of mechanical treatments		
Forest type	**Management goals**	**Overstory**	**Understory**	**Overstory**	**Understory**	**Seasonality risk**
Mixed-conifer forest	Restoration or hazard reduction	Low	Low	Low	Medium (exotic species)	Low
Ponderosa pine forest	Restoration or hazard reduction	Low	Low	Low	Low or medium (exotic species)	Low
Subalpine forests and boreal forests	Hazard reduction	Medium	Medium	High	Medium	Medium
Southeastern pine forests or savannas	Restoration or hazard reduction	Low	Low	Low	Low	Low or medium
Eastern deciduous hardwood forest	Restoration	Low	Low	Low	Low	Low

Note: The “Seasonality risk” column indicates the estimated risk of treatments outside of the historical fire season.

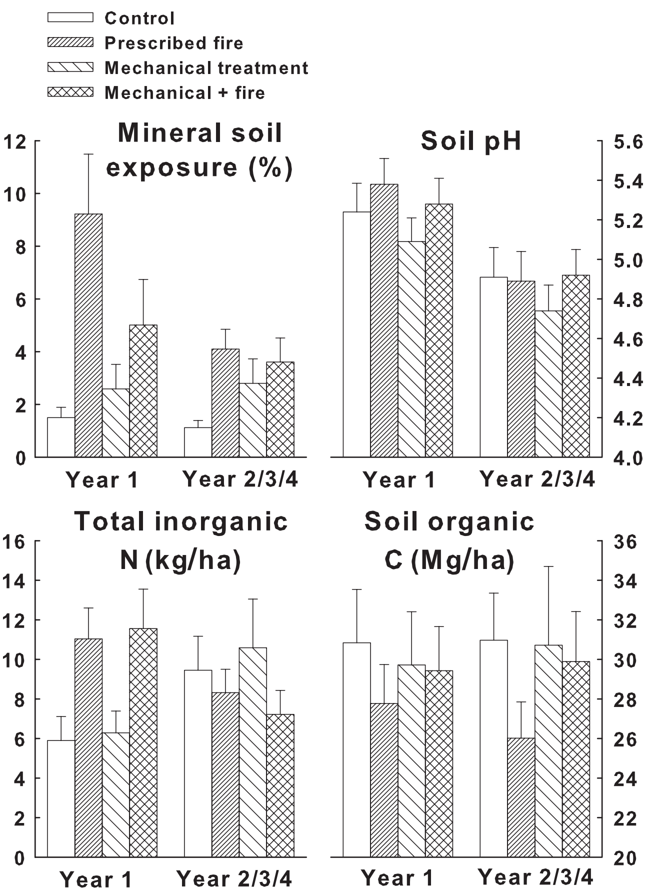

Figure 2. Trends for mineral soil exposure, pH, inorganic nitrogen (N), and organic carbon (C), in response to fire and fire-surrogate treatments measured across a national network of 12 research sites in the United States (part of the national Fire and Fire Surrogates Study). These four variables were selected to represent some of the most important in characterizing soil treatment effects. The values presented are means, and the error bars represent the positive standard error of the mean. Abbreviations: ha, hectares; kg, kilograms; Mg, megagrams.

At the FFS Study–network scale, total inorganic nitrogen increased significantly during the first posttreatment year after all manipulative treatments, but this effect did not persist to the later sampling year (figure 2). Once again, this result is consistent with those of previous studies demonstrating that the increases in dissolved, inorganic nitrogen commonly observed after fire are short lived (Covington et al. 1991, Covington and Sackett 1992). Soil organic carbon content was not significantly affected by any of the treatments during the first posttreatment year and was only marginally reduced by prescribed fire alone during the later sampling year (figure 2; Boerner et al. 2009). Johnson and Curtis (2001) evaluated the effects of various disturbance modes, including fire and logging, on soil carbon, and concluded that the impact of prescribed fire on soil carbon was typically small, whereas Eivazi and Bayan (1996) concluded that no net increase in total soil carbon resulted from more than 40 years of prescribed fire in an oak forest in Missouri. Similarly, neither FFS Study–network scale nor individual-site total soil carbon was affected significantly by any of the manipulative treatments in either sampling year (Boerner et al. 2008a). Overall, the network-wide effects of the FFS Study treatments on soil properties appear to have been modest and transient. Given the scale of the FFS Study and the results from previous research, we expect similar minimal effects on soils properties when areas are treated with fire or mechanical fuel treatments in forests that historically experienced frequent, low- to moderate-intensity fire regimes.

Wildlife

In addition to its use in managing wildfire hazards, the application of prescribed-fire and fire-surrogate treatments is frequently motivated by wildlife–habitat objectives (Yager et al. 2007, Kennedy and Fontaine 2009, Roberts et al. 2010). Research on fire and its effects on terrestrial vertebrates (wildlife) has been conducted since the early 1900s, beginning with research showing the negative effects of fire exclusion in longleaf pine (*Pinus palustris*) forests on northern bobwhite (*Colinus virginianus*; Stoddard 1931). Since then, a large body of work has been developed, particularly in the last 10–15 years (Kennedy and Fontaine 2009), which has shown that many wildlife species depend on fire-maintained habitats or pyrogenic structures, such as the snags, shrubs, and bare ground created by fires of varying severity (Hutto 2008).

Increased applications of fuel-reduction treatments, public scrutiny of land management agencies, and a growing scientific literature on the topic motivated a recent comprehensive review and meta-analysis of the fire–wildlife literature from forests dominated by low- to moderate-intensity fire regimes (Kennedy and Fontaine 2009, Fontaine and Kennedy 2012). On the basis of the characteristics of the available literature, fuel-reduction treatments and high-severity fire were considered at 0–4 years posttreatment. A lack of published longer-term (more than 5 years) studies precluded any analyses of longer-term effects. Importantly, the only thinning treatments included in this analysis were those conducted for fuel reduction, which is generally a lower-intensity treatment (e.g., the median reduction in basal area for the FFS Study was 30%; Schwilk et al. 2009) than those implemented for other silvicultural objectives (see Vanderwel et al. 2007 for a detailed meta-analysis of avian responses to a broader range of thinning intensities). The data from low- and moderate-severity fires were pooled, because neither of these treatments resulted in a large canopy loss (less than 50% canopy mortality, less than 25% in almost all cases), and there are insufficient studies of mixed-severity fire to warrant separation. These categories allowed for a comparison of vertebrate responses (mean abundance, density, and vital rate in treated and reference conditions) to fire surrogates combined with fire, as well as differing levels of fire severity (measured by overstory tree mortality). Data were more abundant for birds than for any other taxon

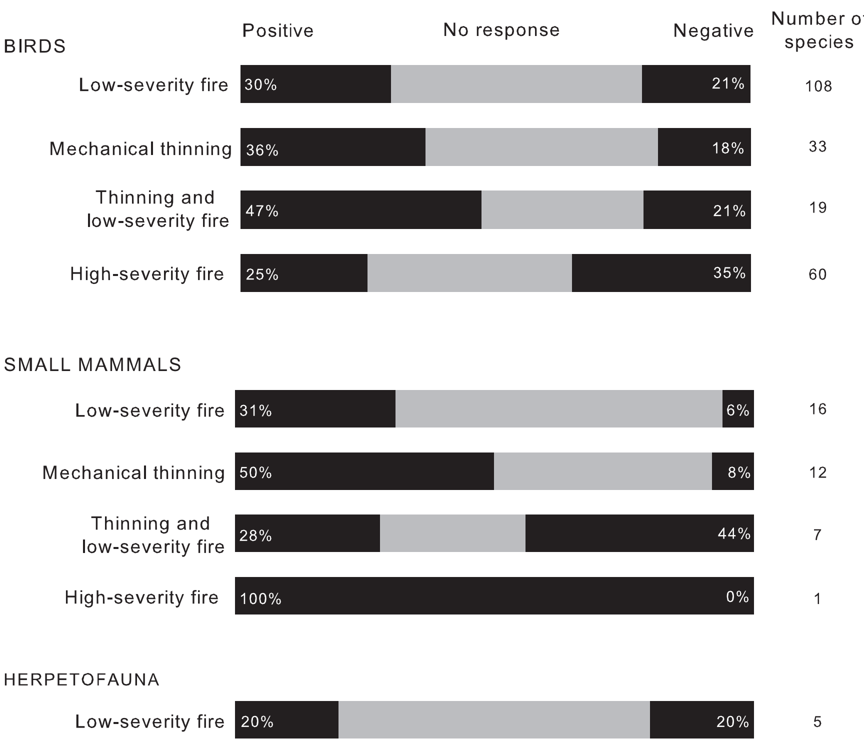

Figure 3. The responses (positive, neutral, and negative; number of species with sufficient data) of birds, small mammals, and herpetofauna to fire and fire-surrogate treatments 0–4 years after fire treatment in seasonally dry forests of the United States. The response classification was based on a meta-analysis of the existing literature and the generation of cumulative effect-size estimates and their 95% confidence intervals with overlap (neutral) or not (positive, negative) with zero.

(figure 3), which underscores a need for further work on other wildlife taxa—particularly herpetofauna, which reside primarily on the forest floor.

One of the most interesting results was the similarity in the pattern of responses between thinning and low- to moderate-severity prescribed fire (figure 3). Across all species of birds, the proportions of species with negative, neutral, and positive effects were quite similar. Thirty percent to 36% of the birds responded positively to low-severity fire and mechanical thinning, with smaller negative responses of 21% and 18%, respectively (figure 3). The sample of small mammals was smaller but with similar response patterns for low-severity fire and an increased positive response for mechanical thinning, probably reflecting some species' negative response to consumption of the litter layer. Combined mechanical thinning and low-severity fire led to an increased positive response in birds (47%) but a decrease in small mammals (28%; figure 3). When responses of the same species were compared between mechanical thinning and low-severity fire (reported in Fontaine and Kennedy 2012), 42% of the birds (n = 31) and 54% of the small mammals (n = 13) showed no change in response. A comparison of fire severity suggested clear differences among treatments for birds (decreased neutral response to high-severity fire; figure 3). Data for only five species of herpetofauna (four amphibians and one turtle) were available for the low-severity fire treatment, and most species did not respond to the treatment.

This similarity in the responses of birds and small mammals to thinning and low-severity prescribed fire suggests that, at the stand scale and in the short term (0–4 years), thinning may adequately mimic low-severity fire in terms of its effects on these taxa. The levels of regeneration of vegetation, fuel dynamics, and nutrient cycling following prescribed fire and following thinning differed substantially (Boerner et al. 2009, Schwilk et al. 2009), but thinning or low-severity prescribed fire have the potential, in the short term, to create forests with similar structure and with habitat conditions favored by many wildlife species. Therefore, the results suggest that the use of thinning in lieu of prescribed fire may be warranted for birds and small mammals, particularly in areas in which the implementation of prescribed fire is problematic. However, the long-term effects of these two treatments on wildlife require further investigation before these results can be fully integrated into management.

Research illustrates that these fuel treatments do not create conditions suitable for all species (see the negative responses in figure 3). Additional analyses demonstrate that low- to moderate-severity surface fire (and presumably its thinning surrogate) does not mimic the early successional habitat conditions created by high-intensity, patchy, stand-replacing fires. When it is feasible, managers may aim for patchy high-intensity prescribed fire to mimic the effects of wildfire (Fulé et al. 2004). In short, there is no one-size-fits-all prescription when it comes to incorporating disturbances into land management (i.e., there is a need for the presence of all successional stages within a forested landscape in order to maximize wildlife diversity; Fontaine et al. 2009).

Bark beetles

Bark beetles are recognized as important tree-mortality agents in the coniferous forests of the southern and western United States. Fuel-reduction treatments may influence the amount and distribution of bark-beetle-caused tree mortality at various spatial and temporal scales (e.g., Fettig and McKelvey 2010, Fettig et al. 2010). For example, these treatments may affect the health and vigor of residual trees; the size, distribution, and abundance of preferred hosts;

and the physical environment within forest stands (Fettig et al. 2007). Carelessly implemented treatments may result in physical damage to residual trees, soil compaction, and increased rates of windthrow, which would increase the likelihood of tree colonization by bark beetles, other subcortical insects, and root pathogens. Furthermore, tree volatiles released during harvest operations and the application of prescribed fire are known to influence the physiology and behavior of bark beetles and the colonization rates of trees by bark beetles (Fettig et al. 2006).

The levels of tree mortality following prescribed fire depend on numerous factors, including tree species; tree size; phenology; the degree of fire-caused injuries; initial and postfire levels of tree vigor; the postfire environment; and the frequency and severity of other predisposing, inciting, and contributing factors (Fettig and McKelvey 2010). Bark beetles may attack and kill trees that were injured by fire but that would otherwise have survived. These trees may then serve as a source of beetles and attractive semiochemicals (i.e., host volatiles and aggregation pheromones produced by many bark beetle species during host colonization) that attract other beetles into the area, which would result in higher levels of tree mortality. The propensity for many species of bark beetles to attack fire-injured trees—particularly in the western United States—has stimulated much research on the effects of fire surrogates on the amount and distribution of bark-beetle-caused tree mortality. In most studies, short-term increases have been reported in bark-beetle-caused tree mortality. However, the rates of tree mortality are generally low (less than 5% of trees) and are concentrated in smaller-diameter trees for most bark beetle species (figure 4). However, there are important exceptions, such as when delayed mortality occurs in the larger-diameter classes (Fettig and McKelvey 2010). In the longer term, thinning has been shown to reduce stand susceptibility to bark beetle attack in many seasonally dry forests (Fettig et al. 2007).

A common management concern is that fire-injured trees may serve as breeding substrates for bark beetles, which later attack adjacent trees at elevated levels, but this has not been well documented. Large numbers of severely stressed trees could provide abundant host material, and once this resource has been exhausted (e.g., within 1–2 years following prescribed burns), bark beetles may attack and kill trees that might otherwise have survived. However, Breece and colleagues (2008) reported that 80% of all bark-beetle-attacked trees were colonized during the first year following the application of prescribed fire. Fettig and colleagues (2010) reported that, in the central Sierra Nevada, California, 38%, 42%, and 20% of bark-beetle-caused tree mortality occurred during the first, second, and third years following prescribed fire, respectively.

Although it appears that most of the delayed mortality attributable to bark beetle attacks occurs during the first few years following prescribed fire within the treated area, this may not be the case for adjacent untreated areas. For example, Fettig and McKelvey (2010) reported large increases in bark-beetle-caused tree mortality on unburned split plots relative to adjacent burned split plots 3–5 years after the application of prescribed fire at Black Mountain Experimental Forest, California. This is likely because of unburned areas' not benefiting from the positive effects of prescribed fire (e.g., increased growing space) that affect tree vigor and, therefore, susceptibility to bark beetle attack (Fettig et al. 2007). Interestingly, Fettig

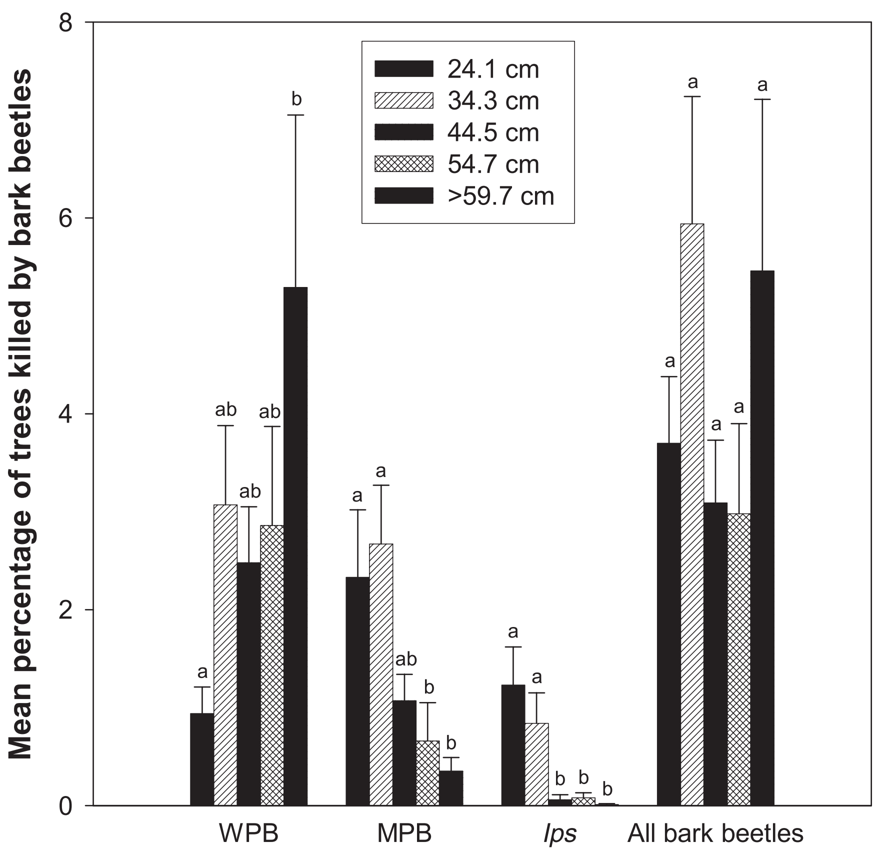

Figure 4. Mean bark beetle colonization rates of available pines among diameter classes on burned split plots for the western pine beetle (WPB), the mountain pine beetle (MPB), **Ips** ***spp. (*****Ips*****), and all bark beetle species combined during a five-year period following a prescribed fire. The means marked with the same letter within a group are not significantly different (Tukey's HSD) from one another. The error bars represent the positive standard error of the mean. Source: Adapted from Fettig and McKelvey (2010).***

and colleagues (2006) observed a similar effect for mechanical fuel treatments involving chipping of sub- and unmerchantable trees, whereby chipping increased the plots' risk of bark beetle attack in the short term through the production of large amounts of attractive monoterpenes. In the longer term, however, this treatment decreased the hazard through an increase in the amount of growing space allocated to each residual tree by reducing stand density through thinning. Surveys along the perimeter of chipped plots revealed large numbers of recently attacked trees in untreated areas that did not benefit from the positive effects of thinning but that suffered a level of risk similar to that associated with high levels of monoterpenes beneath the forest canopy (Fettig et al. 2006).

In some areas, forest managers are concerned about potential increases in the amount of tree mortality—both direct and delayed tree mortality attributable to bark beetle attacks during and immediately following early-season burns. Schwilk and colleagues (2006) found that the probability of bark beetle attack (several species) on pines did not differ for early- and late-season prescribed fires, whereas the probability of attack on firs (*Abies* spp.) was greater following early-season burns. Although more research is needed, it appears that there may be fewer meaningful differences in the levels of tree mortality attributable to bark beetle attack observed between early- and late-season burns than was previously thought (Fettig et al. 2010). Finally, when bark beetles contribute to short-term increases in the levels of tree mortality, the results of this increase may not be entirely negative. Tree mortality after prescribed fires can contribute to important habitat features for wildlife, such as snags and downed logs (Kennedy and Fontaine 2009), which in turn may attract and sustain populations of many vertebrate species.

Carbon sequestration

To assess the potential impact of fuel treatments on forest carbon inventories and sequestration rates in the FFS Study, pretreatment standing stocks of carbon in vegetation, on the forest floor, in dead wood, and in mineral soil were analyzed at 12 sites, using a combination of direct measurements (soil, forest floor, and downed dead wood) and dimension regressions (standing dead wood and biomass). An estimation of the rates of change due to the application of the fuel-reduction treatments over the first posttreatment year and on an annual basis over the following 1–3 years was also performed (Boerner et al. 2008b). Prior to the application of the FFS Study treatments, the total carbon storage across the network averaged 185 megagrams (Mg) of carbon per ha, of which 45% was in vegetation, 38% in soil organic matter, 10% in the forest floor, and 7% in dead wood; the western US forest sites averaged 171 Mg of carbon per ha; and the eastern sites averaged 196 Mg of carbon per ha (Boerner et al. 2008b). In contrast, Heath and colleagues (2003) estimated that the total amount of carbon in US forested ecosystems averaged approximately 203 Mg of carbon per ha (193 Mg of carbon per ha for the western forests and 210 Mg of carbon per ha for the eastern forests). These estimates were probably greater than those reported by the FFS Study, because Heath (2003) included soil carbon to a depth of 1 meter, whereas the FFS Study estimates were based only on the top 30 cm. The amount of carbon stored in vegetation was not significantly affected by prescribed fire but decreased by about 30 Mg per ha as the result of mechanical or combined mechanical and prescribed-fire treatment. In contrast, the amount of forest-floor carbon storage was reduced by about 1–7 Mg per ha by fire or combined mechanical and fire treatment but was unaffected by mechanical treatment alone (Boerner et al. 2008b).

The superficial (O_i) layer of the forest floor is among the most dynamic of forest carbon pools (Yanai et al. 2003) and is also the pool most susceptible to loss from fire (Page-Dumroese et al. 2003). Hall and colleagues' (2006) results suggest, however, that this carbon pool returns rapidly to prefire conditions unless vegetative biomass is reduced for extended periods of time. The reductions in carbon in vegetation produced by modest mechanical fuel treatments are considerably smaller than those that one would expect from commercial harvesting practices (North et al. 2009), and therefore, forest-floor carbon stocks are likely to be rebuilt to pretreatment levels shortly after a prescribed fire, with or without mechanical treatment.

Neither dead-wood carbon nor soil organic carbon was significantly affected by the FFS Study treatments, although changes in these two carbon stocks were highly variable (Boerner et al. 2008b). Furthermore, Boerner and colleagues' (2008b) results suggest that dead-wood carbon stocks will approach pretreatment magnitudes within 2 years after treatment, except in the combined mechanical and prescribed-fire treatment. These results contrast strongly with those of studies of stand-replacing wildfires, in which dead-wood carbon can continue to accumulate for decades (Hall et al. 2006), reflecting the lower intensity of fires used for ecosystem restoration and fuel reduction.

At the FFS Study–network scale, total ecosystem carbon was not significantly affected by prescribed fire, although four individual sites did exhibit significant carbon losses to prescribed fire. Mechanical treatment, with or without prescribed fire, produced significant reductions of 16–32 Mg of carbon per ha during the first posttreatment year, but this was partially balanced by an enhanced net uptake of about 12 Mg of carbon per ha during the subsequent 1–3 years (Boerner et al. 2008b). In terms of carbon storage and uptake, western US coniferous forests responded differently to the FFS Study treatments than did eastern US deciduous, coniferous, and mixed forests, which suggests that the optimal management for fire, harvesting, and carbon sequestration differs between these regions. The greater loss of forest-floor and, to a lesser extent, dead-wood carbon in western US forests, as well as their slower rate of recovery from disturbance, suggests that management strategies for carbon storage will differ.

Costs and utilization

The costs of wildfire suppression in the United States from 1994 to 2004 averaged over $400 per ha burned (Perlack et al. 2005). In addition, associated costs, including the loss of forest products, other values and resources, and personal property, may total several thousand dollars per ha for large fires (e.g., Lynch 2004). The costs of fuel reduction (ignoring any revenues from the materials removed) may range from $100 to several thousand dollars per ha, with mechanical treatments generally being more expensive than prescribed fire (Hartsough et al. 2008). The key factors affecting treatment costs include the amount and type of material to be treated, terrain and weather conditions, and the size of the treatment unit and its proximity to residential or other developments (Fight and Barbour 2005).

Although fuel reduction is focused primarily on small trees and down woody materials, which are expensive to collect or treat, much of the volume to be removed may be in the boles of trees with a 15–20-cm diameter at breast height or larger. These materials have commercial value to sawmills and other conventional processing facilities, and the value may more than cover the costs of their removal. In the FFS Study, for example, product values exceeded the total costs of treatment by averages of nearly $3000 per ha on some western sites but were less than the costs in other locations (Hartsough et al. 2008). The net financial results for similar stands may vary dramatically, depending on the treatment prescription and markets (Hartsough 2003). Studies of various conventional mechanized treatment systems have shown that it is most efficient to handle trees and their residues as few times as possible. For example, whole-tree harvesting systems are usually less expensive than cut-to-length harvesting (Hartsough et al. 1997), especially when it is desirable for fuel-reduction objectives to remove logging debris (activity fuels) from the site.

Although mechanical treatments are the only means of rapidly and predictably removing trees that form ladder fuels, prescribed fire is an effective and relatively inexpensive way of reducing surface fuels and ladder fuels (Agee and Skinner 2005). The combined mechanical and prescribed-fire treatment is quite effective in reducing fire hazards, especially where adjacent residential or other property does not increase the costs of fire management. Mechanical treatment of smaller material has two obvious advantages over prescribed fire: It cannot escape to cause damage to neighboring property, and it can produce material to be utilized in place of nonrenewable fuel sources. The US Department of Energy and the US Department of Agriculture estimate that over 50 million oven-dry metric tons of smaller material could be recovered in fuel treatments across the United States for biomass energy (Perlack et al. 2005).

For mechanical treatment to become widespread, further research is needed on the effectiveness of these treatments to handle small trees and some surface fuels. Although the use of downsized equipment for smaller trees or small treatment units may seem like a worthy idea, it has consistently produced costs per ha and per metric ton of biomass that are substantially higher than those of conventional equipment operating under good conditions (e.g., DeLasaux et al. 2009). Promising efforts are under way to reduce costs through processing and handling small materials in bulk, such as with a masticator that collects the comminuted biomass (Roise et al. 2009). It is substantially more expensive (per megajoule-kilometer) to transport woody biomass by truck than it is to move coal, oil, or natural gas by rail, ship, or pipeline. As a result, the economics of biomass utilization are strongly influenced by the proximity of conversion facilities to the forest (Hartsough et al. 2008).

Conclusions

When they are applied, both prescribed fire and its mechanical surrogates are generally successful in meeting short-term fuel-reduction objectives and in changing stand structure and fuel beds such that treated stands are more resistant and resilient to high-intensity wildfire. Although the numbers of exotic plants tend to increase with levels of treatment disturbance, overall understory species richness also increases (Schwilk et al. 2009), especially that of fire-adapted plants and those plants that are favored by more xeric forest-floor conditions. Although mineral soil exposure, pH, and exchangeable cations respond to treatment in the short term, initial changes tend to disappear after only a few years. Other soil variables, including bulk density, soil carbon, dead-wood carbon, and soil nitrogen exhibit extremely subtle responses to treatment (Boerner et al. 2009). The wildlife literature, which is dominated by studies on birds and small mammals, demonstrates that in the short term and at the stand scale, fire-surrogate forest-thinning treatments effectively mimic low-severity fire, whereas low-severity fire is not a substitute for high-severity fire (Kennedy and Fontaine 2009). Although bark beetles often take advantage of fire-damaged trees—particularly in the western United States—the overall responses by bark beetles tend to be relatively short lived and concentrated in the smaller-diameter classes. In the longer term, thinning effects (e.g., on tree vigor and microclimate) have been shown to reduce stand susceptibility to bark beetle attack (Fettig et al. 2007).

We recommend that a full suite of alternative fuel treatments be implemented in appropriate forests, including prescribed fire, mechanical thinning, and combined mechanical and prescribed fire treatments, and also support the expanded use of managed wildfire (Collins et al. 2009, Collins and Stephens 2010) to meet management objectives. These fuel treatments can be used in combination across a landscape to mimic the landscape heterogeneity characteristic of low- to moderate- and mixed-severity fire regimes (Collins et al. 2011, Perry et al. 2011). Although mechanical treatments cannot serve as complete surrogates for fire, their application can help mitigate costs and liability in some areas, such as the wildland–urban-area interface. Current research has shown that not all fuel treatments are being applied in high-priority forest types in the western United

States, which suggests that some managers may need additional information on local fire regimes to help prioritize restoration activities (Schoennagel and Nelson 2010).

Effective managers should consider the landscape context of their particular area when planning fuel-management strategies. Finney and colleagues (2007) compared the effectiveness of different rates of treatment over several decades in the western United States. Their findings indicated that treatment rates beyond 2% of the landscape per year, based on optimized treatment placement, yielded little added benefit. This figure includes both the maintenance of previously treated units and the installation of new treatments, both of which are critical for a successful strategy. Implementing optimized fuel-reduction treatments in appropriate forest types will allow more of the forest to survive when it burns during wildfires.

Designing more fire-resistant stands and landscapes will likely create forests that are more resistant and resilient to the changes imposed on them by climate change. For this reason, it is more appropriate to design and test a range of specific forest structures in order to learn about their resistance and vulnerabilities rather than trying to restore an ecosystem to presettlement conditions that may not be appropriate for the future (Millar et al. 2007). Most available evidence suggests that fuel-reduction objectives are typically accomplished with few unintended consequences, because most ecosystem components (vegetation, soils, wildlife, bark beetles, carbon sequestration) exhibit very subtle effects or no measurable effects at all; similar results were found in Western Australia forests and shrublands that were repeatedly burned over 30 years (Wittkuhn et al. 2011). The results presented in this article are for forests that once burned frequently with low- to moderate-intensity fire regimes; other ecosystems adapted to different fire regimes would probably exhibit different responses to fuel treatments.

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