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Review

Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States

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A B S T R A C T

Many natural resource agencies and organizations recognize the importance of fuel treatments as tools for reducing fire hazards and restoring ecosystems. However, there continues to be confusion and misconception about fuel treatments and their implementation and effects in fire-prone landscapes across the United States. This paper (1) summarizes objectives, methods, and expected outcomes of fuel treatments in forests of the Interior West, (2) highlights common misunderstandings and areas of disagreement, and (3) synthesizes relevant literature to establish a common ground for future discussion and planning. It is important to understand the strengths and limitations of fuel treatments to evaluate their potential to achieve an objective, develop sensible fire management policies, and plan for their effective use. We suggest that, while the potential of fuel treatment to reduce wildfire occurrence or enhance suppression capability is uncertain, it has an important role in mitigating negative wildfire effects, increasing ecosystem resilience and making wildfire more acceptable.

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1. Introduction

It is generally accepted that past management practices including the successful suppression of many wildland fires in some western United States ecosystems over the last 70 years have resulted in excessive accumulations of surface and canopy fuels which have, in turn, increased the potential for severe fires (Brown and Arno, 1991; Mutch et al., 1993; Kolb et al., 1998; Keane et al., 2002; Stephens and Ruth, 2005). Because productivity exceeds decomposition in most of the West, surface fuels tend to increase in the absence of disturbance. In most coniferous forests, canopy fuels also increase and become more available without disturbance as more shade-tolerant trees become established in the understory and overstory (Keane et al., 2002). Many scientists and natural resource agencies suggest extensive fuel treatments to reduce the possibility of severe and intense wildfires that could damage ecosystems, destroy property, and take human life (USDA Forest Service, 2000; GAO, 2003a,b). However, there are a number of misconceptions and misunderstandings about fuel treatments and their use as a panacea for fire hazard reduction across the United States (Finney and Cohen, 2003; Franklin and Agee, 2003). This paper reviews some common misunderstandings about fuel treatments and discusses ecological and managerial realities. It is important to understand the strengths and limitations of fuel treatments so that they can be properly applied and their potential for achieving management objectives can be realized. We have synthesized relevant literature to establish a common ground for fuel treatment planning. We suggest that the primary objective for treating fuels is to make wildfire more acceptable, that is, less severe, rather than to reduce wildfire extent or make it easier to suppress.

In this paper we focus on forested ecosystems in the western United States. Many of the ideas presented here may apply to areas and other vegetation types, such as rangelands, where some fuel treatment work takes place.

The term fuel treatment, as used in this paper, describes any mechanical, silvicultural, or burning activity whose main objective is to reduce fuel loadings or change fuel characteristics to lessen fire behavior or burn severity (National Wildfire Coordinating Group, 2006). Examples include mastication (e.g., flailing, chipping, and breaking), thinning, raking, and, of course, prescribed fire used separately or in concert with the mechanical treatments (Graham et al., 2004; Agee and Skinner, 2005). Fuel treatments are usually implemented at the stand level, but an increasing number of agencies are conducting landscape-level fuel modification activities, especially as wildland fire use applications (Black, 2004). Fuels, as discussed here, are the live and dead surface and canopy biomass that are burned in wildland fire. Surface fuels include downed, dead woody biomass and live and dead shrub and herbaceous material (DeBano et al., 1998). Canopy fuels are aerial biomass primarily composed of tree branchwood and foliage, but also including arboreal mosses, lichens, and hanging dead material (e.g., needles and dead branches) (Scott and Reinhardt, 2001; Reinhardt et al., 2006). We recognize that fuel treatment objectives and design may differ between wildland and wildland–urban interface (WUI) areas (Radeloff et al., 2005) with fuel treatments in wildland areas mostly designed to mitigate the effects of large, severe wildfires and to restore fire-prone ecosystems. Wildland is considered to be an area in which development is essentially nonexistent, except for roads, railroads, powerlines, and similar transportation facilities. Structures, if any, are widely scattered, while WUI is the zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels (National Wildland Fire Coordinating Group, 2006). The WUI area presents a special challenge to fuel treatment programs because it often contains lands with a variety of ownerships (both public and private) and objectives. Management of these boundary areas often attempts to reduce potential property loss as well as restoring or maintaining ecosystems. Prescribed fire and wildland fire use are the primary fuel treatment methods in wildland settings with a greater emphasis on mechanical fuel reduction treatments in WUI areas.

Planned fuel treatments, whether mechanical or prescribed fire, are only one part of a comprehensive fire management program that includes other tools such as wildland fire use. Wildland fire use is the management of naturally ignited wildland fires to accomplish specific prestated resource management objectives (http://www.fs.fed.us/fire/fireuse/index.html).

2. Objectives for treating wildland fuel

In general, fuel treatments are designed to alter fuel conditions so that wildfire is less difficult, disruptive, and destructive. However, implicitly and explicitly, managers, the public, special interest groups and policy makers often assume different specific objectives for fuel treatments. These differences in expectation can lead to polarization of what could be a non-divisive issue. In this section, we attempt to clarify some common misconceptions. While a number of authors provide specific guidelines for treating fuels in various forest types (for example, Johnson et al., 2007) this paper focuses instead on clarifying the objectives and expectations for treating fuels.

2.1. Wildlands cannot be fire-proofed

Given the right conditions, wildlands will inevitably burn. It is a misconception to think that treating fuels can "fire-proof" important areas. It would be virtually impossible to exclude fire from most temperate terrestrial ecosystems because ignition sources are prevalent and fuels cannot be eliminated. Ignition is rarely affected by fuel treatment, and in the forests of the western United States, which experience dry lightning, ignition is not generally limiting. Unless vegetation is eliminated from a site, even areas with intensive fuel treatments have residual biomass. Biomass, living or dead, can burn given adequate moisture conditions, and in the western US, seasonally dry and hot conditions will inevitably condition fuels to burn. Although land managers in general understand this limitation on fuel treatment, there may still be some unrealistic community expectations.

2.2. Fuel treatments in wildlands should focus on creating conditions in which fire can occur without devastating consequences, rather than on creating conditions conducive to fire suppression

Treating fuels to facilitate suppression is an example in circular logic. If fuel treatment makes suppression more successful in general, then less area will be burned in the short run and more acreage will tend to burn under extreme conditions, when suppression is ineffective. The inevitable result is that more area is burned in fewer, more unmanageable events with greater consequences. In addition, fire suppression leads to continued fuel accumulation and, in turn, more difficult conditions for suppression. This phenomenon has been described as "the wildland fire paradox" (Brown and Arno, 1991). Rather than creating conditions where fire is easier to suppress, fuel treatments should strive to create conditions where fire can occur without the need for suppression.

Additionally, the unexpected behavior of large wildfires may overwhelm the ability of small fuel treatments to facilitate suppression efforts. Graham (2003) discusses in detail the limitations of fuel treatment effectiveness in Colorado's 2002 Hayman fire stating that "extreme conditions and fire behavior permitted intense surface fire through treated areas.... Fuel breaks and treatments were breached by massive spotting and intense surface fires. . .Extreme environmental conditions . . .overwhelmed most fuel treatment effects. . . This included almost all treatment methods including prescribed burning and thinning. . .. *Suppression efforts had little benefit from fuel modifications* (emphasis added)." Even the most intensive fuel treatment may be rendered ineffective by the dynamics of large wildfire behavior, so designing treatments to minimize adverse fire effects may be a more effective strategy than designing treatments that attempt to exclude fires.

Similarly, as demonstrated during the Hayman fire (Graham, 2003) and more recently during the 2007 Angora Fire near Lake Tahoe, CA, WUI fire disasters principally occur during severe environmental conditions resulting in wildfires with rapid growth rates and/or high intensities (Menakis et al., 2003). These are the extreme fire behavior conditions that compromise most fuel treatments for suppression effectiveness. The Lake Tahoe WUI fire disaster associated with the 2007 Angora Fire provides a recent example of how extreme fire behavior conditions can overwhelm the ability to protect ignition-vulnerable homes even with adjacent fuel treatments (USDA Forest Service, 2007). As revealed in the Angora fuel treatment report and other WUI fire disaster reports (Cohen, 2000c, 2003; Graham, 2003; USDA Forest Service, 2007), it was not the high intensity wildfire encroachment that resulted in most of the home destruction. Unconsumed tree canopies existing between the wildfire and totally destroyed homes indicated that destroyed homes ignited directly from firebrands and/or surface fires contacting the structure. In such situations, destruction in the WUI is primarily a result of the flammability of the residential areas themselves, rather than the flammability of the adjacent wildlands. It may not be necessary or effective to treat fuels in adjacent areas in order to suppress fires before they reach homes; rather, it is the treatment of the fuels immediately proximate to the residences, and the degree to which the residential structures themselves can ignite that determine if the residences are vulnerable.

By reducing the flammability of structures, WUI fuel treatments can be designed such that an extreme wildfire can occur in the WUI without having a residential fire disaster. Although general wildfire control efforts may not benefit from fuel treatments during extreme fire behavior, fuel modifications can significantly change outcome of a wildfire within a treatment area. Research has shown that a home's characteristics and its immediate surroundings principally determine the WUI ignition potential during extreme wildfire behavior (Cohen, 2000a,c, 2003, 2004). The area that primarily determines WUI ignition potential is called the *home ignition zone* (Cohen, 2001). WUI fuel treatments can address the home ignition zone by removing flammable materials immediately adjacent to residences, and by decreasing the flammability of the residences themselves (for example by choice in roofing and deck materials). There are opportunities for reducing the home ignition potential during extreme WUI fires without the necessity of changing the broader-scale wildfire behavior. That is, effective WUI fuel treatments for preventing WUI fire disasters can focus on the structures and their immediate surroundings (Agee et al., 2000; Finney and Cohen, 2003). Since the home ignition zone largely occurs on private lands, most land management agencies do not have the authority to mitigate the WUI ignition potential directly (Cohen, 2000b). However, the opportunity exists to explicitly define responsibilities for the WUI fire potential (i.e. the home ignition zone) consistent with areas of jurisdiction and separately from ecological wildfire issues.

2.3. Even extensive fuel treatments may not reduce the amount of area burned over the long-term and furthermore, reduction of area burned may actually be an undesirable outcome

Treating fuels to reduce fire occurrence, fire size, or amount of burned area is ultimately both futile and counter-productive. In the long run, fuel treatments are a sustainable management option only if they increase the acceptability of wildfire.

There is an implicit assumption in much discussion of fuel treatments that treating fuels will reduce future fire occurrence (Laverty and Williams, 2000; GAO, 2003a). Fuel treatments may be effective at reducing fire behavior and severity, especially under moderate burning conditions, but this does not guarantee a similar reduction in fire size and occurrence. The majority of acreage burned by wildfire in the US occurs in a very few wildfires under extreme conditions (Strauss et al., 1989; Brookings Institution, 2005). Under these extreme conditions suppression efforts are largely ineffective. Bessie and Johnson (1995) show weather (fuel moisture and wind) is far more important than fuels in determining fire behavior; reducing fuels may have a limited impact on fire occurrence. And this is especially true if fires burning under moderate conditions are effectively suppressed, so that most acres burn under extreme conditions.

Many studies have investigated the concept of self-organized criticality in fire regimes (Malamud et al., 1998; Ricotta et al., 1999). In short, self-organized criticality is a theory that supports the notion that wildland fire will adjust for changes in burned area over long-time periods, and that any reduction in fire area in the short-term, such as that caused by suppression activities and fire exclusion policies, will eventually be balanced by large burned areas over the long-term if climate remains constant (Pueyo, 2007). If the same amount of area ultimately gets burned, then short-term reductions in fire frequency will eventually result in large fire years. Any fuel treatment designed to reduce fire area may actually cause adverse effects in the long-term. A better approach may be to reduce fire severity to save those ecosystem elements that have survived numerous historical fires.

Additionally, even if it were feasible to reduce burned area, or fire size, it would rarely be desirable in the long-term. Large fires were common on many western US landscapes prior to European settlement, primarily caused by long-term drought, severe wind, low humidity, and high temperatures (Keane et al., in press). Moreover, many western US plant species have adapted to large, severe wildfires by producing propagules that can survive these fires (e.g., serotinous cones, deeply rooted buds and rhizomes) or can disperse from great distances. The perception that all large fires leave vast areas in severely burned wastelands is also false; the burn pattern of large fires is generally very complex with many areas moderately to lightly burned (Turner et al., 1994; Agee, 1998; Keane et al., in press). Large fires may actually be an efficient means of returning fire to ecosystems where it has been excluded for many decades.

Fire management agencies may want to avoid evaluating the success of fuel treatment programs in terms of burned area because it will nearly always fail over long-time periods. Reduced fire occurrence could actually be a possible indicator of the failure of a fuel treatment program—as we have learned from the adverse effects of the fire exclusion era (Mutch et al., 1993; Kolb et al., 1998). Instead, the focus of fuel treatment should be on improving the ability of the treated stand or landscape to withstand the adverse effects of future fires. This can be done be ensuring the modified fuelbed will support a fire that will create or maintain stands similar to those that occurred on the historical landscape (Landres et al., 1999; Fulé et al., 2002). Any fire – lightning or human caused – could offer a unique opportunity to restore fire to historically fire-dominated landscapes and thereby reduce fuels and subsequent effects.

2.4. *Fuel treatments should not be driven by a primary objective of reducing fire's rate-of-spread*

There are two main reasons why rate-of-spread is not an appropriate metric with which to evaluate fuel treatments. First, spread rate is only important in a suppression context, and second, ecologically robust fuel treatments may often increase rate of spread or leave it unchanged.

Fire's potential spread rate is often the focus of fuel treatment analyses (Hirsch et al., 1979; Van Wagtendonk, 1996). This may be due in part to the history of quantitative fire behavior modeling. Rothermel's (1972) model, the basis of most fire behavior modeling in the US, is fundamentally a spread rate model, designed to support suppression efforts. Once a fire is over, however, its spread rate is relatively unimportant. The residual impacts on the site, the vegetation, and the fuel complex remain and determine future risks and benefits.

Some viable fuel treatments may actually result in an increased rate of spread under many conditions (Lertzman et al., 1998; Agee et al., 2000). For example, thinning to reduce crown fire potential can result in surface litter becoming drier and more exposed to wind. It can also result in increased growth of grasses and understory shrubs which can foster a rapidly moving surface fire. Even in cases when fuel treatment reduces surface fire spread rate, spotting can negate these effects. The fundamental goal of fuel treatment should not be to reduce spread rate but to reduce burn severity.

2.5. *Treating fuels may not reduce suppression expenditures*

It is a natural mistake to assume that a successful fuel treatment program will result in reduced suppression expenditures. Suppression expenditures rarely depend directly on fuel conditions, but rather on fire location and on what resources are allocated to suppression. The only certain way to reduce suppression expenditures is to make a decision to spend less money suppressing fires. Already, 1% of fires account for 85% of fire suppression expenditures (Brookings Institution, 2005). Since the location of these large, expensive fires cannot be known in advance, fuel treatment coverage would need to be extremely extensive to prevent these expensive fires. Gebert et al. (2007) examined factors that influence Forest Service large fire suppression costs on over 1,500 fires between 1995 and 2004. For this study vegetation and fuels data were only available for the ignition point. Significant variables included aspect, slope steepness, fuel type (timber, brush and grass), fire intensity, energy release component, nearby housing values, distances to nearest town and wilderness area boundary and time between ignition and discovery. Of these factors only fire intensity (measured as flame length at ignition) would likely be affected by fuel treatment. Liang et al. (in press) examined the effect of 16 potential spatially explicit non-managerial factors representing fire size and shape, private properties within and adjacent to the fire's perimeter, public land attributes, forest and fuel conditions within the fire's perimeter, and geographic settings on total fire suppression expenditures for 100 fires in the USFS Northern Region (R1). The authors found only fire size and private land had strong effect on expenditures. Fuel characteristics had no significant effect. Many years of financial and professional investment in fuel treatments, along with an integrated fire policy that addresses fuel treatment and a commitment to controlling residential development of fire-prone areas and a reduction of all-out suppression efforts, is needed to effectively reduce suppression costs.

2.6. *Treating fuels may not improve ecosystem health*

Ecosystem restoration treatment and fuel treatment are not synonymous. Some ecosystem restoration treatments reduce fuel hazard, but not all fuel treatments restore ecosystems. Ecosystem restoration treatments are often designed to recreate pre-settlement fire regimes, stand structures and species compositions while fuel treatment objectives are primarily to reduce fuels to lessen fire behavior or severity—this is known as "hazard reduction". Achieving fuel hazard reduction goals in the absence of ecosystem restoration is insufficient (Dombeck et al., 2004; Kauffman, 2004). Since many pre-settlement stands were shaped by a long history of recurrent fires, surface fuels were mostly composed of needles, shrubs, and herbaceous plants because most woody fuels were consumed by previous fires and canopy fuels were less dense and discontinuous because fire killed many of the small trees. Therefore, any treatment to recreate pre-settlement conditions would concurrently reduce fire hazard in terms of lessening severity and intensity. Conversely, some fuel treatments can reduce fuels but create stands that are quite dissimilar from their historical analogs. Examples include mastication treatments that break, chip, or grind canopy and surface woody material into a compressed fuelbed and thinning treatments that remove the fire adapted species and leave shade-tolerant, late successional species. It is possible to craft treatments that achieve both ecological restoration and fire hazard reduction, but ecological restoration will also include reintroducing fire and other active management. For instance, thinning out small, dense trees from under a canopy of large ponderosa pine is often the first step in both ecological restoration and fire hazard reduction (Allen et al., 2002).

Fuel treatments that do not include fire may not fully achieve restoration goals in fire-prone ecosystems. It would be difficult to replicate the wide-ranging influences of wildland fire with only mechanical treatments (Nitschke, 2005). Fire's effect is manifest at many scales and across many ecosystem components. Some of the more important direct effects are fuel consumption, plant mortality, and soil heating (DeBano et al., 1998; Ryan, 2002) and each of these have indirect effects on other components such as post-fire vegetation composition, nutrient cycling, and wildlife habitat quality. It would be difficult to mimic these effects without fire, and each direct and indirect effect may have important consequences and cascading influences to overall ecosystem health. For example, fire-caused tree seedling mortality results in the creation of widely spaced savannas or park-like forests that host a uniquely different species assemblage than unburned, closed forests (Agee, 1993). Therefore, the most effective ecosystem restoration treatments should include prescribed fire even though its implementation is costly and risky.

Fuel treatments can also differ from ecological restoration treatments in their spatial implementation. Landscapes that are managed to optimize fire suppression opportunities may not emulate any historical landscape pattern and therefore may not be ecological viable. For example, an effective spatial arrangement of fuel treatment units for minimizing fire spread is a "herring-bone" pattern on the landscape (Finney, 2001). While this spatial design might be optimum for reducing fire spread, it does not resemble the effects of any historical ecological process or landscape pattern. Historical landscapes were composed of near-random mosaics of burn areas with negative exponential size distributions (Gardner et al., 1999; Swanson et al., 1994; Li, 2001). Historical landscape mosaics were also constantly changing. Fire itself can best establish dynamic landscape mosaics that maintain ecological integrity.

2.7. *Treating fuels will not restore pre-European settlement conditions*

Pre-European settlement conditions can provide important insights for establishing restoration goals, but cannot be replicated through restoration. Pre-European settlement conditions are gone for good from American landscapes, due to residential development and invasive species, along with changed patterns of human use.

Historical conditions can provide a valuable reference for managing contemporary landscapes (Covington et al., 1997; Landres et al., 1999; Fulé et al., 2002). However, since historical conditions varied in time and space, selecting a single target stand structure is somewhat arbitrary and inappropriate. Given the wide range of ecosystem conditions that may have occurred in the past, it may be a better idea to restore stand structure to within the range and variation of historical conditions on the entire landscape. This requires an ability to characterize historical conditions with temporal depth. Many landscapes are missing detailed historical evidence of past composition and structures. Simulation modeling can be used to create a historical time series of landscape conditions (Fall, 1998; Wimberly et al., 2000), but, the temporal depth of the simulated historic range of variability (HRV) time series and the size of the analysis landscape have a large effect on the calculation of current departure (Keane et al., 2006).

The assumption that historical conditions provide a useful reference for future management is also somewhat oversimplified in this era of global change. Many exogenous factors now influence the structure and composition of landscapes, such as climate change, exotic weed invasions, and introduced diseases (Keane et al., 2008), and humans will continue to exert their influence on landscape conditions through resource extraction, land development, and pollution effects (Baron, 2002). Although it may not be possible to return to the historical conditions, managers still need a baseline or benchmark to compare the impacts of future landscape treatments in a changed environment, and past historical conditions can provide excellent references, representing time spans that had great climatic variations reference. Historical conditions are still pertinent in a changing environment because they provide the only detailed guide we have for evaluating landscape health and designing ecologically viable fuel treatments. Keane et al. (2008), suggest that land managers and policy makers need to look both forward to the future and back in history using simulation modeling to get a realistic representation of ecosystem and landscape behavior.

3. Other considerations for treating wildland fuel

Fuel treatments can involve a variety of strategies, including prescribed fire, thinning, and mechanical treatment of surface fuel, alone or in combination. Fuel treatment projects also involve decisions about placement, including the strategic placement of fuel treatments to accomplish as much as possible with limited resources. Specific fuel treatment needs vary with land use, current conditions, and the ecology of the site. In this section we outline the most pressing needs for enlightened fuel treatment planning.

3.1. *The need for site specific analysis*

The most appropriate fuel treatment methods vary with forest type and spatial context—there is no such thing as a "one size fits all" fuel treatment design. In part because of spatial context and also because of the myriad combinations of surface, ladder and canopy fuels, as well as site-specific goals and constraints, and considerations such as invasive species, endangered species, local patterns of wind and weather, and resource protection, fuel treatment projects continue to require site specific analyses. Cookbook treatment prescriptions cannot be expected to provide effective fuel treatment plans. Fire ecologists often differentiate between low severity, mixed severity and high severity fire regimes when evaluating fuel conditions and fuel hazard reduction needs (Brown, 1995). A number of authors provide guidelines for fuel treatment by fire regime (Franklin and Agee, 2003; Brown et al., 2004; Dellasala et al., 2004). Wildlands and the WUI require different fuel treatment objectives and long-term effectiveness and sustainability of the fuel treatments may depend on fire regimes and a host of local site conditions. Topography and accessibility may restrict treatment options. The spatial configuration of residential developments, forest conditions, and important values also needs to be considered.

3.2. *Treating fuels by thinning stands to prevent crown fires*

Tree removal can play an important role in treating fuels, especially removal of small understory trees that can provide a ladder into the forest canopy, but is subject to site specific limitations. A common objective of thinning for fuel management is to reduce the chance of crown fire by reducing canopy fuels, especially in forest types that historically burned in low severity fires. However, thinning alone does not typically constitute an effective fuel treatment, but instead must be combined with treatment of surface fuels. In the absence of fire, many stands that historically burned frequently and had open structures have become dense with vertically continuous canopies. This makes them more prone to crown fire and is one of the prime causes of the wildland fuel problem. Thinning stands to reduce crown fire potential is a primary means of reducing fire hazard (Graham et al., 1999, 2004; Brown and Aplet, 2000). Agee and Skinner (2005) summarize guidelines for treating wildland fuels with thinning. They offer four principles of for creating fire resilient stands in dry forests: reduce surface fuels, increase the height to the canopy, decrease crown density, and retain big trees of fire resistant species.

In the absence of surface fuel treatment, thinning will probably increase surface fuel loads (Agee and Skinner, 2005) due to fuels created by the harvest activity. Thinning typically needs to be followed by prescribed fire or pile burning to reduce surface fuel. In some cases prescribed fire alone may accomplish surface fuel reduction, thinning from below with fire-caused mortality, and lifting of the canopy base height due to scorched low branches. Thinning for fire hazard reduction should concentrate in general on the smaller understory trees to reduce vertical continuity between surface fuels and the forest canopy. In many cases the overstory can be left intact, although in some cases it may be desirable to reduce the horizontal continuity of the canopy as well by thinning some bigger trees.

Thinning to reduce crown fire potential requires careful evaluation of the tradeoffs in treatment effects on potential surface fire behavior and crown fire behavior (Scott and Reinhardt, 2001). Thinning will often result in increased potential surface fire behavior, for several reasons. First, thinning reduces the moderating effects of the canopy on windspeed, so surface windspeed will increase (Graham et al., 2004). It also results in increased solar radiation on the forest floor, causing drier surface fuels. It may also cause an increase in flammable grassy and shrub fuels over time, due to the reduced tree competition.

Thinning is not an appropriate option in some forest types and in some geographic locations. Some forest types are prone to windthrow when thinned (Alexander, 1986a,b).

3.3. Spatially designing fuel treatments to protect untreated areas

The primary benefits of fuel treatments occur on the site that is treated, and off-site effects, while they may sometimes occur, should not drive the fuel treatment planning process. A great deal of debate has gone into arguing the relative merits of fuel breaks and other spatially contrived fuel treatment configurations (Ingalsbee, 1997; Agee et al., 2000; Finney, 2001) These strategies share two characteristics. First, they are designed to aid in suppression efforts and reduce ultimate fire size, rather than to increase the resilience of the treated area itself. Their effectiveness at accomplishing this is conceptually appealing but as yet empirically unproved. Second, they do not mimic any kind of natural landscape process. If off-site treatment benefits are considered as positive externalities rather than driving factors in fuel treatment planning, they are likely to be less contentious.

3.4. Need for repeated fuel treatments

Fuel treatments benefits are transient. An ongoing commitment is required to sustain resilient forests. We must think of fuel treatment regimes rather than single fuel treatment projects. A common misconception is that fuel treatments are durable and will last for a long time. In reality, fuel treatments have a somewhat limited lifespan that depends on a number of factors, mainly pretreatment conditions, the effectiveness of the treatment, and the productivity of the vegetation on the treatment site. Prescribed fire treatments can be expected to result in tree mortality with subsequent snagfall contributing to surface fuel loads. 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. Fuel treatment effectiveness spans are also reduced if the treatment did not reduce the seedling layer on the forest floor. Measured litterfall and decomposition rates, along with tree growth rates, can be incorporated into ecosystem models to predict the lifespan of a fuel treatment by specifying acceptable surface and canopy fuel loading thresholds (Keane et al., in press).

More than one treatment may often be needed to reduce fuels and restore ecosystems for many areas. Initial silvicultural and prescribed burning treatments used separately or in concert, and implemented in stands or landscapes where fire has been excluded for many fire intervals may actually *increase* the amount of surface fuels. This is primarily because the trees that are cut for harvest or killed by fire usually contribute substantial branchwood to the surface fuelbed thereby increasing woody fuel loadings. Prescribed fire may consume the resident fine and coarse woody debris, but it will also kill trees, and that dead material will eventually fall onto the fuelbed. This means that additional treatments will be needed to reduce the fuels created by the first treatment. It may take up to seven treatments to return the area to acceptable conditions that mimic some historical range (Baker, 1994).

Fire management should plan and implement programmatic fuel treatment regimes rather than individual fuel treatment projects to be the most effective in accomplishing the goals of the National Fire Plan and Healthy Forest Restoration Act. These treatment regimes should include silvicultural prescriptions and prescribed burn objectives that address the current condition of the stand and the landscape in which it resides in combination with the actual goal of the treatment regime. The goal of treatment regimes probably should not be a target stand structure or a target fire hazard rating, but rather, to save those important ecosystem components (e.g., large, old ponderosa pine trees) and processes that might be lost if an unplanned wildfire happens to visit the landscape (Apfelbaum and Chapman, 1997). This especially applies to the WUI where fuel treatment regimes should minimize those fires that could burn homes. Fuel treatment regimes should be designed and implemented at the landscape level to utilize important spatial configurations and landforms as fire breaks and to integrate the spatial distribution of biophysical settings comprising that landscape with the fire regime to ensure ecosystem sustainability.

3.5. On and off-site effects

In addition to direct impacts on fuel and expected outcomes of wildfire, fuel treatments may have effects on other resources, both on and off-site. Like any manipulation of natural systems, fuel treatments may involve both positive and negative effects, depending on the specifics of the treatment program. It is important to address these but difficult to generalize about them as they are often driven by site-specific details. One common concern is that entry into a site exacerbates potential for exotic weeds to become established. Any treatment that involves removal of biomass from the site has potential adverse consequences in soil disturbance and long-term productivity. Fuel treatments that involve prescribed fire carry risks of escape and of greater than intended fire effects including post-fire insect attacks of residual trees (Ganz et al., 2003), consumption of organic soils, and unwanted smoke production. However, in many cases, no action may carry greater risks from effects of abnormally severe fires (Agee and Skinner, 2005).

Finney et al. (2005) observed reductions in wildfire severity in portions of the Rodeo and Chediski wildfires on the lee side of areas previously treated with prescribed fire. These positive effects can be expected to be more frequent as the portion of the landscape that has been treated increases. Negative off-site effects may include cumulative watershed effects.

3.6. Economics

Treating fuels will be an expensive venture. Some fuel treatments may generate revenue (e.g., from thinning), but in many cases they will require financial support. In the long run, a successful fuel treatment program may make it possible to spend less on suppression or rehabilitation, although, as discussed above, this is not a necessary consequence of successful fuel treatment. However, these fiscal benefits are really positive externalities. Fuel treatment programs should be driven by our desire to create and sustain resilient ecosystems. The nation's public lands are an enormous public asset, currently in degraded condition, and require investment to improve and maintain their value. Similarly, most homeowners value their homes at more than the replacement cost, and thus may be willing to invest in fuel treatment on their private land even if it costs more than a financial risk assessment would indicate that it is worth. We do not currently have the ability to realistically model all the expected costs and benefits of a particular fuel treatment program over time.

There are a number of challenges in understanding the costs and benefits of fuel treatments. Paucity of consistent reporting data maintained by federal wildland agencies and the unique physical and managerial characteristics of fuel treatments have limited thorough assessments of the cost of individual fuel treatment activities (González-Cabán and McKetta, 1986; Cleaves et al., 1999; Calkin and Gebert, 2006). Additionally, data issues are complicated by the fact that agencies may conduct fuel treatments through timber sales, stewardship contracts, or traditional hazardous fuels funding. González-Cabán and McKetta (1986) and

González-Cabán (1997) suggest that managerial factors such as experience, professional fire philosophy, and risk aversion can have a significant influence on fuel treatment costs. Both mechanical and prescribed burning treatments have been shown to have significantly higher treatment costs when located in the WUI (Berry and Hesseln, 2004; Calkin and Gebert, 2006) suggesting that a comprehensive treatment program focusing on interface areas will be costly. Fiedler and Keegan (2003) and Fiedler et al. (2004) suggest that forest restoration treatments in lower mixed conifer forest types in Montana and New Mexico have the potential to significantly reduce the likelihood of crown fire while producing positive net revenue. However, Brown et al. (2004) emphasize that fuel treatments need to be tailored based on the ‘‘context of place’’ and should emphasize removal of small diameter trees first. Additionally, there remains public concern, particularly among members of environmental organizations, that fuel treatments may be used as an excuse to remove merchantable trees for timber products (Brown, 2000). Whether treatments are designed to produce merchantable timber or not, there is growing interest in promoting forest restoration activities as an economic driver to local resource dependent communities that have suffered economic decline due to recent reductions in federal timber harvest volumes (Dellasala et al., 2004).

Given the current budgetary issues faced by the Forest Service and other land management agencies full funding to support an aggressive fuel treatment program is unlikely. The tradeoffs between modifying treatments to produce additional merchantable products and thus being able to conduct a treatment versus the no treatment option may need to be evaluated in terms of the likely effect on the resources of interest.

3.7. Biomass

In some cases, fuel treatments may have an added benefit of providing biomass to meet society’s needs. Residual material (biomass) from mechanical fuel treatments has the potential to provide wood products in some areas of the western United States (USDOE/USDA, 2005). Mechanical fuel reduction and forest health treatments in these forests could result in significant volumes of biomass (Forest Service, 2003; Fried et al., 2003; Barbour et al., 2004; Keegan et al., 2004; Loeffler et al., 2006; Skog et al., 2006). Utilizing this resource for energy production or value-added small diameter forest products could provide an alternative disposal method that could increase the economic returns of treatments, encourage local economic development, reduce negative externalities associated with smoke production from open burning or increased fire hazard due to treatment slash, and offset carbon emissions associated with fossil fuel use. Unfortunately, many areas in the United States where fuel treatments are being considered lack biomass markets that could help reduce the cost of treatments. A number of existing markets have recently emerged to utilize this material such as the Fuels for Schools program (http://www.fuelsforschools.org/). However, issues related to high handling cost and low value of this material still need to be overcome.

4. What next?

4.1. Treating fuels in the face of climate change

The world’s climate is changing, making increased resilience of forest stands an even more important goal. The effect of climate change on fire regimes remains somewhat uncertain, but many reports suggest that climates will become warmer and drier over the next century due to increased atmospheric carbon from anthropogenic sources, and the consequences of this change will be to increase (1) length of fire season, (2) severity and frequency of drought, (3) lightning ignitions, (4) amount of fuel, and (5) fuel contagion (Flannigan and Van Wagner, 1991; Wotton and Flannigan, 1993; Weber and Flannigan, 1997; Flannigan et al., 2005). As a result, ecosystems, especially those in the western US, may experience more frequent fires of greater severity and size than in the recent past. Of special concern is that these changes in fire regime may be quite abrupt rather than gradual and these changes will occur in ecosystems where fire has been excluded for several decades. This does not mean that we can afford to wait and see before responding, but it does mean that fuel treatment analyses should not be driven by specific assumptions about weather patterns and climate. The expected severity of the burns coupled with the extensive land area burned may spell dire consequences for many western US flora that are not adapted to this rapid change. One way to mitigate adverse fire severity is to implement fuel treatments across the landscapes so that when unplanned fires occur they will tend to be less severe. This is especially true in short fire return interval forests that historically burned in low-severity fires.

There is some debate on whether fuel treatments are needed in the wildland if climate, and therefore fire regimes, change. The reasoning is that climate is inherently variable and dynamic and because of this, fire regimes will change and therefore render any fuel treatment ineffective; it may be difficult to craft restoration treatments when the fire regime, and therefore desired stand conditions, are a moving target. However, fuel treatments could become increasingly important in our efforts to protect people and property from fire in the WUI and urban areas as fire seasons lengthen and become drier. Wildland ecosystems also require treatment to buffer the effects of the rapidly changing environment. If future fires tend to be larger and more severe, active fuel management will be needed to minimize adverse effects of high severities and ensure post-fire landscapes contain ecologically viable patterns and composition.

The best way to buffer ecosystems against the adverse effects of future climates is to increase their resilience. Fire was a major process on the historical landscape. Therefore, in the anticipation of more extensive and uncontrollable fires in the future, we must prepare the landscape to accept these changes with minor effects to the biota. The fact that we have had several decades of fire exclusion along with predicted climate change may foster future fires that severely alter landscapes in structure, composition, and function. Ecosystem restoration treatments that reduce fuels may protect ecosystem elements during the climate change transition period.

4.2. Learning by doing—the need for research and action

We will never know everything about the ecological, economic, and sociological effects of fuel treatments and there is no more effective way to learn than by carefully monitored practice. Fire management is as dynamic as the ecosystems and human environments that it protects. New fuels treatments continue to be developed and the effects of those novel treatments must be evaluated. Fuels mastication is the latest in a long line of creative methods that are being used to treat fuels to reduce fire intensity and severity. Research will always be critically needed to assess effects of these novel treatments across multiple ecosystem components and across multiple scales. More importantly, wildland fire remains a complex process that is difficult to study and more extensive research is needed to understand, simulate, and forecast this important keystone disturbance. Research should provide direction for the future of fire management and, at the same time, provide managers with the information they need to design fuel treatment programs.

Research is a vital cog in the fire management system, but there is no need to wait for all research to conclude; we know enough right now to implement effective fuel treatments. There is a sufficient body of research to guide land managers in the design and implementation of fuel treatments (Reinhardt and Crookston, 2003; Stratton, 2006). However, fuel treatment activities must be monitored to determine beneficial and adverse effects in a comprehensive monitoring program to provide specialists the knowledge and data needed to modify and adapt fuel treatments to mitigate observed adverse effects at the local level. Managers need standardized monitoring tools such as FIREMON (Lutes et al., 2006) and the Fire Monitoring Handbook (USDI, 2001) to design, implement, and maintain effective long-term monitoring of ecosystem effects. A number of recent studies (e.g., Pollet and Omi, 2002; Martinson and Omi, 2003; Outcalt and Wade, 2004; Raymond and Peterson, 2005) provide take advantage of situations where wildfire has burned through previously treated areas alongside untreated areas in order to evaluate directly the effectiveness of specific fuel treatments in specific ecosystems. This kind of study provides important information that needs to be collected opportunistically whenever possible.

5. Conclusions

Fuel treatment is an important management tool for reducing fire hazard. However, confusion exists as to the purpose and potential effectiveness of fuel treatment activities. We feel that fuel treatments should be used to reduce fire severity and intensity instead of fire occurrence. We also believe that fuel treatments should attempt to increase ecosystem resilience, especially in wildland settings. The range and variation of historical stand and landscape composition and structures should be used as guides but not targets. While WUI areas should be managed primarily for protection of structures and people, care should be given to ensure these fire hazard reduction treatments produce conditions that are within the historical range of variation. Exotics, climate change, and other human-induced factors will influence fuel treatment effects in the future and these factors should be addressed in all fire management plans. However, the influence of these factors will not diminish the need to treat fuels and restore fire-prone ecosystems. In fact, these factors increase the need to create landscapes that are as resilient as possible.

Successful integration of fire management and land management programs and objectives can result in treatments that restore ecosystems as well as treating fuels. We believe that the primary goal of fuel treatment should be to create landscapes in which fire can occur without devastating consequences. Once these conditions have been achieved, wildfire need not be as vigorously suppressed and can itself play a role in maintaining these landscapes. Fuel treatments should not be used to reduce or eliminate fire from landscapes. Fuel treatment programs should be designed in concert with new fire suppression policies to encourage a return of fire to the landscape and improve the resilience and sustainability of US ecosystems.

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