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Fuel treatment effects on snags and coarse woody debris in a Sierra Nevada mixed conifer forest

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Abstract

Snags and coarse woody debris are important elements of the structure and function of mixed conifer forests in the Sierra Nevada. In this paper, we report on the impacts of several replicated fuel treatments including, prescribed fire, commercial thinning (crown thinning and thinning from below) followed by rotary mastication of understory trees, mechanical followed by prescribed fire, and control, on snag and CWD quantity and structure. Post-treatment, the density of snags greater than 15 cm DBH in decay class 1 significantly increased in fire only and mechanical plus fire treatments compared with mechanical only and control treatments. Snag volumes (m^3 ha^{-1}) were not significantly different between treatments for all decay classes. CWD (density, percent cover, volume) in decay classes 1 and 2 was not significantly altered by any treatment when aggregated across all diameter classes. Volume of CWD in decay class 3 was significantly reduced in the fire only treatment when compared to controls. Density and volume of CWD in class 4 was significantly reduced in mechanical plus fire and fire only treatments when compared with the controls and mechanical only treatments. Retention of large CWD levels may benefit some wildlife species short-term but increases in fire hazards and increased difficulties in fire control are the negative consequence. High overall fuel loads also increase the probability of snag and CWD consumption when an area inevitably burns. The influences of altering snag and CWD characteristics should be analyzed in the context of long-term forest management goals, including the reintroduction of fire as an ecosystem process and creation of forest structures that can incorporate wildfire without tree mortality outside a desired range.

Keywords: Prescribed fire; Fuels; Forest restoration; Downed logs; Fire hazard; Coarse wood

1. Introduction

Snags and coarse woody debris (CWD) are important elements of the structure and function of mixed conifer forests in the western United States (US). Snags and CWD derived from mixed conifer species provide habitat for cavity nesting birds, small and large mammals, and insect populations within CWD can be a food source for both mammals and avian species (Parks et al., 1997; Bate et al., 1999; Payer and Harrison, 2002; Lehmkuhl et al., 2003).

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On steep slopes, CWD can assist in the stabilization of forest soils, particularly after extensive removal of organic matter by wildfire or management activities (Brown et al., 2003). The creation and maintenance of appropriate biological legacies (including CWD) is a critical element of forest management strategies that attempt to conserve biodiversity (Franklin et al., 2002; Lindenmayer and Franklin, 2002). Repeated harvesting of large trees in many western US forests has reduced the amount of large snags and CWD that provide important ecosystem services to many forests.

With respect to fire, the presence of CWD and snags can increase the probability of crowning, torching, and spot fires in forests because of high heat generation during combustion (Brown et al., 2003; Stephens, 2004). Snags can pose a danger to firefighters during suppression and prescribed burn operations because they can become structurally unsound and fall. CWD can make suppression activities, such as fire line construction, much more difficult (Brown et al., 2003). In addition, snags and CWD can increase the amount and duration of smoldering combustion, in turn increasing emitted particulate matter and potentially contributing to reduced air quality and visibility in local and regional airsheds (Reinhardt et al., 1997). Prolonged burnout times of CWD can also increase the severity of soil heating (Reinhardt et al., 1997).

Several studies have examined the amount, quality, distribution, and rates of decay of CWD and snags in forest ecosystems, though many of these studies were conducted in forests that have experienced fire suppression for much of the 20th century (Harmon et al., 1987; Spies et al., 1988; Mellen and Ager, 2002; North et al., 2002). Frequent fires have been shown to be a common ecosystem process in California's mixed conifer forests prior to the current era of fire suppression (Drumm, 1999; Beatty and Taylor, 2001; Taylor and Skinner, 2003; Stephens and Collins, 2004) making the results of contemporary studies difficult to interpret if managers are interested in pre-settlement levels of CWD and snags.

While some studies provide an overview of fire and CWD (Skinner, 2002) and others concentrate on the effects of fire on CWD dynamics in old-growth forests (Innes and North, 2004), there are currently no published papers which examine the effects of prescribed fire and mechanical fuel treatments on CWD in second-growth Sierra Nevada mixed conifer forests. In addition, many studies involving CWD are non-replicated and/or do not use an experimental approach with pre- and post-treatment measurements (Robertson and Bowser, 1999).

An understanding of how fuel treatments affect CWD and snag dynamics will help managers estimate the impacts of restoration treatments in Sierra Nevada mixed conifer forests. This paper reports results from CWD and snag research done using both prescribed fire, mechanical, and combined fuel treatments implemented under the National Fire and Fire Surrogate Study (FFS) (Weatherspoon, 2000). The FFS study has implemented a series of controlled empirical experiments to study the effects of fuel treatments on CWD, vegetation structure, fuel loads, and a suite of other ecological variables at 13 locations across the continental US. In this paper, we report the effects of several fuel treatments on snag and CWD dynamics. The fuel treatments used in this study are being applied to large areas of Sierra Nevada forests. These results reach beyond the discipline of fire behavior and fuels and will help form a basis of how common fire hazard reduction treatments affect forest structure.

The objective of this study is to determine how four different fuel treatments affect snag and CWD structure, density, and volume. The four treatments include: (1) control (no treatment), (2) commercial thinning (crown thinning and thinning from below) followed by rotary mastication of understory trees, (3) prescribed fire, and (4) a combination of commercial thinning, rotary mastication, and prescribed fire. The null hypothesis is that there will be no significant differences ($p < 0.05$) in CWD (density, volume, and cover) and snags (density and volume) between treatments.

2. Methods

2.1. Study location

The study was conducted in mixed conifer forests in the north-central Sierra Nevada at the University of California Blodgett Forest Research Station (Blodgett Forest), approximately 20 km east of Georgetown, CA. Mixed conifer forests cover approximately 3.2

million ha (7.8%) of California's total land base (CDF, 2003).

Blodgett Forest is located at 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* 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.) Rehder), bush chinkapin (*Chrysolepis sempervirens* (Kell.) Hjelmg.), and Pacific madrone (*Arbutus menziezii* Pursh).

Soils at Blodgett Forest are well-developed, well-drained Haploxeralfs (Alfisols), derived from either andesitic mudflow or granitic/granodiorite parent materials (Hart et al., 1992). Soils are deep, weathered, sandy-loams overlain by an organic forest floor horizon. Common soil depths range from 85 to 115 cm. Slopes across Blodgett Forest average less than 30%.

Climate at Blodgett Forest is Mediterranean with a summer drought period that extends into the fall. Winter and spring receive the majority of precipitation, which 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 (averaging 4 cm over the summer months from 1960 to 2000) (Stephens and Collins, 2004).

Fire was a common ecosystem process in the mixed conifer forests of Blodgett Forest before the policy of fire suppression began early in the 20th century. Between 1750 and 1900, median composite fire intervals at the 9–15 ha spatial scale was 4.7 years with a fire return interval range of 4–28 years (Stephens and Collins, 2004). Forested areas at Blodgett Forest have been repeatedly harvested and subjected to fire suppression for the last 90 years reflecting a management history common to many forests in California (Laudenslayer and Darr, 1990; Stephens, 2000) and elsewhere in the western US (Graham et al., 2004).

2.2. Treatments

The primary objective of the fuel treatments was to modify stand structure such that 80% of the dominant and co-dominant trees in the post-treatment stand would survive a wildfire modeled under 80th percentile weather conditions (Weatherspoon, 2000). The secondary objective was to create a stand structure that maintained or restored several forest attributes and processes including, but not limited to, snag and CWD abundance and recruitment. To meet these objectives, four different treatments including no treatment (control), mechanical only, mechanical plus fire, and prescribed fire only were each randomly applied (complete randomized design) to 3 of 12 experimental units that varied in size from 14 to 29 ha. Total area for the 12 experimental units was 225 ha. To reduce edge effects from adjoining areas, data collection was restricted to a 10 ha core area in the center of each treatment unit.

Control units received no treatment during the study period (2000–2005). Mechanical only treatment units had a two-stage treatment. In 2001, trees greater than 25 cm in diameter (DBH) were commercially thinned from below to maximize crown spacing while retaining 28–34 m^2 ha^{-1} of basal area with the goal to produce an even species mix of residual conifers (in some areas an even species mix was not possible because of initial stand composition). Individual trees were cut using a chainsaw and removed with either a rubber tired or track laying skidder. During harvests, hardwoods, primarily California black oak, were coppiced to facilitate their regeneration (McDonald and Tappeiner, 1996).

All residual trees were well spaced with little overlap of live crowns in dominant and co-dominant trees. Following the commercial harvest, approximately 90% of understory conifers and hardwoods between 2 and 25 cm DBH were masticated in place using an excavator mounted rotary masticator. Mastication shreds and chips small diameter (2–25 cm DBH) live and dead trees in place. Masticated material was not removed from the experimental units. The remaining unmasticated understory trees were left in scattered clumps of 0.04–0.20 ha in size.

Mechanical plus fire experimental units underwent the same treatment as mechanical only units, but in addition, they were prescribed burned using a backing fire (Martin and Dell, 1978) after the mechanical treatment was completed. Fire only units were burned with no pre-treatment using strip head-fires (Martin and Dell, 1978), one of the most common ignition patterns used to burn forests in the western US. All prescribed burning was conducted during a short period (10/23/2002–11/6/2002) (Knapp et al., 2004). Night burning was preferred because relative humidity, air temperature, wind speed, and fuel moistures were within pre-determined levels to produce the desired fire effects. Prescribed fire prescription parameters for temperature, relative humidity, and wind speed were 0–10 °C, >35%, and 0.0–5 km h^{-1}, respectively. Desired 10-h fuel stick moisture content was 7–10%.

2.3. Field measurements

Before and after treatments, CWD was sampled on a random selection of 10 plots on each of the 12 treatment units (120 plots total). At each plot, a random azimuth was chosen and CWD was measured within a 4 m × 20 m belt transect (Bate et al., 2004). Only logs greater than 1 m in length and with a large end diameter at least 15 cm within the belt transect were measured (Bate et al., 2004). For each qualifying piece, the following attributes were measured: large end diameter, small end diameter, total length, length within plot, and whether or not the mid-point of the piece fell within the plot (Waddell, 2002). In addition, the decay class (Waddell, 2002) of each piece was given a classification of 1–5 (sound to rotten) as described in Table 1. For each treatment unit, CWD percent cover per hectare, density per hectare, and volume per hectare (m^3 ha^{-1}) were computed using equations described by Bate et al. (2004).

Before and after treatment, snags were measured using 0.04-ha circular plots installed on a systematic grid within each treatment unit. Individual plots were placed on a systematic 60 m grid with a random starting point. Plot centers were permanently marked with a pipe and three witness trees were tagged to facilitate plot relocation after treatments. Two hundred and forty plots were inventoried in the 12 experimental units (20 in each experimental unit). Species, DBH, total height, and decay stages 1–5 (Table 1) (Raphael and Morrison, 1987) were recorded for all snags greater than 11 cm DBH. Similar information was also recorded for all snags greater than 1.37 m tall on a 0.004-ha nested subplot in each of the circular plots. Snag volume (m^3 ha^{-1}) was computed using species specific volume equations described by Wensel and Olson (1995). California black oak volumes (m^3 ha^{-1}) were computed using equations described by McDonald (1982).

Table 1
Classification of the stage of decay for coarse woody logs (Waddell, 2002) and snags (Raphael and Morrison, 1987)

Decay class	Structural integrity	Wood texture	Wood color	Presence of invading roots	Condition of branches and twigs	Snag description
1	Sound	Intact, no rot; conks on stem absent	Original color	Absent	If branches present, fine twigs still attached with tight bark	Needles present; twigs present; greater than 20 limbs at least 1 m long
2	Heartwood sound, sapwood somewhat decayed	Mostly intact; sapwood partly soft and starting to decay; wood cannot be pulled apart by hand	Original color	Absent	If branches present, many fine twigs gone; fine twigs still present have peeling bark	Needles absent; twigs present; greater than 20 limbs at least 1 m long
3	Heartwood sound; log supports its weight	Large, hard pieces sapwood can be pulled apart by hand	Red-brown or original color	Present in sapwood only	Large branch stubs will not pull out	Needles absent; twigs absent; greater than 20 limbs at least 1 m long
4	Heartwood rotten; log does not support its weight, but shape is maintained	Soft, small, blocky pieces; metal pin can push apart heartwood	Red-brown or light brown	Present throughout log	Large branch stubs pull out easily	Needles absent; twigs absent; 1–19 limbs at least 1–m long
5	No structural integrity; no longer maintains shape	Soft, powdery when dry	Red-brown to dark brown	Present throughout log	Branch stubs and pitch pockets have rotted away	Needles present; twigs present; zero limbs at least 1 m long

Table 2
Average pre-treatment vegetation structure (standard error) for all trees greater than 2.5 cm DBH at Blodgett Forest Research Station, CA

	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Basal area ($m^2\ ha^{-1}$)	55.1	3.1	51.9	2.0	55.1	1.5	49.4	2.2
Trees ha^{-1}	1100.9	67.3	972.0	226.2	823.3	187.3	850.1	16.8
Average quadratic mean diameter (cm)	25.3	0.7	27.3	3.4	30.3	3.2	27.2	0.5
Tree height (m)	15.6	0.8	16.7	1.1	16.5	1.2	15.8	0.5
Tree height to crown base (m)	7.6	0.6	7.9	0.6	7.8	0.8	6.8	0.4
Percent canopy cover	69	6.0	66	4.0	63	5.0	68	1.0

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$)

2.4. Data analysis

Analysis of covariance (ANCOVA) was used to determine if significant differences ($p < 0.05$) existed in snag density and volume (m^3) per hectare and CWD volume (m^3), density, and cover per hectare (Miliken and Johnson, 2002). Statistical analysis was preformed at $n = 3$ (three replicates of four treatments). Frequency distributions for all variables were right skewed, and therefore, were log transformed to meet assumptions of parametric statistical tests (Zar, 1999). Pre-treatment data collected on CWD and snag characteristics were included in the model as a covariate. Snags were analyzed by decay classes 1–5 (Raphael and Morrison, 1987) and by size classes condensed from size classes used by Laudenslayer (1999). If a significant difference was detected, a Tukey–Kramer HSD test was performed to determine which treatments were different from another (Zar, 1999). The Jump Statistical Software package (Sall et al., 2001) was used in all analyses.

3. Results

There was no significant difference in experimental unit forest structure prior to treatment implementation (Table 2). There was no significant difference in pre-treatment density and volume for CWD or snags (Tables 3 and 4). Post-treatment density of snags greater than 15 cm DBH in decay class 1 significantly increased in fire only and mechanical plus fire treatments compared with mechanical and control

Table 3
Pre-treatment density (ha^{-1}) and volume ($m^3\ ha^{-1}$) of snags greater than 15 cm DBH by decay class in mixed conifer forests at Blodgett Forest

Decay class	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
1	10.3	5.4	22.2	10.6	23.8	3.4	3.8	3.8
2	11.2	2.6	15.8	5.6	11.9	1.9	7.8	2.6
3	5.9	1.6	7.1	2.3	9.3	2.7	2.8	1.6
4	0.0	0.0	1.9	1.0	2.4	0.6	5.6	3.3
5	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6
All decay classes	27.5	8.9	47.0	13.7	47.6	4.3	20.7	10.6
Volume								
1	0.9	0.6	14.2	5.7	11.4	8.0	1.8	1.8
2	2.6	1.3	5.1	2.3	1.2	0.1	1.2	0.5
3	2.0	0.4	5.3	2.2	6.6	2.5	1.1	1.1
4	0.0	0.0	0.1	0.1	0.5	0.3	0.8	0.6
5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
All decay classes	5.6	1.2	24.7	6.8	19.7	6.5	5.0	4.0

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

Table 4
Pre-treatment density (pieces) ha^{-1}, percent cover (ha^{-1}), and volume ($m^3\ ha^{-1}$) of CWD by decay class in mixed conifer forests at Blodgett Forest

Decay class	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
1	54.2	22.1	20.8	4.2	20.8	4.2	45.8	25.4
2	45.8	25.4	45.8	22.1	66.7	15.0	54.2	15.0
3	58.3	22.1	79.2	4.2	91.7	16.7	66.7	4.2
4	25.0	0.0	58.3	23.2	33.3	8.3	70.8	8.3
5	4.2	4.2	16.7	4.2	4.2	4.2	16.7	4.2
All decay classes	187.5	21.7	220.8	39.8	216.7	44.1	254.2	23.2
Percent cover								
1	0.5	0.2	0.2	0.1	0.2	0.1	0.3	0.2
2	0.5	0.2	0.9	0.4	0.6	0.2	0.4	0.2
3	0.7	0.2	0.5	0.1	0.8	0.0	0.7	0.1
4	0.3	0.1	0.4	0.1	0.3	0.2	0.7	0.1
5	0.0	0.0	0.3	0.1	0.2	0.1	0.2	0.1
All decay classes	2.0	0.3	2.3	0.4	2.2	0.5	2.3	0.3
Volume								
1	8.5	5.2	3.6	1.6	2.5	1.7	5.3	3.9
2	13.9	10.2	23.4	11.2	10.2	3.0	7.4	3.2
3	18.7	4.9	10.2	3.2	17.5	3.8	12.2	2.3
4	10.9	4.8	7.9	2.7	6.5	3.6	16.6	1.3
5	0.1	0.1	6.3	2.1	15.3	7.7	11.1	8.4
All decay classes	52.3	15.2	51.5	10.5	52.0	11.2	52.7	3.4

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

treatments (Table 5). Densities of snags in all other decay classes were not significantly different between treatments (Table 5). Pre-treatment covariates were not significant in this analysis.

Snag volumes ($m^3\ ha^{-1}$) were not significantly different between treatments for all decay classes (Table 5). Volumes and densities of snags in decay classes 4 and 5 (greater than 15 cm DBH) were present

Table 5
Post-treatment density (ha^{-1}) and volume ($m^3\ ha^{-1}$) of snags greater than 15 cm DBH by decay class in mixed conifer forests at Blodgett Forest

Decay class	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
1	7.1 a	1.5	3.9 a	2.1	20.7 b	2.6	20.3 b	1.9
2	15.7	10.7	10.8	6.5	4.7	4.7	6.4	0.6
3	5.8	3.3	1.8	1.0	1.9	1.0	1.7	0.9
4	0.9	0.9	0.5	0.5	0.0	0.0	0.6	0.6
5	0.0	0.0	0.5	0.5	0.7	0.7	0.0	0.0
All decay classes	29.5	12.1	17.6	6.4	28.0	7.2	29.0	3.6
Volume								
1	5.5	3.9	3.4	2.6	25.0	17.4	7.5	5.0
2	1.9	0.9	3.2	1.6	0.6	0.6	0.7	0.6
3	1.5	0.7	4.6	2.3	0.5	0.4	0.2	0.2
4	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
5	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.0
All decay classes	9.0	2.6	11.4	1.5	26.1	16.9	8.4	5.4

Mean values in a row followed by the same letters (a and b) are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

Table 6
Post-treatment density (ha^{-1}) and volume ($m^3\ ha^{-1}$) of hard snags (decay classes 1–3) by diameter class in mixed conifer forests at Blodgett Forest

Diameter class (cm)	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
1–14.9	105.4 a	41.7	10.9 b	9.2	37.8 ab	29.5	322.0 a	68.8
15–29.9	20.2 ab	10.5	8.8 b	4.6	19.1 ab	4.6	26.5 a	2.6
30–44.9	5.3	1.7	2.6	1.3	1.5	1.5	1.3	1.3
45–59.9	0.9	0.9	3.2	0.8	4.6	3.1	0.0	0.0
60+	0.7	0.7	1.8	1.0	1.0	1.0	0.6	0.6
15+	28.6	12.5	16.5	6.6	27.3	7.6	28.4	3.2
Volume								
1–14.9	0.7 ab	0.1	0.1 b	0.1	0.5 b	0.1	1.6 a	0.5
15–29.9	1.7	0.8	1.0	0.6	2.9	0.3	3.8	0.9
30–44.9	2.3	1.0	1.1	0.6	0.9	0.9	0.3	0.3
45–59.9	0.5	0.5	4.4	2.0	5.7	3.0	0.0	0.0
60+	4.1	4.1	4.6	2.3	16.4	16.4	4.3	4.3
15+	8.9	2.7	11.1	1.5	26.1	16.9	8.4	5.4

Mean values in a row followed by the same letters (a and b) are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

in relatively low numbers across all treatments, including the controls, and were not significantly changed by treatments (Table 5).

When snags were analyzed by diameter class, hard snag (decay classes 1–3 combined) density increased in the 1–15 cm and 15–30 cm diameter classes in fire only treatments compared with the mechanical only treatment (Table 6). Snag density in the 1–15 cm size class significantly decreased in the mechanical only treatment when compared with the control (Table 6). The

Table 7
Post-treatment density (pieces) ha^{-1}, percent cover (ha^{-1}), and volume ($m^3\ ha^{-1}$) of CWD by decay class in mixed conifer forests at Blodgett Forest

Decay class	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
1	16.7	8.3	70.8	29.2	20.8	11.0	4.2	4.2
2	70.8	33.4	104.2	16.7	41.7	29.2	37.5	0.0
3	79.2 ab	23.2	66.7 a	4.2	8.3 ab	8.3	4.2 b	4.2
4	62.5 a	19.1	58.3 a	11.0	0.0 b	0.0	0.0 b	0.0
5	25.0 ab	12.5	33.0 a	8.3	0.0 ab	0.0	0.0 b	0.0
All decay classes	254.2 a	27.4	333.3 a	32.6	70.8 b	33.4	45.8 b	4.2
Percent cover								
1	0.1	0.0	0.3	0.2	0.3	0.1	0.2	0.2
2	0.5	0.1	0.6	0.1	0.3	0.3	0.2	0.0
3	1.1	0.6	0.4	0.2	0.2	0.0	0.0	0.0
4	1.0 a	0.4	0.6 ab	0.2	0.0 b	0.0	0.0 b	0.0
5	0.1	0.1	0.4	0.2	0.1	0.1	0.0	0.0
All decay classes	2.8 a	0.6	2.3 ab	0.5	0.8 ab	0.5	0.4 b	0.1
Volume								
1	1.2	0.6	4.4	2.3	7.5	3.5	5.9	5.5
2	8.2	2.1	8.6	2.3	10.6	9.6	3.2	1.4
3	48.7 a	28.9	10.6 ab	5.3	5.8 ab	2.6	0.7 b	0.7
4	37.9 a	22.3	14.8 a	5.6	0.0 b	0.0	0.0 b	0.0
5	1.5	1.1	16.7	9.0	4.7	4.7	0.0	0.0
All decay classes	97.4 a	23.1	55.1 a	15.9	28.6 ab	17.3	9.8 b	4.7

Mean values in a row followed by the same letters (a and b) are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

only significant change in snag volume (m^3 ha^{-1}) was an increase in the density of 1–15 cm DBH hard snags in the fire only units when compared with the mechanical only and mechanical plus fire treatments (Table 6).

By all metrics (density, percent cover, volume), CWD in decay classes 1 and 2 was not significantly altered by any of the treatments when aggregated across all diameter classes (Table 5). Volume of CWD in decay class 3 was significantly reduced in the fire only treatment when compared with control (Table 7). In terms of density, there was significantly less decay class 3 CWD in the fire only treatment when compared with mechanical only treatment (Table 7).

CWD in decay class 4 (density, volume) was significantly reduced in mechanical plus fire and fire only treatments when compared with controls and mechanical only treatments (Table 7). Percent cover of decay class 4 CWD was significantly lower in both burn treatments compared with the control (Table 7). Density of CWD in decay class 5 was significantly reduced in the fire only treatment when compared with mechanically only treatment (Table 7). For all decay classes (1–5) combined, CWD density was significantly reduced in areas treated with fire (fire only and mechanical plus fire) when compared with non-burn treatments (Table 7). CWD for all decay classes combined in the fire only treatment was significantly lower than the control in terms of percent cover and volume (Table 7).

For CWD with a large end diameter of 15–30 cm in decay classes 1–3, volume per hectare was significantly reduced in units treated with fire when compared with controls (Table 8). CWD in decay classes 4 and 5 for the same diameter and decay classes, density was significantly reduced in units treated with fire when compared with control and mechanical only treatments (Table 9). CWD 30–45 cm in diameter in decay classes 1–3 was not significantly altered by any treatment (Table 8). CWD in decay classes 4 and 5 for the same diameter class (30–45 cm diameter), density was reduced in the mechanical plus fire treatment when compared with mechanical only (Table 9).

There were no significant changes in CWD in the 45–60 cm diameter class in terms of density and volume per hectare for all decay classes (Tables 8 and 9). There was no significant change in any CWD metric in any decay class for materials greater than 60 cm diameter (Tables 8 and 9). Overall, total CWD in decay classes 1–3 with a large end diameter greater than or equal to 15 cm were unchanged in terms of volume, though density was lower in the fire only treatment when compared with mechanical only treatment (Table 8). CWD density greater than or equal to 15 cm in diameter in decay classes 4 and 5 was significantly reduced in burn treatments (fire only and mechanical plus fire) when compared with non-burn treatments (Table 7). CWD in decay classes 4 and 5 in the fire only treatment was significantly reduced in terms of volume per hectare (Table 9) when compared with mechanical only and control treatments.

Table 8
Density (ha^{-1}) and volume (m^3 ha^{-1}) of coarse woody debris by diameter class (decay classes 1–3) combined in mixed conifer forests at Blodgett Forest

Diameter class (cm)	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
15–30	145.8	43.6	200.0	19.1	58.3	27.4	37.5	12.5
30–45	16.7	16.7	37.5	0.0	4.2	4.2	8.3	8.3
45–60	0.0	0.0	0.0	0.0	8.3	8.3	0.0	0.0
60+	4.2	4.2	4.2	4.2	0.0	0.0	0.0	0.0
15+	166.7 ab	41.1	241.7 a	18.2	70.8 ab	33.4	45.8 b	4.2
Volume								
15–30	1.0 a	2.6	0.6 ab	3.4	0.0 b	1.6	0.0 b	0.7
30–45	3.3	1.7	6.7	1.6	1.6	0.9	1.9	1.9
45–60	3.9	3.9	0.0	0.0	16.5	13.5	5.4	5.4
60+	39.3	30.0	2.4	2.4	3.2	3.3	0.0	0.0
15+	58.0	30.4	23.6	6.8	23.9	12.6	9.8	4.7

Mean values in a row followed by the same letters (a and b) are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

Table 9
Density (ha^{-1}) and volume ($m^3 ha^{-1}$) of coarse woody debris by diameter class (decay classes 4 and 5) combined in mixed conifer forests at Blodgett Forest

Diameter class (cm)	Control	S.E.	Mechanical only	S.E.	Mechanical and fire	S.E.	Fire only	S.E.
Density								
15–30	62.5 a	26.1	58.3 a	8.3	0.0 b	0.0	0.0 b	0.0
30–45	8.3 ab	4.2	25 a	12.5	0.0 b	0.0	0.0 ab	0.0
45–60	0.0	0.0	4.2	4.2	0.0	0.0	0.0	0.0
60+	16.7	16.7	4.2	4.2	0.0	0.0	0.0	0.0
15+	87.5 a	14.5	91.7 a	15.0	0.0 b	0.0	0.0 b	0.0
Volume								
15–30	5.1	4.2	3.0	1.5	0.0	0.0	0.0	0.0
30–45	5.0	2.6	8.5	4.3	0.0	0.0	0.0	0.0
45–60	1.5	1.5	8.6	4.9	0.0	0.0	0.0	0.0
60+	1.6	1.6	1.2	1.0	5.5	2.8	4.7	4.7
15+	39.4 ab	21.4	31.5 ab	14.4	4.7 abc	4.7	0.0 c	0.0

Mean values in a row followed by the same letters (a–c) are not significantly different ($p < 0.05$). S.E.: standard error of the mean.

4. Discussion

Recruitment and removal of snags and CWD are of concern to managers when planning treatments including prescribed burning and thinning because of their importance as habitat elements and their contribution to fire hazards. The density of snags 1–15 cm DBH in decay classes 1–3 was significantly higher in fire only and mechanical plus fire treatments when compared with control treatments (Table 6). These snags were recruited from scorch induced tree mortality from the prescribed fires. A similar pattern of small snag recruitment in burned areas was reported for the Sierra Nevada by Morrison and Raphael (1993).

While snags of this size do not typically form habitat for many cavity nesting bird species (Laudenslayer, 1999), they can contribute to increased fire hazards (Landrum et al., 2002). Once on the ground, they can contribute to surface fuels loads resulting in increased fire line severity when burned (Brown et al., 2003; Stephens and Moghaddas, 2005). Managers burning in stands where high amounts of small tree mortality is expected should plan additional prescribed fires to reduce the additional surface fuels from tree mortality. The overall low abundance of ‘‘soft’’ snags (decay classes 4 and 5) in this study may be the result of harvest activities in the treatment units over the past 100 years. Standing soft snags can take over 80 years to create in ponderosa pine and Douglas-fir trees (Everett et al., 1999).

In this study, total sound CWD (decay classes 1 and 2) was not significantly reduced by treatments. North et al. (2002) noted a reduction in CWD volume of 70% in burned and thinned and burned plots. The most dramatic change of CWD in this study was the reduction of rotten CWD, especially in decay class 4, as a result of prescribed fire treatments. Though this reduction was significant, it is important to understand the role of rotten CWD in mixed conifer forests prior to fire suppression. Prior to 1900, the average fire return interval at Blodgett Forest was 4.7 years at the 9–15 ha scale (Stephens and Collins, 2004). Given that fires typically occurred in fall and that rotten CWD is highly susceptible to ignition when dry, it is unlikely that these forests could have sustained high levels of rotten CWD (decay classes 4 and 5) under the historical fire regime.

Consumption of rotten 1000 h timelag fuels (fuels with diameter larger than 7.5 cm) by prescribed fires has been reported to range from 76 to 99% (Covington and Sackett, 1992; Stephens and Finney, 2002). This suggests that CWD in the rotten decay classes is highly susceptible to burning and was probably maintained at a relatively low level prior to the era of fire suppression. Increased patchiness of surface and ground fuels from an intact surface fire regime could provide isolation of some rotten CWD allowing it to persist in mixed conifer forests.

The hypothesis that there were lower overall amounts of CWD in mixed conifer forests prior to fire suppression is supported in other studies (Skinner, 2002; Mount, 2002; Brown et al., 2003). Current US Forest Service Sierra Nevada Forest Plan Amendment (USDA, 2004) guidelines for CWD retention range from 59 to 118 m^3 ha^{-1} and are substantially higher than the CWD remaining in our burn units after prescribed fire.

US Forest Service CWD and snag guidelines may not be reached immediately post burn, though they may be fulfilled in the future by additional snags recruited from fire and post fire insect related mortality. Some have suggested that flexibility in snag retention guidelines may be needed to accomplish retention goals across landscapes (Everett et al., 1999; Ganey, 1999; Stephens, 2004). The high variability in CWD from this and previous studies suggests that a single average or range may not be appropriate to manage CWD and snags over a wide range of landscapes. One of the limitations on information from CWD and snag dynamics is the rarity of forests with intact disturbance regimes in western North America; most of our contemporary data come from forests that have been significantly modified by anthropogenic influences such as logging and fire suppression. The management decisions in the 20th century have probably increased CWD and snag abundance in many forest types in the western US. However, repeated harvesting that focused on larger trees has reduced the abundance of snags and CWD in larger size classes in many western US forests.

With respect to habitat, there are concerns that significant reductions in CWD can negatively impact some wildlife populations. This has been documented for several avian and mammalian species (Bull, 1999; Bunnell et al., 1999) although Pyare and Longland (2002) did not find a relationship between the abundance of CWD or snags and the occurrence of flying squirrels (*Glaucomys sabrinus* Show) in Sierra Nevada old-growth forests. This suggests that the influence of increasing or decreasing CWD and snags may be species and site specific. It is also important to note that snags created by wildfires or within prescribed burns eventually fall over and become CWD at faster rates than snags created by drought (Morrison and Raphael, 1993; Landrum et al., 2002).

5. Conclusion

Many managers are interested in soft snag and CWD availability (Everett et al., 1999; USDA, 2004). A key question is to what degree do managers protect and recruit soft snags and decayed CWD (decay classes 4 and 5) in forest types where fire was once a common ecosystem process? Active recruitment and retention of soft snags is probably not a goal that is easily integrated with the reintroduction of fire at a landscape level, particularly in forests that once experienced frequent, low–moderate intensity fire regimes. High fuel continuity from a century of fire suppression will make it difficult to retain large amounts of decayed snags and CWD during the first prescribed fires. Subsequent fires may retain more snags and CWD because fuel continuity will be reduced allowing more large woody materials to persist.

The loss of decayed CWD and snags may be an undesirable forest management outcome in some cases, though other studies have suggested that current levels of CWD are in part due to fire exclusion (Robertson and Bowser, 1999; Skinner, 2002). Retention of relatively high CWD levels and snags may benefit some wildlife species in the short-term but increases in fire hazards and increased difficulties in fire control are the consequence. High fuel loads also increase the probability of snag and CWD consumption when an area inevitably burns (Brown et al., 2003; Stephens, 2004). The influences of altering CWD and snag characteristics should be analyzed in the context of long-term forest management goals, including the reintroduction of fire as an ecosystem process and production of forests that can incorporate wildfire without tree mortality outside a desired range.

Work by Knapp et al. (2005) and data presented in this work indicated that prescribed burns implemented in the fall will have higher rates of CWD consumption than those implemented in the spring season. The higher burn severity of fall burns may result in higher rates of snag recruitment, though these snags will take time to develop into the advanced decomposition states. Managers should emphasize restoring the process of fire, which along with other agents of mortality and decay, creates and removes CWD and snags at a landscape scale.

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