Available online at www.sciencedirect.com
SCIENCE DIRECT®
Biological Conservation 125 (2005) 369–379
BIOLOGICAL CONSERVATION
www.elsevier.com/locate/biocon

Silvicultural and reserve impacts on potential fire behavior and forest conservation: Twenty-five years of experience from Sierra Nevada mixed conifer forests

Scott L. Stephens *, Jason J. Moghaddas

Division of Ecosystem Science, Department of Environmental Science, Policy and Management, 137 Mulford Hall, University of California, Berkeley, CA 94720-3114, USA

Received 22 February 2005
Available online 23 May 2005

Abstract

Most administrators and ecologists agree that reducing the levels of hazardous fuels on forests is essential to restore healthy watersheds and protect adjacent human communities. The current debate over the appropriateness, technique, and timing of treatments utilized to restore vegetation structure and composition is currently on-going at local, state, and national levels. To provide information for these forums, the efficacy of seven traditional silvicultural systems and two types of reserves used in the Sierra Nevada mixed conifer forests is evaluated in terms of vegetation structure, fuel bed characteristics, modeled fire behavior, and potential wildfire related mortality. The systems include old-growth reserve, young-growth reserve, thinning from below, individual tree selection, overstory removal, and four types of plantations. These are the most commonly used silvicultural systems and reserves on federal, state, and private lands in the western United States. Each silvicultural system or reserve had three replicates and varied in size from 15 to 25 ha; a systematic design of plots was used to collect tree and fuel information. The majority of the traditional silvicultural systems examined in this work (all plantation treatments, overstory removal, individual tree selection) did not effectively reduce potential fire behavior and effects, especially wildfire induced tree mortality at high and extreme fire weather conditions. Overall, thinning from below, and old-growth and young-growth reserves were more effective at reducing predicted tree mortality.

Keywords: Wildfire; Fire hazard; Forest restoration; Crown fire

1. Introduction

Public concern over wildfire prevention has eclipsed other forest values (Williams and DellaSala, 2004) and this trend will probably continue for the next few decades. The impacts from wildfires can be separated into two categories, the direct impacts of the fires (including possible salvage harvests) and the impacts of the treatments used to "fix" the problem that will influence far more area than the wildfires themselves.

It is estimated that over 15 million hectares of forests in the western US have moderate or high fire hazards and many of these areas will be treated in the next several decades (NWCG, 2001). No other management activity is scheduled to influence more forest area in the US in the next 20 years, particularly in the western US where annual wildfire areas have increased in the last 60 years (Stephens, 2005). Much of the recent Healthy Forest Restoration Act (HFRA, 2003) is based on the assumption that there are alternatives to fire in affecting forest structure and health (Kauffman, 2004), but quantitative information on the consequences of fire and fire "surrogate" treatments is very limited and is the focus of this study.

* Corresponding author. Tel.: +510 642 7304; fax: +510 643 5438.
E-mail address: stephens@nature.berkeley.edu (S.L. Stephens).

0006-3207/$ - see front matter
doi:10.1016/j.biocon.2005.04.007

Conservation biologists have recognized the need to manage matrix lands along with reserves for the conservation of forest biodiversity (Lindenmayer and Franklin, 2002). The creation and maintenance of appropriate biological legacies is a critical element of any management strategy that attempts to conserve biodiversity (Franklin et al., 2002; Lindenmayer and McCarthy, 2002). Many traditional silviculture systems such as clear-cutting, seed tree, and shelterwood have little in common with most natural disturbance regimes except for creating a light environment suitable for shade intolerant tree species (Franklin et al., 2002).

Mixed conifer forests are widespread in California, occurring in mid-elevations of the Klamath, Cascade, North Coast, Sierra Nevada, Transverse, and Peninsular Mountains (Minnich et al., 1995). Sierra Nevada mixed conifer forests are diverse and are the primary habitat for more vertebrate species than any other Sierra Nevada forest type (North et al., 2002). Conservation of the ecosystems of the Sierra Nevada is critical and has been the subject one of the largest ecosystem assessments in the US (SNEP, 1996) and continues to be addressed in on-going US Forest Service land management planning for this region (USDA, 2004).

Alternative views toward restoring fire-excluded forest have been characterized as a debate between "process restorationists" – who argue that restoration of key ecological processes, especially fire, will eventually restore natural ecological conditions, and "structural restorationists" – who argue that forest structure and fuels must be restored before reintroduction of fire (Agee and Huff, 1986; Stephenson, 1999; Covington et al., 2001). One critical element of any restoration strategy is how proposed treatments affect fuel structure and potential wildfire behavior (Stephens, 1998), particularly in the western US forests that once experienced frequent, low-moderate intensity fire regimes. Though there have been qualitative and comparative studies on the effectiveness of various fuel treatments, replicated, empirical research on fuel reduction techniques are rare (van Wagtendonk, 1996; Stephens, 1998; Miller and Urban, 2000; Fulé et al., 2001; Keyes and O'Hara, 2002; Pollet and Omi, 2002; Brown et al., 2004; Graham et al., 2004; Stephens and Moghaddas, 2005).

The null hypothesis investigated is that there will be no difference in vegetation structure, fuel load, fire behavior, and predicted tree mortality between the seven silvicultural systems and two reserves when subjected to wildfire at different environmental conditions. Information from this study can be used to assist in the selection forest treatments that increase the probability of conserving the forests of the Sierra Nevada. There are other important conservation consequences of silvicultural systems and reserves but this study concentrates on one of their most critical structural aspects: their response to simulated wildfires.

2. Methods

2.1. Study site

This study was done in Sierra Nevada mixed conifer forests in the north-central Sierra Nevada at the University of California Blodgett Forest Research Station (Blodgett Forest). Blodgett Forest is approximately 20 km east of Georgetown, California (latitude 38°54′45″N, longitude 120°39′27″W), between 1100 and 1410 m above sea level, and encompasses an area of 1780 ha. Tree species in this area include sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Dough. Ex Laws.), white fir (*Abies concolor* Gord. & Glend.), incense-cedar (*Calocedrus decurrens* [Torr.] Floren.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), California black oak (*Quercus kelloggii* Newb.), tan oak (*Lithocarpus densiflorus* Hook. & Arn.), and madrone (*Arbutus menziezii* Pursh.).

Climate at Blodgett Forest is Mediterranean with a summer drought period that extends into the fall. Winter and spring receive the majority of precipitation that averages 160 cm (Stephens and Collins, 2004). Average temperatures in January range between 0 and 8 °C. Summer months are mild with average August temperatures between 10 and 29 °C with infrequent summer precipitation from thunderstorms. Slopes across Blodgett Forest average less than 30%.

Surface fire was common in the mixed conifer forests at Blodgett Forest before the policy of fire suppression began early in the 20th century. Composite fire return intervals at the 3–5 ha spatial scale varied from 6 to 14 years (fire interval range 4–28 years) (Stephens and Collins, 2004). Fires were very rare after 1910 and this agrees with other research that has documented the impacts of fire suppression in the northern Sierra Nevada. Blodgett Forest has been repeatedly harvested during the last 100 years, reflecting a management history common to most forests in the Sierra Nevada (Laudenslayer and Darr, 1990; Stephens, 2000) and elsewhere in the western US (Graham et al., 2004).

Fuel loads, potential fire behavior, and modeled forest mortality after wildfire were analyzed for seven traditional silvicultural systems and two types of reserves that received treatments from 1978 to 2002. Each silvicultural system or reserve had three replicates (27 total experimental units) and each varied in size from 15 to 25 ha. Criteria for selection of treatment units included: (a) areas were selected that only experienced a single entry from a given silvicultural system, including reserves, (b) pre and post-treatment fuel and vegetation data was available (collected 1–3 years before and after each treatment was installed), and (c) no secondary silvicultural treatments (i.e., prescribed burning, pile burning) were utilized before post-harvest measurement.

This study used data over a 25-year period because this amount of time was necessary to produce the relatively high number of treatments and replicates. Treatments were installed throughout the 25-year period (none of the treatments were installed in one short period) and descriptions of the management systems investigated are given below. The same Blodgett Forest manager and equipment operator were used throughout the 25-year period (1978–2002) and this improved operational consistency. All silvicultural treatments and reserves experienced fire suppression for the last 90 years.

2.2. Un-even aged silvicultural treatments: (dominant and co-dominant trees 80–100 years old)

(1) Individual tree selection. Lop and scatter limb wood and tree tops from the harvested trees to an average depth of less than 75 cm. The goal is to develop an uneven sized (possibly uneven aged) forest structure with multiple canopy layers.
(2) Thin from below. Lop and scatter limb wood and tree tops from the harvested trees to an average depth of less than 75 cm. The goal is to produce an open understory structure with many large overstory trees.
(3) Over story removal. Lop and scatter limb wood and tree tops from the harvested trees to an average depth of less than 75 cm. The goal is to produce stands dominate by small trees or to generate wood volume.

2.3. Even aged management treatments (dominant and co-dominant trees 1–20 years old)

All of these treatments were produced by clear-cutting followed by tractor piling and burning of harvest residues. After harvesting and burning of piled residues, 1-year-old seedlings were planted in a systematic grid pattern with a spacing of 3.5 m. Some logging residues and duff were left on the soil surface to reduce soil erosion. Four different plantation types were analyzed in this work:

(4) Plantations less than 5 years old.
(5) Plantations 15–19 years old that have been precommercially thinned once at 11–13 years of age using a chainsaw (approximately half of the trees removed, all thinned trees left on site, lop and scatter limbs to an average depth of less than 75 cm.). Manual spot-application of herbicides to individual shrubs was used to maintain shrub cover below 15%; this is a common practice in industrial lands designed to enhance the growth of the planted seedlings.
(6) Plantations 15–19 years old that have been precommercially thinned once at age 15 or 16 using a rotary masticator (a rotary masticator is a self-propelled machine that has a long hydraulically controlled arm with a spinning disc that is used to shred trees into pieces approximately 30 cm long and 5 cm wide. All shredded material was left on site). Manual spot-application of herbicides to individual shrubs was used to maintain shrub cover below 15%. Mastication is becoming one of the most common fuel treatments in federal and privately owned plantations.
(7) Plantations 15–19 years old that have received no additional treatments since they were established using similar methods as in 4, 5, and 6 above.

2.4. Reserves: (dominant and co-dominant trees 100–300+ years old)

(8) Old-growth reserves. Reserve stands with a significant component of residual old-growth trees. Dominant and co-dominant trees are 100–350 years old (Stephens and Collins, 2004).
(9) Young-growth reserves. These stands were harvested in the early 1900s. After the initial harvest and burning of residual woody materials, they have not been manipulated. Natural regeneration from the remaining seed trees regenerated these stands. Dominant and co-dominant trees are 80–100 years old.

2.5. Fuels and vegetation data

Vegetation and fuels data were extracted from the Blodgett Forest Research Station Interactive Database (Center for Forestry, 2004). Vegetation data was acquired from161 permanent 0.04 ha circular inventory plots installed across the 27 treatment units (three replicates of nine different treatments, minimum of five inventory plots for each treatment unit). Individual plots were placed on a systematic 120 m grid with a random starting point. Plot centers are permanently marked with a pipe; three witness trees next to plot center are also tagged to facilitate plot relocation after treatments.

Tree species, DBH, total height, height to live crown base, and crown position (dominant, co-dominant, intermediate, suppressed) was recorded for all trees greater than 10.5 cm DBH. Similar information was also recorded for all trees greater than 1.4 m tall in a 0.004 ha nested subplot located in each 0.04 ha circular inventory plot. Canopy cover was recorded at 25 points (5×5 grid) on each 0.04-ha plot using a GRS site-tube densitometer (Gill et al., 2000). Shrub cover was measured in all plantations using seven 10-m line transects initiated from plot center. Ocular estimates of shrub cover were taken on plot centers of all other treatment types.

Surface and ground fuel loads were measured using two transects from each permanent plot using the line-intercept method (Brown, 1974). One-hour (0–0.64 cm in diameter) and 10-h (0.64–2.54 cm in diameter) fuels were sampled from 0 to 2 m, 100-h (2.54–7.62 cm in diameter) fuels from 0 to 3 m, and 1000-h (>7.62 cm in diameter) and larger fuels from 0 to 11.3 m on each transect. Duff and litter depth (cm) was measured at 0.3 and 0.9 m on each transect. Fuel height (cm) was measured at 0.3, 0.6, and 0.9 m along each transect.

Surface and ground fuel loads were calculated using appropriate equations developed for Sierra Nevada forests (van Wagtendonk et al., 1996; van Wagtendonk et al., 1998). Coefficients required to calculate all surface and ground fuel loads were arithmetically weighted by the basal area fraction (percent of total plot basal area by species) to produce accurate and precise estimates of fuel loads (Stephens, 2001).

2.6. Fire modeling

Fire behavior was modeled under three fire weather conditions: upper 80th, 90th, and 97.5th percentile. Percentile weather was computed using Fire Family Plus (Main et al., 1990). Forty-one years (1961–2002) of weather data from the Bald Mountain Remote Access Weather Station (RAWS) (NFAM, 2004), located 4 km west of Blodgett Forest, were analyzed to determine percentile fire weather conditions (Table 1). 80th, 90th, and 97.5th percentile fire weather represent moderate, high, and extreme fire weather, respectively.

Fuels Management Analyst (FMA) was used to model fire behavior, crowning index (wind speed needed to produce an active crown fire), torching index (wind speed needed to produce a passive crown fire), scorch height, and tree mortality (Carlton, 2004). FMA incorporates established published methodologies for computing crown bulk density, fire behavior, crown scorch, and mortality. FMA uses information from field measurements (tree species, DBH, tree crown ratio, tree crown position, tree height, percent canopy cover, surface and ground fuel loads), topography, and fire weather data to model fire behavior and effects at the stand scale. Table 2 summarizes the methodologies used for these computations.

2.7. Data analysis

Analysis of variance (ANOVA) was used to determine if significant differences ($p < 0.05$) existed in vegetation (trees ha^{-1}, basal area ha^{-1}, height to live crown base, canopy cover, crown bulk density) and fuels (fuel depth, litter and duff load, 1, 10, 100, 1000-h sound and rotten time-lag fuel loads, total fuel load) for each silvicultural system and reserve ($n = 3$). If significant differences were detected, a Tukey-Kramer HSD test was performed to determine which specific silvicultural system or reserve was different from another (Zar, 1999). The Jump Statistical Software package (Sall et al., 2001) was used in all analyses.

3. Results

3.1. Vegetation structure

The inventory plots in the 27 treatment units included 3534 live trees. Forty-two line transects were used to measure shrub cover in the plantations. Ocular estimates of shrub cover in all non-plantation treatments, including reserves, were all below 5%.

Average basal area ha^{-1} was significantly higher in thin from below, old-growth reserve, young-growth reserve, and individual tree selection treatments when compared to all plantation treatments (Table 3). Average basal area in the overstory removal treatment was similar to un-thinned, masticated, and pre-commercially thinned plantations. Average tree density (trees ha^{-1}) was not significantly different between all treatments (Table 3).

Average height to live crown base was significantly higher in thin from below, old-growth reserve, and

Table 1
Upper 80th, 90th, and 97.5th percentile fire weather from 1961 to 2002 for Blodgett Forest, California

Weather parameter	80th percentile conditions	90th percentile conditions	97.5th percentile conditions
Probable maximum 1-min wind speed (km h^{-1})	20	27	31
Wind direction	North to northeast	North to northeast	North to northeast
Dry bulb temperature (C)	29	32	33
Relative humidity (%)	25	17	15
1-h fuel moisture (%)	3.9	3	1.8
10-h fuel moisture (%)	5.2	3.7	2.3
100-h fuel moisture (%)	7.7	6.6	4.2
Herbaceous fuel moisture (%)	62.1	30	30
Foliar fuel moisture (%)	100	80	75

young-growth reserve when compared with all plantation treatments (Table 3). Average tree height was significantly higher in all non-plantation treatments with the exception of overstory removal.

Percent canopy cover was significantly higher in old-growth reserve, young-growth reserve, and overstory removal treatments when compared with plantations (Table 3). Average canopy cover in thin from below treatments was similar to chainsaw pre-commercially thinned, mastication pre-commercially thinned, and untreated plantations. Average canopy cover in individual tree selection treatments was similar to that of the untreated plantations (Table 3). Crown bulk density was similar across all treatments with the exception of the plantations less than 5 years old, which was significantly lower than old-growth reserves, young-growth reserves, overstory removal, and masticated plantations (Table 3).

3.2. Fuels characteristics

A total of 436 fuel transects were analyzed over all silvicultural systems and reserves to estimate surface and ground fuel loads in the 27 experimental units. Fuel loads across all time-lag fuel size classes (1, 10, 100, 1000 h) and fuel depth were not significantly different among treatments or reserves (Table 4). Average litter and duff load (ground fuels) were significantly lower in all plantation treatments when compared with the young-growth reserve (Table 4). Litter and duff loads were significantly lower in masticated plantations when compared with the old-growth reserves (Table 4). Shrub cover was less than 5% in all non-plantation units resulting in a minimal contribution to fire behavior when compared with surface, ladder, and crown fuels.

3.3. Potential fire behavior and tree mortality

Under 80th percentile conditions, fire behavior and tree mortality was relatively low for all treatments. Fireline intensity was similar in all treatments at 90th percentile weather conditions (Table 5). When modeled under 97.5th percentile weather conditions, fireline intensity was similar in all treatments with the exception of the un-thinned plantations that were higher (Table 6).

Under 90th and 97.5th percentile conditions, torching index was similar in the thin from below and old-growth reserve treatments (Tables 5,6). The young-growth reserve had the highest torching index; torching index in overstory removal and single tree selection treatments were similar to that of plantations (Tables 5,6).

Under 90th percentile weather conditions, predicted mortality for trees 2.5–25 cm DBH was similar in all treatments except the young-growth reserve. For trees 51–76 cm DBH, all non-plantation treatments had similar predicted mortality. For trees >76 cm DBH,

Table 2
Methodologies used by Fuels Management Analysis to compute stand fire behavior and effects characteristics

Variable	Input data	Output	Reference
Canopy bulk density (CBD)	Individual tree measurements taken from 0.04 ha plots	Treatment unit average CBD (kg/m^3) from allometric equations	Brown (1978) Snell and Little (1983)
Fire rate of spread (ROS)	Stand characteristics, fuel model, topography, and weather data	ROS (m min^{-1})	Rothermel (1972)
Fire line intensity	Stand characteristics, fuel model, topography, and weather data	Fire line intensity (kW m^{-1})	Albini (1976)
Fire type, crown fire initiation, rate of spread	Stand characteristics, fuel model, topography, and weather data	Surface fire, passive crown fire, active crown fire plume dominated	Alexander (1988) van Wagner (1993)
Probability of mortality	Stand characteristics, fuel model, weather data, and fire behavior outputs	Percent probability of mortality on an individual tree basis	Reinhardt et al. (1997)
Torching index	Stand characteristics, fuel model, weather data, and fire behavior outputs	Windspeed required to initiate torching (km s^{-1})	Scott and Reinhardt (2001)
Crowning index	Stand characteristics, fuel model, weather data, and fire behavior outputs	Windspeed required to sustain crowning (km s^{-1})	Scott and Reinhardt (2001)

Table 3
Average post-treatment vegetation structure for all trees greater than 2.5 cm DBH at Blodgett Forest, California

Treatment	Tree height (m)	Height to crown base (m)	Canopy cover (%)	Basal area (m^2 ha^{-1})	Trees ha^{-1}	DBH (cm)	Crown bulk density (kg m^{-3})
Old growth reserve	17^{ab}	10^{a}	75^{a}	73^{a}	948	31^{ab}	0.098^{a}
Young growth reserve	19^{a}	11^{a}	68^{a}	64^{b}	662	35^{a}	0.089^{a}
Thin from below	16^{ab}	10^{a}	57^{ab}	48^{bc}	567	33^{a}	0.076^{ab}
Individual tree selection	16^{ab}	6^{abc}	59^{ab}	40^{bc}	574	30^{ab}	0.061^{ab}
Overstory removal	14^{bc}	6^{abc}	71^{a}	25^{cd}	639	23^{bc}	0.066^{ab}
Plantation un-thinned	9^{c}	3^{cd}	48^{bc}	11^{d}	693	14^{d}	0.075^{ab}
Plantation chainsaw PCT	8^{c}	2^{cd}	45^{bc}	14de	510	18^{cd}	0.09^{a}
Plantation mastication PCT	10^{c}	3^{cd}	39^{c}	19de	435	23^{bc}	0.086^{a}
Plantation < 5 years old	1^{d}	0.3^{d}	1^{d}	0.0^{e}	890	1^{e}	0.008^{b}

Mean values in a column followed by the same letter are not significantly different.
PCT – pre-commercial thinning.

Table 4
Average post-treatment fuel loads (metric tons ha^{-1}) by treatment type at Blodgett Forest, California

Treatment	Litter and duff	0–0.64 cm	0.64–2.54 cm	2.54–7.62 cm	>7.62 cm sound	>7.62 cm rotten	1–1000 h plus litter, duff	Fuel depth (cm)
Old growth reserve	122^{ab}	0.9	3.7	5.7	16.4	21.6	170^{a}	17
Young growth reserve	138^{a}	0.7	3.5	4.4	19.9	14.0	180^{a}	12
Thin from below	76^{abc}	0.6	4.1	12.1	25.4	58.3	177^{a}	7
Individual tree selection	110^{abc}	1.3	6.6	17.6	33.2	11.7	180^{a}	9
Overstory removal	75^{abc}	0.8	6.2	15.5	33.0	39.4	170^{ab}	3
Plantation un-thinned	55^{bc}	0.2	1.2	6.9	13.7	7.7	85^{bc}	10
Plantation chainsaw PCT	54^{bc}	0.5	2.2	6.0	10.2	9.0	82^{bc}	16
Plantation mastication PCT	45^{c}	0.5	2.0	3.9	1.6	1.4	55^{bc}	11
Plantation < 5 years old	56^{b,c}	0.6	3.8	9.9	16.9	7.0	94^{bc}	8

Mean values in a column followed by the same letter are not significantly different.
PCT – pre-commercial thinning.

Table 5
Average post-treatment modeled fire behavior under 90th percentile weather conditions at Blodgett Forest, California

Treatment	Fire type	Rate of spread (m min^{-1})	Fireline intensity (kW min^{-1})	Torching index (km h^{-1})	Crowning index (km h^{-1})
Old growth reserve	100% Surface fire	3.9	805	82	30
Young growth reserve	100% Surface fire	3.9	805	111	34
Thin from below	100% Surface fire	3.8	794	74	37
Individual tree selection	100% Surface fire	4.0	817	54	44
Overstory removal	100% Surface fire	3.9	805	58	43
Plantation un-thinned	66% Passive crown fire, 33% active crown fire, plume dominated	17.4	2614	0	47
Plantation chainsaw PCT	66% Passive crown Fire, 33% active crown fire, wind driven	13.0	2692	7	32
Plantation mastication PCT	100% Passive crown fire	3.7	773	9	34
Plantation < 5 years old	100% Surface fire	4.2	17	0	114

PCT – pre-commercial thinning.

Table 6
Average post-treatment modeled fire behavior under 97.5th percentile weather conditions at Blodgett Forest, California

Treatment	Fire type	Rate of spread (m min^{-1})	Fireline intensity (kW min^{-1})	Torching index (km h^{-1})	Crowning index (km h^{-1})
Old growth reserve	100% Surface fire	5.2	1158	66	27
Young growth reserve	100% Surface fire	5.2	1158	89	30
Thin from below	100% Surface fire	4.9	1067	62	35
Individual tree selection	33% Passive crown fire, 66% surface fire	5.3	1173	43	39
Overstory removal	33% Passive crown fire, 66% surface fire	5.2	1158	46	39
Plantation un-thinned	66% Passive crown fire, 33% active crown fire, plume dominated	23.7	3880	0	43
Plantation chainsaw PCT	100% Active crown fire, plume dominated	14.5	3233	6	29
Plantation mastication PCT	33% Passive crown fire, 66% active crown fire, plume dominated	5.0	1116	6	31
Plantation < 5 years old	100% Surface fire	5.6	25	0	104

PCT – pre-commercial thinning.

Table 7
Average post-treatment percent predicted mortality for conifer species by diameter class and treatment type at Blodgett Forest, California

Percentile weather	DBH range (cm)	Old growth reserve	Young growth reserve	Thin from below	Individual tree selection	Overstory removal	Plantation un-thinned	Plantation chainsaw PCT	Plantation mastication PCT	Plantation < 5 years old
80th	2.5–25	58.9	67.0	51.1	77.6	72.8	97.1	97.3	92.4	100.0
	25–51	20.8	19.2	21.7	25.7	24.6	65.2	58.8	67.5	†
	51–76	7.0	6.2	5.5	5.7	5.5	9.0	23.7	63.0	†
	> 76	3.3	2.7	2.5	3.7	5.5	†	†	†	†
	All	39.0	36.2	36.6	51.8	54.4	86.1	91.5	83.4	100.0
90th	2.5–25	93.7	90.3	95.3	97.1	93.8	99.7	99.5	99.2	100.0
	25–51	37.9	39.3	37.4	55.8	57.4	88.9	83.0	95.3	†
	51–76	7.1	6.3	8.0	8.5	7.2	50.0	75.2	93.5	†
	>76	3.3	2.7	2.5	5.0	7.2	†	†	†	†
	All	63.1	52.9	67.1	73.3	77.3	94.7	97.2	97.8	100.0
97.5th	2.5–25	98.7	96.3	98.8	99.3	99.5	99.7	99.5	99.2	100.0
	25–51	62.8	57.0	57.7	78.8	78.5	93.4	98.0	98.2	†
	51–76	9.6	8.0	9.6	29.9	41.6	52.5	95.5	93.5	†
	>76	3.5	2.7	2.5	13.8	41.6	†	†	†	†
	All	73.7	62.0	75.5	84.2	88.7	96.4	99.2	98.8	100.0

† = no trees in this diameter class for this silvicultural system.
PCT – pre-commercial thinning.

predicted mortality was highest in overstory removal and individual trees selection, though this mortality was still below 10% of all trees in this diameter class. Under 97.5th percentile conditions, mortality was similar across all treatments for trees 2.5–25 cm DBH (Table 7).

4. Discussion

The use of mechanical treatments and/or prescribed fire as management tools should be considered within an overall restoration strategy that may include multiple ecosystem objectives (Agee, 1996). Prescribed burning can be used to reintroduce a fundamental ecosystem process into forests but has the disadvantages of smoke production, risk of fire escaping prescribed boundaries, and difficulty in implementation because of constraints from weather, access, and availability of field crews.

Mechanical treatments in forests can produce negative ecosystem effects such as soil disturbance and compaction (Neary et al., 1999), disruption of nutrient cycling (Jurgensen et al., 1997), damage to residual trees, and enhancement of root pathogens (Slaughter and Rizzo, 1999); the advantage of mechanical systems are increased precision, no smoke production, low risk of treatments leaving prescribed boundaries, and the ability to produce forest commodities.

Traditional silvicultural systems used in the Sierra Nevada have primarily been used to balance the growth and yield of wood products while protecting soil and biological resources. The majority of the traditional silvicultural systems examined in this work (all plantation treatments, overstory removal, individual tree selection) did not effectively reduce potential fire behavior and effects, especially wildfire induced tree mortality at high and extreme fire weather conditions. Overall, thinning from below, and old-growth and young-growth reserves were more effective at reducing predicted mortality in trees up to 51 cm DBH when compared with other treatments (Table 7). Untreated stands of mixed evergreen forests in southwestern Oregon subjected to a wildfire experience lower mortality than those that were only thinned (Raymond, 2004); those that were thinned and then underburned experienced the lowest mortality.

In both pre-commercially thinned and un-thinned plantations, overall tree mortality is well above 80% at all modeled fire weather conditions (Tables 5,6). This suggests that modifying plantation tree density alone will not reduce the probability of mortality if surface fuel loads remain high enough to kill trees through scorching of live foliage independent of crown fire. This assertion is also supported by modeled plantation crowning and torching indexes which were all relatively low regardless of how the plantations were treated silviculturally (Tables 5,6).

Older plantations have a similar crowning index as compared to reserve and all un-even age treatments, though the torching index remains lower than that of reserves (Tables 5,6). Young plantations less than 5 years old experienced 100% mortality under all percentile weather conditions. Patchy fuels in young plantations may result in lower tree mortality than is predicted here, but as the plantations mature, fuels will become more continuous and fire effects more uniform.

In California alone, nearly 120,000 hectares of forest plantations have never been treated since their initial site preparation and planting of seedlings (Sapsis and Brandow, 1997). Seedling mortality in these plantations has been low, and in most cases, an extensive shrub layer has developed because of high resource availability and the presence of a soil-stored seed bank. Most of these plantations currently have high fire hazards. Other research has identified high fire hazards in even aged silvicultural systems (Weatherspoon and Skinner, 1995; Odion et al., 2004).

In both even aged and un-even aged treatments, it is often assumed that harvest related slash will decompose over time thereby reducing fire hazards. In reality, logging slash may persist for long periods, and therefore, will influence fire hazards for extended periods. Rates of woody fuel decay are highly variable (Lahio and Prescott, 2004). The rates of decomposition of understory fuels are primarily dependant upon several factors including temperature, soil moisture, insect activity, and material size (Lahio and Prescott, 2004). Decaying conifer activity fuels have been reported to persist for 30 years in xeric forest environments (Stephens, 2004).

Fuels management should be part of a broader strategy of restoring watershed health rather than designed solely on the basis of fuels alone (Dellasala et al., 2004; Dombeck et al., 2004). The potential for treatments to spread exotic forest diseases and plants needs to be addressed when planning fuel treatments (Odion et al., 2004). Adaptive management programs must be used to learn from management actions since there is insufficient information on the ecological effects of fuels treatments (Stephens and Ruth, 2005).

Further increases in fire behavior and extent may occur from a predicted lengthening of the fire season due to global warming (McKenzie et al., 2004). Even for a conservative climate change scenario, it has been predicted that the area burned will roughly double by the end of this century in most western states (McKenzie et al., 2004). Current forest structure and composition in many areas of the western US could be severely impacted in a changing climate that increased drought frequency and corresponding damage from wildfire.

In spite of a century of fire suppression, we have learned that the question is not if forests will burn but when, where, and with what intensity (Dombeck et al., 2004). The majority of the traditional silvicultural systems used in the Sierra Nevada over the last several decades do not produce forests that can incorporate fire without high levels of tree mortality. Reserves preformed better than most of the silvicultural systems investigated in this work. Predicted wildfire effects in the two reserves indicates that a management program utilizing the existing Wildland Fire Use Program (managed lightning ignitions for resource benefit) (Stephens and Ruth, 2005) could produce positive ecosystem benefits in similar forests.

A new group of silvicultural treatments is needed to restore western US forests. New silvicultural systems can be created to produce greater congruence with natural disturbance regimes (Franklin et al., 1997; Fries et al., 1997). The major challenge in writing new silvicultural prescriptions is determining the kinds, numbers, and spatial patterns of retained structures required to achieve defined management objectives (Franklin et al., 2002). Modern silvicultural treatments should address both live and dead fuel components, including surface, ladder, and canopy fuels. Complicating this further is the need to produce structures that can incorporate fire without mortality outside the natural range of variation, particularly in forests that once burned under frequent, low-moderate intensity fire regimes.

Acknowledgements

Funding from the Resource Legacy Fund Foundation is greatly appreciated. We thank Andrew Corr and past BFRS research assistants for data collection. Carrie Salazar and John Battles finished the BFRS database and we thank them for completing this project. Thank you to the staff of Blodgett Forest for their cooperation in this project. Some data used in this publication was obtained by researchers of Blodgett Forest; this publication has not been reviewed by those researchers.

References

Agee, J.K., 1996. Achieving conservation biology objectives with fire in the Pacific Northwest. Weed Technology 10, 417–421.

Agee, J.K., Huff, M.H., 1986. Structure and process goals for vegetation in wilderness areas. In: Lucas, R.C. (Ed.), Proceedings of the National Wilderness Research Conference: Current Research. Gen. Tech. Rep. INT-GTR-212. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Fort Collins, Colorado, pp. 17–25.

Alexander, M.E., 1988. Help with making crown fire hazard assessments. In: Fisher, W.C., Arno, S.F. (Eds.), Protecting People and Homes from Wildfire in the Interior West: Proceedings of the Symposium and Workshop. Gen. Tech. Rep. INT-GTR-251. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Ogden, Utah.

Albini, F., 1976. Estimating Wildfire Behavior and Effects. Gen. Tech. Rep. INT-GTR-30. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Ogden, Utah.

Brown, J.K., 1974. Handbook for Inventorying Downed Woody Material. Gen. Tech. Rep. INT-GTR-16. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Ogden, Utah.

Brown, J.K., 1978. Weight and Density of Crowns of Rocky Mountain Conifers. Gen. Tech. Rep. INT-GTR-197. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Ogden, Utah.

Brown, R.T., Agee, J.K., Franklin, J.F., 2004. Forest restoration and fire: principals in the context of place. Conservation Biology 18, 903–912.

Carlton, D., 2004. Fuels Management Analyst Plus Software, Version 3.8.19. Fire Program Solutions. LLC, Estacada, Oregon.

Center for Forestry, 2004. Blodgett Forest on-line vegetation database. University of California, Berkeley, CA [accessed August, 2004]. Available from: <http://ecology.cnr.berkeley.edu/blodgett/getinfo.html>.

Covington, W.W., Fuel, P.Z., Hart, S.C., Weaver, R.P., 2001. Modeling ecological restoration effects on ponderosa pine forest structure. Restoration Ecology 9, 421–431.

Dellasala, D.A., Williams, J.E., Williams, C.D., Franklin, J.F., 2004. Beyond smoke and mirrors: a synthesis of fire policy and science. Conservation Biology 18, 976–986.

Dombeck, M.P., Williams, J.E., Woods, C.A., 2004. Wildfire policy and public lands: integrating scientific understanding with social concerns across landscapes. Conservation Biology 18, 883–889.

Franklin, J.F., Berg, D.E., Thornburgh, D.A., Tappeiner, J.C., 1997. Alternative silvicultural approaches to timber harvests: variable retention harvest systems. In: Kohm, K.A., Franklin, J.F. (Eds.), Creating New Forestry for the 21st Century. Island Press, Washington, DC, pp. 111–139.

Franklin, J.F., Spies, T.A., Van Pelt, R., Carey, A.B., Thornburgh, D.A., Berg, D.R., Lindenmayer, D.B., Harmon, M.E., Keeton, W.S., Shaw, D.C., Bible, K., Chen, J., 2002. Disturbance and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management 155, 399–423.

Fries, C., Johansson, O., Petterson, B., Simonsson, P., 1997. Silvicultural models to maintain and restore natural stand structures in Swedish forests. Forest Ecology and Management 94, 89–103.

Fulé, P.Z., McHugh, C., Heinlein, T.A., Covington, W.W., 2001. Potential Fire behavior is reduced following forest restoration treatments. In: Vance, R.K., Edminster, C.B., Covington, W.W., Blake, J.A. (Eds.). Ponderosa Pine Ecosystems Restoration and Conservation: Steps Towards Stewardship. Gen. Tech. Rep. RMRS-GTR-22. Rocky Mountain Research Station, Forest Service, US Department of Agriculture, Fort Collins, Colorado, pp. 28–35.

Gill, S.J., Biging, G.S., Murpy, E., 2000. Modeling tree crown radius and estimating canopy cover. Forest Ecology and Management 126, 405–416.

Graham, R.T., McCaffrey, S., Jain, T.B., 2004. Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity. Gen. Tech. Rep. RMRS-GTR-120. Rocky Mountain Research Station, Forest Service, US Department of Agriculture, Fort Collins, Colorado. 43 p.

HFRA, 2003. Healthy forest restoration act. H.R., 1904. United States Congress, Washington, DC. Available from: <http://www.house.gov/dunn/leg/108-1/billspassed/HR1904.pdf> (accessed January 2004).

Jurgensen, M.F., Harvey, A.E., Graham, R.T., Page-Dumroese, D.S., Tonn, J.R., Larsen, M.J., Jain, T.B., 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. Forest Science 42, 234–251.

Kauffman, J.B., 2004. Death rides the forest: perceptions of fire, land use, and ecological restoration of Western forest. Conservation Biology 18, 878–882.

Keyes, C.R., O'Hara, K.L., 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry 17, 101–109.

Lahio, R., Prescott, C.E., 2004. Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis. Canadian Journal of Forest Research 34, 763–777.

Laudenslayer, W.F., Darr, H.H., 1990. Historical effects of logging on forests of the Cascade and Sierra Nevada Ranges of California. Transactions of The Western Section of the Wildlife Society 26, 12–23.

Lindenmayer, D.B., Franklin, J.F., 2002. Conserving Forest Biodiversity. A Comprehensive Multiscaled Approach. Island Press, Washington DC.

Lindenmayer, D., McCarthy, M.A., 2002. Congruence between natural and human forest disturbance: a case study from Australia montane ash forests. Forest Ecology and Management 155, 319–335.

Main, W.A., Paananen, D.M., Burgan, R.E., 1990. Fire Family Plus. Gen. Tech. Rep. NC-GTR-138. North Central Forest and Range Experiment Station, Forest Service, US Department of Agriculture, St. Paul, Minnesota.

McKenzie, D., Gedalof, Z., Peterson, D.L., Mote, P., 2004. Climate change, wildfire, and conservation. Conservation Biology 18, 890–902.

Miller, C., Urban, D.L., 2000. Modeling the effects of fire management alternatives on Sierra Nevada mixed-conifer forests. Ecological Applications 10, 85–94.

Minnich, R.A., Barbour, M.G., Burk, J.H., Fernau, R.F., 1995. Sixty years of change in California conifer forests of the San Bernardino Mountains. Conservation Biology 9, 902–914.

Neary, D.G., Klopatek, C.C., DeBano, L.F., Ffollitt, P.F., 1999. Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management 122, 51–71.

NFAM, 2004. National Fire and Aviation Management Web Applications, Bald Mountain Weather Station, Station I.D. 042603. Boise, Idaho. Available from: <http://famweb.nwcg.gov/weatherfirecd/california.htm>.

North, M., Oakley, B., Chen, J., Erickson, H., Gray, A., Izzo, A., Johnson, D., Ma, S., Marra, J., Meyer, M., Purcell, K., Rambo, T., Rizzo, D., Roath, B., Schowalter, T., 2002. Vegetation and Ecological Characteristics of Mixed-conifer and Red Fir Forests at the Teakettle Experimental Forest. Gen. Tech. Rep. PSW-GTR-186. Pacific Southwest Research Station, Forest Service, US Department of Agriculture, Albany, California.

NWCG, 2001. Review and update of the 1995 federal wildland fire management policy. National Wildfire Coordinating Group. Interagency Fire Center. Boise, Idaho.

Odion, D.C., Frost, E.J., Strittholt, J.R., Jiang, H., Dellasala, D.A., Moritz, M.A., 2004. Patterns of fire severity and forest conditions in the western Klamath Mountains, California. Conservation Biology 18, 927–936.

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

Raymond, C.L., 2004. The effects of fuel treatments on fire severity in a mixed evergreen forest of southwestern Oregon. M.S. thesis. University of Washington, Seattle, WA.

Reinhardt, E.D., Keane, R.E., Brown, J.K., 1997. First Order Fire Effects Model: FOFEM 4.0, user's guide. Gen. Tech. Rep. INT-GTR-344. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture Ogden, Utah, 43 p.

Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wild Land Fuels. Res. Pap. INT-RP-115. Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Ogden, Utah.

Sall, J., Lehman, A., Creighton, L., 2001. JMP Start Statistics. A Guide to Statistics and Data Analysis Using JMP and JUMP IN Software, Second ed. Duxbury, Pacific Grove, California.

Sapsis, D., Brandow, C., 1997. Turning Plantations into Healthy, Fire Resistant Forests: Outlook for the Granite Burn. Fire and Resource Assessment Program. California Department of Forestry and Fire Protection. Sacramento, California, 16 p.

Scott, J.H., Reinhardt, E.D., 2001. Assessing Crown Fire Potential by Linking Models of Surface and Crown Fire Behavior. Res. Pap. RMRS-RP-29. Rocky Mountain Research Station, Forest Service, US Department of Agriculture, Fort Collins, Colorado.

Slaughter, G.W., Rizzo, D.M., 1999. Past forest management promoted root disease in Yosemite Valley. California Agriculture 53, 17–24.

Snell, K.J.A., Little, S.N., 1983. Predicting Crown Weight and Bole Volume of Five Western Hardwoods. Gen. Tech. Rep. PNW-GTR-151. Pacific Northwest Forest and Range Experiment Station, Forest Service, US Department of Agriculture, Portland, Oregon.

SNEP, 1996. Sierra Nevada Ecosystem Project, Status of the Sierra Nevada. Final Report to Congress. University of California, Centers for Water and Wildland Resources, Davis, California.

Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in the Sierra Nevada mixed-conifer forests. Forest Ecology and Management 105, 21–35.

Stephens, S.L., 2000. Mixed conifer and red fir forest structure and uses in 1899 from the central and Northern Sierra Nevada, California. Madrono 47, 43–52.

Stephens, S.L., 2001. Fire history of adjacent Jeffrey pine and upper montane forests in the Eastern Sierra Nevada. International Journal of Wildland Fire 10, 161–167.

Stephens, S.L., 2004. Fuel loads, snag density, and snag recruitment in an unmanaged Jeffrey pine-mixed conifer forest in northwestern Mexico. Forest Ecology and Management 199, 103–113.

Stephens, S.L., 2005. Forest fire causes and extent on United States Forest Service Lands. International Journal of Wildland Fire 14 (3).

Stephens, S.L., Collins, B.M., 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Science 78, 12–23.

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. Forest Ecology and Management (in press).

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

Stephenson, N.L., 1999. Reference conditions for giant sequoia forest restoration: structure, process, and precision. Ecological Applications 9, 1253–1265.

USDA, 2004. Sierra Nevada Forest Plan Amendment, Final Supplemental Environmental Impact Statement, R5-MB-019. USDA Forest Service Pacific Southwest Region, Vallejo, California.

van Wagner, C.E., 1993. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research 23, 442–449.

van Wagtendonk, Jan W., 1996. Use of a deterministic fire model to test fuel treatments. In: Sierra Nevada Ecosystem Project: Final Report to Congress Volume II. Centers for Water and Wildland Resources, University of California, Davis, California, pp. 1155–1167.

van Wagtendonk, J.W., Benedict, J.M., Sydoriak, W.M., 1996. Physical properties of woody fuel particles of Sierra Nevada Conifers. International Journal of Wildland Fire 6, 117–123.

van Wagtendonk, J.W., Benedict, J.M., Sydoriak, W.M., 1998. Fuel bed characteristics of Sierra Nevada conifers. Western Journal of Applied Forestry 13, 1145–1157.

Weatherspoon, C.P., Skinner, C.N., 1995. An assessment of factors associated with damage to tree crowns from the 1987 wildfires in northern California. Forest Science 41, 430–451.

Williams, J.E., DellaSala, D.A., 2004. Wildfire and conservation in the western United States. Conservation Biology 18, 872–873.

Zar, J.H., 1999. Biostatistical Analysis, fourth ed. Prentice Hall, Upper Saddle River, New Jersey.