Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 238 (2007) 268–279
Forest Ecology and Management
www.elsevier.com/locate/foreco

Fuel mass and stand structure after post-fire logging of a severely burned ponderosa pine forest in northeastern Oregon

J.D. McIver [a,*], R. Ottmar [b]

[a] Forestry and Range Sciences Laboratory, Pacific Northwest Research Station, La Grande, OR, USA
[b] Forestry Sciences Laboratory, Pacific Northwest Research Station, Seattle, WA, USA

Received 12 August 2006; received in revised form 20 October 2006; accepted 20 October 2006

Abstract

Stand structure and fuel mass were measured before and after a post-fire logging operation conducted 2 years after the 1996 Summit Wildfire (Malheur National Forest), in a ponderosa pine-dominated forest in northeastern Oregon. Variables were measured both pre- and post-logging in four replicate units for each of three treatments [un-logged control, commercial harvest (most dead merchantable trees removed), fuel reduction harvest (most dead merchantable trees removed plus most dead trees >10 cm diameter)]. Post-fire logging resulted in a significant decrease in mean basal area, down to 46% pre-treatment level in commercial units, and down to 25% in fuel reduction units. Logging significantly reduced tree density, especially for the smallest (<22 cm diameter) and intermediate (23–41 cm) diameter classes. Fuel reduction units also had significantly fewer snags (dead trees >30 cm diameter—4 ha^{-1}), compared to both commercial (23 ha^{-1}) units and to un-logged controls (64 ha^{-1}) in the year following timber harvest. Logging did not change ladder height or tree species composition (% ponderosa pine, Douglas-fir and grand fir). Total woody fuel mass increased significantly in fuel reduction units when compared to controls, with the greatest difference among treatments occurring in the slash fuel (<7.6 cm diameter) component (mean of 6.2 Mg/ha for fuel reduction stands versus 1.3 Mg/ha for un-logged stands). Logging activity caused no change in the mass of the forest floor (litter or duff). Model projections of the fuel bed using the fire and fuels extension of the forest vegetation simulator (FVS–FFE) indicate that the disparity in slash fuel mass between fuel reduction and un-logged units would be sustained until about 15 years post-logging, but a re-burn of moderate intensity occurring during this time would likely kill all young trees, even in un-logged units, because of the influence of other components of the fuel bed, such as grasses and shrubs. Model projections of 1000-h fuels (woody fuels >7.6 cm diameter) indicate that standing structure in all stands would collapse quickly, with the result that un-logged stands would contain two- or three-fold greater masses at 25 and 50 years post-logging, leading to much higher consumption rates of fuel in the event of a re-burn in the same place. Variation in dead tree fall and decay rates did not change the relationship among treatments in 1000-h fuel loads, but changed the time at which treatment differences were projected to disappear. Despite treatment differences in heavy fuel accumulations over time however, FVS–FFE predicts no differences among treatments in mortality of young trees due to either moderate or high intensity fire occurring in the same place at 25, 50, or 100 years post-fire logging. The lack of a re-burn effect is in part due to the reliance on flame length as the primary mechanism leading to tree death in the fire effect models used by FVS–FFE. If tree death turns out to be caused more by root burning or cambial heating, the observed variations in 1000-h fuel loadings among treatments could be significant in the event of a future re-burn.

Keywords: Salvage logging; Re-burn hypothesis; Restoration

1. Introduction

After stand replacement fires in the western United States, standard policy on most lands has been to salvage fire-killed trees as quickly as possible to recoup their economic value before decay (USDA, 1996; Aho and Cahill, 1984). Considerable public debate has focused on the merits of post-fire logging on federal lands, as evidenced from extensive public comment received on both the east-side and interior Columbia River basin environment impact statements (USDA and USDI, 1997a, b). Proponents of post-fire logging argue that the practice is one of a suite of rehabilitation methods, designed to mitigate the adverse environmental effects of the wildfire itself (Amman and Ryan, 1991; Poff, 1989), that removal of large woody structure reduces the risk of a severe re-burn (the ‘‘re-burn hypothesis’’;

* Corresponding author at: P.O. Box E, Eastern Oregon Agricultural Research Center, Oregon State University, Union, OR 97883, USA.
Tel.: +1 541 562 5129; fax: +1 541 562 5348.
E-mail address: james.mciver@oregonstate.edu (J.D. McIver).

0378-1127/$ – see front matter
doi:10.1016/j.foreco.2006.10.021

Poff, 1989), and that the sale of burned timber can be used to offset the cost of post-fire rehabilitation (Barker, 1989). Opponents argue that post-fire logging causes increases in erosion and sediment transport to streams as a result of the harvest operations themselves (Beschta et al., 2004; Minshall et al., 1994), and removes structure that has important ecological functions (Maser, 1996; Stone, 1993).

The debate has taken place in the context of relatively little scientific information on the ecological effects of post-fire logging. McIver and Starr (2000, 2001) found only 21 studies worldwide that have examined the environmental effects of post-fire logging, 14 of which had an un-logged control, and just seven of which were replicated experiments. In particular, few studies have explored the extent to which post-fire logging significantly changes forest structure. Exceptions are three recent studies on cavity-nesting birds of the northern Rocky Mountains, in which most cavity nesters are less common and build fewer nests in post-fire logged stands (Caton, 1996; Hitchcox, 1996; Saab and Dudley, 1998). Importantly, no studies have documented that post-fire logging reduces the risk of a severe re-burn (McIver and Starr, 2000, 2001) despite the conventional wisdom that removal of dead large woody structure would be expected to reduce ground fuels at some point in the future (Poff, 1989; the ‘‘re-burn’’ hypothesis).

This study was designed to evaluate the change due to logging in stand structure and fuels after a typical post-fire logging operation, and to predict future re-burn severity. The 16,000 ha Summit Fire was caused by a lightning storm on 13 August 1996, on the North Fork John Day Ranger District (Umatilla National Forest), burned south onto the Long Creek Ranger District of the Malheur National Forest, and was declared officially controlled on 16 September 1996 (Fig. 1). In the summer of 1997, three treatments (un-logged control, commercial, and fuel reduction) were applied to 12 experimental units on the Malheur National Forest. Trees (both living and dead) and fuels (down wood and the forest floor) were measured to test the ‘‘re-burn’’ hypothesis, or the extent to which removal of dead large woody structure changed the present and future fuel complex and its influence on fire severity should a re-burn occur. We also compare post-logging structure at Summit to recent studies that have examined post-fire logging effects on cavity-nesting birds.

2. Study area and treatments

The study area is located on lands in the southern portion of the burned area (Fig. 1: 44°40′49″–44°42′57″N; 118°41′40″–118°45′55″W), at relatively low elevations (1250–1400 m). The forests of the study area are considered to be in the ‘warm/dry’ biophysical type, historically dominated by ponderosa pine (*Pinus ponderosa*) in the overstory (with some representation of *Pseudotsuga menziesii* and *Abies grandis*), and pine grass (*Calamagrostis rubescens*) in the under-story. Soils are stony, clay loam to clay soils with moderate to high surface erosion and compaction hazard, and low displacement hazard (McIver and McNeil, 2006). Soils are derived from Clarno breccia parent material, but some soils have up to a 25 cm cap of Mt. Mazama ash, especially on their lower boundaries (USDA, 1997). Like most of the Blue Mountains of northeastern Oregon, management activities of the last 80 years, namely fire suppression and the harvest of large pines, have had significant effects on vegetation and fire regimes within the Summit Fire project area (Agee, 1996). During pre-settlement times, the fire regime for ponderosa pine forests growing in the project area consisted of low severity fires (<20% mortality of large trees) occurring at intervals of

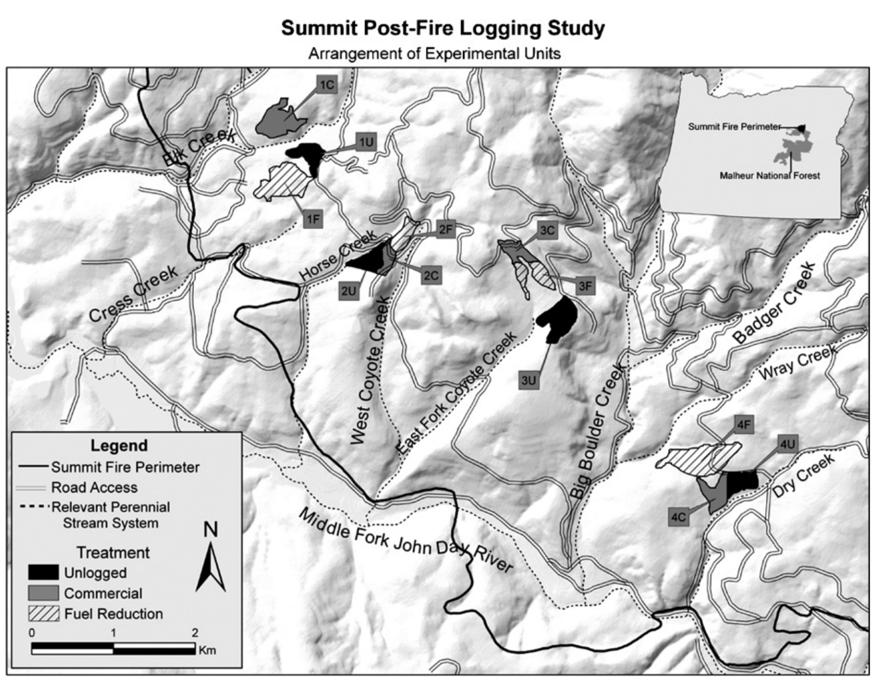

Fig. 1. Map showing location of the 12 experimental units within the southern portion of the Summit Fire, Malheur National Forest, northeastern Oregon.

between about 10 and 35 years (Agee, 1996). As a consequence of fire suppression over the past 80 years, these forests have therefore missed between two and eight wildfires in recent times, with the result that surface fuels have accumulated and become more continuous, and tree species such as grand fir and Douglas fir have become more prevalent. Coupled with the widespread removal of large pines over the same time period, these forest management practices have led to a shift toward higher wildfire severity compared to pre-settlement times (Agee et al., 1994). Not surprisingly, therefore, within the Malheur Forest portion of the Summit Fire, 8103 ha (72%) were judged to have burned at high severity (>80% large trees killed), including much of the area in the lower elevation dry forests, which typically experience lower severity fires (USDA, 1997).

Twelve experimental units ranging in size from 6 to 16 ha were established in four blocks in August 1997 (Fig. 1). Each block was located in a separate drainage, with perennial streams that flow past each block (Elk, Coyote, Wray Creeks) emptying into the Middle Fork of the John Day River. Nine of the study units (three complete blocks) were dominated by ponderosa pine, ranging from 64 to 100% overstory dominance in stem number (Table 1). The fourth block (West Coyote) had one unit about equally dominated by ponderosa pine and Douglas-fir (421), and two units (422 and 424) dominated by Douglas-fir or grand fir.

Within each block, three treatments (control, commercial, fuel reduction) were assigned randomly to units, for a complete randomized block design. Control units received no logging treatment. The prescription for commercial units was to remove most (about 2/3) of dead merchantable trees, leaving at least 17 snags/ha, greater than 30 cm DBH. The prescription for fuel reduction units was to remove most dead merchantable trees (leaving minimum 6 snags/ha), and to remove most non-merchantable trees down to 10 cm diameter. The logging prescriptions were conceived such that the commercial treatment would reflect the results of a typical modern logging operation, while the fuel reduction treatment would result in sufficient fuel mass reduction such that the severity of a future re-burn might be significantly diminished. All logging was required to take place on frozen or dry ground, to minimize soil disturbance. A total of 88 ha were logged between October 1998 and August 1999 (Table 1). Each commercial unit was entered once, while fuel reduction units were entered twice, once to remove the largest boles as part of a timber sale contract, and a second time to remove smaller boles as part of a service contract. While logs from all commercial units and the first entry of fuel reduction units were removed from the site and sold, logs from the second fuel reduction entry were stacked on the landings and left on site. Trees were felled by hand, whole trees (with limbs still attached) were cable-winched into skid trails with a tracked D6 Crawler-tractor, and retrieved to landings with a Caterpillar 518 rubber-tire grapple-skidder. No additional treatment of the material left after logging (slash) occurred on any of the treated units. Pine seedlings were planted within each of the twelve experimental units, within two years after logging, at a density of 960 stems/ha.

3. Methods and materials

All variables were measured pre- and post-logging from the same permanently established grid points. A total of 273 grid points were laid out in the 12 experimental units in August 1997, between 14 and 47 points per unit (Table 1). Grid points were positioned 50 m apart, and at least 50 m from unit boundaries. Pre-treatment data were taken in the nine units of the Elk Ck, W. Coyote, and Wray Ck blocks between August and October 1997; the three units of the E. Coyote block were sampled in September 1998. All post-treatment data were taken from July to September 1999, immediately following the termination of logging.

Trees (DBH > 10 cm) were tallied from within a 200 m^2 circular plot centered on each grid point. We recorded species, status (dead or alive), diameter at breast height, total height, and ladder fuel height (height to the lowest stem) for each tree. Basal area (m^2/ha) was calculated from tree diameter data.

Dead and down woody fuel was measured using the planar intercept method (Brown, 1974). Three 30.5 m transects were originated from each grid point, the first selected randomly, and the other established at 120° and 240° from the first. Dead and down woody fuel less than 2.5 cm diameter was tallied for the

Table 1
Key features of Summit Fire experimental units in September 1997 (Elk Ck, W. Coyote, Wray Ck blocks), and September 1998 (E. Coyote block)

Unit	Rx	Block	Area (ha)	# Grid points	Elev (m)	% Slope/ aspect	% Pond pine	% Trees killed	Forest floor (Mg/ha)	Woody fuel (Mg/ha)
1 U	Unlog	Elk Ck	8	20	1353	20/W	90	66	3.58	1.12
1 C	Comm	Elk Ck	15	35	1347	25/SW	96	96	0.90	2.91
1 F	Fuel	Elk Ck	19	47	1311	15/W	98	55	3.36	3.36
2 U	Unlog	W Coyote	6	15	1372	20/W	14	92	1.77	6.98
2 C	Comm	W Coyote	5	16	1402	20/W	22	100	0.57	6.50
2 F	Fuel	W Coyote	7	19	1402	15/S	43	98	1.45	7.51
3 U	Unlog	E Coyote	16	29	1372	10/SW	64	86	5.42	3.80
3 C	Comm	E Coyote	6	16	1402	20/S	65	100	3.49	6.26
3 F	Fuel	E Coyote	10	14	1387	20/S	86	100	1.49	7.63
4 U	Unlog	Wray Ck	7	15	1250	20/S	100	100	0.67	1.34
4 C	Comm	Wray Ck	9	18	1271	15/S	97	97	0.67	3.36
4 F	Fuel	Wray Ck	13	29	1274	20/W	99	100	0.90	2.24

Summit Fire occurred between 13 August and 16 September 1996.

first 1.9 m of each transect, and fuel between 2.5 and 7.6 cm was tallied along the full 30.5 m. Fuel >7.6 cm diameter was tallied along the full transect and recorded as to species, decay class, and diameter at intersection point. Woody fuel masses were calculated using standard equations (Brown, 1974).

Litter and duff (forest floor) was measured to the nearest 0.25 cm depth at the 12, 18, and 24 m points on the transect. Depths were converted to mass using standard bulk density values (2.9 Mg/ha cm for litter, and 11.8 Mg/ha cm for duff; Ottmar et al., 1993).

Snag, fuel bed, and tree response variables were analyzed with analysis of variance (SPSS, 2001), as a complete randomized block design (Hinklemann and Kempthorne (1994), with four blocks for each of the three treatments, and $p = 0.05$ as the standard significance level. For the four size classes of snags, and the nine components of the fuel bed, treatment type was analyzed as the only main factor for each year (1997 – pre-treatment; 1999 – post-treatment) and for the change from 1997 to 1999. For trees, each of six variables (basal area, density, % ponderosa pine, % Douglas Fir, % Grand Fir, and ladder height) was analyzed for each combination of year (1997, 1999, change) and status (dead, live, total), with treatment as the only main factor. The issue of multiplicity was dealt with by making a Bonferroni adjustment for each family of variables in which multiple ANOVAs were run (snags, fuel bed, trees) (Westfall et al., 1999). All variables were normally distributed, and thus no transformations were made. Three pair-wise comparisons (un-logged versus commercial; un-logged versus fuel reduction, commercial versus fuel reduction) were planned apriori for each analyzed variable, and were examined by least-significant difference (Hinklemann and Kempthorne, 1994).

3.1. Fuel simulation model inputs

To perform a model test of the re-burn hypothesis, post-treatment tree and fuels data for all stands were input into the FVS–FFE program (Forest Vegetation Simulator-Fire and Fuel Effects Extension; Reinhardt and Crookston, 2003). The FVS–FFE model starts with existing stands, consisting of both living and dead trees, and a fuel bed, described by masses of the forest floor and various sizes of woody material. Living trees grow, age and die, according to growth and yield equations. Dead trees decay slowly, and fall down at rates dependent on DBH (Landram et al., 2002; Mellon and Harmon, unpublished data). The fuel bed changes in accordance with the fall and decay of various stand components. For the purposes of this study, simulations were run to: (1) grow new stands of ponderosa pine in each experimental unit for 100 years, starting with the 960 stems/ha planted within two years after the fire; and (2)

Table 2
Decay and fall rates used for the 'intermediate' class, and weather conditions for light, moderate, and high intensity wildfires in FVS–FFE model simulations ('Fast' and 'Slow' decay and fall rates were ±50% of 'intermediate' class)

Surface fuel decay	Ponderosa pine	Douglas-Fir	W. Larch	Grand Fir	W. Juniper
Duff	0.0008	0.0008	0.0008	0.0008	0.0008
Litter	0.2000	0.2000	0.2000	0.2000	0.2000
Wood <2.5 cm diameter	0.1000	0.1000	0.1000	0.1000	0.1000
Wood 2.6–7.6 cm	0.0900	0.0800	0.0800	0.0950	0.0800
Wood >7.6 cm	0.0300	0.0200	0.0200	0.0350	0.0200
Snag decay—all Sizes	0.0150	0.0100	0.0100	0.0180	0.0090
Snag fall, <25 cm diameter	0.1260	0.0680	0.0620	0.0730	0.0245
Snag fall, 26–75 cm	0.0780	0.0430	0.0450	0.0485	0.0245
Snag fall, >75 cm	0.0300	0.0180	0.0280	0.0240	–

Weather conditions	Fire intensity		
	Light	Moderate	High
Fuel moisture			
Duff	75%	50%	15%
Wood, <2.5 cm diameter	12%	8%	4%
Wood, 2.6–7.6 cm	15%	10%	5%
Wood, >7.6 cm	20%	15%	10%
Live fuel	150%	110%	70%
Wind speed	5 km/h	10 km/h	36 km/h
Temperature	22 °C	22 °C	22 °C

Information source used for setting 'intermediate' fall and decay rates
Litter: litter bag decomposition data (McIver, unpublished data)
Duff: 1/250th of litter decay rate (Reinhardt and Crookston, 2003)
Woody fuel: <2.5 cm diameter (Abbot and Crossley, 1982)
Woody fuel: 2.5–7.5 cm diameter (Mellon[a] and Harmon[b], unpublished data)
Woody fuel, >7.5 cm diameter (Busse, 1994; Harmon et al., 1996, 2004, Mellon and Harmon, unpublished data)
Snag decay (Mellon and Harmon, unpublished data)
Snag fall (Mellon and Harmon, unpublished data, Landram et al., 2002).

[a] Kim Mellon, Regional Wildlife Ecologist, USDA Forest Service, PNW Region, Portland, Oregon.
[b] Mark Harmon, Forest Ecologist, Department of Forest Science, Oregon State University, Corvallis, Oregon.

generate fuel loadings every 5 years for 100 years post-logging, given fuel loads and stand conditions that existed in the year after post-fire logging; (3) run simulated fires through the new stands at various time intervals, to determine the effect of variation in the fuel bed (caused by post-fire logging) on tree mortality.

Obviously, the manner in which the fuel bed develops in burned stands that have been logged will depend in part on the rate at which dead trees fall and decay. We used available empirical evidence to set fall rates for each relevant species (Table 2). Because of uncertainty in fall rates for dead trees in the Blue Mountains of Oregon, we ran simulations at our best estimate using available empirical data ('intermediate' rate), and at ±50% of this rate ('fast' and 'slow' rate, respectively). Once dead trees fall to the ground, they are counted as woody fuel, and they begin to decay at a much higher rate than when standing. We used three different decay rates, an 'intermediate' rate that was our best estimate for decay given available empirical information in similar forest types (Table 2), and a 'fast' and 'slow' rate that were ±50% of the intermediate rate, respectively. Simulations were run for each experimental unit with each possible combination of fall and decay rates. Then we applied both high (very dry conditions; Table 2) and moderate (dry) intensity fires at 25, 50, and 100 years post-fire harvest, using tree mortality as a measure of fire severity. Projected characteristics of the fuel bed at the time of the simulated fire were first used to select the appropriate fuel model. Fire severity was then estimated given prescribed weather conditions to determine flame length and scorch height, both of which influenced tree mortality. Surface fire severity was calculated using Rothermel's 1972 fire behavior prediction model, as implemented in FIREMOD (Albini, 1976). Results are presented descriptively, because ANOVA is inappropriate due to non-independence of the fire severity variable (tree mortality) after application of the model.

4. Results

4.1. Pre-logging conditions

Since no pre-fire data were taken, estimates of Summit Fire severity depend on the assumption that the great majority of dead trees observed 1 year after the fire (1997) were killed by the wildfire. Given this assumption, the Summit Fire was relatively severe for a ponderosa pine dominated forest (see also USDA, 1997), with nine of the 12 experimental units having more than 92% of their stems classified as dead in 1997 (Table 1). Tree mortality was patchy within the study area, with the northwestern Elk Creek block averaging 70%, compared to 99% mortality for trees in the southeastern Wray Creek block. Variation in tree mortality among blocks was not due to dominant tree species, as both Elk Creek and Wray Creek were dominated by ponderosa pine, while the two Coyote Creek blocks that had intermediate tree mortality were represented by a greater percentage of Douglas-fir (Fig. 1, Table 1). Pre-logging analysis found no significant differences in basal area, stem density, snag density, tree species composition, ladder height, or for any component of the fuel bed (Table 3).

Table 3

Mean (±S.E. in parentheses) basal area (m^2/ha), density (trees/ha), species composition (% stems Ponderosa pine, Douglas Fir, Grand Fir), and ladder height (m) of dead and live trees pre-logging (1997/1998), post-logging (1999), and change between pre- and post-logging for unlogged, commercial, and fuel reduction units at Summit

Variable	1997 (pre-log)			1999 (post-log)			Change (post–pre)		
	Unlogged	Commercial	Fuel red	Unlogged	Commercial	Fuel red	Unlogged	Commercial	Fuel red
Dead									
Basal area (m^2/ha)	11.4 (2.7)	14.3 (2.7)	13.9 (1.3)	11.7 (2.5)[*a]	7.0 (0.7)[ab]	3.2 (0.5)[b]	**0.2 (0.6)**[*a]	**−7.3 (3.1)**[b]	**−10.7 (1.3)**[b]
Tree density (# ha^{-1})	181 (52)	261 (16)	283 (22)	185 (44)	151 (24)	114 (10)	**4 (9)**[*a]	**−110 (34)**[b]	**−169 (17)**[b]
% Pond pine	64.9 (19.6)	69.4 (17.8)	78.4 (12.9)	63.3 (18.9)	68.4 (17.9)	80.6 (11.7)	**−1.6 (2.2)**	**−1.0 (1.8)**	**2.1 (1.8)**
% Doug. Fir	23.1 (14.6)	21.8 (16.2)	17.3 (12.8)	11.1 (5.7)	15.9 (15.7)	3.7 (3.7)	**−12.1 (10.7)**	**−5.9 (2.9)**	**−13.7 (9.3)**
% Grand Fir	7.7 (4.5)	6.6 (5.2)	0.4 (0.4)	21.9 (11.6)	14.5 (9.6)	10.3 (9.1)	**14.2 (9.2)**	**7.9 (4.6)**	**9.9 (9.2)**
Ladder height (m)	4.2 (0.2)	3.7 (0.4)	4.1 (0.3)	3.9 (0.6)	3.0 (0.5)	3.2 (0.2)	**−0.3 (0.7)**	**−0.7 (0.5)**	**−0.9 (0.3)**
Live									
Basal area (m^2/ha)	3.8 (1.4)	1.6 (1.0)	4.7 (1.7)	2.6 (1.1)	0.3 (0.2)	1.4 (1.4)	**−1.2 (0.4)**	**−1.3 (0.9)**	**−3.3 (1.2)**
Tree density (# ha^{-1})	37 (16)	13 (7)	47 (24)	23 (11)	3 (2)	19 (19)	**−14 (5)**	**−10 (6)**	**−28 (10)**
% Pond pine	74.2 (16.1)	100.0 (0)	82.2 (16.9)	60.9 (20.3)	100.0 (0)	98.6 (1.4)	**−13.3 (13.3)**	**0 (0)**	**16.4 (16.4)**
% Doug. Fir	20.4 (12.8)	0 (0)	17.6 (17.0)	30.8 (13.5)[a]	0 (0)[b]	0 (0)[b]	**10.4 (10.4)**	**0 (0)**	**−17.6 (17.0)**
% Grand Fir	4.5 (3.4)	0 (0)	0 (0)	8.3 (8.3)	0 (0)	0.7 (0.7)	**3.7 (3.7)**	**0 (0)**	**0.7 (0.7)**
Ladder height (m)	3.5 (1.0)	3.8 (0.5)	4.9 (0.6)	2.2 (0.7)	1.9 (0.4)	9.7 (5.9)	**−1.3 (1.3)**	**−1.9 (0.9)**	**4.8 (4.8)**
Total									
Basal area (m^2/ha)	15.2 (1.8)	15.9 (2.2)	18.7 (1.9)	14.3 (1.7)[*a]	7.3 (0.9)[b]	4.6 (1.2)[b]	**−0.9 (0.4)**[a]	**−8.5 (2.5)**[b]	**−14.0 (2.4)**[b]
Tree density (# ha^{-1})	218 (40)	274 (10)	330 (33)	209 (34)	154 (25)	133 (13)	**−10 (6)**[*a]	**−120 (29)**[b]	**−197 (26)**[c]
% Pond pine	67.0 (19.3)	69.9 (17.7)	78.5 (13.2)	64.7 (19.0)	68.5 (17.9)	80.8 (11.4)	**−2.3 (2.4)**	**−1.4 (1.7)**	**2.3 (1.9)**
% Doug. Fir	22.3 (14.5)	21.5 (16.1)	17.6 (13.3)	12.4 (6.3)	15.9 (15.7)	3.6 (3.6)	**−9.9 (10.3)**	**−5.6 (2.9)**	**−14.0 (9.8)**
% Grand Fir	7.0 (4.0)	6.6 (5.2)	0.4 (0.4)	19.5 (11.4)	14.5 (9.7)	10.0 (8.9)	**12.5 (8.7)**	**7.9 (4.6)**	**9.6 (9.1)**
Ladder height (m)	3.8 (0.3)	3.7 (0.4)	4.1 (0.3)	3.8 (0.5)	3.0 (0.5)	3.4 (0.3)	**−0.1 (0.6)**	**−0.7 (0.5)**	**−0.7 (0.1)**

All variables analyzed for each year (pre-logging, post-logging, and pre–post change) and status (dead, live, total) with ANOVA (indicated in bold), with different letters in superscript representing significant difference in paired comparisons (LSD test) among treatments for that year and status. [*]Denotes significant difference overall among treatment means for that variable ($p < 0.01$ after Bonferroni adjustment), within the given year and status class.

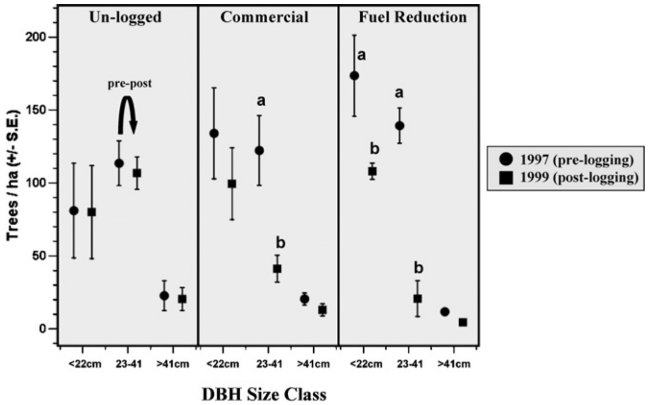

Fig. 2. Trees/ha for all trees (living + dead) measured pre- and post-logging (1999) in un-logged, commercial, and fuel reduction units, Summit Fire study, northeastern Oregon. Different letters over bars indicate significant difference ($p < 0.01$, after Bonferroni adjustment) between pre- and post-treatment densities in paired comparisons within each treatment type.

4.2. Logging effects

Tree density was reduced by logging in all units, and paired comparisons indicated that controls differed significantly from both commercial and fuel reduction units ($p = 0.01$; Table 3). The great majority of stems removed were in the intermediate diameter classes: thus while logging in the fuel reduction units lowered the number of the smallest stems (10.2–22.9 cm diameter class) down to 68% of initial density, logging reduced stem density down to 15% and 30% in the 23.0–40.6 cm and 40.7–63.4 cm diameter classes respectively (Fig. 2). The same pattern of logging effects on stem density was observed for dead trees, with logging significantly reducing stem density in both commercial ($p = 0.01$) and fuel reduction units ($p = 0.01$) compared to controls. No differences were observed for live trees, because so few live trees survived the fire, and the variability among units within each treatment was so large.

Logging resulted in significantly fewer numbers of snags/ha (dead trees larger than 30 cm diameter), especially in fuel reduction units, which averaged four snags per ha, compared to 64 ha^{-1} for the un-logged controls ($p = 0.01$). Thus while snag numbers remained about the same in un-logged controls, snags were reduced by an average of 52 and 54 ha^{-1} in the commercial and fuel reduction units, respectively (Table 4).

Stem removal by logging resulted in a significant decrease in basal area of trees (living + dead), down to 46% of pre-treatment level in commercial units, and down to 23% in fuel reduction units ($p = 0.01$; Table 3). In paired comparisons, controls differed significantly ($p < 0.01$) in basal area change from both commercial and fuel reduction units, while there was no significant difference in basal area change between the two logged units. The same patterns of logging effect were observed for dead trees, with logging having removed significantly greater basal area compared to controls ($p = 0.01$). No treatment effects were observed for live trees, because so few live trees remained after the fire, and the variability among units within each treatment was relatively large.

The reduction in tree density and basal area due to logging led to a substantial difference among treatments in standing dead tree mass. Thus, three of the four control units had the highest mass of standing dead trees in the year after post-fire logging (1999), ranging from 30 to 55 Mg/ha (Fig. 3). Un-logged unit 1U had a fairly low post-logging mass of standing dead trees, because nearly 50% of the trees were still alive at the time of post-treatment measurements in 1999 (Table 1). Commercial units ranged from 10 to 25 Mg/ha stand dead tree mass, while fuel reduction units ranged from 4 to 14 Mg/ha, the year after post-fire logging.

There were no significant logging effects on ladder height or tree species composition (% ponderosa pine, % Douglas-fir, % grand fir) for dead, live or total trees (Table 3). Most units however, irrespective of treatment, experienced a decline in the percentage of standing Douglas-fir, and an increase in the percentage of standing grand fir (Table 3). Mean height and mean ladder height also declined in all units, indicating that stands were already beginning to collapse three years after the Summit Fire.

Total surface fuel mass (forest floor + woody fuel) increased in all experimental units by 1999 (3 years post-fire and 1 year post-logging) (Table 5). Although there was no significant difference among treatments in total surface fuel mass change, logging resulted in significant increases in the mass of 10- and 100-h fuel ($p < 0.01$; Table 5). In addition, fuel reduction units experienced a significant increase in 1000-h fuels, relative to un-logged controls ($p < 0.01$). No difference in mass change among treatments was observed for the forest floor (Table 5). The increase in forest floor mass observed in all treatments between 1997 and 1999 was largely due to needle fall.

Table 4
Mean number/ha (±S.E. in parentheses) of small (30–39.9 cm DBH), medium (40–49.9 cm DBH) and large (>50 cm DBH) snags (dead trees) in unlogged, commercial, and fuel reduction units, pre-logging (1997), post-logging (1999), and change (1999 minus 1997), Summit post-fire logging study, northeastern Oregon

Snag DBH	1997			1999			Change		
	Unlogged	Commercial	Fuel red	Unlogged	Commercial	Fuel red	Unlogged	Commercial	Fuel red
30–39.9 cm	44 (8)	59 (24)	49 (6)	49 (12)^{*a}	10 (2)^{b}	1 (1)^{b}	**5 (6)**^{*a}	**−49 (25)**^{b}	**−48 (6)**^{b}
40–49.9 cm	15 (9)	13 (5)	5 (1)	12 (6)	12 (4)	2 (1)	**−3 (4)**	**−1 (2)**	**−3 (2)**
>50 cm	2 (1)	3 (1)	4 (4)	3 (2)	1 (1)	1 (1)	**1 (1)**	**−2 (1)**	**−3 (5)**
Total	61 (17)	75 (29)	58 (8)	64 (20)^{*a}	23 (5)^{ab}	4 (2)^{b}	**3 (7)**^{*a}	**−52 (27)**^{b}	**−54 (9)**^{b}

All variables analyzed for each year (pre-logging, post-logging, and post minus pre-change) with one-way ANOVA (indicated in bold), with different letters in superscript representing significant difference in paired comparisons (LSD test) among treatments for that year and status. *Denotes significant difference overall among treatment means for that variable ($p < 0.01$ after Bonferroni adjustment), within the given year.

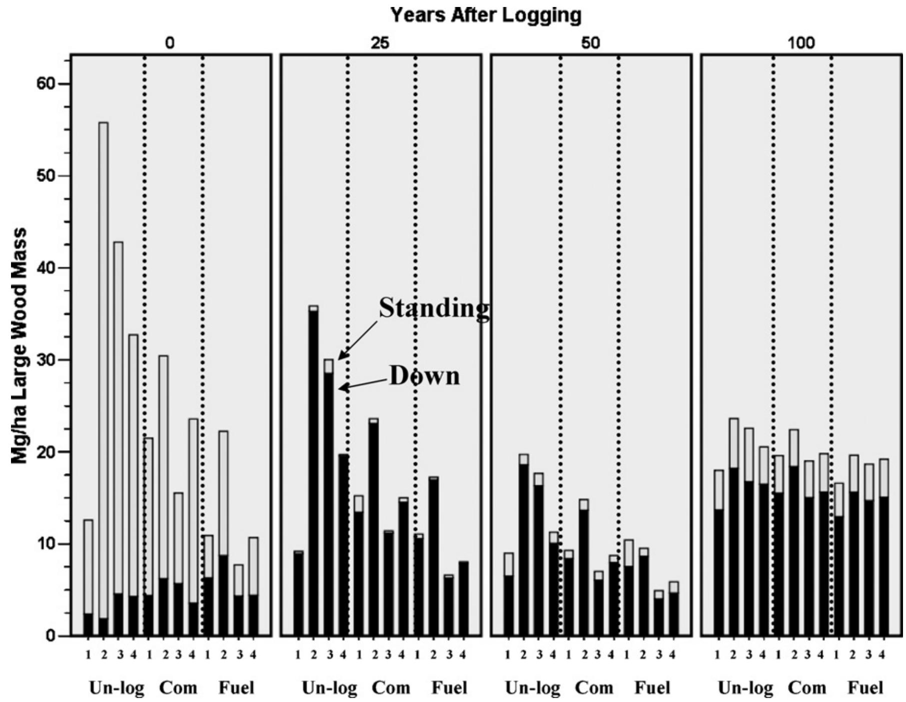

Fig. 3. Estimated mass (Mg/ha) of woody fuel (1000 and 10 + 100-hr) <1, 25, 50, and 100 years post-fire logging, for un-logged, commercial, and fuel reduction units at Summit. *Masses at <1 years post-fire logging are actual measurements from Brown's transects; masses at 25, 50, and 100 years are projections using FVS–FFE.

4.3. Fuel and fire simulations

The general effect of variation in fall and decay rates can be seen by simulating fuel loadings for a representative un-logged unit (4U) for a 100-year time span (Fig. 4). A glance at surface fuel mass projections for intermediate fall and decay rates (middle curve of the nine-curve set) indicates a steep rise to a peak mass at about 25 years post-logging, a leveling out between 25 and 50 years, and then a steady increase to 100 years. The shape of this curve is due primarily to the fall of dead tree mass for the first 25 years, a balance between tree fall and decay for the next 25 years, and then an accumulation of fuel due to the increasing dominance of the new stand for the final 50 years of the simulation. Thus, under conditions of intermediate fall and decay rate (our best estimates using available empirical data; Table 2), the influence of factors affecting the original stand becomes negligible after about 50 years post-logging. Differences in fall rate simply change the rate at which the stand peaks in mass (15 years versus 45 years for fast and slow fall rates, respectively), while differences in decay rate change the magnitude of mass in the surface fuel bed, especially after about 50 years post-logging. These simulations suggest that it would be most informative to compare how fuel beds develop for the three treatments over the

Table 5
Mean mass (Mg/ha, S.E. in parentheses) forest floor and woody fuel pre-logging, post-logging, and change in control, commercial and fuel treatment units, Summit post-fire logging study, northeastern Oregon, 1997–1999

Fuel class	1997 (pre-log)			1999 (post-log)			Change (pre–post)		
	Unlogged	Commercial	Fuel	Unlogged	Commercial	Fuel	Unlogged	Commercial	Fuel
Forest floor (litter + duff)	2.9 (1.0)	1.4 (0.7)	1.8 (0.5)	6.2 (1.7)	4.8 (1.5)	5.5 (1.2)	**+3.3 (2.1)**	**+3.4 (1.9)**	**+3.7 (0.8)**
Woody fuel	3.3 (1.4)	4.8 (0.9)	5.2 (1.4)	4.7 (0.8)[a*]	9.3 (1.5)[b]	11.4 (1.0)[b]	**+1.3 (1.7)**[a*]	**+4.5 (0.9)**[ab]	**+6.2 (1.3)**[b]
<2.5 cm	0.1 (0.1)	0.1 (0.1)	0.2 (0.1)	0.6 (0.1)[a*]	1.3 (0.5)[ab]	1.8 (0.2)[b]	**+0.5 (0.1)**[a*]	**+1.2 (0.5)**[ab]	**+1.6 (0.1)**[b]
2.6–7.6 cm	0.4 (0.1)	0.3 (0.1)	0.5 (0.1)	0.9 (0.1)[a*]	3.0 (0.6)[b]	3.6 (0.3)[b]	**+0.4 (0.2)**[a*]	**+2.7 (0.5)**[b]	**+3.2 (0.3)**[b]
7.7–15.2 cm	0.6 (0.2)	0.7 (0.1)	0.8 (0.2)	0.9 (0.1)[a*]	1.5 (0.1)[a]	2.8 (0.3)[b]	**+0.3 (0.2)**[a*]	**+0.8 (0.1)**[a]	**+2.0 (0.2)**[b]
15.3–22.9 cm	0.9 (0.4)	0.7 (0.2)	0.6 (0.2)	1.3 (0.3)	1.8 (0.3)	1.8 (0.6)	**+0.4 (0.7)**	**+1.1 (0.1)**	**+1.2 (0.3)**
23–50.8 cm	1.1 (0.6)	1.9 (0.6)	2.2 (0.9)	0.9 (0.3)	1.4 (0.3)	1.2 (0.4)	**−0.2 (0.8)**	**−0.5 (0.5)**	**−1.0 (0.6)**
>50.8 cm	0.1 (0.1)	1.1 (0.4)	1.0 (0.5)	0.1 (0.1)	0.3 (0.2)	0.2 (0.2)	**0.0 (0.0)**	**−0.8 (0.6)**	**−0.8 (0.4)**
Total fuel (forest floor + woody)	6.2 (1.7)	6.2 (1.4)	7.0 (1.4)	10.9 (1.2)	14.1 (2.9)	16.9 (1.9)	**+4.7 (1.2)**	**+7.9 (2.8)**	**+9.9 (2.0)**

All variables analyzed with ANOVA (indicated in bold), with different letters in superscript representing significant difference in paired comparisons among treatments (LSD test) within each sampling year (1997, 1999), and for change. *Denotes significant difference overall among treatment means for that variable ($p < 0.005$ after Bonferroni adjustment) within each sampling year and for change.

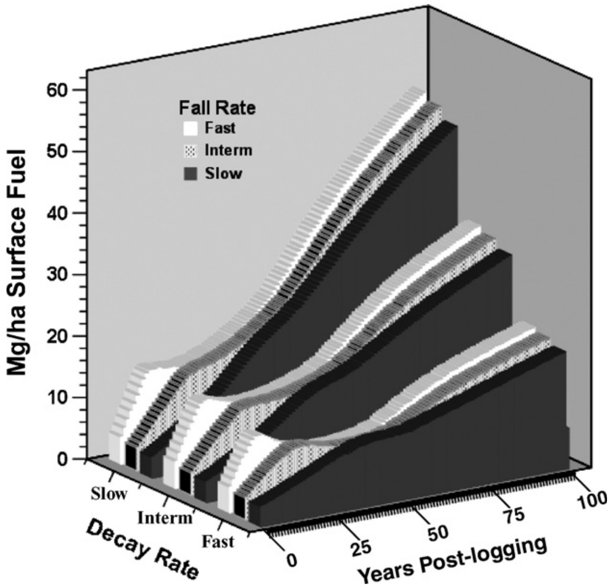

Fig. 4. Estimated mean mass of surface fuel (Mg/ha ± S.E.) in 100-year simulation for un-logged unit 520, given variation in fall and decay rates (see Table 2 for specifications).

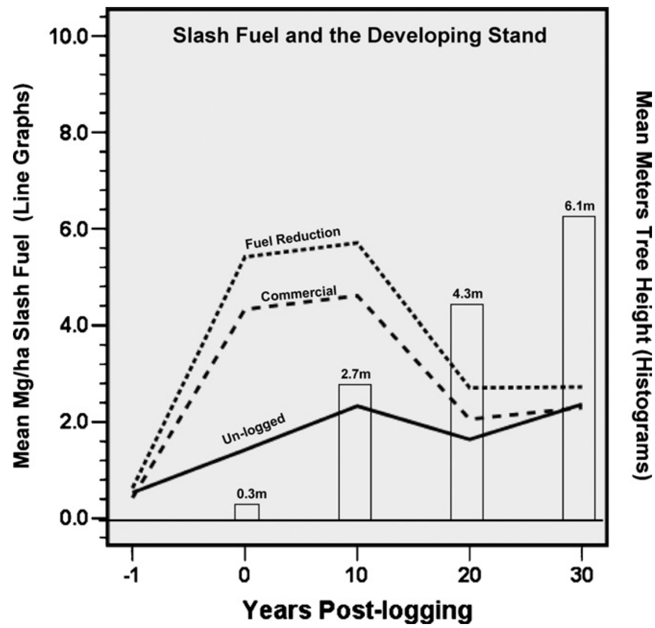

Fig. 5. Mean mass (Mg/ha) of slash fuel (<7.6 cm diameter wood) in un-logged, commercial, and fuel reduction units pre-logging (years = −1), immediately post-logging (years = 0), and in ten-year increments up to 30 years post-logging, and mean tree height (m) of the new developing stand projected for each experimental unit. *Pre-logging and immediate post-logging data are actual measurement using Brown's transects; masses for post-logging years 10–30 are projections (intermediate decay rates) using FVS–FFE.

first 50 years post-logging. For the most part, we will use intermediate fall and decay rates for the simulations, because they represent our best estimates using available data. Variation in fall and decay rate would likely change only the absolute estimates of fuel mass and tree mortality in the simulations, not the relative patterns that we see among treatments. Finally, since the principal differences among treatments immediately after logging were higher slash fuel masses in logged units, and higher standing fuel masses in un-logged units, we will present simulations first of how the slash component (10 + 100-h fuel) of the fuel bed develops through time, followed by projections of how the log component (1000-h fuel) develops.

Given intermediate decay rates, the initial post-logging difference in slash fuel mass among treatments is projected to disappear by 20 years post-logging, with the maximum divergence among treatments occurring at about 10 years (Fig. 5). Because the developing stands at 10 years post-logging are composed of a high density of very small trees (mean height 2.7 m), the effects of even a moderate wildfire will tend to be relatively severe. For example, a moderate wildfire at 10 years post-logging would generate scorch heights exceeding mean tree height, and would be projected to kill over 95% of all young trees, regardless of post-fire logging treatment. A light intensity wildfire at 10 years post-logging would be expected to kill about half of the trees in the developing stand, with no difference expected among logging treatments. This is because other components of the fuel bed (live fuels such as grasses and shrubs) are similar in both logged and un-logged stands at 10 years post-logging, and thus the logging-induced disparity in slash fuels is not great enough to result in differences in tree mortality. At 20 years post-logging, the logging-induced disparity in slash fuels has disappeared (Fig. 5), and so projections of tree mortality among stands are equivalent beyond this point in time. In conclusion, FVS–FFE predicts that the slash fuels generated in the 1998/1999 logging operation would have no fire severity consequences for the developing stand.

While the slash component of the fuel bed converges among treatments by 25 years post-logging, temporal patterns of the log component differ markedly among treatments (Fig. 3), and differences persist for a longer period of time. First, total dead tree fuel mass (standing + down) just after logging (year 0) is much higher in the un-logged controls compared to the logged stands. The only exception to this pattern is un-logged unit 1U, a stand that initially experienced only 66% mortality of trees due to the 1996 Summit Fire (Table 1). For this stand, total dead tree masses shown in Fig. 3 are substantially lower compared to other un-logged controls for year 0, because a much higher proportion of trees in this stand survived the 1996 wildfire, and were alive at the time the stands were measured in 1999. Thus, given the objectives of this study, we compare only results of un-logged control stands 2, 3, and 4U, with the logged stands. By year 25, most of the dead trees are projected to fall and become surface fuel, and un-logged control stands (2, 3, and 4U) have double the log mass of commercial stands (28 Mg/ha versus 14 Mg/ha) and triple the log mass of fuel reduction stands (28 Mg/ha versus 9 Mg/ha). These differences still persist at 50 years post-logging, with un-logged stands having 15 Mg/ha of log mass, compared to 9 and 6 Mg/ha for commercial and fuel reduction stands, respectively (Fig. 3). When a moderate fire (see Table 2 for specifications) at post-fire year 25 is simulated to occur, log masses are projected to consume proportionately, with the three un-logged units (2, 3, and 4U) having the highest consumption rates. In fact, for each fire simulation, fuel consumptions are closely related to loadings of 1000-h fuels, for both moderate and high intensity fires. Despite these much higher consumptions of 1000-h fuel in the un-logged units however, the proportion of small stems (10–22 cm DBH) projected to be killed in a moderate re-burn at 25 years did not differ according to treatment, with mortality of these trees ranging from 60 to 85%, regardless of initial logging treatment. In the event of a high intensity fire at 25 years post-logging, all trees, regardless of size and treatment, are projected to be killed. Similar patterns of tree mortality are projected to occur in the event of a re-burn 50 years post-logging, with the proportion of medium stems (23–41 cm DBH) killed by a moderate fire ranging from 14 to 25% among units, and with mortality ranges among units evenly distributed within each logging treatment type. If a high intensity fire were to occur 50 years post-logging, mortality of medium sized trees ranges from 80–90%, and again ranges of mortality within each treatment are nearly identical. These results, in which mortality of trees is unrelated to loadings of 1000-hr fuels, are due to the simple fact that the fire behavior and effects models used by FVS–FFE (BEHAVE and FOFEM), predict tree mortality due to the extent of crown scorch and bole char, which vary in accordance with loadings of 10 and 100 fuels, not 1000-h fuels. Thus, despite two- or three-fold differences among units in 1000-h fuels at each time period, the fuel models [primarily fuel models 2 (trees with grass under-story), and 9 (moderate surface fuels), Anderson, 1982], that are assigned to these stands are closely similar for all units at each point in time post-treatment, for both moderate and high intensity fires. Results

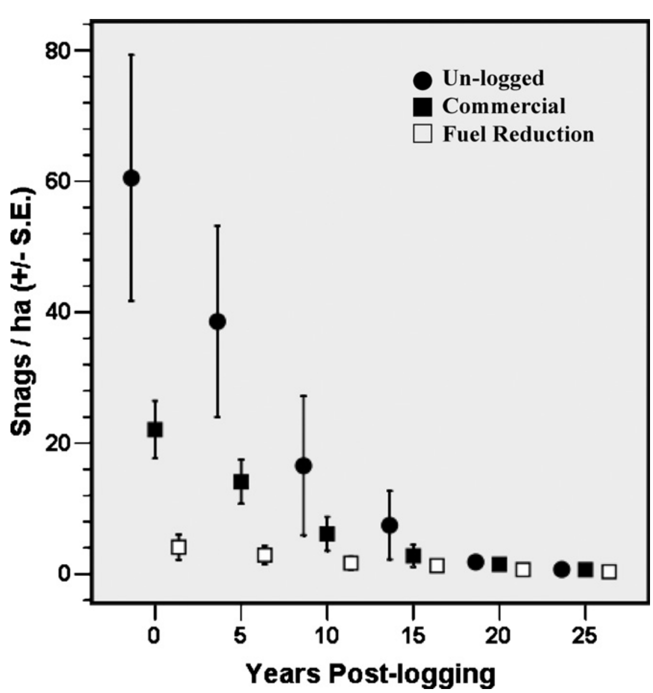

Fig. 6. Number of snags per ha (mean ± S.E.) in un-logged, commercial, and fuel reduction units at Summit, from immediately post-logging (<1 year) to 25 years post-fire logging. Immediate post-logging data from Brown's transects; densities from 5 to 25 years estimated using FVS–FFE Model (intermediate fall rates).

using FVS–FFE therefore do not support the hypothesis that post-fire logging will result in lower mortality of trees in the event of a future re-burn.

Given intermediate snag fall rates (see Table 2), snag numbers are projected to decline to near zero by 25 years post-logging. Logging treatments however, are projected to cause lower numbers of snags through 15 years post-logging (Fig. 6). By 20 years, this treatment effect is projected to disappear.

5. Discussion

The 1996 Summit Fire was relatively severe for a forest dominated by ponderosa pine. In the year following the fire, the average stand consisted of between 200 and 300 stems/ha of largely dead, charred tree boles, standing above a forest floor with a substantial amount of exposed mineral soil. By 1999, three years after the fire, un-logged control units had already begun to change. About 10% of standing dead trees had fallen over, increasing woody fuels from about three to five Mg/ha. Forest floor mass had more than doubled, and consisted of needles that had fallen from dead trees, and grasses that had either sprouted or planted themselves after the fire. Exposed mineral soil had declined from 17 to 1%, due largely to litterfall from dead trees, and to the development of the grass and forb community. These changes in control units demonstrate that in the absence of post-fire management activities, the standing structure of a severely burned forest can be expected to collapse quickly. On the other hand, the accumulation of forest floor and woody fuel mass, and the re-establishment of the under-story quickly mask the initial ground-level effects of the burn.

Post-fire logging had significant effects on this process of stand collapse. On average, logged units had about half the density of trees and less than half the basal area compared to pre-harvest levels. Logging activity doubled the mass of woody fuels, particularly in the smaller size classes. The increase in total woody fuel was the result both of logging activity creating slash, and the natural fall-down of dead trees. Forest floor mass also doubled, to an extent similar to controls, and was largely a consequence of needle fall. Exposed mineral soil fell off precipitously, from 42 to 3% in commercial units, and from 23 to 0.5% in fuel reduction units. Given these results, how has post-fire logging of stands burned by the Summit Fire changed the likely progression of forest function and structure in the study area, for the short- and long-term? We will discuss possible implications of post-fire logging at Summit including: (1) the potential effects of tree removal on fire-dependent bird species; (2) the effects of logging activity and tree bole removal on short and long-term fuel loadings, and on potential severity of wildfires that may burn in the future.

On average, fuel reduction units had about two-thirds as many trees and about one-third as much basal area as un-logged control units after the logging of 1998. Much of the difference between fuel reduction and un-logged units was in the intermediate and larger size classes of trees, most of which were dead, and it is these larger snags that are considered to be critical habitat for fire-associated bird species (Hutto, 1995;

Kotliar et al., 2002). In particular, many fire-associated birds are cavity-nesters, and use large fire-killed snags for primary nesting habitat. Many of these same bird species also find burned forests excellent foraging habitat, especially those species that feed primarily on insects. Several recent bird studies in post-fire logged mixed-conifer stands similar to Summit suggest that despite some idiosyncrasies among sites, in most cases cavity-nesting birds that use burned forests tend to select nesting sites that have higher densities of the larger snags (Caton, 1996; Hitchcox, 1996; Saab and Dudley, 1998; Haggard and Gaines, 2001). Thus, postfire logging prescriptions that require significant retention of the largest snags will generally provide higher quality nesting and foraging habitat for cavity-nesting bird species. For example, the 'partial' cut of Caton (1996) (retention of ~10 m^2/ha basal area trees), the 'wildlife' treatment of Saab and Dudley (1998) (retention of ~1/2 of snags >30 cm DBH), and the 'medium' treatment of Haggard and Gaines (2001) (retention of 15–35 snags/ha), each produced conditions that were relatively more favorable to cavity-nesting birds, while still allowing some level of tree harvest. By comparison, the 'commercial' treatment of the present study produced stands that averaged ~17 large snags/ha, and thus likely provided higher quality habitat for cavity-nesting birds, compared to stands that experienced the fuel reduction treatment.

In general, the process of felling trees and retrieving them to landings generates slash, composed of relatively small diameter woody debris (<7.6 cm diameter). Slash is created even in thinning operations that remove only a portion of the overstory (Weatherspoon, 1996; McIver et al., 2003), and tends to increase short-term fire risk by providing the kind of fuel necessary to introduce ground fires into the canopy, thereby increasing the probability of tree-killing crown fires (Weatherspoon and Skinner, 1995). The positive relationship between slash and short-term fire risk is of special concern in cases where it is desirable to protect either a residual or a developing stand. For thinning operations designed to create growing space for residual trees, it is obviously desirable to minimize the risk of future crown fire, by treating slash fuels left by the thinning activities. In the case of post-fire logging, it is similarly desirable to protect the developing stand, whether it has been planted or has regenerated naturally. For this reason, Donato et al. (2006) argued that the significant increase in slash fuels generated by logging after the 2002 Biscuit Fire in southwest Oregon (mean of ~6.7 Mg/ha for logged stands versus ~1.3 Mg/ha for un-logged stands) created an undesirable fire risk hazard for the developing stand. At Summit, we measured closely similar post-logging masses of slash fuels as those measured for the Biscuit Fire (mean of 6.2 Mg/ha for logged stands versus 1.3 Mg/ha for un-logged stands; Table 5). Yet the projected risk of the greater mass of slash fuels in our logged stands was likely no higher than for the un-logged stands, for two reasons. First, because slash decays so quickly, the period of time during which un-logged and logged units have meaningfully different slash fuel masses is short, somewhat less than 20 years. Thus, a wildfire would have to re-occur at the same place during this relatively short period of time, in order for the difference between logged and un-logged stands to be expressed in terms of tree mortality. Second, and most importantly, the developing stand that is at risk in the short-term would initially be composed of very small trees, many of which would not survive even a relatively light intensity fire (see Table 2 for specifications used in our analysis), let alone a moderate wildfire. In particular, a moderate wildfire burning in either un-logged or logged stands 10 years post-logging at Summit would be projected to generate scorch heights higher than the mean height of trees in the developing stand, with the result that all of these small trees would be killed. These scorch heights would likely be generated even in un-logged control stands that have very low masses of slash fuels, due to the influence of other components of the fuel bed such as grasses and shrubs. As for the conclusions drawn in the Biscuit Fire study (Donato et al., 2006), it is possible that the conditions in southwest Oregon that drive rates of slash fuel decay and tree growth are different enough from those at Summit in northeast Oregon, such that the observed slash fuel masses in logged units could conceivably create relatively greater fire risk problems in the short term. For example, higher annual precipitation in the Biscuit Fire ecosystem could drive more rapid re-growth and colonization of live fuels such as shrubs, which could interact with slash fuels in such a way as to create significantly higher short-term fire risks. Of course, higher precipitation would also drive higher decay rates of the slash fuels, thus decreasing the window of time during which risk would be a significant issue. In general, how logging-generated slash fuels influence future stand development will tend to vary from site to site, in accordance with a wide variety of factors. For this reason, real-time experimental studies such as those of Donato et al. (2006), as well as the current study, will always need to be interpreted in the context of these factors, in order for us to fully understand the range of possible outcomes of postfire logging. At the present time, probably our best alternative means of understanding how slash fuels generated by postfire logging influence short-term fire risk is to conduct retrospective studies in forests that have burned twice within a 25-year time period, in which we can measure fire severity in stands that were either logged or un-logged after the first burn. An excellent opportunity is the Bisquit Fire itself, where a portion of the fire burned over the Silver Fire of 1988.

Model projections of post-logging fuels at Summit indicate that post-fire logging is likely to have a significant effect on heavy fuel loadings for about 50 years after the initial fire. The time it takes for residual heavy fuels to become incorporated into the forest floor depends on both tree fall and wood decay rate, but the among-treatment patterns projected by the FVS–FFE model are consistent regardless of these rates, with un-logged controls having significantly higher masses of 1000-hr fuel for several decades after harvest. While fuel consumption correlates closely with 1000-hr fuel loadings for fire simulations conducted at 25, 50, and 100 years, mortality of trees planted in 1999 does not correlate with fuel consumption. This is because FVS–FFE uses a fire-effects model (FOFEM) that may not fully capture long duration smoldering effects that would be expected to result from the consumption of large woody fuel on the forest floor. While FOFEM does use bark thickness, calculated from DBH, as a measure of resistance to cambial heating from fuel burning on the forest floor, the model may not be sensitive enough to trigger differences in tree mortality, even given our observed two-fold differences in 1000-hr fuel mass between un-logged and fuel reduction stands at 25–50 years post-logging. A similar result was reported by Reinhardt and Ryan (1998) in their simulations of the effects of postfire logging in a high density ponderosa pine/Douglas fir stand in the Bitterroot Valley. While postfire logging would be expected to generate a stand having about triple the mass of large woody fuel for four decades after harvest, compared to an un-logged control, projected flame lengths (and presumably tree mortality), would be only marginally higher through the same time period. Yet it is generally known that even large trees can also be damaged or killed by fire through cambial heating that results from smoldering combustion of litter and duff that accumulates at their base over time (Sackett, 1980; Haase and Sackett, 1998; Agee, 1993). It stands to reason that smoldering combustion of large woody debris could also damage or kill trees growing nearby. Thus a fire-effects model that incorporated the effects of the smoldering combustion of large woody debris on tree mortality could demonstrate that the un-logged units at Summit were at somewhat greater risk in the future due to much higher accumulations of large woody fuel. Until we know more about the mechanisms of fire-induced tree mortality, and incorporate this knowledge into fire-effects models, we will remain uncertain on the extent to which postfire logging reduces re-burn severity, at least with respect to experimental studies that involve the use of fire behavior models. On the other hand, retrospective studies (e.g. Weatherspoon and Skinner, 1995; Omi and Martinson, 2002), in which twice-burned forests are compared with or without postfire logging after the first burn, could potentially provide valuable information on the re-burn issue.

Acknowledgements

Stephanie Rebain (USDA Forest Service, Washington Office) performed the final FVS–FFE simulations; Kylie Kramer (Missoula Fire Lab), and Morris Johnson (PNW Research Station) conducted preliminary simulations. We thank Glen Fisher, Barb Boaz, Hugh Snook, and Pam Uebler for working with field crews, and for planning and supervising the logging operations. Karen Scharf (Malhuer National Forest), Karen Erickson, and Colette Coiner (Oregon State University) prepared the map for Fig. 1. Funding for the study was provided by the Malheur National Forest (Region 6) and the Blue Mountains Natural Resources Institute (USDA Forest Service, PNW Research Station). The paper was improved by comments from Jim Agee (University of Washington), Carl Skinner, Sally Haase, John Szymoniak (USDA Forest Service, PSW Research Station), Vicky Saab (USDA Forest Service Rocky Mt. Station), Jane Hayes, Clint Wright (USDA Forest Service, PNW Research Station), and four anonymous reviewers.

References

Abbot, D.T., Crossley, D.A., 1982. Woody litter decomposition following clear-cutting. Ecology 63, 35–42.

Agee, J.K., 1996. Fire in the Blue Mountains: a history, ecology, and research agenda. In: Jaindl, R.G., Quigley, T.M. (Eds.), Search for a Solution: Sustaining the Land, People and Economy of the Blue Mountains. American Forests, Washington, D.C., pp. 119–145.

Aho, P.E., Cahill, J.M., 1984. Deterioration rates of blowndown timber and potential problems associated with product recovery. USDA For. Serv. Gen. Tech. Rep. PNW-167, 11 pp.

Albini, F.A., 1976. Computer-based Models of Wildland Fire Behavior: A User's Manual. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 68 pp.

Amman, G.D., Ryan, K.C., 1991. Insect infestation of fire-injured trees in the greater Yellowstone area. USDA For. Serv. Res. Note INT-398, 9 pp.

Anderson, H., 1982. Aids to determining fuel models for estimating fire behavior. USDA Forest Service General Technical Report, INT-122, Intermountain Forest and Range Experiment Station, Ogden, UT.

Barker, P.F., 1989. Timber salvage operations and watershed resource values. In: Proceedings of the Symposium on Fire and Watershed Management, Berg, NH (Tech. Coord.). USDA For. Serv. Gen. Tech. Rep. PSW-109, pp. 1–2.

Beschta, R.L., Rhodes, J.J., Kauffman, J.B., Gresswell, R.E., Minshall, G.W., Karr, J.R., Perry, D.A., Hauer, F.R., Frissell, C.A., 2004. Post-fire management on forested public lands of the western United States. Conserv. Biol. 18, 957–967.

Brown, J., 1974. Handbook for inventorying downed woody material. General Technical Report, USDA Forest Service Intermountain Station, GTR-INT-16, 24 pp.

Busse, M.D., 1994. Downed bole-wood decomposition in lodgepole pine forests of central Oregon. Soil Sci. Soc. Am. J. 58, 221–227.

Caton, E.L., 1996. Effects of fire and salvage logging on the cavity-nesting bird community in northwestern Montana. Ph.D. Dissertation. University of Montana, Missoula, 115 pp.

Donato, D.C., Fontaine, J.B., Campbell, J.L., Robinson, W.D., Kauffman, J.B., Law, B.E., 2006. Post-wildfire logging hinders regeneration and increases fire risk. Science 311, 352.

Haggard, M., Gaines, W.L., 2001. Effects of stand-replacement fire and salvage-logging on a cavity-nesting bird community in Eastern Cascades, Washington. Northwest Sci. 75, 387–396.

Haase, S.M., Sackett, S.S., 1998. Effects of prescribed fire in giant sequoia-mixed conifer stands in Sequoia and Kings Canyon National Parks. In: Pruden, T.L., Brennan, L.A. (Eds.), Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20, Tall Timbers Research Stations, Tallahassee, FL, pp. 236–243.

Hinklemann, K., Kempthorne, O., 1994. Design and Analysis of Experiments. vol. I. Introduction to Experimental Design. John Wiley and Sons, Inc., New York, 495 p.

Hitchcox, S.M., 1996. Abundance and nesting success of cavity-nesting birds in un-logged and salvage-logged burned forest in northwestern Montana. M.Sc. Thesis. University of Montana, Missoula, 89 pp.

Hutto, R.L., 1995. Composition of bird communities following stand-replacement fires in northern Rocky Mountain (USA) conifer forests. Conserv. Biol. 9 (5), 1041–1058.

Kotliar, N.B., Hejl, S.J., Hutto, R.L., Saab, V.A., Melchier, C.P., McFadzen, M.E., 2002. Effects of fire and post-fire salvage logging on avian communities in conifer-dominated forests of the western United States. Stud. Avian Biol. 25, 49–64.

Landram, F.M., Laudenslayer, W.F., Atzet, T., 2002. Demography of snags in eastside pine forests of California. In: Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests, November 2–4, 1999. Reno, NV. General Technical Report, USDA Forest Service Pacific Southwest Research Station, PSW-GTR-181, pp. 605–620.

Maser, C., 1996. Salvage logging: the loss ecological reason and moral restraint. J. Ecofor. 12, 176–178.

McIver, J.D., McNeil, R., 2006. Soil disturbance and hill-slope sediment transport after logging of a severely burned site in northeastern Oregon. Western J. Appl. For. 21 (3), 123–133.

McIver J.D., Starr, L., 2000. Environmental effects of postfire salvage: literature review and annotated bibliography. USDA Forest Service General Technical Report, PNW-GTR-486, Portland, OR.

McIver, J.D., Starr, L., 2001. A literature review on the environmental effects of post-fire logging. Western J. Appl. For. 16, 159–168.

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. Economics and environmental effects of mechanized logging for fuel reduction in northeastern Oregon mixed-conifer stands. Western J. Appl. For. 18, 238–249.

Minshall, G.W., Meyer, J.L., Stanford, J.A., Karr, J.A., Frissell, C.A., 1994. Letter dated 19 September 1994 to President Clinton on fire and salvage logging. File with Pacific Rivers Council, Eugene, OR, p. 2.

Omi, P., Martinson, E.J., 2002. Effect of fuels treatment on wildfire severity. Final Report to the Governing Board, Joint Fire Science Program.

Ottmar, R.D., Burns, M.G., Hanson, A.D., Hall, J.N., 1993. CONSUME users guide. Gen. Tech. Rep. PNW-GTR-304. USDA, Forest Service, PNW Research Station, Portland, OR, 137 pp.

Poff, R.J., 1989. Compatibility of timber salvage operations with watershed values. In: Berg, N.H. (Tech. Coord.), Proceedings of the Symposium on Fire and Watershed Management. USDA For. Serv. Gen. Tech. Rep. PSW-109, pp. 137–140.

Reinhardt, E.D., Crookston, N.L., 2003. The fire and fuels extension to the forest vegetation simulator. USDA Forest Service Rocky Mt. Research Station, General Technical Report, RMRS-GTR-116, 220 pp.

Reinhardt, Elizabeth D., Ryan, Kevin C., 1998. Analyzing effects of management actions including salvage, fuel treatment, and prescribed fire on fuel dynamics and fire potential. In: Teresa, L., Pruden, Leonard, A., Brennan, (Eds.), Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription. Tall Timbers Fire Ecology Conference Proceedings, No. 20, Tall Timbers Research Station, Tallahassee, FL.

Saab, V., Dudley, J., 1998. Responses of cavity-nesting birds to stand-replacement fire and salvage logging in ponderosa pine/Douglas-fir forests of southwestern Idaho. USDA For. Serv. Res. Pap. RMRS-RP-11, 17 pp.

Sackett, S.S., 1980. Reducing Natural Ponderosa Pine Fuels Using Prescribed Fire: Two Case Studies. Research Note RM-392. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.

SPSS, 2001. SPSS Professional Statistics, Version 10.0. Chicago, Illinois.

Stone, R., 1993. Spotted owl plan kindles debate on salvage logging. Science 261, 287.

USDA, 1996. Forest health and salvage. Forest health issue paper, USDA Forest Service Washington Office (Available from Dave Hessel, Director, Forest Management, P.O. Box 96090, Washington, DC).

USDA, 1997. Summit Fire Recovery Project Final Environmental Impact Statement. R6-MAL-97-0003a, USDA Forest Service, Region 6, Malheur National Forest.

USDA and USDI, 1997a. Eastside Draft Environmental Impact Statement, vol. 1. USDA Forest Service, USDI Bureau of Land Management, Portland, OR.

USDA and USDI, 1997b. Upper Columbia River Basin Draft Environmental Impact Statement, vol. 1. USDA Forest Service, USDI Bureau of Land Management, Portland, OR.

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

Weatherspoon, C.P., 1996. Fire–silviculture relationships in Sierra forests. In: Sierra Nevada Ecosystem Project: Final Report to Congress. vol. II. Assessments and Scientific Basis for Management Options. University of California, Centers for Water and Wildland Resources, Davis, CA, pp. 1167–1176.

Westfall, P., Tobias, R.D., Rom, D., Wolfinger, R.D., Hochberg, Y., 1999. Multiple Comparisons and Multiple Tests Using SAS. SAS Institute Inc., Cary, NC, 397 pp.