Basic principles of forest fuel reduction treatments

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Abstract

Successful fire exclusion in the 20th century has created severe fire problems across the West. Not every forest is at risk of uncharacteristically severe wildfire, but drier forests are in need of active management to mitigate fire hazard. We summarize a set of simple principles important to address in fuel reduction treatments: reduction of surface fuels, increasing the height to live crown, decreasing crown density, and retaining large trees of fire-resistant species. Thinning and prescribed fire can be useful tools to achieve these objectives. Low thinning will be more effective than crown or selection thinning, and management of surface fuels will increase the likelihood that the stand will survive a wildfire. Five empirical examples of such treatment are discussed: Hayfork fires, California, 1987; Tyee fire, Washington, 1994; Megram fire, California, 1999; Hayman fire, Colorado, 2002; and the Cone fire, California, 2002. Applying treatments at an appropriate landscape scale will be critical to the success of fuel reduction treatments in reducing wildfire losses in Western forests.
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1. Introduction

Western forests are burning with uncharacteristic severity and scale. A significant contributor has been the paradox of successful fire exclusion: as we have become more efficient at suppressing wildfires, the wildfire problem has only become worse (Brown and Arno, 1991). In the past decades, several record years for wildfire area burned have occurred. Federal agencies have exhausted fire suppression funds during both 2002 and 2003, and the crisis has prompted a

"healthy forests" initiative to address the problem (Bush, 2002). Although the problem is well defined in such policy documents, the solutions have remained diffusely defined, other than proposals that recognize that fuel reduction is needed at a scale unprecedented in US history. In this paper, we summarize a set of principles that will be important to address when fuel reductions of any scale are proposed. We provide examples through modeling and empirical evidence that restoration of more fire-resilient forests is possible. We define resiliency in this context as a forest capable of maintaining substantial live basal area after being burned by a wildfire. Just as importantly, we provide examples of forest management that will be ineffective in restoration.

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The history of the problem dates back to the early 20th century, when a fire exclusion policy was applied to all forests without regard to a context of place. Driven by the large 1910 fires in Idaho and Montana, the fledgling Forest Service lobbied Congress for legislation and funds to emplace sustainable forest management on the new national forests (Pyne, 2001). The policy included the suppression of all fires, as they were known to kill small trees and scar large trees reducing their commercial value (Show and Kotok, 1924). In the drier forests of the West, where fires were historically large but generally of low severity, the arguments of "light burners" who wanted to maintain fire as a natural process were snuffed out during the policy debates (Agee, 1993). A one-size-fits-all fire exclusion policy was applied to all forests. Protected forests soon had more tree regeneration (Benedict, 1930), and the early fires were easy to suppress with generally light fuel loading (Show and Kotok, 1929). Selective removal of large, fire-resistant trees added to the problem, so that by the late 20th century, we had widespread continuous forests with, on average, smaller trees and much greater fuel loads (Fig. 1). Areas that were once forest openings became forested (Skinner, 1995). Fires that once spread as surface fires were now more intense, and capable of jumping into the canopy of the forest as crown fires. This problem continues unabated into the 21st century, not only in high elevation or wet forests where that type of behavior was characteristic, but widely across all forest types (Covington et al., 1994; Hardy, 2005).

There is a critical need for widespread restoration of lower fuel amounts across the West. Yet fuels come in all shapes, sizes, and arrangements. There are live and dead fuels, herb and shrub fuels, litter, twigs and branches, ladder fuels (small trees), and canopy fuels (larger trees). A fuel reduction treatment might address any or all of these fuels, but depending on which are targeted, the treatment may not be relevant to either the easier suppression of unwanted wildfires, or the ability of the forest to sustain itself in the presence of wildfire.

2. Principles of fire resilient forests

The first principle to address in solving our widespread fuel problems is the context of place.

This means that not every forest is a high priority candidate for treatment. Many forest types, including wet Sitka spruce, coastal Douglas-fir, and high-elevation forests such as mountain hemlock or subalpine fir, historically burned infrequently but with high intensity (Agee, 1993). Where trees that are 300–800 years old have never experienced a wildfire, it is difficult to argue that a serious fuels problem exists (Brown et al., 2004). There is certainly a lot of biomass on site, but much of it is unavailable for combustion under most conditions. Conversely, there are other forests that have long dry seasons each year and have easily combusted forest floors, such as ponderosa pine, mixed conifer, and drier Douglas-fir forests (Skinner, 2002), where the types of fires occurring today are very uncharacteristic of the historic fires. While some intense fire activity did occur in such forests, it was not the modal type of fire severity that exists today in such forests. There is broad consensus that active management of some type is needed in such forests (Allen et al., 2002; McKelvey et al., 1996), and that such treatment will be needed as a continued maintenance activity.

Broad scale, national assessments of fire risk have been made (Schmidt et al., 2002) but have been criticized as being too coarse. A finer scale classification based on potential vegetation (sensu Daubenmire, 1968) may be a more effective method to locally identify forests most at risk. Although the finest-scale classification unit is the plant association, aggregations of associations known as plant association groups (PAGs) are better planning units because they are of intermediate scale. These classifications are widely available across the West (e.g., Steele et al., 1981; Henderson et al., 1989; Atzet et al., 1996) and can be consistent with the coarser-scale national classifications. Where they do not work as well (as in parts of California) other fine-scale vegetation classifications may be utilized. While fuel treatments to address specific problems (such as the wildland–urban interface) may be appropriate in all forest types, large scale treatment of watersheds should receive highest priority in the drier forest types.

Once a context of place is defined, a set of "firesafe principles" can be defined (Table 1). Forests treated with these principles will be more resilient to wildfires. The principles are based on what we

Fig. 1. Typical increase in surface fuels, ladder fuels, and canopy bulk density in a ponderosa pine forest, 1908–1948, in western Montana. Most of the historical trees are ponderosa pine, and most of the trees in the more recent photo are Douglas-fir. Photos from Gruell et al., 1982 (figure 19 p. 32).

currently know about crown fire. They occur when surface fires create enough energy to preheat and combust live fuels well above the ground. There are two stages to the crown fire process: the initiation of crown fire activity, known as ''torching'', and the process of active crown fire spread, where fire moves from tree crown to tree crown (Van Wagner, 1977; Agee et al., 2000).

Table 1
Principles of fire resistance for dry forests (adapted from Agee, 2002 and Hessburg and Agee, 2003)

Principle	Effect	Advantage	Concerns
Reduce surface fuels	Reduces potential flame length	Control easier; less torching[a]	Surface disturbance less with fire than other techniques
Increase height to live crown	Requires longer flame length to begin torching	Less torching	Opens understory; may allow surface wind to increase
Decrease crown density	Makes tree-to-tree crown fire less probable	Reduces crown fire potential	Surface wind may increase and surface fuels may be drier
Keep big trees of resistant species	Less mortality for same fire intensity	Generally restores historic structure	Less economical; may keep trees at risk of insect attack

[a] Torching is the initiation of crown fire.

Torching occurs when the surface flame length exceeds a critical threshold that is defined by moisture content in the crown and the vertical distance to live crown, called canopy base height or height to live crown. Moisture content of the crown is highest in the spring, particularly for new foliage, and declines to the level of older foliage (about 100% by dry weight, or equivalent to 1 g of water for each g of foliar dry weight) as the summer progresses (Agee et al., 2002). It is usually the late season moisture value that is used for planning purposes, so torching becomes primarily a function of canopy base height. At 100% foliar moisture, a 2 m canopy base height will require a flame length of 1.3 m to initiate torching, while a 6 m canopy base height will require a 2.8 m flame length (Agee, 1996).

Active crown fire spread begins with torching, but is sustained by the density of the overstory crowns and the rate of spread of the crown fire. The fire must consume a mass above a critical rate, known as mass flow rate, in order to sustain active crown fire. The critical mass flow rate has been defined as $0.05 \text{ kg m}^{-2} \text{ s}^{-1}$, and is a function of the crown fire rate of spread (m s^{-1}) and the density of the crowns, known as canopy bulk density (kg m^{-3}). Canopy bulk density represents the mass of foliage in a given volume of crown, and is a stand-level variable, as contrasted to crown bulk density, which is the density within a single tree crown. A "crowning index" can be defined either as the minimum windspeed (an index to rate of spread) required to maintain crown fire activity, for a given canopy bulk density (Scott and Reinhardt, 2001) or alternatively, the minimum canopy bulk density under assumed worst case fire weather, where rate of spread is considered the "constant" (Agee, 1996). From a silvicultural perspective, the latter method is preferable, but requires assumptions about rate of spread, which are now based on a simple regression empirically derived from Rocky Mountain crown fires (Rothermel, 1991).

Although crown fire theory is largely based on boreal forest experiments and observations, it is nevertheless a useful tool is defining fire resilient conditions (Table 1). First, surface fire behavior must be controlled, so that treatments should either reduce such potential behavior or at least not contribute to increased fire behavior. Because such treatments often open the understory so that midflame windspeed will increase and fine fuel moisture will decline (van Wagtendonk, 1996; Weatherspoon, 1996), maintaining no change in surface fire behavior generally requires a reduction in surface fuels or significant greenup of grasses and low shrubs (Agee et al., 2002). Second, a reduction in torching potential requires a comparison of potential surface fire flame length with a critical flame length, which is a function of canopy base height. At best, a reduction in potential surface fire behavior plus an increase in canopy base height will minimize torching potential. Third, reduction in potential active crown fire spread can be accomplished by a reduction in canopy bulk density. Where thinning is followed by sufficient treatment of surface fuels, the overall reduction in expected fire behavior and fire severity usually outweigh the changes in fire weather factors such as wind speed and fuel moisture (Weatherspoon, 1996).

The fourth principle in a fire resilient forest strategy for the short-term is to keep the large trees in the stand if they are present. These are the most fire-resistant trees in the stand, as they have the tallest crowns and thickest bark (Peterson and Ryan, 1986). In the longer term, provision must be made for sufficient spatial variation in age classes to provide for replacement of the larger trees as they die. Where large trees are not present, and a thinning prescription is considered, the largest of the small trees should be reserved.

3. Creating fire resilient stands with fuel treatments

Application of these principles to forests clearly implies a three-part objective: reduce surface fuels, reduce ladder fuels, and reduce crown density. Prescribed fire is effective at surface fuel reduction (van Wagtendonk, 1996), and it can also increase canopy base height by scorching the lower crown of the stand. It is generally less effective at reducing canopy bulk density, as fires intense enough to kill larger trees often exceed the desired severity thresholds (Miller and Urban, 2000). Initial fires will consume substantial biomass, but will also create fuels by killing understory trees, so that surface fuel biomass may return to or exceed pre-burn levels within a decade, but with an increased canopy base height (Agee, 2003) (Fig. 2). Often, staged treatments

Fig. 2. Accumulation of dead material four years after a single prescribed fire following more than 70 years without fire in the Blacks Mountain Experimental Forest in northeastern California. Photo: C.N. Skinner, USDA Forest Service, Pacific Southwest Research Station.

of prescribed fires (Allen et al., 2002) can do an effective job of reducing fire hazard (McCandliss, 2002), particularly where canopy bulk density is already low enough that active crown fire spread is unlikely (e.g., stands in Fule et al., 2002).

Thinning is another silvicultural tool that may be effective in creating fire resilient stands (Graham et al., 1999), but it is no panacea. Consider three types of classic thinning: low, crown, and selection thinning (Fig. 3, Table 2). All three will reduce average canopy bulk density, but may not necessarily reduce the maximum canopy bulk density as calculated by the Scott and Reinhardt (2001) method. A textbook low thinning (Fig. 3) will simultaneously increase canopy base height, while crown and selection thinning will not. The latter two methods will generate more income, because they focus on larger trees (Hartsough, 2003), but large trees are also the most fire-resistant ones. In most dry forest stands (Figs. 1 and 4) there is often a thick, unmerchantable (<10 cm dbh) understory (three columns on the left, Fig. 4, comprising about 60% of the total tree stems), so that even a low thinning that ignores the smallest trees will not have much effect on canopy base height. With the unmerchantable material left on site, the low thinning is, in effect, a crown thinning. Subsequent treatment to

remove smaller trees manually or with equipment can help reduce the unmerchantable material, but this adds expense to the operation.

Thinning will have either little effect or create an increase in surface fuels, depending on the method of yarding (Table 3). Whole tree harvest, with disposal of tops at the landing (chipping, burning) is most effective at preventing surface fuel increases in the residual stand, and helicopter yarding, the best system for minimizing immediate soil impacts from harvest, usually causes the highest surface fuel increases because tops from harvested trees are left in the woods. Harvester–forwarder operations increase surface fuels but concentrate and compact the fuels.

The influence of type of thinning and use of prescribed fire on stand survival after wildfire is illustrated by a simulation (Figs. 5 and 6) using fire behavior and effects models (NEXUS (Scott, 1999)) and First Order Fire Effects Model (FOFEM (Reinhardt et al., 2002)). A forest type with a historic low-severity fire regime (low elevation ponderosa pine/Douglas-fir/grand fir) and trees up to 100 cm dbh is subjected to thinning. The thinning reduces basal area from about $34 \, m^2 \, ha^{-1}$ to about $14 \, m^2 \, ha^{-1}$ ($\sim$60 $ft^2 \, ac^{-1}$), but several different types of thinning are applied: (1) no thin (the unharvested stand; (2) low
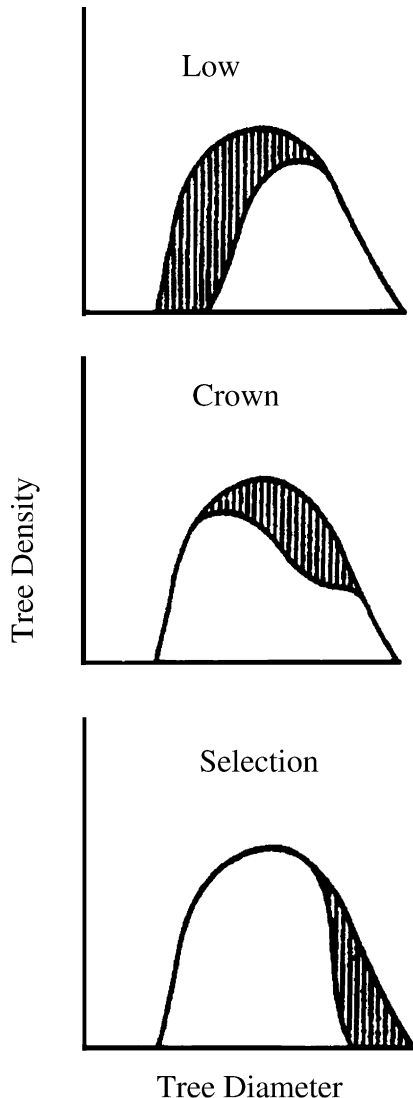
Fig. 3. Types of thinning in an even-aged stand. Low thinning removes trees from smaller diameter classes, crown thinning focuses on mid-canopy trees, and selection thinning focuses on the largest trees in the stand.

thinning where all small trees are removed, and cutting of successively larger trees continues until the basal area criterion is reached; (3) low thinning with a lower commercial size limit (15 cm), so the thinning begins with trees 15 cm and larger until the basal area criterion is reached; (4) selection thinning, where trees are removed from largest to smallest until the basal area criterion is reached; and (5) post-treatment

Table 2
Effect of thinning method on canopy characteristics

Method	Effect on canopy characteristics	
	Canopy base height	Canopy bulk density
Low thinning	I[a]	NE/D
Crown thinning	NE	D
Selection thinning	NE	D

I: increase; D: decrease; NE: no effect.
[a] If unmerchantable small trees also removed.

prescribed fire where flame length is limited to 0.6 m. Although the vertical scales differ between the graphs in Fig. 5, quite different structures are created by the various treatment combinations, and they have differential survival in a severe weather wildfire simulated to occur after the treatments. Species composition is not shown, but is primarily ponderosa pine in the large size classes, with Douglas-fir in medium size classes and grand fir dominating the smaller size classes. Weather conditions for the simulated wildfire are described in Fig. 6, and mortality from surface fire was predicted from FOFEM using the predicted flame lengths. Where active crown fire was predicted, mortality was adjusted to 100% (Beukema et al., 2000), and where torching activity was predicted, mortality was adjusted up from the FOFEM prediction by the crown fraction burned.

The unmanaged stand (UM) was predicted to sustain active crown fire, and a stand replacement event was predicted (Fig. 6). Mortality was almost the same, but over a lower basal area, for the low thin with commercial limit (LT-CL) and the selection thin (ST) stand. In the former stand, the canopy base height was low, encouraging torching, and for the selection stand, no large, fire-tolerant trees remained. Where the selection thin stand was treated with prescribed fire, basal area was reduced by the fire but the stand did have some residual basal area after wildfire. Where small trees were removed, either by thinning or prescribed fire, survival after wildfire was a much higher proportion of total basal area (columns to right, Fig. 6). The unharvested stand that was treated with prescribed fire alone (UM/PF) lost some basal area, but its residual basal area after wildfire was above that of all the thinned stands. Any standing dead fuels created by the prescribed fire will, of course, fall to the ground (Fig. 2), and such future additions are not
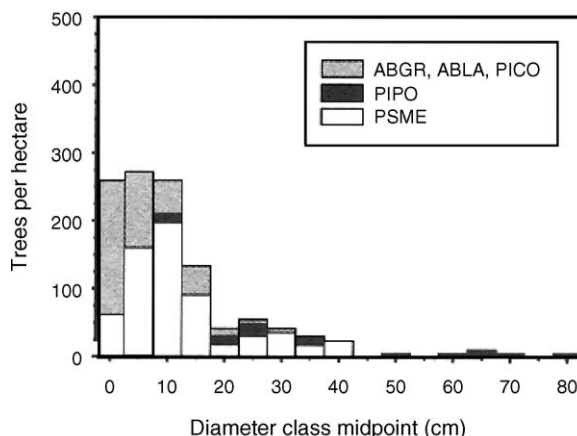
Fig. 4. Structure of a dry forest (from Scott and Reinhardt, 2001) indicating the predominance of very small, unmerchantable trees in the current structure (similar to bottom photo, Fig. 1. A low thinning of merchantable trees would begin at about 10 cm diameter, and crown or selection thinning would concentrate on even larger stems. Commercial harvest without treatment of the unmerchantable material will leave canopy base height unchanged and could increase surface fuel loads. ABGR = grand fir (*Abies grandis*), ABLA = subalpine fir (*Abies lasiocarpa*), PICO = lodgepole pine (*Pinus contorta*), PIPO = ponderosa pine (*Pinus ponderosa*), PSME = Douglas-fir (*Pseudotsuga menziesii*).

accounted for in these simulations. Within 5–10 years after treatment, potential surface fire intensity will increase where such fuels were created, although height to live crown will have been increased by the prescribed fire. A second prescribed fire treatment would be required in such cases to maintain low surface fuel loads.

If different stand structures or wildfire conditions were selected, the results shown would have varied somewhat, but likely remained in roughly the same order of effectiveness. The implications of these simulations are (1) Not every fuel reduction treatment will reduce fire problems. Treatments should be planned using principles of firesafe forests: treat surface fuels, ladder fuels, and although thinning of the crown may be desirable, leave large trees. Those treatments that focused on smaller trees and ladder fuels were effective, and prescribed fire alone was

effective, too. (2) The conventional wisdom that under severe fire weather fuel conditions are irrelevant is not true: fuels and forest structure do make a difference (Agee, 1997). The large ponderosa pines all across the West in pre-fire-exclusion times attest to the fire resistance of those forests, which commonly burned over the centuries under severe fire weather as well as under more benign weather. Current stands with fire-resistant species, treated to reduce fire hazard, are also capable of surviving wildfires in worst case fire weather.

4. Empirical evidence for efficacy of fuel treatments

There is no opportunity to conduct experimental crown fire work in the dry forests of western North

Table 3
Effects of yarding method on surface fuel quantity and arrangement

Method	Effect on surface fuel amount/depth
Feller-buncher or cable/whole tree	NE/NE
Feller/buncher or cable/lop and scatter	I/I
Harvester–forwarder	I/NE or I/I
Helicopter	I/I

Whole tree yarding is usually restricted to ground-based methods; helicopter yarding leaves tops in the field. Surface fuel amounts: I: increase; D: decrease; NE: no effect. Surface fuel depth: I: increase; D: decrease; NE: no effect.
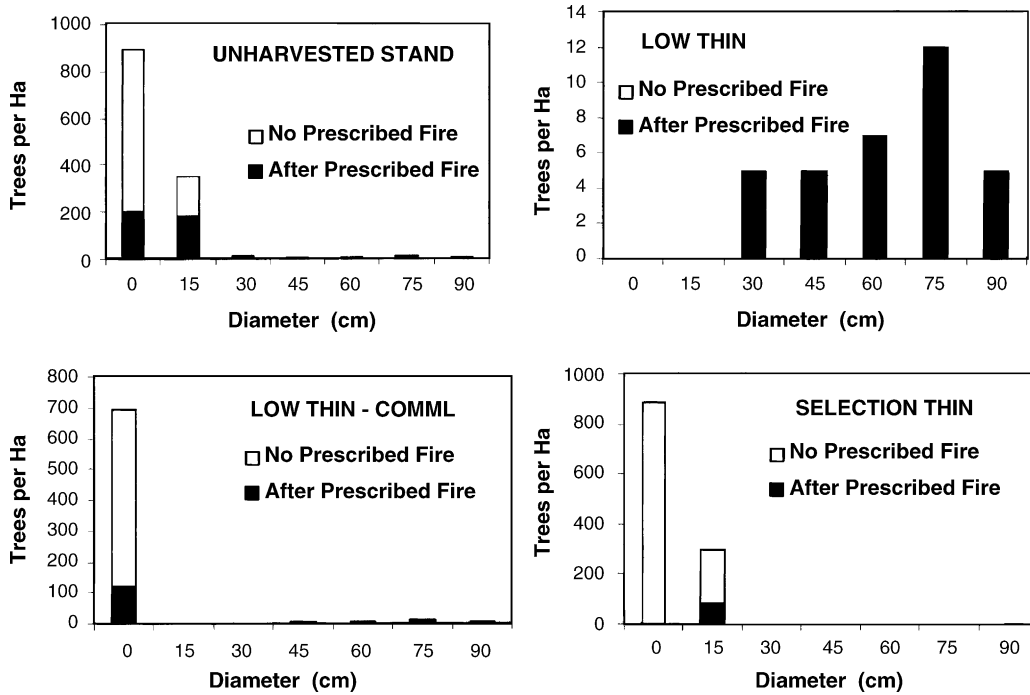
Fig. 5. Various forest structures created in the same stand by thinning, and thinning/prescribed fire. In each graph, the density of each size class after thinning is shown by the total height of the column. Structure after application of prescribed fire is shown in black. Note the vertical scales differ between each graph.
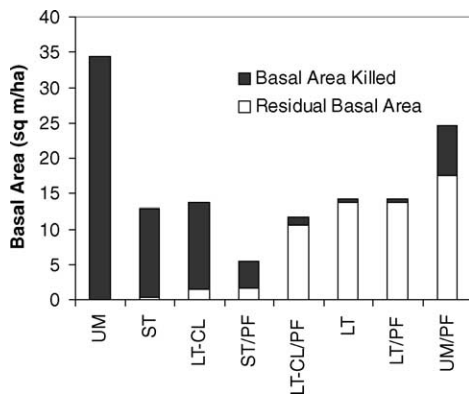

Fig. 6. Survival from a severe-fire-weather wildfire of the stand structures shown in Fig. 4. Columns are organized by absolute amount of residual basal area (white part of column). UM: unmanaged, ST: selection thin, LT: low thin, CL: commercial limit (>15 cm), PF: prescribed fire. The unharvested stand was assumed to be NFFL fuel model 10, harvested stands with no prescribed fire were assumed to be NFFL Model 11, and any stand treated with prescribed fire was assumed to be NFFL model 9. Fuel moistures for 1-, 10-, and 100-h fuels were 4, 5, and 6% for models 9 and 11 and 5, 6, and 7% for model 10. Open windspeed of 36 kph was adjusted to 0.4 for models 9 and 11 and 0.2 for model 10.

America. So possibilities of experimentally treating stands and then purposely subjecting them to a worst-case wildfire are non-existent. However, we do have the ability to observe wildfires as they move into previously treated stands, and although inference drawn from such events must be limited, such observations indicate that fuel treatment, scale, and time since treatment affect changes in wildfire behavior and effects.

4.1. Hayfork Fires, California, 1987

The Hayfork fires covered roughly 20,000 ha in 20 separate fires on the Shasta-Trinity National Forest in Douglas-fir dominated mixed-conifer forest, and were evaluated after the fact by Weatherspoon and Skinner (1995). "Treated" stands were not specifically treated for fire resiliency, as the stands were harvested largely via selective cutting of large trees, and fuel treatment after harvest was either lop and scatter or under-burning. Severity was indexed by crown scorch. Uncut stands (generally old growth) had the lowest fire

damage classes, because they contained the largest trees and had less surface fuel compared to stands with a harvest history. Yet, where logging had been followed by treating the surface fuels, the damage classes were not statistically different from the uncut stands (Weatherspoon and Skinner, 1995; Weatherspoon, 1996). The lesson here is that treatment without regard to residual fuel and forest structure, may exacerbate fire severity rather than ameliorate it.

4.2. Tyee Fire, Washington, 1994

The Tyee fire covered 50,000 ha on the Wenatchee National Forest. Small (5–20 ha) treated areas of second growth, which included 60-year-old mixed conifer forest, underburned while adjacent untreated areas of the same age burned with crown fires. The heated air created by the crown fires passed over the treated areas and scorched the tops of the trees that were later underburned. Many of these trees later died from the sandwiched scorch effect (Agee, personal observation), suggesting that scale of treatment is important. The Goman Peak fuelbreak (Fig. 7) created in the 1970s transformed a crown fire (coming from left) to a surface fire, which then became a crown fire again as it exited the fuelbreak. The trees in the fuelbreak had grown much larger than those in the
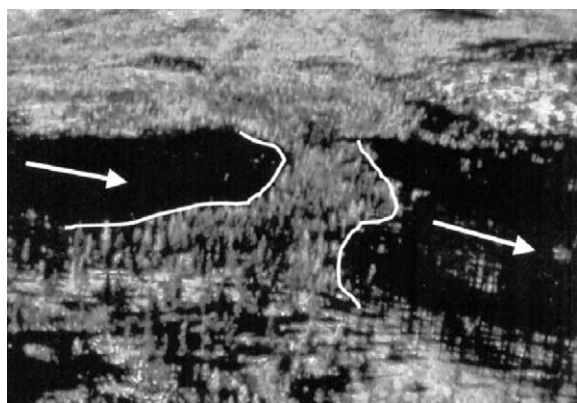

Fig. 7. Post-fire condition of the Goman Peak fuelbreak, Wenatchee National Forest, Washington. The crown fire came from the west (white arrow at left), moved as a surface fire through the fuelbreak (area bracketed by white lines), and then transitioned back to a crown fire to the east (white arrow at right) of the fuelbreak. Created in the 1970s, the fuelbreak received a low thin (to about 10 m^2 ha^{-1}), pruning to 3 m height, and pile burning of debris. USDA Forest Service photo.

untreated areas, which also helped their survival. However, many of the trees in the fuelbreak subsequently died, although the fuelbreak remains a green line up the hill. The lesson here is that scale matters: treatments with substantial edge adjacent to untreated units are likely to suffer substantial mortality, even if fire behavior is reduced.

4.3. Megram Fire, California, 1999

The 50,000 ha Megram fire burned on the Shasta-Trinity and Six Rivers National Forests in northwestern California in mixed-conifer forests dominated mostly by Douglas-fir. It burned through 12,000 ha of forest affected by a large windsnap–windthrow event in the winter of 1995–1996. Limited areas of 250-m wide fuelbreaks were established within these wind-affected zones, due to much of the area being within wilderness and administrative appeals on larger-scale fuel treatment. At least some of the fuel-treated area was reached after the main intense pulse of the fire subsided, and little to no suppression was attempted as the fires approached and entered the fuelbreaks. Stand replacement fires outside of the fuelbreaks quickly transitioned to surface fires in the fuelbreaks. Although crown scorch from heat generated in adjacent untreated forest did cause mortality on the windward side of some fuelbreaks, mortality was minimal by the time the fires reached the lee sides. Some effective fuelbreaks had only surface fuels and ladder fuels treated, with residual canopy cover exceeding 60–70% (Fig. 8). Even though canopy bulk density was insignificantly reduced, fire severity was significantly reduced, suggesting that reductions in canopy bulk density are not always needed to reduce wildfire severity.

4.4. Hayman Fire, Colorado, 2002

The 50,000 ha Hayman fire burned within the Pike-San Isabel National Forest southwest of Denver. It contained a major and severe fire run of 25,000 ha in 1 day. Many areas where fuels had been treated before the fire experienced lower severity effects than adjacent untreated areas (Finney et al., 2002). Fuel treatment was not always successful in reducing fire severity, particularly during periods of incredibly severe fire weather (winds to 135 kph (85 mph) and

Fig. 8. Example of a change in fire severity due to fuel treatment on the Megram fire. Upper left portion of photo is untreated forest that was affected by a windsnap event in 1996. Lower right is a fuel-treated area where surface and ladder fuels were removed. The fire burned in 1999. USDA Forest Service photo.

fuel moistures of below 6% in all size classes). Under less severe conditions, fuel treatments such as prescribed fire apparently altered fire severity, except where the treatments were of very small extent (less than 100 ha), or where they had been applied more than 10–15 years previously. Timber stand improvement work without treatment of fuels created by such activity were burned more severely than unmodified areas.

4.5. Cone Fire, California, 2002

The Cone Fire covered 800 ha and burned as a crown fire into the ponderosa pine dominated forests of the Black's Mountain Experimental Forest (BMEF) within the Lassen National Forest where it encountered three 100-ha stands experimentally thinned, or thinned and underburned (Oliver, 2000). Two stand structures were created in the BMEF project. One structure emphasized retaining the largest trees and is referred to as high structural diversity (HiD). The other structure removed the smallest and largest trees, leaving regularly spaced, intermediate sized trees, and is referred to as low structural diversity (LoD). For two of the stands (one LoD and the HiD) treatment had been completed 5 years previous to the Cone fire. Treatments had been completed in the third stand (LoD) two years before the fire. Each stand was split with surface fuels on one half treated with prescribed

fire and the other half treated with lop and scatter. Where the Cone Fire encountered thinned and burned stands, the fire went out (Fig. 9). Where it encountered thinned stands with only lop and scatter of fuels created by the harvest, it burned as a surface fire with patches of scorched tree crowns in the stand. Though both the HiD and LoD treatments where prescribed fire had followed the thinning worked well in halting the high intensity fire, there were differences. The fire stopped at the edge of the LoD treatments. It continued as a very low intensity surface fire through needles up to approximately 100 m into the HiD stand before going out. The difference appears to result from the litter cast from the larger trees in the HiD stand, which covered the surface more completely than in the LoD stands (Skinner et al., in press).

Empirical evidence from other wildfires also supports the concept that forests treated with fire-hazard reduction objectives burn with less severity than adjacent untreated areas (Omi and Martinson, 2002; Pollet and Omi, 2002).

5. The challenges of temporal and spatial scales

Scale must be considered in restoring fire resistant forests. If fuel treatments are small and scattered, or a long time has elapsed since treatment (generally 10–15 years or more), they will be less effective in

Fig. 9. Left photo shows surviving trees in the half of Unit 46 that was thinned and burned. Right photo shows dead burned trees in the untreated area immediately adjacent to Unit 46. Both photos were taken back-to-back from same location on the treatment boundary. Photos: C.N. Skinner, USDA Forest Service, Pacific Southwest Research Station.

fragmenting the landscape fuel loads, and their efficacy at the stand level can be overwhelmed by intense fires burning in adjacent areas.

Temporal scale is not well understood, both for effective staging times for treatments and the length of time that treatments are effective. Thinning with fuel treatment is a ''one-stop shopping'' solution: bring the stand back into its natural range of variability in one operation (e.g., Fule et al., 2002). Allen et al. (2002), while noting a consensus for some action exists, cautions that staged treatments may be more effective. One example of staged treatment is the King's River project on the Sierra National Forest, California, where some areas are being restored with prescribed fire alone. Most units are large (50–600+ ha), and of 5000 ha burned over 6 years, 35% has been reburned (McCandliss, 2002). Once initial restoration treatments are complete, length of effectiveness is likely a matter of place. Where fuels build up quickly, efficacy

may be less than a decade (e.g., Brose and Wade (2002) in the southeast US). Observations of montane red fir ecosystems in Yosemite National Park where most natural fires are allowed to burn indicate that most natural fires have stopped at old fire boundaries up to 15-year old (van Wagtendonk, 1995). Fire histories in dry forests suggest that historical fires have occurred in successive years, and intervals as short as 3 years are not uncommon in ponderosa pine dominated stands, although the median or mean fire return intervals are often longer (Swetnam and Baisan, 1996; Heyerdahl et al., 2001). Such closely timed fires would almost certainly have been patchy and of low severity. McKenzie and Hessl (in press) present a neutral model of historical low-severity fire regimes that suggest both topography and fuels constrained historical fire spread.

Spatial scale of ecosystem treatment is also place-specific, whether prescribed fire alone or thinning plus

fuel treatment is done. In the Sierra Nevada mixed-conifer type, some units are quite large (>600 ha; McCandliss, 2002), and this is true for the eastern Cascades mixed conifer type as well (Wenatchee-Okanogan National Forest). Median area burned by historical fire in the Klamath Mountains was slightly over 100 ha (Taylor and Skinner, 2003). The use of physical features such as streams and ridges (McCandliss, 2002) to design fuel treatments is consistent with natural fire boundaries (Taylor and Skinner, 2003). Constraints on the use of fire at coarse scale include air quality concerns and health effects on local residents.

Where thinning is used, there will be impact from the removal process. The soil impact of ground-based systems (Kellogg, 1995) will generally restrict extremely large-scale thinning operations. Silvicultural operations that have little soil impact usually have a negative fuels impact (e.g. helicopter yarding), but fuel increases can be ameliorated with prescribed fire. Existing road systems may not be entirely congruent with the needs for access for yarding, so that in some cases temporary road construction will be needed. Beginning in areas that are already appropriately roaded will limit the erosional impact of roads, and also introduce opportunities for rehabilitation or removal of old roads.

While the impacts of thinning and burning can be predicted, and may have some negative environmental impacts, these impacts need to be evaluated against the option of "no action". "No action" is not a risk-free option, as dry climates regularly predispose forests to burn in a typical dry summer (Heyerdahl et al., 2001; Skinner, 2002; Swetnam and Baisan, 2003). The impacts of "no action" in dry forest ecosystems must incorporate the probability of stand-replacing, intense fire where stand density has increased and dead fuel accumulated in excess of historical levels. The probabilities of wildfire in space and time are not well defined: wildfire may not occur here this year, or there next year, but at some scale the spatial loss per time period can be defined. It may be quite difficult to point to a particular stand and define its probability of burning in some given future period, but the probability that substantial areas of dry forest will continue to be burned by severe wildfire is known, and it is high.

Very few landscapes will receive fuel treatment over the entire area, due to the constraints mentioned above as well as economic constraints. The landscape challenge is to define how much of a landscape needs to be treated, and where strategic fuel treatment will be most effective at reducing wildfire damage (Agee, 1996; Weatherspoon and Skinner, 1996; Taylor and Skinner, 1998). Some simulations of such work have been completed (Finney, 2001, 2003; Keane and Finney, 2003) and efforts are underway to apply these principles to real landscapes (Finney, Joint Fire Sciences Program, project in progress). The challenges are real, and become more important each year. Dry forests continue to burn at unprecedented rates, emplacing undesirable landscape patterns for a century or more, and reducing opportunities for restoration. Restoration activities are critical. We know what to do, and know, at least at a stand scale, how to do it right. Our greatest challenge is to expand that scale with socially accceptable treatments to sustain these dry forest landscapes into succeeding centuries.

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