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The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California

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Abstract

Wildfire behavior can be modified by altering the quantity, structure, and arrangement of fuel (flammable vegetation) by silvicultural treatments such as forest thinning and prescribed burning. The type and arrangement (including landscape location) of treated areas have been demonstrated to influence wildfire behavior. This study analyzes the response of several key fire behavior variables to variation in the type, amount, and spatial arrangement of fuel treatments for simulated wildfires in mixed-conifer forests of the southern Cascades in the Goosenest Adaptive Management Area (GAMA). NEXUS and BehavePlus were used to simulate pre- and post-treatment stand-level fire behavior. Fire area simulator (FARSITE) was used to simulate landscape-level wildfire behavior in both untreated and treated forest landscapes. In the forest landscape, treatment areas were placed in the landscape according to two strategically designed arrangements and one random treatment arrangement. Treatments included thinning by prescribed burning (burn-only), mechanical thinning (mechanical-only), mechanical thinning followed by burning (mechanical-burn), and no treatment (control). At the stand level, the mechanical-burn treatment most effectively reduced both surface fire (e.g., decreased flame length) and crown fire behavior (e.g., torching index). At the landscape level, treatment type, amount, and arrangement had important effects on both fire spread and fire intensity. In this landscape the most effective treatment arrangement was Finney's optimal SPLATs design. This study shows that there is potential to efficiently reduce high-intensity fire behavior while treating less area by relying on strategically placed treatments.
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Keywords: Fire behavior; Fuels treatment; Fire hazard; Landscape burning; Fuels management; Mixed-conifer forests; FARSITE; NEXUS

1. Introduction

The accumulated impact of fire suppression on forest ecosystems is one of the major causes of the recent increase in the extent and severity of wildfires in the western United States (Arno and Allison-Bunnell, 2002; Stephens and Sugihara, 2006). During the last century fire suppression has caused an increase in forest fuels (Dodge, 1972; Agee, 1993; U.S. GAO, 1999), particularly in pine-dominated forests that once experienced frequent low-intensity surface fires (Covington and Moore, 1994; Skinner and Chang, 1996). Higher fuel loads and increased horizontal and vertical continuity of fuels has increased the risk of high-intensity fire, including crown fire (Scott and Reinhardt, 2001; Fulé et al., 2004; Hardy, 2005). Fuel reduction treatments provide efficient methods of reducing the risk of intense fire and extreme fire behavior, although they are not necessarily intended to stop a fire (Omi and Martinson, 2002; Finney and Cohen, 2003; Graham et al., 2004; Finney et al., 2005). Partly in response to the severe 2000 fire season in the USA, the National Fire Plan (NFP, 2001) and the Healthy Forests Restoration Act (HFRA, 2003) were enacted to ensure that hazardous fuels reduction was a centerpiece of national fire policy. Yet, strategies for implementing treatments are hindered by a poor understanding of how stand-scale fuel treatment effects on fire behavior can be scaled up to forest landscapes, as well as how the spatial arrangement of treatment units influences fire behavior and the effectiveness of treatments to reduce the risk of severe fire in forested landscapes.

At the level of forest stands (tens of hectares), the most common fuel treatments are prescribed burning, mechanical thinning, or a combination of the two (Graham et al., 1999, 2004; Arno and Allison-Bunnell, 2002). The most effective treatments are designed to reduce surface fuels, canopy cover, and stand density while increasing canopy base height (Scott and Reinhardt, 2001; Agee and Skinner, 2005). Prescribed

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burning has been used as a treatment to reduce surface fuels in Western forests since at least the 1950s (Biswell, 1989). Although mechanical thinning is a more precise treatment method than burning for creating particular stand structures, mechanical thinning alone can increase surface fuels and the risk of intense fire if unutilized tops and limbs are left untreated (van Wagtendonk, 1996; Stephens, 1998; Agee and Skinner, 2005). The increased light penetration to the forest floor caused by thinning can dry surface fuels more completely, potentially elevating fire hazard and risk (Weatherspoon, 1996; Agee and Skinner, 2005). On the other hand, the reduction in fire intensity achieved through reducing fuels may more than offset the increase in risk of fire associated with opening the stand (Weatherspoon, 1996; Agee and Skinner, 2005).

Fuels management at the landscape scale (thousands of hectares) is focused on treating fuels to either help suppression forces more easily contain fire or reduce area burned by high-intensity fire. This is accomplished by modifying fire behavior through strategic placement and arrangement of fuel reduction treatments on the landscape (Martin et al., 1989; Weatherspoon and Skinner, 1996; Finney, 2001; Finney and Cohen, 2003; Graham et al., 2004). At this scale, individual stands may be unrelated to overall fire severity patterns (Weatherspoon and Skinner, 1996; Finney and Cohen, 2003). Strategic placement designs use existing natural (streams, rock outcrops, ridgetops, bare areas) and unnatural (roads, reservoirs, irrigated fields) barriers to fire spread as anchors for any additional fuel treatments (Weatherspoon and Skinner, 1996). Typically, such treatments are implemented in non-wilderness or relatively accessible terrain. Little research has evaluated whether differences in the effectiveness of stand-scale fuel treatments scale up to forest landscapes, or how the spatial arrangement of treatment units influence the effectiveness of treatments to reduce fire risk across forested landscapes (Finney, 2001; Loehle, 2004).

One approach to treatment placement across the landscape is to use ‘‘strategically placed area treatments’’ (SPLATs; Finney, 2001). This approach is based on a mathematically derived geometric arrangement (width, length, spacing, and alignment) of fuel treatments to minimize treatment area while simultaneously maximizing their effect on interrupting fire spread across the landscape. Severe wildfires encountering SPLATs are forced to burn through and around ‘‘speed bumps’’ of reduced fuel (Finney, 2001). The effect is similar to the observed behavior of fires as they reach the mosaic of fragmented fuels caused by earlier wildfires in a landscape (van Wagtendonk, 1995). In practice, construction and placement of SPLATs is constrained by factors that affect implementation of any fuel management strategy such as cost, topography, access, the need to maintain critical wildlife habitat, and legal or regulatory requirements.

The concept and potential implementation of SPLATs is based, in part, on the theory and practice of using shaded fuelbreaks and defensible fuel profile zones (DFPZs) to modify landscape-scale fire behavior. Shaded fuelbreaks have been shown to be effective under many conditions (Salazar and González-Cabán, 1987; Omi, 1996; Sessions et al., 1996; van Wagtendonk, 1996; Agee et al., 2000). Typical fuelbreaks in California mixed-conifer forests, for example, have widths that range from 90 to 400 m (Green, 1977; Quincy Library Group, 1994) and a canopy cover of $\leq$40% (Olson, 1977). Defensible fuel profile zones, in contrast to shaded fuelbreaks, are rapid implementation, high-priority treatments designed to treat a larger percentage of a landscape (10–25%) focusing more explicitly on the strategic spatial location of the treatments within a landscape (Weatherspoon and Skinner, 1996).

Recently, several wildfires have burned through treated or previously burned areas providing some assessment of the efficacy of fuel treatments on reducing fire severity (Salazar and González-Cabán, 1987; Martinson and Omi, 2003; Martinson et al., 2003; Skinner et al., 2004; Finney et al., 2005; Strom and Fulé, 2007; Ritchie et al., 2007). However, a more formal testing of the effectiveness of fuel treatments at landscape scales is impractical and unacceptably risky because it requires igniting large wildfires under severe fire weather conditions and then observing fire behavior and effects in treated and untreated areas. An alternative approach to testing potential fuel treatment effectiveness is to use spatially explicit fire simulations to compare the effects of different fuel treatments and treatment location (Bahro et al., 2007).

The objectives of this study were to: (1) compare the relative effectiveness of thinning, thinning and burning, and burning on simulated stand-scale fire behavior and (2) compare the relative effectiveness of a random, DFPZ, and SPLATs arrangement of the three treatments on simulated landscape fire behavior, at three levels of area treated (10%, 20%, 27%). Given the importance of weather on fire behavior (Rothermel, 1983), we simulated fire behavior for 80th, 90th, and 97.5th percentile conditions in stands and across the landscape. For this study we use fuels data derived from replicated fuel treatment experiments installed in the field to identify appropriate fuel models for use in fire behavior simulations. These data were collected as part of the National Fire and Fire Surrogates study (FFS). The FFS was designed to evaluate the effects of different silvicultural prescriptions on reducing fire hazard at the stand-scale (Weatherspoon and McIver, 2000). However, treatment effectiveness may be scale dependent. Large differences in simulated fire behavior associated with treatments at the stand-scale may be unimportant for fuels management designs at the landscape scale depending on the spatial arrangement of treatments and the total area treated on the landscape.

2. Study area

The study area is located 117 km northeast of Redding, California in the Southern Cascades physiographic province and covers 280 km^2 of the Klamath National Forest (KNF) (Fig. 1). The landscape is young and is comprised of Tertiary and Quaternary aged volcanic rock. Soils are mainly well-drained Andisols and Entisols with xeric soil moisture regimes (Miles and Goudey, 1998). Overall, the topography is gentle, but steep slopes (>33°) occur on the flanks of several peaks. Antelope Creek is the only perennial stream in the study area. Elevations in the study area range from 1400 to 2500 m. The

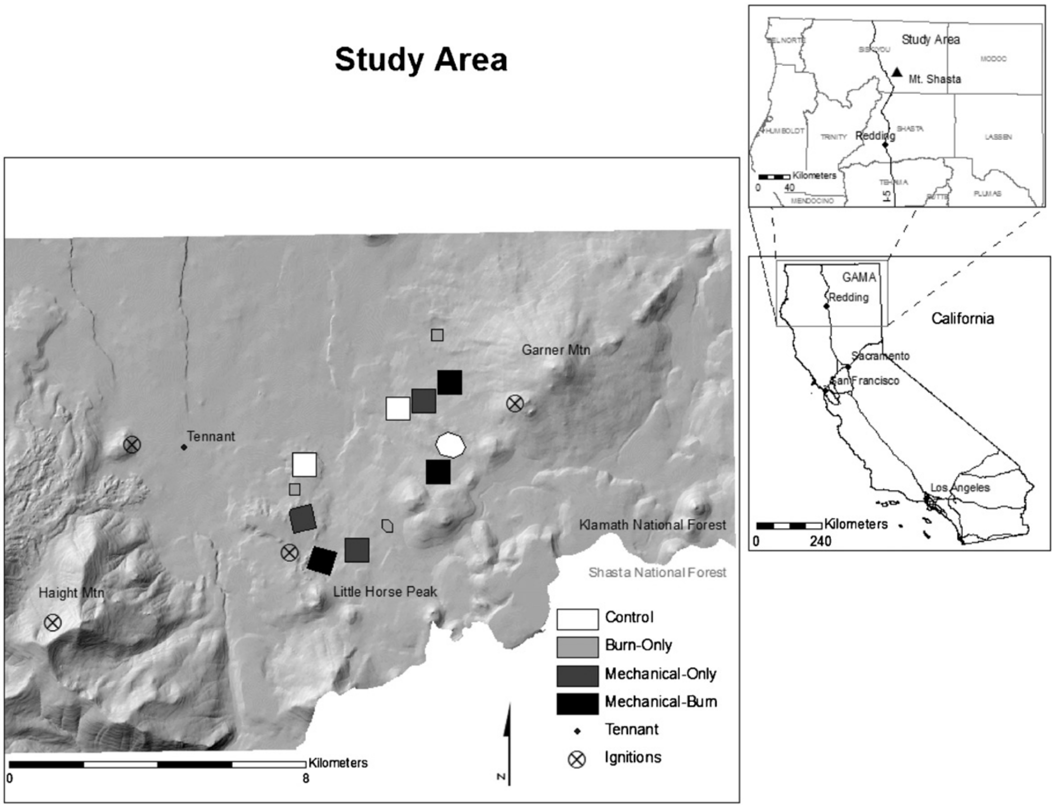

Fig. 1. Location of study area, the town of Tennant, and the four ignition points for the landscape fire simulations.

climate is characterized by warm, dry summers and cold, wet winters. Mean monthly temperatures at the Mount Hebron Ranger Station (1295 m), 26 km northwest of the study area, are lowest in January (−2.6 °C) and highest in July (17 °C). Annual precipitation averages 29.4 cm, most of which (73%) falls as snow between November and May.

Forest composition in the study area varies with elevation, slope aspect, and topographically influenced patterns of soil moisture (Rundel et al., 1977). Ponderosa pine (*Pinus ponderosa*) mixed with western juniper (*Juniperus occidentalis*) and an understory of antelope bitterbrush (*Purshia tridentata*) typically occurs on xeric sites with deep soils between 1000 and 2100 m and covers *ca*. 25% of the study area (nomenclature follows Hickman, 1993). Stands of ponderosa pine-white fir (*Abies concolor*) cover another 25% and they occupy cooler, more mesic, north- and east-facing slopes between 1200 and 1800 m. Mixed-conifer-fir and white fir (23%) forests occur between 1400 and 2300 m. Stands are usually dominated by white fir at higher elevations, especially on north-facing slopes, while ponderosa pine and incense cedar (*Calocedrus decurrens*) are most abundant at lower elevations on xeric sites. Sugar pine (*P. lambertiana*) is most abundant on north-facing slopes. Stands of montane chaparral occupy approximately 4% of the area on south- and west-facing aspects. Stands of montane chaparral are maintained by infrequent, high severity fire or poor soils (Nagel and Taylor, 2005) and they are dominated by greenleaf manzanita (*Arctostaphylos patula*), snowbrush (*Ceanothus velutinus*), or bitter cherry (*Prunus emarginata*). Lodgepole pine (*P. contorta* var. *murrayana*) forests (8%) occupy sites between 1400 and 2500 m with high water tables, poor soils, cold-air accumulation, or recent severe disturbance. Shasta red fir stands (*Abies magnifica* var. *shastensis*) (9%) dominate upland sites at the highest elevation (1700–2300 m), especially those that have deep soils (Rundel et al., 1977).

Euro-Americans have strongly influenced forest conditions since their arrival in 1849. Livestock were introduced in 1858 and extensive grazing continued into the early 20th century. The forests were also logged and by the early 1900s most of the large pines (≥80 cm DBH) in the area had been removed (Ritchie and Harcksen, 2005). The KNF was established in 1905 and timber harvesting became regulated, but by 1909 railroad logging had resulted in removal of most of the original pine and mixed-conifer forest. Fire suppression, together with the selective harvesting of large pines, created dense second-growth forests that are now more strongly dominated by white fir than the original forest (Ritchie and Harcksen, 2005).

The Goosenest Adaptive Management Area (GAMA) was created in 1994 to test silvicultural techniques designed to accelerate late-successional forest attributes (USDA-USDI, 1994). Subsequently, the GAMA Ecological Research Project was initiated in 1995 to see if and how combinations of tree harvesting and prescribed fire would contribute to achievement of GAMA goals (Ritchie, 2005). Four treatments were

Table 1
Treatments applied to plots at the Southern Cascades National Fire and Fire Surrogates site in California

Treatment	Description
Control	No treatment.
Mechanical	Thin from below (29.5 cm maximum dbh) and selection cut (species leave preference: sugar pine > incense cedar > ponderosa pine > red fir > white fir). Whole trees removed to central landing for processing. Material processed at the landing and then transported for utilization as either logs or chips for pulp or biomass fuel. No follow-up fuel treatment.
Burn	Underburn with eventual goal of 80% of overstory basal area surviving a head fire at 80th percentile weather conditions. No pre-burn stand/fuels treatments.
Mechanical + burn	Mechanical treatment followed by prescribed burn treatment.

All treatments except the control have the same 80/80* rule objective (Skinner et al., 2001).

implemented on 1600 ha of mixed-conifer forest dominated by ponderosa pine and white fir (all harvest treatments were thinning from below and whole tree harvest): (1) pine retention emphasis, no prescribed fire; (2) pine retention emphasis followed by prescribed fire; (3) large tree retention emphasis, no prescribed fire; and (4) untreated controls. Treatments were initiated in 1998 and completed in 2002 (Ritchie, 2005). The National Fire and Fire Surrogates Study (FFS), designed to study the effects of altering stand structure to reduce fire hazard, used a subset of plots (treatments 1, 2, and 4) and added a prescribed fire-only treatment as the Southern Cascades Site of the FFS network (Weatherspoon and McIver, 2000). The prescribed fire-only treatments were also completed in 2002.

3. Methods

3.1. Stand-level treatments and fuel characteristics

Surface and canopy fuels and stand structure data were collected in 12 units (10 ha each) that had one of four silvicultural treatments allocated using a completely randomized design (Skinner et al., 2001; Ritchie, 2005). The fuels treatments included mechanical thin-only (M), mechanical thin followed by burning (M + B), burn-only (B), and a no treatment control (C) (Table 1). All field data were collected according to FFS protocols (Weatherspoon and McIver, 2000) with the exceptions noted by Skinner et al. (2001). A brief summary of the data collected in each treatment unit is provided below. Additional details are provided by Ritchie (2005). All burn treatments were fall prescribed burns.

Sampling in each treatment unit was conducted on a 50 m × 50 m grid ($n = 36$ points). Ten 20 × 50-m plots (i.e., Whittaker, 1960) were established at the same grid points in each unit to sample post-treatment surface and canopy fuels. Forest canopy characteristics (DBH, height, canopy base height) were measured for all trees $\geq$10 cm and forest cover (horizontal fraction of the ground covered by tree canopy) was measured in each plot in each unit. Surface fuels were measured in three time-lag size classes (1 h, $\leq$0.64 cm; 10 h, 0.64–2.54 cm; 100 h, 2.55–7.62 cm) along two 20.1 m standard line transects (Brown, 1974) at each grid point in each unit. The azimuth of the first transect was randomly selected and the second was offset 120° from the first. Depth (cm) of dead and down woody fuel in the litter layer was also measured at 3.1, 6.1, and 9.1 m along each transect.

3.2. Surface and canopy fuels

Surface fuel loads were calculated for each unit using fuel parameters and procedures described in Brown (1974), Kiefer et al. (2006), and van Wagtendonk et al., 1998. The fuel characteristics in the units were then used to choose the most similar standard fuel models (i.e., Anderson, 1982; Scott and Burgan, 2005) which were then used for estimating fire behavior parameters for each of the four treatments. We used standard fuel models, rather than custom models, because the standard models have been parameterized and calibrated with observed fire behavior under the conditions to be simulated (Rothermel and Rinehart, 1983; Burgan and Rothermel, 1984). Fuel models chosen for each treatment are given in Table 2. We chose two fuel models for the control plots to bracket the expected behavior of fire (surface and crown) for conditions when primarily surface fuels dominate and when ladder fuels are present. Crown fuel variables (canopy bulk density, canopy base height, and crown cover) were calculated using the stand structure measurements and FFE-FVS software (Reinhardt and Crookston, 2003) as described in Scott and Reinhardt (2002).

Table 2
Mean (range) post-treatment surface fuel characteristics

Treatment	Fuel model selected	1-h (mg ha^{-1})	10-h (mg ha^{-1})	100-h (mg ha^{-1})	Total 1-, 10-, and 100-h fuels	Fuel depth (cm)
Control	FBM 9[a] FBM 10[a]	0.81^{a} (0.6–0.9)	2.62^{a} (2.3–3.0)	3.95 (3.0–5.2)	7.38 (6.2–8.4)	$6.58^{a,b,c}$ (4.8–7.9)
Mechanical	SB1[b]	0.69^{b} (0.5–1.0)	2.35^{b} (1.9–2.8)	5.81^{a} (3.9–7.3)	8.85^{a} (6.3–11.1)	9.55^{a} (8.2–11.0)
Burn	TL1[b]	$0.16^{a,b}$ (0.1–0.2)	$0.56^{a,b}$ (0.5–0.7)	1.55^{a} (1.2–1.8)	2.27^{a} (2.2–2.4)	$1.89^{a,b}$ (1.5–2.3)
Mechanical + burn	FBM 8[a]	$0.20^{a,b}$ (0.2–0.2)	$1.46^{a,b}$ (1.2–1.8)	4.15 (3.1–5.5)	5.81 (5.1–7.2)	$2.37^{a,c}$ (1.8–3.1)

Values in a column followed by the same letter were significantly different ($P < 0.01$; ANOVA with Tukey's HSD).

[a] Fire behavior model from Anderson (1982).

[b] Fire behavior model from Scott and Burgan (2005).

The spatial distribution of fuel types for the landscape simulations of fire behavior in our study area were provided by the KNF. Fuel types with the greatest coverage in the study area were TU2 (36%) (moderate fuel load with shrubs, moderate spread rate, low flame length), TL9 (15%) (very high fuel load, moderate spread rate, moderate flame length), FM9 (14%) (moderate fuel load, moderate spread rate, moderate flame length), and TL7 (10%) (heavy fuel load including large logs, low spread rate, low flame length) (Anderson, 1982; Scott and Burgan, 2005).

3.3. Landscape-scale treatments

The effectiveness of different spatial patterns of fuel treatments on landscape fire behavior was determined by comparing fire behavior simulations for total area burned and proportion of the area burned by low (surface fire) and high-intensity (passive or active crown fire) fire. Simulations were conducted for three spatial arrangements (DFPZ, SPLATS, random) and four stand treatments (control, M, M + B, B). To test the relative importance of treatment area, each of the three non-control spatial arrangements was applied in three treatment amounts—10%, 20%, and 27% of the study area. The first spatial arrangement was DFPZs that were located based on designs by the KNF for a Stewardship and Fireshed Assessment workshop (Bahro et al., 2007). The primary goal of the DFPZs was to alter wildland fire behavior to protect the town of Tennant (Fig. 1) while providing safe ingress and egress for fire fighters. Other factors considered were likely ignitions from roads and along ridgetops. The percentage of the area treated was increased by enlarging individual DFPZs or by creating additional DFPZs. The second spatial arrangement is based on a mathematically determined arrangement of louvered, overlapping treatment areas (SPLATs) designed to simultaneously minimize area treated and maximize the reduction of fire spread and intensity across the landscape (i.e., Finney, 2001). We altered the area covered by SPLATs by increasing the width of each SPLAT from 133 m (10%) to 267 m (20%) or 360 m (27%). The location of SPLATs was fixed for all simulations. The random spatial arrangement consisted of randomly placed non-overlapping circular treatments. The radius of treatment units was fixed and chosen so that the size of the unit was similar to a realistic fuel treatment size (≈60 ha). Area treated was varied by randomly placing different numbers of circular treatments across the landscape. All treatments were designed without regard for the location of simulated ignitions (Fig. 2).

3.4. Fire weather and fuel moisture

The overriding goal of the fuel treatments was to increase the resistance of stands to severe effects of wildfire. The specific objective was to alter stand conditions so that projected fire severity would result in at least 80% of the dominant and co-dominant trees surviving a wildfire under the 80th percentile fire weather conditions. However, this standard was only a minimum requirement and stricter agency or local standards were intended to be integrated. While recognizing that this minimum standard would likely not appreciably reduce tree

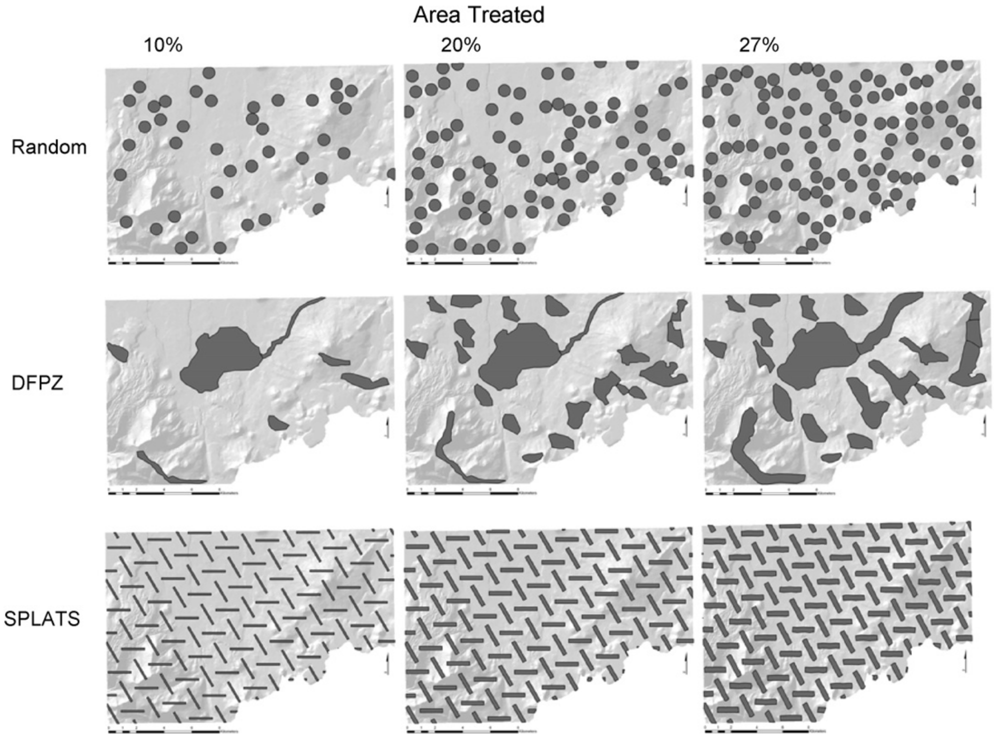

Fig. 2. Spatial pattern of treatments (random, DFPZ, SPLATs) and proportion of area treated (10%, 20%, and 27%) for the landscape fire simulations. See Fig. 1 for location of ignition points and town of Tennant.

Table 3
Upper 80th, 90th, and 97.5th percentile conditions for weather and fuel moisture used for fire behavior simulations

Weather	80th percentile	90th percentile	97.5 percentile
Low temperature (°C)	13.9	15.6	18.3
High temperature (°C)	28.9	30.6	33.6
Low relative humidity (%)	15	12	7
High relative humidity (%)	18	15	11
Wind speed (km h^{-1})	16.1	19.3	32.2
Fuel moisture			
1-h (%)	3.1	2.6	1.9
10-h (%)	3.8	3.0	2.0
100-h (%)	6.7	6.9	4.8
Live woody (%)	60	60	60
Foliar moisture content (%)	100	100	80

Data are from the Van Bremmer, California remote automated weather station May–October 1993–2004. Live woody fuel moisture was provided by personnel from the KNF.

mortality or significantly enhance fire suppression capabilities under more severe fire weather conditions, the FFS team believed it would support more widespread use of less aggressive fire suppression responses and wildland fire use under more common fire weather conditions (Weatherspoon and McIver, 2000).

For this FFS site, fire behavior was modeled under three sets of weather and fuel moisture conditions. We used the 80th, 90th, and 97.5th percentile fire weather conditions (conditions that are only exceeded 20%, 10%, and 2.5% of the fire season, respectively) obtained from the Van Bremmer Butte remote automated weather station (station ID #040243), located approximately 9 km northeast of the study site. Fire weather conditions and fuel moistures were calculated using FireFamily Plus software (Bradshaw and McCormick, 2000) (Table 3), except for wind speeds, which were adjusted from the mountain-top location based on local experience (Jacoby, personal communication, 2005). We used these weather data to develop simplified weather stream inputs for FARSITE. The individual weather parameters we report may not occur simultaneously and any attempt to simulate absolute, rather than relative, fire behavior would require more detailed local weather data.

3.5. Fire behavior simulations

Three modeling tools were used to estimate fire behavior in the treatment blocks and across the landscape. We used NEXUS (Scott, 1999) to calculate surface (flame length, rate of spread, heat release, flame length) and crown fire behavior (torching index, crowning index) in the treatment blocks (average values), except for scorch height which was calculated using BehavePlus. We used a wind reduction factor of 0.3 for the C and B treatments and 0.4 for the M and M + B treatments (Finney, 2004). For NEXUS available canopy fuel load (C and B = 26.9 mg/ha, M and M + B = 13.4 mg/ha) was calculated using the method described in Skinner (2005) and average stand structure data for each treatment**.** Slope was set to 15% and wind direction was set to upslope for all simulations. For the landscape analysis we used the landscape fire spread simulator FARSITE (Finney, 2004). A total of 84 scenarios representing the three fire weather conditions applied to each of the four fuel treatments in the three different spatial arrangements and at three levels of area treated were simulated. We first simulated burning through a landscape with no fuel treatments to represent the control. We then applied each of the three fuel treatments exclusively to each of the three arrangements and amounts of stand treatments across the landscape.

FARSITE simulations were run for 3 days under weather conditions specified in Table 3. The weather conditions were held constant during the 3 days. Wind direction (from the southwest) was also held constant for all simulations; only the wind speed varied (Table 3). Fuel moistures were preconditioned by FARSITE. Foliar moisture content was assumed to be 100% under both 80th and 90th percentile (Scott and Reinhardt, 2001; Finney, 2004) and 80% under 97.5th percentile (Agee et al., 2002) fire weather conditions.

This period length was chosen so that simulated fires burned enough area during a simulation to compare among treatments without burning beyond the study area boundaries. We constrained simulation of fire activity to the 18 h period between 06.00 and 24.00 h to minimize over-prediction of overnight fire spread. If we were primarily interested in absolute fire behavior we would have calibrated the burn period to reproduce known fire behavior. We did not calibrate fire behavior variables (i.e., rate of spread, flame length, area burned) for the FARSITE simulations with data from actual wildfires because our interest was only to compare relative fire behavior among treatments and spatial arrangements rather than predicting the actual behavior of individual fires.

We used four lightning strikes as ignitions for the fires because that is a typical ignition scenario in the KNF (Fig. 1). These were placed on the landscape randomly before the treatments were designed. Values for fire behavior were integrated for 30-min time steps and the perimeter and distance resolution were 60 and 30 m, respectively. FARSITE controls were enabled to estimate crown fire behavior and the probability of spot fire growth was set to 0.08% (Bahro, personal communication, 2005). Although this introduces some stochastic variation into the simulations, spotting is an important mechanism of fire spread in these dry mixed-conifer forests. Each simulation was replicated six times to estimate the variability in fire size (cf. Stratton, 2004). The

Table 4
Mean (range) post-treatment forest structure characteristics

Treatment	Basal area (m^2 ha^{-1}) Trees	Density (ha^{-1}) Trees	Basal area (m^2 ha^{-1}) Saplings	Density (ha^{-1}) Saplings	Diameter (cm) Trees
Control	44.5^{a} (41.1–48.9)	682^{a} (538–880)	$1.2^{a,b,c}$ (1.0–1.4)	$1348^{a,b,c}$ (1156–1546)	$30.6^{a,b}$ (27.9–34.0)
Mechanical	$27.7^{a,b}$ (22.7–32.7)	$177.3^{a,b}$ (166–185)	$0.0^{a,b}$ (0.0–0.0)	$8.0^{a,b}$ (2–16)	$47.3^{a,c}$ (43.9–53.2)
Burn	40.3^{b} (29.6–52.1)	586.7^{b} (500–730)	$0.1^{a,b,c}$ (0.1–0.2)	$106.7^{a,b,c}$ (90–136)	33.3^{c} (30.5–37.0)
Mechanical + burn	$18.8^{a,b}$ (13.9–26.2)	$118.3^{a,b}$ (91–168)	$0.0^{a,c}$ (0.0–0.0)	$3.3^{a,c}$ (0.0–6.0)	$49.8^{a,b,c}$ (43.9–53.2)

There were three replicates of each treatment and diameter is quadratic mean diameter. Trees are >10 cm dbh and saplings are <10 cm dbh. Values in a column followed by the same letter were significantly different ($P < 0.01$; ANOVA with Tukey's HSD).

simulation was then repeated until output from a single run was approximately equal to the mean of the initial six runs and could then be preserved for further analysis and display.

We used area burned and potential crown fire activity as the key FARSITE outputs for determining treatment effectiveness. For area burned we compared the total area burned in each scenario to area burned in its corresponding control scenario. We used the categorical crown fire type output (surface fire, passive crown fire, or active crown fire) to gauge treatment effectiveness in reducing fire hazard. Finally, we compared area burned by each categorical fire type for each treatment scenario to area burned by fire type in the control simulations.

4. Results

4.1. Stand characteristics

Forest structure was different after the treatments were completed. Tree density and tree basal area were lower, and quadratic mean diameter was higher in the M and M + B treatments than in the control plots ($P < 0.01$; all P-values are from ANOVA with Tukey's HSD) (Table 4). Moreover, basal area and tree density were lower and quadratic mean diameter was larger in the M + B than in the M plots ($P < 0.01$). On the other hand, tree density, basal area, and quadratic mean diameter in B plots remained similar to the control ($P > 0.05$). Tree basal area and density were still higher $P < 0.01$) in B than M or M + B after treatment and tree size remained smaller in B too ($P < 0.01$). Sapling density and basal area were lower in all the treatments compared to the control ($P < 0.01$) and they were lower in M and M + B than in the B treatment ($P < 0.01$).

4.2. Surface and canopy fuels

The three treatments had different effects on surface fuels. The M + B and B units had lower quantities of 1- and 10-h fuels than the control or M units after treatment ($P < 0.01$) (Table 2). Moreover, 10-h fuels were lower in B than in M, M + B, or the control ($P < 0.01$). Large 100-h fuels and total fuel load were also lower in B than in M ($P < 0.01$) but not in M + B or the control ($P > 0.05$). Fuel depth in M was greater than in C or any of the other treatments ($P < 0.01$) and fuel depths in both B and M + B were lower than in C.

The treatments also affected canopy fuel characteristics. Mechanical treatments (M, M + B) increased stand height and canopy base height compared to B or C ($P < 0.01$) (Table 5). Similarly, canopy bulk density was significantly reduced by M and M + B compared to B or C ($P < 0.01$) and the pattern among treatments was similar for canopy cover, except that M was not lower than B ($P > 0.05$).

4.3. Potential fire behavior

4.3.1. Stand-scale

Fire behavior in all treatments, including the C treatment, was strongly influenced by fire weather and fuel moisture conditions (Table 6). As expected, fire intensity was more extreme for all treatments under more extreme fire weather conditions. For the C plots fire behavior was more extreme for FM10 than FM9. In fact, for FM10 passive or active crown fire was predicted under each weather condition, but conditional crown fire was predicted for FM9 only under 97.5th percentile conditions.

The B, M, and M + B treatments had different and consistent effects on potential fire behavior under 80th and 90th percentile weather conditions (Table 6). Rate of spread, heat release, flame length, scorch height, and percent of crown burned were much lower for the B treatment and M + B treatments than the M treatment. The effect of treatments on the torching index for 80th and 90th percentile conditions was similar. Torching index was highest for B and M + B and much lower for M. On the other hand, the crowning index wind speed was lower for the B and M

Table 5
Mean (range) post-treatment canopy fuel characteristics

Treatment	Canopy bulk density (kg m^{-3})	Canopy base height (m)	Stand height (m)	Crown cover (%)
Control	$0.133^{a,b,c}$ (0.105–0.172)	$2.3^{a,b,c}$ (2.1–2.4)	$15.4^{a,b,c}$ (14.5–16.1)	$56.0^{a,b,c}$ (52.7–61.2)
Mechanical	$0.043^{a,c}$ (0.041–0.045)	$8.8^{a,c}$ (5.8–13.4)	$22.6^{a,c}$ (20.1–26.1)	37.5^{a} (33.7–43.4)
Burn	$0.159^{b,c}$ (0.125–0.184)	$3.6^{b,c}$ (2.1–4.3)	$15.5^{b,c}$ (13.8–17.6)	$52.2^{b,c}$ (43.5–63.4)
Mechanical + burn	$0.030^{a,b,c}$ (0.023–0.44)	$10.0^{a,b,c}$ (9.1–11.0)	$21.2^{a,b,c}$ (19.8–22.3)	$28.7^{a,b,c}$ (23.9–37.5)

Values in a column followed by the same letter were significantly different ($P < 0.01$, ANOVA with Tukey's HSD).

Table 6
Mean simulated fire behavior under 80th, 90th, and 97.5th percentile weather conditions for each fuels treatment

	Control[a] FBM9[b]	Control[a] FBM10[b]	Mechanical[a] SB1[b]	Burn[a] TL1[b]	Mechanical + burn[a] FBM8[b]
80th percentile					
Fire type	Surface	Passive crown	Surface	Surface	Surface
Crown % burned	0	20	0	0	0
Rate of spread (m/min)	2.0	4.5	2.3	0.2	0.7
Heat release (kJ/m^2)	5098	27,194	7648	1411	2552
Flame length (m)	0.8	2.9	1.0	0.2	0.4
Scorch height (m)	3.7	11.6	4.3	0.0	0.6
Torching index (km/h)	37.4	12.7	132.0	884.2	604.2
Crowning index (km/h)	27.2	27.2	60.8	23.0	78.7
90th percentile					
Fire type	Surface	Passive crown	Surface	Surface	Surface
Crown % burned	0	42	0	0	0
Rate of spread (m/min)	7.7	8.2	8.5	0.9	2.7
Heat release (kJ/m^2)	5101	37,717	7754	1425	2562
Flame length (m)	0.9	5.6	1.2	0.2	0.4
Scorch height (m)	4.6	14.6	5.2	0.0	0.6
Torching index (km/h)	37.4	12.6	129.3	870.5	600.7
Crowning index (km/h)	27.2	27.2	60.7	23.0	78.5
97.5th percentile					
Fire type	Conditional crown	Active crown	Surface	Conditional crown	Surface
Crown % burned	100	100	0	100	0
Rate of spread (m/min)	31.5	31.5	6.0	31.5	2.0
Heat release (kJ/m^2)	53,980	66,822	8419	49,960	2757
Flame length (m)	24.8	28.6	1.7	23.5	0.6
Scorch height (m)	7.6	22.7	7.9	0.0	0.6
Torching index (km/h)	32.7	11.1	11.3	762.7	529.6
Crowning index (km/h)	25.7	25.7	57.7	21.7	74.7

Fire behavior variables were calculated using NEXUS, except for scorch height which was calculated using BehavePlus.

[a] Treatment.

[b] Fuel model.

treatments than for the M + B treatment. Both the torching and crowning indices are related to the wind speed threshold necessary to push the fire into the crowns (torching) and keep it there (crowning). Thus, a higher torching or crowning index represents lower fire hazard because it would take a higher wind speed to initiate the torching activity and maintain crowning (Scott and Reinhardt, 2001).

There was a different pattern of treatment effects on fire behavior characteristics under 97.5th percentile conditions, except for scorch height (Table 6). Fire type was surface fire for both M and M + B and conditional crown fire for the B treatment. Though surface fuels were low in the B treatment, the dense canopy left after the prescribed fire created conditions that would allow a crown fire entering the stand to continue through it as a crown fire. Therefore, rate of spread, percent crown burned, heat release, and flame length were lowest for the M + B treatment, highest for the B treatment, and intermediate for the M treatment. However, based on fires burning only within the stands, scorch height was highest for M and lowest for B, and intermediate for M + B (low torching or crowning index indicates greater susceptibility to crown fire). Similarly, the torching index was lowest for M, highest for B, and intermediate for M + B. In contrast the crowning index was lowest for B, highest for M + B, and intermediate for the M treatment.

4.3.2. *Landscape-scale*

4.3.2.1. Area burned. For all spatial arrangements and for all categories of area treated, the B treatment decreased area burned the most compared to the control, followed by M + B and then M (Tables 7a–7c). In fact, in four of the nine random spatial arrangements with an M treatment more area burned than in the equivalent control scenario (80% weather and 20% and 27% area treated; 90% weather and 20% area treated; 97.5% weather and 20% area treated). All three SPLATs arrangements with an M treatment and 10% area treated also burned more than the equivalent control scenario for each weather condition (Table 7b).

The spatial arrangements and treatment combinations that produced the most significant decreases in area burned (measured as percent of control area burned under the same weather condition) were as follows: the SPLATs arrangement treated by B under 80th percentile weather with 20% area treated, 90th percentile weather with 20% and 27% area treated, and 97.5th percentile weather with 27% area treated by M + B; and the DFPZ arrangement treated by B under 97.5th percentile weather with 27% area treated.

Increasing area treated did not always produce a decrease in area burned but it did for all of the SPLATs arrangements and all but two of the DFPZ arrangements (Tables 7b and 7c). For most types of treatments with a random spatial arrangement the

Table 7a
Mean (range) total area burned (ha) and area burned expressed as a percentage of control area burned for each treatment type when treatments were randomly distributed across the study landscape

Weather conditions (%)	Proportion treated (%)	Treatment			
		Control	Mechanical	Burn	Mechanical + burn
80	None	810 (796–829)			
	10		732 (715–767) (90%)	469 (451–504) (58%)	540 (529–570) (67%)
	20		875 (861–918) (108%)	711 (703–721) (88%)	756 (746–793) (93%)
	27		829 (818–840) (102%)	629 (623–646) (78%)	668 (661–681) (82%)
90	None	1135 (1113–1166)			
	10		732 (715–767) (90%)	692 (681–714) (61%)	540 (529–570) (67%)
	20		1273 (1256–1294) (112%)	1040 (1028–1051) (92%)	1111 (1085–1132) (98%)
	27		1125 (1109–1152) (99%)	855 (834–870) (75%)	911 (892–928) (80%)
97.5	None	3481 (3199–3940)			
	10		3328 (3107–3592) (96%)	2037 (1886–2182) (59%)	2597 (2477–2674) (75%)
	20		3715 (3480–3853) (107%)	2766 (2591–2973) (79%)	3118 (2960–3321) (90%)
	27		3272 (3076–3401) (94%)	2234 (2152–2345) (64%)	2492 (2407–2654) (72%)

Fire size was simulated using FARSITE (Finney, 2004).

10% area treated scenarios produced the smaller area burned, followed by 27% area treated and then 20% area treated (Table 7a). Moreover, increasing weather severity did not always produce an increase in area burned. In fact, the DFPZ spatial arrangement almost uniformly produced less burned area as the weather severity increased (Table 7c). This pattern was also evident for the 27% area treated for the random and SPLATs spatial arrangement of treatments (Tables 7a and 7b).

When comparing the three arrangements, the random arrangement performed best at 10% area treated but worst at higher percentages (Tables 7a–7c). The SPLATs arrangement was best with the B and M + B treatments at 20% and 27% area treated.

4.4. Fire intensity

The top performing combinations of spatial arrangement and fuel treatments for reducing area burned at high intensity (measured as percent of control area burned at high intensity under the same weather conditions) were all SPLATs, B treatment, and either 20% or 27% area treated (Tables 8a–8c). This was consistent across all weather conditions. There were also combinations that did not reduce percentage of area burned at high intensity. These combinations were all 10% area treated, with M treatments (except for one M + B), and most occurred under 80th or 90th percentile weather conditions. In most cases, for each type of treatment and spatial arrangement, area burned at high intensity decreased as treated area increased. The exception was for SPLATs with B treatment under 80th percentile weather scenario where more area burned at high intensity with 27% area treated than with 20% area treated (Tables 8a–8c).

Weather conditions influenced area burned at high intensity. For each spatial arrangement, type of treatment, and proportion of area treated, as fire weather became more extreme area burned at high intensity increased (Tables 8a–8c).

Table 7b
Mean (range) total area burned (ha) and area burned expressed as a percentage of control area burned for each treatment type when treatments were distributed as SPLATs across the study landscape

Weather conditions (%)	Proportion treated (%)	Treatment			
		Control	Mechanical	Burn	Mechanical + burn
80	None	810 (796–829)			
	10		831 (823–840) (103%)	565 (552–590) (70%)	660 (650–674) (81%)
	20		795 (789–812) (98%)	409 (408–410) (50%)	533 (525–562) (66%)
	27		780 (775–790) (96%)	424 (423–426) (52%)	494 (492–496) (61%)
90	None	1135 (1113–1166)			
	10		1186 (1170–1214) (104%)	798 (770–832) (70%)	945 (931–961) (83%)
	20		1125 (1110–1133) (99%)	564 (551–599) (50%)	760 (739–816) (67%)
	27		1039 (1031–1053) (92%)	478 (476–480) (42%)	634 (630–638) (56%)
97.5	None	3481 (3199–3940)			
	10		3634 (3331–3850) (104%)	2122 (1914–2424) (61%)	2768 (2572–3097) (80%)
	20		3387 (3129–3776) (97%)	1595 (1551–1682) (46%)	2031 (1883–2276) (58%)
	27		2886 (2691–3125) (83%)	1263 (1220–1334) (36%)	1660 (1578–1749) (48%)

Fire size was simulated using FARSITE (Finney, 2004).

Table 7c
Mean (range) total area burned (ha) and area burned expressed as a percentage of control area burned for each treatment type when treatments were distributed as DFPZs across the study landscape

Weather conditions (%)	Proportion treated (%)	Treatment			
		Control	Mechanical	Burn	Mechanical + burn
80	None	810 (796–829)			
	10		778 (765–800) (96%)	751 (744–770) (93%)	766 (751–773) (94%)
	20		801 (790–823) (99%)	690 (677–710) (85%)	705 (697–715) (87%)
	27		759 (757–763) (94%)	522 (519–529) (64%)	566 (563–573) (70%)
90	None	1135 (1113–1166)			
	10		1076 (1041–1104) (95%)	996 (984–1008) (88%)	1007 (998–1015) (89%)
	20		1065 (1052–1090) (94%)	893 (887–901) (79%)	921 (907–956) (81%)
	27		1013 (999–1028) (89%)	691 (683–704) (61%)	753 (746–764) (66%)
97.5	None	3481 (3199–3940)			
	10		2849 (2612–3137) (82%)	2364 (2242–2504) (68%)	2569 (2409–2815) (74%)
	20		2532 (2416–2834) (73%)	1973 (1810–2332) (57%)	2012 (1988–2055) (58%)
	27		2746 (2647–2866) (79%)	1553 (1526–1572) (45%)	1802 (1746–1905) (52%)

Fire size was simulated using FARSITE (Finney, 2004).

5. Discussion

Current fuel loads and forest structure in many dry forests in the western United States that once experienced frequent low-intensity fire require some kind of fuels treatment to reduce the increased risk of high-intensity fire (Agee and Skinner, 2005; Husari et al., 2006). Reducing this risk may best be achieved by identifying specific treatment objectives related to potential fire behavior, fire spread, and fire effects (Weatherspoon and Skinner, 1996; Agee et al., 2000; Agee and Skinner, 2005; Stephens and Ruth, 2005). Fuel treatments are unlikely to stop wildfires or eliminate all risk of damage to natural or human resources (Finney and Cohen, 2003; Martinson et al., 2003). However, the concept of fire-resilient forests, or forests that experience decreased fire severity when burned, leads to guidelines for fuel treatments that integrate potential fire behavior, ability of fire to spread across the landscape, and likely fire effects (Finney, 2001; Agee and Skinner, 2005; Stephens and Ruth, 2005). These guidelines specify for the stand-scale, in order from greatest to least effect on fire hazard, that (1) surface fuels be managed to limit surface fireline intensity, (2) ladder fuels be managed to limit the ability of the fire to climb into the overstory (i.e., increase canopy base height), (3) the continuity of canopy fuels be limited to reduce the probability of crown fire spread (i.e., decrease canopy bulk density), and (4) the larger, fire-tolerant trees be retained (Agee and Skinner, 2005). Additionally, sufficient area treated in strategically designed spatial pattern is required to interrupt the flow of high-intensity fire across the landscape when the entire landscape is not planned for treatment (Finney, 2001). The effects of fuel treatments on surface and canopy fuel structure and the spatial arrangements identified in this study indicate that mechanical thinning, and prescribed fire, or combinations of both, meet these guidelines but in different ways.

Since the primary goal of forest management in the Goosenest Adaptive Management Area is to accelerate late-successional conditions and there is a paucity of large trees, all

Table 8a
Mean area burned (ha) at high intensity and area burned at high intensity expressed as a percentage of the control area burned at high intensity for each treatment type when treatments were distributed randomly across the study landscape

Weather conditions (%)	Proportion treated (%)	Treatment			
		Control	Mechanical	Burn	Mechanical + burn
80	None	277			
	10		277 (100%)	255 (92%)	265 (96%)
	20		236 (85%)	211 (76%)	227 (82%)
	27		206 (74%)	179 (65%)	181 (65%)
90	None	411			
	10		418 (102%)	362 (88%)	371 (90%)
	20		362 (88%)	314 (76%)	342 (83%)
	27		295 (72%)	286 (70%)	293 (71%)
97.5	None	1366			
	10		1305 (95%)	1089 (80%)	1152 (84%)
	20		1230 (90%)	1059 (78%)	1106 (81%)
	27		934 (68%)	839 (61%)	802 (59%)

Fire size and intensity were simulated using FARSITE (Finney, 2004).

Table 8b
Mean area burned (ha) at high intensity and area burned at high intensity expressed as a percentage of the control area burned at high intensity for each treatment type when treatments were distributed as SPLATs across the study landscape

Weather conditions (%)	Proportion treated (%)	Treatment			
		Control	Mechanical	Burn	Mechanical + burn
80	None	277			
	10		261 (94%)	170 (61%)	213 (77%)
	20		228 (82%)	80 (29%)	145 (53%)
	27		196 (71%)	104 (37%)	120 (43%)
90	None	411			
	10		403 (98%)	296 (72%)	344 (84%)
	20		348 (85%)	143 (35%)	240 (58%)
	27		299 (73%)	128 (31%)	178 (43%)
97.5	None	1366			
	10		1361 (100%)	840 (62%)	1094 (80%)
	20		1133 (83%)	516 (38%)	790 (58%)
	27		812 (59%)	470 (34%)	536 (39%)

Fire size and intensity were simulated using FARSITE (Finney, 2004).

treatments, including the control plots, were designed to retain the larger, fire-tolerant trees (Ritchie, 2005).

5.1. Stand-scale

Prescribed burning was the most effective treatment for reducing surface fuels. Fuel depth, 1, 10, and 100-h fuels and total fuel load were reduced, on average, by 60–80% in the B plots compared to controls. The magnitude of the prescribed fire effect on surface fuels in M + B plots was similar for fuel depth and 1-h fuels but less for 10-h and total fuels. In contrast, 100-h fuels were higher in the M + B plots than in controls. This suggests that prescribed burning did not consume all the 100-h fuels added by the mechanical treatment, even though we used whole tree removal to minimize inputs of surface fuels associated with mechanical treatment. Surface fuels after prescribed burning of stands treated with mechanical methods that do not use whole tree removal would likely be higher still. On the other hand, mechanical treatment only (M) achieved 10–15% reduction in 1 and 10-h fuels. It may be that much of this smaller material was ground into the loose, pumice soils by the harvesting machines. However, 100-h fuels, total fuels, and fuel depth were higher after the M treatment compared to controls. Total surface fuels often increase after mechanical treatment but post-treatment burning usually reduces this effect (Agee and Skinner, 2005; Stephens and Moghaddas, 2005).

Mechanical thinning mainly affected ladder and canopy fuels. Mechanical thinning reduced canopy bulk density by 66%, and crown cover by 34% from the control values and both were reduced further when mechanical treatment was followed by prescribed burning. Mechanical treatment was also very effective at increasing canopy base height and stand height. Similar reductions in canopy fuels by mechanical thinning have been identified in fire-prone conifer forests in Oregon (McIver et al., 2003; Raymond and Peterson, 2005), Arizona (Fulé et al., 2001) and California (Stephens and Moghaddas, 2005). Burning alone, in contrast, had little immediate effect on canopy fuel characteristics. This is due to the treatment killing

Table 8c
Mean area burned (ha) at high intensity and area burned at high intensity expressed as a percentage of the control area burned at high intensity for each treatment type when treatments were distributed as DFPZs across the study landscape

Weather conditions (%)	Proportion treated (%)	Treatment			
		Control	Mechanical	Burn	Mechanical + burn
80	None	277			
	10		270 (98%)	271 (98%)	276 (100%)
	20		238 (86%)	229 (83%)	237 (86%)
	27		222 (80%)	200 (72%)	211 (76%)
90	None	411			
	10		416 (101%)	401 (98%)	397 (97%)
	20		350 (85%)	336 (82%)	328 (80%)
	27		328 (80%)	304 (74%)	319 (78%)
97.5	None	1366			
	10		1357 (99%)	1129 (83%)	1227 (90%)
	20		1076 (79%)	944 (69%)	906 (66%)
	27		1013 (74%)	821 (60%)	849 (62%)

Fire size and intensity were simulated using FARSITE (Finney, 2004).

only the smallest trees in the stand. As fire-damaged trees die over time, canopy bulk density and canopy cover may decrease and canopy base height and stand height increase (Kiefer et al., 2006). However, the accumulation of these dead trees on the forest floor is likely to increase the intensity of surface fires such that they would be able to reach the canopy anyway (Skinner, 2005).

The fuel treatments influenced potential stand-level fire behavior. Though prescribed burning was the most effective treatment in terms of reducing rate of spread, heat release, flame length, scorch height, and percent of crown burned under more moderate weather conditions (80th and 90th), it was only marginally more effective than mechanical plus burning (M + B). That the mechanical-only treatment would increase surface fire behavior is not unexpected, as it did not include a surface fuel treatment component and a decrease in canopy cover would increase wind exposure. In contrast, under extreme weather conditions (97.5th), treatment by prescribed burning was least effective at influencing fire behavior and conditional crown fire was predicted for B stands because of minimal effect on canopy fuels, whereas surface fires were expected in the other treatments. Under extreme conditions surface fire behavior was reduced most by M + B followed by M treatment. The modeling results under extreme conditions are consistent with recent observational studies of treated stands burned by wildfires. Crown scorch, bole char, and tree mortality were lower in stands that were thinned and burned than those that were thinned alone (Raymond and Peterson, 2005; Ritchie et al., 2007).

All three non-control treatments were effective in altering indices of crown fire behavior. While control stands could be expected to torch with wind speeds of 13–37 km h^{-1}, torching within post-treatment stands was highly unlikely (wind speeds >120 km h^{-1}). Mechanical thinning also raised the crowning index compared to the burn-only treatment ($\leq$23 km h^{-1}), which had little effect. The crowning index exceeded 70 and 55 km h^{-1} under all weather conditions in the M + B and M treatments, respectively. Torching indices are high in treatments that include prescribed fire (e.g., Stephens and Moghaddas, 2005) because burning reduces the surface fuels that contribute to the likelihood of torching.

5.2. Landscape-scale

Fuel treatments are intended to modify fire spread through a forest and the spatial arrangement and proportion of a landscape treated are important treatment characteristics that contribute to reduction of area burned (Weatherspoon and Skinner, 1996; Agee et al., 2000). Dispersed, strategically arranged treatments are most effective at reducing fire spread and area burned (Finney, 2001). However, the implementation of a strict mathematical pattern is not likely to be practical because of terrain, administrative land boundaries, threatened and endangered species habitat, or other regulations that affect the placement of treatments.

As weather conditions became more extreme (i.e., 90–97.5% conditions) total area burned in untreated control stands quadrupled while the area burned at high intensity increased nearly fivefold. Treatments that included prescribed burning were most effective at reducing burned area and the effect became more pronounced as weather conditions became more extreme. There was little effect of the M treatment on total area burned except under extreme (97.5th) weather conditions. Under these conditions the maximum reduction of area burned for any simulation was only 27% with the M treatment but it was 64% with the M + B or B treatments.

Simulated area burned in our landscape was influenced by treatment area. Burned area declined as treatment area increased regardless of treatment type and the effect was greatest under extreme (97.5th) weather conditions. Large fires that burn under extreme conditions are often oriented along a particular axis that depends on wind direction and slope (Finney, 2001). Thus, a dispersed louvered treatment theoretically has greater potential than a DFPZ to slow fire spread across a landscape at least under extreme weather conditions when fires are able to encounter multiple treatment units. A more important goal of fuel treatments than reducing area burned is reducing the area burned at high intensity and this is the main focus of fire policy, at least on federal land (NWCG, 2001). Both the random and SPLATS strategies in our simulations were more effective at reducing area burned at high fire intensity than total area burned (Tables 7a–7c and 8a–8c). This was not the case with the DFPZ strategy probably because larger areas were left untreated between treated areas than in the other two strategies (Fig. 2). The B and M + B treatments reduced area burned at high intensity more than the M treatment and the effects were most pronounced under extreme weather conditions. The maximum reduction of area burned at high intensity was 41% with the M treatment and 71% with the M + B or B treatment. Thus, landscape fuel treatments may provide an additional benefit by supporting the increased use of wildland fire to reduce fire hazard (Stephens and Ruth, 2005).

Treatment longevity is an important management consideration in planning and implementing fuel treatments. Accumulation of post-treatment surface and canopy fuels depend on both treatment type and stand-level factors such as forest type and site productivity. Prescribed burning is often immediately effective at reducing surface fuels and it can increase canopy base height by scorching the lower crown of trees (van Wagtendonk, 1996). Prescribed burns, however, are generally less effective at reducing crown bulk density and the reduction of the smaller surface fuels is relatively short-lived. Burns kill understory trees that can return fuel biomass to levels equal to or above pre-burn levels within a few years when they fall (Skinner, 2005). In mixed-conifer forests treated with prescribed fire in Yosemite National Park total surface fuels returned to 85% of pre-burn levels within 10 years (Keifer et al., 2006). Thus, there is likely to be a large difference in the duration of the different fuel treatments. The M + B treatment will likely last much longer than B treatment. The canopy density has been reduced and the smaller trees have been removed in the mechanical thinning operations so they are not available to be killed and become additional surface fuel following the prescribed burn. In stands where only prescribed fire was used, little was done to canopy density and the smaller trees killed by the fire will fall to the ground within a few years and replace the surface fuels consumed in the prescribed burn. Even though the treatment using only mechanical thinning was the least effective to begin with, its effects will likely last longer than the B treatment since the removal of the small trees and reduction of the canopy density will last until the space is again occupied by re-growth of woody vegetation (Skinner et al., 2004; Ritchie et al., 2007).

In regard to landscape arrangement and the Ranger District's goal of protecting the community of Tennant, it appears that the simulated DFPZ strategy would protect the community better than the simulated SPLATs strategy. This is due to the large area of treatment surrounding the community in the DFPZ strategy. In comparing the different treatments within the SPLATs strategy, both of the treatments using prescribed fire would appear to be more effective. This is because the M treatment allows the fire to burn through the treated areas more readily than the other two, although with much less intensity than in the controls. This is largely due to the smaller individual treatment units that were used in the SPLATs strategy adjacent to Tennant than in the DFPZ strategies. It is likely that a combination of the two types of strategies would provide better protection to the community and the forested landscape as a whole.

Overall, the M + B treatment appears to be the most effective at reducing fire behavior both immediately and in the long-run because it combines the best effects of the B (i.e., immediate reduction in surface fire behavior) and M treatment (i.e., reduction in crown fire initiation and potential spread), at least at the stand scale. At the landscape scale, the treatment scenarios appear to be effective in reducing both area burned and area burned at high intensity, even with extreme weather. Treatment type is important at the landscape scale as well as at the stand scale; treatments involving burning were most effective at reducing both area burned and area burned at high intensity. Treatment amount is critical, as is arranging treatments strategically.

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References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211, 83–96.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., Weatherspoon, C.P., 2000. The use of shaded fuelbreaks in landscape fire management. For. Ecol. Manage. 127, 55–66.

Agee, J.K., Wright, C.S., Williamson, N., Huff, M.H., 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. For. Ecol. Manage. 167, 57–66.

Anderson, H.E., 1982. Aids to determining fuel models. USDA Forest Service, Intermountain Research Station, General Technical Report INT-122.

Arno, S.F., Allison-Bunnell, S., 2002. Flames in our Forest: Disaster or Renewal. Island Press, Washington, DC.

Bahro, B., Barber, K.H., Sherlock, J.W., Yasuda, D.A., 2007. Stewardship and fireshed assessment: a process for designing a landscape fuel treatment strategy. In: Powers, R. F. (Ed.), Restoring fire-adapted ecosystems: Proceedings of the 2005 National Silviculture Workshop. USDA Forest Service Pacific Southwest Research Station, General Technical Report PSW-GTR-203, pp. 41–54.

Biswell, H.H., 1989. Prescribed Burning in California Wildlands Vegetation Management. University of California Press, Berkeley, California, USA.

Bradshaw, L., McCormick, E., 2000. FireFamily Plus user's guide, Version 2.0. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-67WWW.

Brown, J.K., 1974. Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Research Station, General Technical Report INT-16.

Burgan, R.E., Rothermel, R.C., 1984. BEHAVE: fire behavior prediction and fuel modeling system FUEL subsystem. USDA Forest Service, Intermountain Research Station, General Technical Report INT-167.

Covington, W.W., Moore, M.M., 1994. Southwestern ponderosa pine forest structure: changes since Euro–American settlement. J. For. 92, 39–47.

Dodge, M., 1972. Forest fuel accumulation—a growing problem. Science 177, 139–142.

Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci. 47, 219–228.

Finney, M.A., 2004. FARSITE: fire area simulator-model development and evaluation (Revised 2004). USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-4.

Finney, M.A., Cohen, J.D., 2003. Expectation and evaluation of fuel management objectives. In: Omi, P.N., Joyce, L.A. (Eds.) Fire, Fuel Treatments, and Ecological Restoration. Proceedings RMRS-P-29. USDA Forest Service, Rocky Mountain Research Station, pp. 353–366.

Finney, M.A., McHugh, C.W., Grenfell, I.C., 2005. Stand and landscape-level effects of prescribed burning in two Arizona wildfires. Can. J. For. Res. 35, 1714–1722.

Fulé, P.Z., Crouse, J.E., Cocke, A.E., Moore, M.M., Covington, W.W., 2004. Changes in canopy fuels and potential fire behavior 1880–2040: Grand Canyon, Arizona. Ecol. Model. 175, 231–248.

Fulé, P.Z., Waltz, A.E.M., Covington, W.W., Heinlein, T.A., 2001. Measuring forest restoration effectiveness in reducing hazardous fuels. J. For. 99, 24–29.

Graham, R.T., Harvey, A.E., Jain, T.B, Tonn, J.R., 1999. The effects of thinning and similar stand treatments on fire behavior in Western forests. USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-463.

Graham, R.T., McCaffrey, T.S., Jain, T.B., 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-120.

Green, L.R., 1977. Fuelbreaks and Other Fuel Modification for Wildland Fire Control. Agriculture Handbook 499. USDA Department of Agriculture, Washington, DC.

Hardy, C., 2005. Wildfire hazard and risk: problems, definitions, and context. For. Ecol. Manage. 211, 73–82.

Healthy Forests Restoration Act of 2003. P.L. 108–148. http://www.healthyforests.gov/initiative/legislation.html (last accessed 15 July 2005).

Hickman, J.C. (Ed.), 1993. The Jepson Manual: Higher Plants of California. University of California Press, Berkeley, CA.

Husari, S., Nichols, H.T., Sugihara, N.G., van Wagtendonk, J.W., Schaffer, K.E., Fites-Kaufman, J., Stephens, S.L., 2006. Fire and fuel management. In: Sugihara, N.S., van Wagtendonk, J.W., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, pp. 444–465.

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

Loehle, C., 2004. Applying landscape principles to fire hazard reduction. For. Ecol. Manage. 198, 261–267.

Martin, R.E., Kauffman, J.B., Landsberg, J.D., 1989. Use of prescribed fire to reduce wildfire potential. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-109.

Martinson, E.J., Omi, P.N., 2003. Performance of fuel treatments subjected to wildfires. In: Omi, P.N., Joyce, L.A. (Eds.), Fire, Fuel Treatments, and Ecological Restoration. Proceedings RMRS-P-29. USDA Forest Service, Rocky Mountain Research Station, pp. 7–13.

Martinson, E.J., Omi, P.N., Shepperd, W., 2003. Effects of fuel treatments on fire severity. In: Graham, R.T. (Ed.), Hayman Fire Case Study. General Technical Report RMRS-GTR-114. USDA Forest Service, Rocky Mountain Research Station, pp. 96–126.

McIver, J.D., Adams, P.W., Doyal, J.A., Drews, E.S., Hartsough, B.R., Kellogg, L.D., Niwa, C.G., Ottmar, R., Peck, R., Taratoot, M., Torgersen, T., Youngblood, A., 2003. Environmental effects and economics of mechanized logging for fuel reduction in northeastern Oregon mixed-conifer stands West. J. Appl. For. 18, 238–249.

Miles, S.R., Goudey, C.B., 1998. Ecological subregions of California, section and subsection descriptions. http://www.fs.fed.us/r5/projects/ecoregions/ (last accessed 15 July 2005).

Nagel, T.A., Taylor, A.H., 2005. Fire and persistence of montane chaparral in mixed conifer forest landscapes in the northern Sierra Nevada, Lake Tahoe Basin, California. J. Torrey Bot. Soc. 132, 442–457.

National Fire Plan, 2001. U.S. Department of Agriculture. http://www.fireplan.gov/ (last accessed 15 July 2005).

NWCG [National Wildfire Coordinating Group], 2001. Review and Update of the 1995 Federal Wildland Fire Management Policy. National Interagency Fire Center, Boise, Idaho, USA.

Olson, R., 1977. Appraising a forest fuel treatment: the DFPZ concept, Lassen National Forest. Unpublished report on file Lassen National Forest Supervisors Office, Susanville, California.

Omi, P.N., 1996. The role of fuelbreaks. In: Proceedings of the 17th Forest Vegetation Management Conference, Churn Creek Vegetation Management Inc., Redding, CA, pp. 89–96.

Omi, P.N., Martinson, E.J., 2002. Effect of fuel treatment on wildfire severity. http://www.cnr.colostate.edu/frws/research/westfire/FinalReport.pdf (last accessed 16 April 2005).

Quincy Library Group, 1994. Fuels management for fire protection. http://www.qlg.org/pub/agree/penney.htm (last accessed 13 April 2004).

Raymond, C.L., Peterson, D.L., 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Can. J. For. Res. 12, 2981–2995.

Reinhardt, E.D., Crookston, N.L. (Eds.), 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. General Technical Report RMRS-GTR-116. USDA Forest Service, Rocky Mountain Research Station.

Ritchie, M.W., 2005. Ecological Research at the Goosenest Adaptive Management Area in Northeastern California. General Technical Report PSW-192. USDA Forest Service, Pacific Southwest Research Station.

Ritchie, M.W., Harcksen, K.A., 2005. Accelerating development of late-successional features in second-growth pine stands of the Goosenest Adaptive Management Area. In: Ritchie, M.W., Maguire, D.A., Youngblood, A. (Eds.). Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management. General Technical Report PSW-GTR-198. USDA Forest Service, Pacific Southwest Research Station, pp. 81–93.

Ritchie, M.W., Skinner, C.N., Hamilton, T.A., 2007. Probability of wildfire-induced tree mortality in an interior pine forest: effects of thinning and prescribed fire. For. Ecol. Manage. 247, 200–208.

Rothermel, R.C., 1983. How to predict the spread and intensity of wildfires. General Technical Report INT-143. USDA Forest Service, Intermountain Research Station.

Rothermel, R.C., Rinehart, G.C., 1983. Field procedures for verification and adjustment of fire behavior predictions. General Technical Report INT-142. USDA Forest Service, Intermountain Research Station.

Rundel, P., Parsons, D., Gordon, D., 1977. Montane and subalpine vegetation of the Sierra Nevada and Cascade ranges. In: Barbour, M.G., Major, J. (Eds.), Terrestrial Vegetation of California. John Wiley and Sons, New York, pp. 559–599.

Salazar, L.A., González-Cabán, A., 1987. Spatial relationships of a wildfire, fuelbreaks, and recently burned areas. West. J. Appl. For. 2, 55–58.

Scott, J.H., 1999. NEXUS: a system for assessing crown fire hazard. Fire Manage. Notes 59, 20–24.

Scott, J.H., Burgan, R.E., 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-153. USDA Forest Service, Rocky Mountain Research Station.

Scott, J.H., Reinhardt, E.D., 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Research Paper RMRS-29. USDA Forest Service, Rocky Mountain Research Station.

Scott, J.H., Reinhardt, E.D., 2002. Estimating canopy fuels in conifer forests. Fire Manage. Today 62, 45–50.

Sessions, J., Johnson, K.N., Sapsis, D.B, Bahro, B., Gabriel, J.T., 1996. Methodology for simulating forest growth, fire effects, timber harvest, and watershed disturbance under different management regimes. Sierra Nevada Ecosystem Project, Final report to Congress, vol. II. Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. Center for Water, Wildland Resources, University of California Davis, CA, pp. 115–174.

Skinner, C.N., 2005. Reintroducing fire into the Blacks Mountain Research Natural Area: effects on fire hazard. In: Ritchie, M.W., Maguire, D.A., Youngblood, A. (Eds.), Proceedings of the Symposium on Ponderosa Pine: Issues, Trends, and Management, 2004. General Technical Report PSW-GTR-198. USDA Forest Service, Pacific Southwest Research Station, pp. 245–57.

Skinner, C.N., Chang, C., 1996. Fire regimes, past and present. Sierra Nevada Ecosystem Project, Final report to Congress, vol. II. Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37, Center for Water, Wildland Resources, University of California Davis, CA, pp. 1041–1069.

Skinner, C.N., Boerner, R., Fettig, C., Otrosina, W., Zack, S., 2001. Study plan for the Southern Cascades site of the National Study of the Consequences of Fire and Fire Surrogate Treatments. http://www.fs.fed.us/ffs/docs/studyplans2001/scascades-study-plan2001.pdf (last accessed 24 April 2004).

Skinner, C.N., Ritchie, M.W., Hamilton, T., Symons, J., 2004. Effects of prescribed fire and thinning on wildfire severity: the Cone Fire, Blacks Mountain Experimental Forest. In: Proceedings of the 25th Annual Forest Vegetation Management Conference, Redding, CA, 20–24 January, pp. 80–91.

Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. For. Ecol. Manage. 10, 21–35.

Stephens, S.L., Moghaddas, J.J., 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a mixed conifer forest. For. Ecol. Manage. 215, 21–36.

Stephens, S.L., Ruth, L.W., 2005. Federal forest fire policy in the United States. Ecol. Appl. 15, 532–542.

Stephens, S.L., Sugihara, N.G., 2006. Fire management and policy since European settlement. In: Sugihara, N.G., van Wagtendonk, J., Shaffer, K.E., Fites-Kaufman, J., Thode, A.E. (Eds.), Fire in California's Ecosystems. University of California Press, Berkeley, pp. 431–443.

Stratton, R.D., 2004. Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. J. For. 102, 32–40.

Strom, B.A., Fulé, P.Z., 2007. Pre-wildfire fuel treatments affect long-term ponderosa pine forest dynamics. Int. J. Wildland Fire 16, 128–138.

U.S. General Accounting Office, 1999. Western national forests—a cohesive strategy is needed to address catastrophic wildfire threats. U.S. General Accounting Office GAO/RCED-99-65, Washington, D.C.

USDA-USDI, 1994. Record of decision for amendments to Forest Service and Nureau of Land Management planning documents within the range of the northern spotted owl: standards and guidelines for management of late successional and old-growth forest related species with the range of the northern spotted owl. USDA Forest Service and USDI Bureau of Land Management, Portland, OR.

van Wagtendonk, J.W., 1995. Large fires in wilderness areas. In: Brown, J.K., Mutch, R.W., Spoon, C.W., Wakimoto, R.H. (Eds.) (Technical Coordinators), Proceedings of the Symposium on Fire in Wilderness and Park Management. General Technical Rpt. INT-GTR-320. USDA Forest Service Intermountain Research Station, pp. 113–116.

van Wagtendonk, J.W., 1996. Use of a deterministic fire growth model to test fuel treatments. Sierra Nevada Ecosystem Project, Final report to Congress, vol. II. Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37, Center for Water, Wildland Resources, University of California, Davis, CA, pp. 1155–1165.

van Wagtendonk, J.W., Benedict, J.M., Sydoriak, W.M., 1998. Fuel bed characteristics of Sierra Nevada conifers. West. J. Appl. For. 13, 73–84.

Weatherspoon, C.P., 1996. Fire-silviculture relationships in Sierra forests. Sierra Nevada Ecosystem Project, Final report to Congress, vol. II. Assessments and Scientific Basis for Management Options. Wildland Resources Center Report No. 37. Center for Water, Wildland Resources, University of California, Davis, CA, pp. 1471–1492.

Weatherspoon, C.P., McIver, J., 2000. A national study of the consequences of fire and fire surrogate treatments-amended March 2000. http://www.fs.fed.us/ffs/docs/FFSfinalProposal–17april2000.doc (last accessed 15 July 2005).

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

Whittaker, R.H., 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecol. Monogr. 30, 279–338.