Fuel mass and forest structure following stand-replacement fire and post-fire logging in a mixed-evergreen forest

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Abstract

Following severe wildfires, managing fire hazard by removing dead trees (post-fire logging) is an important issue globally. Data informing these management actions are relatively scarce, particularly how fuel loads differ by post-fire logging intensity within different environmental settings. In mixed-evergreen forests of Oregon, USA, we quantified fuel profiles 3-4 years after stand-replacement fire—assessing three post-fire logging intensities (0%, 25-75%, or >75% basal-area cut) across two climatic settings (mesic coastal, drier interior). Stand-replacement fire consumed ~17% of aboveground biomass. Post-fire logging significantly reduced standing dead biomass, with high-intensity treatment leaving a greater proportion (28%) of felled biomass on site compared to moderate-intensity treatment (14%) because of less selective tree felling. A significant relationship between logging intensity and resulting surface fuels (0.4–1.2 Mg ha^{-1} increase per m^2 ha^{-1} basal-area cut) indicated a broadly applicable predictive tool for management. Down wood cover increased by 3-5 times and became more spatially homogeneous after logging. Post-fire logging altered the fuel profile of early-seral stands (standing material removed/transferred, short-term increase in surface fuels, likely reduction in future large fuel accumulation), with moderate-intensity and unlogged treatments yielding surface fuel loads consistent with commonly prescribed levels, and high-intensity treatment resulting in greater potential need for follow-up fuel treatments.

Keywords: biomass, Biscuit Fire, coarse woody debris, dead wood, fuel succession, Klamath-Siskiyou, legacy, logging intensity, post-fire management, salvage logging, snag

Summary: We quantified the effects of post-fire logging on forest fuel profiles as influenced by harvest intensity (% basal area cut) and biophysical setting (mesic to drier forests). Post-harvest

fuel loads varied significantly across each of these gradients, and suggested a broadly applicable management tool relating post-fire logging intensity (basal area cut) to subsequent surface fuel loads.

Introduction

Stand-replacing fires affect many forest ecosystems globally (Bond and Keeley 2005) and are key drivers of woody biomass dynamics (Spies et al. 1988, Everett et al. 1999, Pedlar et al. 2002, Hall et al. 2006). Following wildfires, managing fuels (biomass) is often a key concern, as the eventual fall of fire-killed trees may function as a positive feedback mechanism by providing fuel for subsequent fires, or 're-burns' (Brown et al. 2003). The widespread practice of post-fire logging (i.e., salvage) often carries an objective of reducing woody fuel loads and thus fire behavior/effects in the event of a re-burn (e.g., McIver and Starr 2001, McGinnis et al. 2010). However, little empirical information exists to inform these management actions—in particular how post-fire fuel loads are affected by different post-fire logging intensities across different forest settings (McIver and Starr 2001, Peterson et al. 2009).

Although post-fire logging often aims to reduce future fire severity, the few empirical studies of actual fires occurring after post-disturbance logging have shown equivocal results, including reduced severity (Buma and Wessman 2011), increased severity (Hansen 1983, Thompson et al. 2007), or unchanged or mixed results (Kulakowski and Veblen 2007, Fraver et al. 2011). Mechanisms behind these varying observations remain unclear. Timber harvest in general is known to increase surface woody fuel loads by transferring non-merchantable branches and tree tops (‘slash’) to the surface, where most fires propagate (Snell and Brown 1980, Pyne et al. 2006, Stephens et al. 2009). Exactly how this premise extends to logging of dead trees has not been well quantified for most forest types. Recent studies indicate that surface fine fuel loads (<7.6 cm diameter) are indeed elevated following post-fire logging (Donato et al. 2006a, McIver and Ottmar 2007, Keyser et al. 2008, McGinnis et al. 2010), and empirical data and models suggest these elevated loads may persist for ~20 years in some settings (McIver and

Ottmar 2007, McGinnis et al. 2010). Yet coarse woody fuels (>7.6 cm diameter) may accumulate less on the surface over the intermediate term (~10-50 yr) if stems are removed, which could reduce potential fire effects such as soil heating (McIver and Ottmar 2007, Keyser et al. 2008, Monsanto and Agee 2008). Post-fire management can also influence live vegetation (Stuart et al. 1993), and this may further affect subsequent fire behavior. To better identify relationships between post-fire fuels, management treatments, and observed fire effects, data are needed on specific impacts of individual activities such as logging, slash burning, and vegetation management (McIver and Starr 2001, Donato et al. 2006b).

The quantity and distribution of fuels remaining after post-fire logging may vary widely by harvest method and biophysical setting. Treating slash fuels after felling of live trees is well known to be important for reducing total fuel loads and fire potentials (e.g., Weatherspoon and Skinner 1995, Graham et al. 2004, Agee and Skinner 2005). For fire-killed trees, however, the relative need for such follow-up treatments after differing levels of logging intensity has scarcely been reported, and no information exists on how this varies across forest types or settings. Such information is essential to informed post-fire decisions and meeting fuel management objectives (Peterson et al. 2009).

In this study, we investigated fuel dynamics in stand-replacement (high-severity) portions of the 2002 Biscuit Fire, a large wildfire in southwest Oregon, USA. Our objectives were to: (1) quantify aboveground biomass, composition, and vertical distribution following stand-replacement fire relative to intact mature/old growth forest, including all material (fine/coarse, live/dead) in both the aerial and surface fuel strata; and (2) quantify immediate changes in these profiles resulting from post-fire logging, as influenced by harvest intensity and biophysical setting (mesic coastal forest type vs. drier inland forest type). We focused on empirically measured fuel profiles rather than modeled fire behavior because available models have not been calibrated or tested for post-fire environments, especially for the necessary custom fuel models (Passovoy and Fulé 2006, Cruz and Alexander 2010).

Methods

Study area

The study was conducted in the Klamath-Siskiyou Mountains, a coastal range in the state of Oregon, USA (Fig. 1), within the mixed-evergreen and *Abies concolor* zones (Franklin and Dyrness 1973). The region experiences a moist Mediterranean climate with warm, dry summers (mean max. July temperature: 27 °C) and cool, wet winters (mean min. January temperature: 2 °C) (Fontaine et al. 2010). Mean annual precipitation ranges from 140-500 cm over the burn area, with <15% falling from May-September (Daly et al. 2002; prismclimate.org). Forests are dominated by conifers Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and sugar pine (*Pinus lambertiana*); evergreen hardwoods tanoak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and canyon live oak (*Quercus chrysolepis*); and shrubs greenleaf manzanita (*Arctostaphylos patula*) and snowbrush (*Ceanothus velutinus*). Fire regimes are complex, described as low- to mixed-severity with median return intervals ranging from 5-35 years in drier plant associations to 50- >100 years in higher elevation and wetter associations (Agee 1991, Agee 1993, Wills and Stuart 1994, Taylor and Skinner 1998, Stuart and Salazar 2000, USDA 2004). Stand-replacement fire effects (≥90% overstory mortality) typically occur in variably-sized patches as part of a burn mosaic (Donato et al. 2009a, Halofsky et al. 2011).

All sample areas were mature to old-growth (M/OG) Douglas-fir-dominated forests currently or prior to stand-replacement fire (see Thornburgh 1982, Agee 1993 for developmental/structural descriptions). Study areas were on steep slopes (generally >20°) between ~600-1300 m elevation, at mid-slope positions on a full range of aspects. Soils were derived from metasedimentary, metavolcanic, and coarse-grained igneous parent materials (USDA 2004). We excluded conditions generally irrelevant to post-fire logging: extremely steep rocky areas, riparian zones, ultramafic soils (see Whittaker 1960), areas burned with low or moderate severity (USDA 2004), and pre-existing plantations and shrub fields.

The Klamath-Siskiyou region is renowned for floristic diversity due in part to sharp topoedaphic and climatic gradients (Whittaker 1960); among the most important gradients are west-to-east trends in moisture and productivity. Western portions of the area (Fig. 1) receive greater maritime influence, experience less severe summer moisture deficits, and have longer fire return intervals than inland sites to the east (Daly et al. 2002, USDA 2004). As such, mesic western areas tend to support higher basal area and aboveground biomass than drier eastern areas.

Study fire

The Biscuit Fire of 2002 burned with mixed severity over 200,000 ha of the Klamath-Siskiyou Mountains. Relative proportions of low, mixed, and high severity (as assessed by vegetation change) were ~30%, 27%, and 43%, respectively (USDA 2004). The fire perimeter encompassed a broad range of biophysical conditions and spanned both western and eastern plant associations (Fig. 1). Following the fire, the Rogue River-Siskiyou National Forest implemented post-fire logging in limited areas of the burn. In addition to recouping economic value, stated objectives included reducing fire hazards associated with residual wood (USDA 2004).

Post-fire logging occurred mostly during the fall-spring of 2004-2005 (2-3 yr post-fire) with some additional logging during the winter-summer of 2005-2006 (3-4 yr post-fire). Logging occurred in stand-replacement patches ranging from ~4 to over 1000 ha. Harvest units (spatially distinct logging parcels within timber sales) ranged from 1-70 ha in size (mean= 8 ha). Trees were hand-felled and de-limbed on site, generating slash in place. Logs were removed by cable- or helicopter-yarding. Prescriptions for down wood retention in severely burned sites varied from 24 to 106 Mg ha^{-1} depending on plant association (USDA 2004). Slash treatment (prescribed burning of slash accumulations) occurred in <30% of sampled stands. All post-logging data presented here from the Biscuit Fire reflect effects of tree harvest only (which was the only dead wood treatment in >70% of the stands), and not any subsequent treatments. Harvest prescriptions called for retention of 3-29 large (>41 cm) snags per hectare, and variable retention of smaller (<41 cm) snags depending on merchantability (USDA 2004).

We categorized stands into three levels of treatment intensity: unlogged (*U*), logged at moderate intensity (*M*), and logged at high intensity (*H*). Moderate-intensity harvest units were helicopter-yarded with 25-75% basal area cut at the hectare scale (mean 46% ±5.5 SE); high-intensity harvest included a mix of cable and helicopter yarding with >75% basal area cut at the hectare scale (mean 89% ±3.5 SE).

Data collection

We sampled all large Biscuit Fire timber sales completed by late 2005, with one exception in the extreme west of the fire due to access logistics. We sampled 26 stands in the eastern portion of the fire and 12 in the western portion (68% east, 32% west), corresponding to the distribution of Biscuit post-fire logging (67% east, 33% west by area). Study areas were identified *a priori* from Forest Service spatial data layers on proposed sale boundaries, burn severity, and pre-fire forest cover/type. We interspersed treatment and control stands by sampling unlogged burn areas in and around each sampled sale. Unburned mature/old-growth (*M/OG*) stands were also sampled over a broad area corresponding to the distribution of sampled burn stands (Fig. 1). Study plots (no more than one per harvest unit) were located randomly within harvest units and adjacent unlogged areas. Pre-treatment measurements occurred in the summer of 2004; post-treatment measurements (including re-measurement of control stands) occurred in the summers of 2005 and 2006, within 3-9 months of logging. The 26 eastern stands consisted of eight *U* stands, seven *M* stands, six *H* stands, as well as five unburned mature/old-growth stands. The 12 western stands included three each of the four treatments.

We sampled each stand with a one-hectare plot with a layout based on regional forest inventory protocols (USDA 2003b). All aboveground biomass pools were measured, partitioned by fuel stratum (sensu Pyne et al. 1996). Aerial biomass was defined as standing over- and mid-story components (live and dead trees >10 cm dbh). Surface biomass was defined as standing understory components (live and dead small trees, shrubs, forbs, grasses), down woody detritus, stumps, and forest floor (litter and duff). Aerial and standing surface biomass were each measured in four regularly-spaced circular subplots ranging from 2-meter radius for the surface stratum to 17-meter radius for the aerial stratum (surface and aerial subplots were concentric) (see USDA 2003b). For each tree we recorded species, diameter at breast height (dbh), total height, decay class (per Cline et al. 1980), and percent of stem surface with bark and wood charring. For understory hardwoods, shrubs, forbs and grasses we recorded percent cover by species. Hardwoods and woody shrubs were further measured on an individual basis for live crown dimensions (l, w, h), basal diameter of live stems, and height and count of dead stems by

2-cm basal diameter class. Forest floor mass was quantified by collecting eight systematically located 5.6-cm-diameter cores down to the mineral surface in each subplot (32 samples per plot), then separating litter and duff components, and drying at 70 °C to constant mass.

We sampled down woody detritus by size class (see Agee 1993) along four 75-meter planar intercept transects (Brown 1974, Harmon and Sexton 1996) radiating from plot center in subcardinal directions. Coarse woody detritus (CWD; 7.63-20.32 cm and >20.32 cm classes) was surveyed along all 75 m of each transect and recorded for diameter, species, decay class, and charring (Donato et al. 2009b). Fine woody detritus (FWD) was tallied by size class and char presence; survey lengths were, beginning from the distal end of transects: <0.62 cm class, 5 m; 0.63-2.54 cm class, 15 m; 2.55-7.62 cm class, 25 m.

--*Biomass computations*-- We computed stem mass for all trees using species- and region-specific allometric diameter-volume equations and wood densities (Walters et al. 1985, Means et al. 1994, Van Tuyl et al. 2005). Masses of tree foliage, bark, branch, and unmerchantable tops were estimated directly from species-specific allometric equations (Means et al. 1994). Merchantable mass was defined as sound conifer stemwood >20 cm diameter (USDA 2004). All biomass components were adjusted for individual-specific metrics of bark/wood charring, top breakage, and decay class status (Harmon and Sexton 1996, Appendix 1); as well as plot-specific ocular estimates of foliage and branch consumption (sensu USDA 2003a). Due to confounding of fire effects with definitions of decay class 1-2 characteristics (e.g., fine branch loss; Cline et al. 1980), recently fire-killed trees were assigned mean decay class 1-2 inputs. We computed biomass of surface-layer hardwoods and shrubs via empirically derived allometric equations (Donato 2009c). Mass of forbs and low shrubs was estimated from regional equations relating cover to mass per area (Means et al. 1994). We computed mass of down woody detritus from line intercept data using standard geometric scaling and species- and decay-specific wood density values (Brown 1974, Harmon and Sexton 1996). Down wood was corrected on an individual piece basis for mass loss due to charring (Donato 2009b).

Statistical analysis

--*Fire effects*-- To quantify apparent fire effects on aboveground biomass pools, we compared mature/old-growth stands to three-year post-fire stands (unlogged). For this comparison we present means and 95% confidence intervals (CIs) by biomass category to evaluate magnitude of differences rather than obtain test-statistics. Data for fire effects assessment were pooled across western and eastern stands because exploratory two-way analysis of variance (ANOVA; Ramsey and Schafer 2002) showed that fire effects did not differ strongly by forest type (P>0.05 for all burn*forest type interaction terms).

--*Post-fire logging effects*-- To assess how post-fire logging effects varied by logging intensity and biophysical setting, we analyzed fuel loads as a function of the three treatment levels (*U, M, H*); two forest types (mesic, drier); and a treatment*forest type interaction term in a two-way ANOVA. The forest type term allowed biomass levels in each treatment to vary between mesic vs. drier stands, while the interaction term tested whether treatment effects varied by forest type. We analyzed live and dead total biomass by stratum as well as fine and coarse down woody fuels. To provide management-relevant information on the implemented prescriptions, we also present trends in basal area and snag density among treatments.

Analysis of forest type and treatment differences was focused on post-treatment comparisons (n= 30 burn stands [*U*= 11, *M*= 10, *H*= 9]). Because treatments were not implemented randomly (per the agency management plan), we also present results of a two-way ANOVA for the subset of stands for which we were able to collect before-after data (n= 19 [*U*= 8, *M*= 7, *H*= 4]) to assess whether strong differences among treatments existed prior to logging and whether the pre-post change was greater in treated stands than in controls. We could use only this subset for before-after analyses because 'reconstructing' stand density in logged stands for which we did not have pre-treatment data was precluded by the incidental felling, fragmentation, and burial of an unquantifiable amount of small- and medium-sized stems. For all analyses, models were evaluated via residual-vs.-fit plots using standard diagnostics (Ramsey and Schafer 2002). We $\log_e$-transformed basal area and snag density data to reduce heteroscedasticity. Biomass data were not transformed because the data were symmetrically distributed and showed no consistent pattern in residual spread. Specific treatment comparisons were performed by computing 95% CIs for each treatment within each forest type; lack of overlap of CIs with means of other groups was interpreted as evidence for differences (Ramsey and Schafer 2002).

Results

Fire effects

Most aboveground biomass persisted through stand-replacement fire. Mean residual dead mass after fire was 515 Mg ha^{-1}, 83% of the 616 Mg ha^{-1} in *M/OG* stands (Table 1). Aside from converting live biomass to dead (mean post-fire live:dead ratio = 1:99), the primary effect of fire was to consume the forest floor and fine fuels in the surface layer (Table 1). Mean forest floor mass after fire (1.1 Mg ha^{-1}) was 96% lower than in *M/OG* stands (27.2 Mg ha^{-1}) (Table 1). Mean surface wood mass was also lower in post-fire stands by 47-73% for all size classes except the >20.32 cm class, which was similar (Table 1). Live surface biomass (regenerating vegetation) three years post-fire was already similar to that in *M/OG* stands (Table 1, Fig. 2).

Consumption of aerial biomass was minimal (Table 1, Fig. 3). Foliage consumption approached 100% but most aerial wood consumption was of twigs (needle-bearing and adjacent branchlets), which compose a small fraction of total mass. Consumption of larger branches and stems was negligible (Table 1, Fig. 3, Donato 2008).

Following fire, mesic stands had higher residual biomass (mean 709 Mg ha^{-1}, 95%CI: 555-864) than drier stands (mean 435 Mg ha^{-1}, 95%CI: 340-530). Tree biomass drove this difference, associated with larger mean snag diameter (44.9 vs. 36.5 cm) and dead basal area (94.3 vs. 68.1 m^2 ha^{-1}). Post-fire dead basal area averaged 83% Douglas-fir, 3% incense cedar, and 3% white fir in mesic stands; and 65% Douglas-fir, 21% sugar pine, and 6% white fir in drier stands. Hardwoods constituted a mean of 11% of total basal area in mesic stands (mainly tanoak) and 4% in drier stands (mainly Pacific madrone).

Post-fire logging effects

--Pre-treatment comparisons-- We detected no significant pre-existing differences among treatments in terms of basal area, stem densities, fine and coarse woody fuels, or live and dead biomass (Table 2). Change magnitudes (post-treatment value minus pre-treatment value) were significantly greater in logged vs. unlogged stands for all variables except live biomass and density of small snags (Appendix 2).

--Post-treatment comparison-- Aerial dead biomass decreased monotonically with increasing harvest intensity in both forest types (Fig. 3, Tables 3-4). Conversely, surface dead biomass increased monotonically with harvest intensity in both forest types, with treatment effects greater in mesic stands (Fig. 3, Table 3). Post-fire logging reduced standing dead basal area and large snag densities to a greater degree in mesic stands than in drier stands (Table 3). Live surface-layer biomass remained similar to unlogged stands after moderate-intensity logging, but was lower after high-intensity logging (Fig. 2).

In mesic sites, total biomass removal was estimated at 50% and 66% of post-fire biomass in *M* and *H* stands, respectively (Table 3). In drier sites, estimated total removal was 58% and 63% in *M* and *H* stands, respectively (Table 3). Total dead biomass remaining after logging did not differ strongly between moderate- and high-intensity logged stands in either forest type, with broadly overlapping confidence intervals (Table 3). Thus, with high-intensity harvest, more biomass was felled but not removed.

Surface woody fuel loads of all size classes increased following moderate- and high-intensity logging (Fig. 3, Tables 3-4). Relative to drier stands, logging in mesic stands resulted in greater increases in both fine and coarse surface fuels (Fig. 3, Table 3). When harvest intensity was assessed as a continuous variable, post-logging surface fuel loads were significantly positively related to basal area cut (Fig. 4). As a reference, both moderate- and high-intensity logging resulted in surface fuel loads exceeding those in *M/OG* stands, except for the smallest size class (Tables 1, 4).

Surface woody fuel loads became more spatially homogeneous following logging, while spatial patterns of live biomass remained similar. Mean surface cover of woody detritus was 6.3%, 20.4%, and 34.1% in *U*, *M*, and *H* stands respectively, compared to 14.5% in *M/OG* (Fig.

5A). Hectare-scale heterogeneity in CWD mass (coefficient of variation [CV%] among transects within a stand; Fraterrigo and Rusak 2008) decreased with logging intensity, with a CV% of 110.9, 56.7, and 40.3 in *U*, *M*, and *H* stands respectively, compared to 72.0 in *M/OG* stands (Fig. 5D). These effects were similar in each forest type.

Discussion

The effect of post-fire logging on fuel profiles and stand structures varied significantly with harvest intensity and among forest types. Our findings yield several inferences regarding post-disturbance biomass dynamics and for developing post-fire management prescriptions.

Fire Effects

Our estimate of total biomass consumption by stand-replacement fire (17%) agrees well with literature estimates for Douglas-fir and mixed-conifer forests (16-24%) (Fahnestock and Agee 1983, Campbell et al. 2007, Meigs et al. 2009). Even active crown fires that kill ~all trees tend to consume little aerial biomass—primarily leaves and small branches (Call and Albini 1997)—with most actual consumption occurring in the surface stratum.

Post-fire logging effects

--*Treatment effects by biophysical setting and intensity*-- As expected, post-fire logging removed some aerial biomass and transferred some to the surface, but these effects varied by biophysical setting and logging intensity. Surface fuel loads increased more with logging in mesic versus drier stands; mesic stands had more basal area standing, more basal area cut, and thus larger increases in surface fuels. This was reflected in the positive relationship between the amount of basal area cut and resulting surface fuels (Fig. 4). This relationship likely has applicability across forest types, as the structural metric of basal area is generally a strong predictor of bole and branch biomass even as stand composition varies. For example, while post-fire logging in comparatively low-basal-area *Pinus ponderosa* forests resulted in much lower surface fuel loads than we report (McIver and Ottmar 2007, Keyser et al. 2009), the relationships between basal area cut and surface fuel accumulation in those studies correspond well to the association shown in Figure 4. This predictive relationship could be used as a tool for post-fire management to anticipate ranges of surface fuel loads given different harvest intensities.

An important factor in post-disturbance stands is fuel continuity (Fraterrigo and Rusak 2008, Donato et al. in press). In the case of fire, consumption of ground and surface fuels generally results in highly patchy residual fuel and low horizontal continuity. Re-burns are thus unlikely to carry through young stands initially. Post-fire logging decreased this spatial heterogeneity, resulting in more spatially continuous woody surface fuels (Fig. 5). In high-intensity logged stands, percent cover of wood was higher, and stand-scale variation in CWD mass lower, than in burn-only or *M/OG* stands. The areal cover of live vegetation was little affected, however. Increased continuity of woody fuels may become important if it helps close the window of low fire spread capacity sooner, or if, in combination with other fuel components, post-harvest fuels contribute to meeting a threshold for fire propagation. In highly productive fire-prone regions such as the Klamath-Siskiyou, the low fire-spread window may close relatively quickly as regenerating vegetation and new litter inputs accumulate on the surface, likely within 5-10 years (Table 1, Fig. 2; Stuart et al. 1993, Fontaine et al. 2009). Assessing the effects of changes in fuel continuity is difficult because common fire models do not adequately address stand-scale spatial heterogeneity (e.g., Stephens and Moghaddas 2005).

--*Relevance to follow-up treatments*-- These data indicate that with moderate-intensity logging, a mean of ~86% of felled tree biomass was actually removed from the site while ~14% remained on the ground as slash (6.1 to 1 ratio), compared to high-intensity logged stands in which the ratio averaged ~72 : 28% (2.6 to 1 ratio). In general, moderate-intensity logging on the Biscuit Fire occurred when only fire-killed trees deemed merchantable were felled, while high-intensity logging occurred when nearly all fire-killed trees were felled and only merchantable logs then yarded. This greater selectivity of moderate-intensity treatment suggests a more deliberate approach to post-fire wood management that is more likely to result in prescribed down wood levels, versus high-intensity treatment in which resulting levels become more dependent on timber decay status and merchantability, regardless of prescription (see Rickards 1989).

From a management perspective, optimum ranges of down wood in fire-prone forests aim to balance the ecological functions of dead wood with its contribution to fire potentials (Brown et al. 2003). Though not derived specifically for the Klamath-Siskiyou region, the range given for cooler forests (23-68 Mg ha^{-1} of CWD) provides context for the post-logging fuel loads we measured. After moderate-intensity logging or no treatment, surface CWD loads were within or near this range (Fig. 2). High-intensity logging generated surface fuel loads well above these levels. This suggests that moderate-intensity logging or no treatment may result in acceptable (or even prescribed) fuel loads in the short term, while high-intensity logging may require additional treatments to mitigate short-term fire potentials.

Data following timber harvest alone provide insight as to when slash treatments may be warranted, and are relevant to operations in which slash is left on site (e.g., McIver and Ottmar

2007, and much of the Biscuit Fire). Studies in both young and mature stands have reported increased fire severity associated with untreated slash from logging and fuel-reduction treatments (e.g., Weatherspoon and Skinner 1995, Stephens 1998, Raymond and Peterson 2005, Stephens and Moggohdalus 2005). Our empirical data suggest a potential need for follow-up slash treatments after dead tree (snag) removal as well, primarily after high-intensity logging, consistent with a modeling study conducted in the Sierra Nevada mountains of California, USA (Stephens 1998). Relatively few of our sampled stands from the Biscuit Fire received secondary treatments, precluding sufficient sample size or timing to assess their effects.

--Influence of harvest timing-- The time period between fire and logging may play a role in the amount of surface fuels generated (longer time → greater snag decay → lower merchantability → more material left on ground after felling). Our data suggest this was not a major driver in the case of the Biscuit fire because a) no fine fuels have timber merchantability in any case, and b) nearly all coarse fuel increases could be accounted for by non-merchantable species/parts, pre-fire decay, and standard timber defect/breakage rates (Snell and Brown 1980). Based on our biomass data and allometries for merchantable boles (Means et al. 1994), we estimate that at least ~40% of post-fire biomass is not merchantable, even immediately post-fire. This again highlights the importance of considering the non-merchantable component of post-fire wood (fine and fragmented/rotted coarse fuels) where management of early-seral fire potentials is an objective.

Longer term considerations

These data provide information on immediate changes in fuel profiles with post-fire logging, and are short-term in nature. Over time, slash fuels left in place will decay, and snags left in place will fragment and fall to the surface. Studies from dry continental-interior forest types (e.g., *Pinus ponderosa* or *P. contorta*) indicate that unlogged stands eventually accumulate greater surface fuel loads (Keyser et al. 2008, Monsanto and Agee 2008). McIver and Ottmar (2007), also working in interior dry forests, used models to project post-fire surface fuel loads and suggested that fine fuel loads remained greater in logged stands for ~20 years, but coarse fuel loads would be lower in logged stands from ~20-50 years post-fire. Passovoy and Fulé (2006) concluded that, in the absence of management, CWD loads up to 27 years post-fire in a ponderosa pine system remained within acceptable ranges outlined by Brown et al. (2003), and suggested that post-fire logging for fuel reduction appeared unnecessary. The need for and outcomes of management treatments may depend largely on forest type as well as yarding method and slash treatment, but the latter have not always been clear for studies of older fires (Monsanto and Agee 2008) and considerable uncertainties remain.

Initial studies in the Klamath-Siskiyou region suggest that unlogged stands may not have higher fuel loads until at least 2-3 decades after fire (Donato 2008). Longer-term snag dynamics are poorly understood for mixed-evergreen forests of the western U.S., but forest inventory data suggest relatively rapid wood decay in this region (Hudiburg et al. 2009), which may lessen the surface accumulation of snag biomass. Consistent with this pattern is evidence of greatly diminished woody biomass in 18-year-old fires in this region, and little to no difference in surface fuel loads between managed and unmanaged stands at that post-fire age (Donato 2008). Evidence also suggested rapid decay of snag and down wood biomass, with single-exponential decay constants (Harmon et al. 1986) of ~0.30-0.40 for all standing and down material combined; a value comparable with other studies in Douglas-fir forests (Sollins 1982, Agee and Huff 1987, Spies et al. 1988). Those findings agree well with observations 10 years after another fire in the region (56.5 vs. 56.8 Mg ha^{-1} in logged vs. unmanaged stands; BLM 2003), as well as a recent study from the Sierra Nevada which reported higher dead fuel loads in post-fire logged stands up to 21 years after fire (McGinnis et al. 2010). In highly productive fire-prone systems, fast decay may reduce the contribution of residual post-fire wood to early-seral fire potentials, while the live component of regenerating vegetation, which accumulates biomass and continuity quickly, may be a much more important driver of fire potentials in young stands (Donato 2008).

Uncertainties and future research

An important research direction is better quantifying regional differences in snag decay rates, standing biomass, and productivity within the context of post-fire fuel profile development. Remarkably few studies have quantified the overall decay rate of post-disturbance snags—integrating fragmentation, falling, and mineralization during both the standing and down phases (see Donato et al. in press). We hypothesize that discrepancies in fuel loads between post-fire logged and unmanaged stands are greater for drier, continental interior forest types, and less so for mesic and coastal forest types, owing to higher rates of vegetation growth and wood decay in the latter systems.

Another seldom addressed issue for post-fire logging is that of fire regime context. Management of post-fire residual wood is often concerned with avoiding surface fuel loads deemed to be excessive with respect to fire potentials (Brown et al. 2003); however, pulses of dead wood are a characteristic feature of mixed- and high-severity fire regimes (e.g., Spies et al. 1988). Within the context of historic variation, therefore, the ecological basis for reducing post-fire fuels may be most pertinent in low-severity fire regimes where large pulses of fire-killed trees are considered outside the historic range of variation (see Monsanto and Agee 2008).

Although the applicability of common fire models to post-fire settings is not well established (Passovoy and Fulé 2006), known relationships between fuel loads and surface fire behavior (Rothermel 1983) suggest that post-fire logging may elevate fire potentials in the short term, other factors being equal. Exploratory analysis using the model BehavePlus 3.0 (Andrews et al. 2005) supported this inference, with predicted fire behavior (e.g., rate of spread, surface flame length, soil heat flux) simply scaling upward with increased fine and coarse fuel loads in treated stands (Donato 2008). Slash from logging/fuel-reduction treatments has been associated with increased fire severity in both young and mature stands in various settings (e.g., Weatherspoon and Skinner 1995, Raymond and Peterson 2005, Stephens and Moghaddas 2005). Nevertheless, local fire behavior depends on many factors such as fuel continuity, weather, etc., in addition to fuel load. While we observed greater homogeneity in surface fuels after treatments, fuel continuity is poorly addressed in fire models (Stephens and Moghaddas 2005). Predicted effects could be lessened if fire cannot spread in very young stands due to low continuity, or amplified if post-logging fuels meet a threshold for fire propagation. Other uncertainties include the role of localized pockets of snag-fall (or slash) accumulation, and how the landscape context of post-fire logging units affects larger-scale fire spread.

Snags may contribute to fire behavior via ‘candling’ and providing ember sources that can lead to spot fires. Oregon’s 1933 Tillamook Burn, which re-burned three times at six-year intervals, is a commonly cited example of the fire contribution of snags since fires ceased to occur following extensive snag removal (Kemp 1967). However, the Tillamook Burn narrative is complicated by the fact that all three re-burns were started by post-fire logging operations and burned through a mix of both logged and unlogged areas (Kemp 1967, Peterson et al. 2009). Surface/ground fuels are the primary carrier of wildfire and contribute most to soil heating and regeneration mortality (Pyne et al. 1996). The role of snags in fire behavior has received little quantitative study, is not captured by available fire modeling frameworks, and warrants future research.

Conclusions and Management Implications

Post-fire logging in this high-biomass, fire-prone system reduced standing fuel mass as expected, but the amount of material transferred to the surface varied by both environmental setting and treatment. Post-logging fuel loads were greater in higher basal-area mesic forests and with higher-intensity harvest. These findings suggest that reports of either increased or decreased fire severity following post-disturbance logging (Hansen 1983, Kulakowski and Veblen 2007, Thompson et al. 2007, Buma and Wessman 2011, Fraver et al. 2011) may stem in part from variation among studies in terms of harvest intensity and pre-disturbance forest structure. We also found that the efficiency of biomass removal (the proportion of biomass felled and removed versus felled and left on site) and the spatial heterogeneity of surface fuels both decreased with increasing harvest intensity. The general relationship we identified between harvest intensity (basal area cut) and resulting surface fuels likely has applicability across diverse forest types and could provide a useful predictive tool for developing post-fire management prescriptions.

Post-fire timber harvest is generally an economic rather than restorative undertaking (Peterson et al. 2009). From a fire management perspective, studies from several regions have reported inherently high fire potentials in early-seral stands, with limited efficacy of stand-level fuel treatments in reducing these potentials (Roloff et al. 2005, Stephens and Moghaddas 2005, McIver and Ottmar 2007, Thompson et al. 2007, McGinnis et al. 2010, but see Weatherspoon and Skinner 1995). As such, alternative or additional treatments may be necessary where objectives include reducing fire potentials, such as landscape fuel breaks (Agee et al. 2000) and managing for diverse vegetation structure (Donato et al. 2012). Where post-fire logging is conducted, our results suggest that moderate-intensity treatment results in surface fuel loads most consistent with prescribed levels when compared to high-intensity treatment, and may reduce the potential need for follow-up fuel treatments (e.g., slash piling, burning). Because moderate-intensity treatment leaves a greater proportion of snags standing, it may also be most compatible with objectives pertaining to the many other ecological roles of snags (e.g., wildlife habitat; Fontaine et al. 2009). Longer-term impacts of post-fire logging on snag-fall inputs and coarse fuel loads remain an important research direction. Finally, given the paucity of data on post-fire management effects, designing management projects with replication, pre-treatment data, and controls as in this study will best clarify the tradeoffs of various post-fire interventions.

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Table 1. Mean (95% CI) aboveground biomass pools in mature/old-growth sites and 3 years after stand-replacement wildfire (Mg ha^{-1}). N= 8 M/OG stands and 11 burned stands.

Biomass Category	Mature/old-growth		Post-fire	
DEAD MASS				
Aerial stratum				
Branch	1.4	(0.2 - 2.6)	69.0	(49.5 - 88.4)
Stem [A]	20.0	(5.8 - 34.2)	421	(288 - 555)
Total Aerial Dead	21.4	(6.1 - 36.6)	490	(352 - 628)
Surface stratum				
Stem + branch	2.4	(0.0 - 5.5)	3.7	(2.0 - 5.4)
Stumps	0.0	(0.0 - 0.0)	0.2	(0.0 - 0.4)
<0.62 cm fuels	1.1	(0.9 - 1.4)	0.3	(0.1 - 0.4)
0.62-2.54 cm fuels	1.9	(1.1 - 2.7)	0.8	(0.5 - 1.1)
2.54-7.62 cm fuels	3.8	(2.9 - 4.6)	1.1	(0.7 - 1.6)
7.63-20.32 cm fuels	3.0	(1.7 - 4.2)	1.6	(0.7 - 2.5)
>20.32 cm fuels	12.8	(5.0 - 20.5)	11.9	(0.0 - 24.2)
Forest floor (L+D)	27.2	(20.6 - 33.8)	1.1	(0.5 - 1.7)
Total Surface Dead	52.1	(43.2 - 61.1)	19.6	(6.1 - 33.0)
LIVE MASS				
Aerial stratum				
Foliage	15.9	(10.2 - 21.6)	0.0	(0.0 - 0.0)
Branch	54.3	(22.9 - 85.7)	0.0	(0.0 - 0.0)
Stem	467	(248 - 685)	0.0	(0.0 - 0.0)
Total Aerial Live	537	(294 - 780)	0.0	(0.0 - 0.0)
Surface stratum				
Foliage	1.0	(0.2 - 1.7)	1.4	(0.9 - 1.9)
Stem + branch	3.3	(1.4 - 5.1)	2.2	(1.4 - 3.1)
Forbs/low shrubs	1.2	(0.0 - 2.5)	1.4	(0.6 - 2.3)
Total Surface Live	5.4	(2.9 - 7.9)	5.1	(3.6 - 6.5)
Grand Total Dead	73.5	(55.9 - 91.2)	510	(363 - 656)
Grand Total Live	542	(300 - 784)	5.1	(3.7 - 6.5)
Grand Total Biomass	616	(376 - 855)	515	(368 - 661)

[A] Stem masses include bark.

Table 2. Assessment of pre-treatment similarity for the subset of stands with before-after data (n=19), via two-way ANOVA.

Stand characteristic	Pre-treatment			
	Comparison [A]	$F_{2,13}$	P	M-D [B] diff.
Standing dead basal area	U ≈ M ≈ H	1.81	0.203	Y
Snags ha^{-1} [>30 cm dbh]	U ≈ M ≈ H	3.24	0.072	N
Snags ha^{-1} [10-30 cm dbh]	U ≈ M ≈ H	3.19	0.077	N
Snags ha^{-1} [<10 cm dbh]	U ≈ M ≈ H	2.96	0.087	N
Dead biomass total	U ≈ M ≈ H	1.63	0.233	Y
Dead biomass aerial	U ≈ M ≈ H	1.93	0.184	Y
Dead biomass surface	U ≈ M ≈ H	0.56	0.587	Y
Fine woody detritus [<7.62 cm diam.]	U ≈ M ≈ H	0.16	0.851	N
Coarse woody detritus [>7.62 cm diam.]	U ≈ M ≈ H	0.55	0.590	Y
Live biomass total	U ≈ M ≈ H	1.30	0.306	N
Live biomass aerial [c]	U ≈ M ≈ H	na	Na	N
Live biomass surface	U ≈ M ≈ H	1.30	0.306	N

[A] *U*= burned, unlogged, *M*= burned, moderate-intensity logged, *H*= burned, high-intensity logged. Comparisons are results of Fisher's *F*-protected least significant difference comparisons with α set at 0.05 to aid interpretation (Ramsey and Schafer 1997).
[B] *F*-statistics and *P*-values are shown for treatment effect only; for variables with significant mesic-dry (M-D) differences, mesic stands had higher absolute amounts. See Appendix 2 for side/interaction terms, means and 95% CIs by treatment, and analysis of pre-post change values.
[c] Live biomass aerial = 0 in all plots.

Table 3. Post-treatment stand characteristics (point estimate, 95% CI[A]) and statistical comparisons of unlogged (*U*), moderate-intensity logged (*M*), and high-intensity logged (*H*) burn stands.
N= 8, 7, 6 for *U, M, H* in drier stands; and 3 each for *U, M, H* in mesic stands. See Table 5 for standard errors and individual biomass pools.

Stand characteristic	Mesic stands			Drier stands			Two-way ANOVA result (*P*)		
	U	*M*	*H*	*U*	*M*	*H*	Trt [B] (df=2,24)	FType [B] (df=1,24)	Trt*Ftype (df=2,24)
Standing dead basal area (m^2 ha^{-1})	94.3 (41.8-213)	41.5 (18.4-93.6)	2.5 (1.1-5.7)	68.1 (41.4-112)	23.7 (13.9-40.3)	9.7 (5.4-17.1)	<0.0001	0.586	0.019
Snags ha^{-1} [>30 cm dbh]	137 (50.8-368)	55.7 (20.7-150)	2.5 (0.9-6.7)	165 (90.1-303)	72.5 (37.9-139)	29.4 (14.6-59.3)	<0.0001	0.007	0.015
Snags ha^{-1} [10-30 cm dbh]	211 (69.5-640)	303 (99.8-918)	2.8 (0.9-8.5)	237 (120-468)	149 (71.9-308)	45.9 (20.9-101)	<0.0001	0.060	0.002
Snags ha^{-1} [<10 cm dbh]	124 (20.9-736)	334 (56.4-1981)	10.2 (1.7-60.7)	717 (241-2132)	622 (194-1994)	39.0 (11.1-137)	0.0005	0.049	0.733
Dead biomass total (Mg ha^{-1})	709 (555-864)	355 (201-510)	244 (89.5-398)	435 (340-530)	182 (80.8-283)	161 (51.9-270)	<0.0001	0.002	0.336
Dead biomass aerial (Mg ha^{-1})	681 (537-825)	253 (109-398)	21.2 (0.0-166)	419 (330-507)	113 (18.0-207)	43.0 (0.0-145)	<0.0001	0.015	0.076
Dead biomass surface (Mg ha^{-1})	28.1 (0.0-63.1)	102 (66.9-137)	223 (188-258)	16.4 (0.0-37.8)	69.5 (46.6-92.4)	118 (93.4-141)	<0.0001	0.0003	0.010
Fine woody detritus (Mg ha^{-1}) [<7.62 cm diameter]	1.4 (0.0-5.1)	12.8 (9.1-16.5)	19.0 (15.3-22.7)	2.5 (0.2-4.8)	5.7 (3.3-8.1)	15.6 (13.0-18.2)	<0.0001	0.019	0.041
Coarse woody detritus (Mg ha^{-1}) [>7.62 cm diameter]	25.6 (0.0-56.8)	72.0 (40.8-103)	173 (142-205)	8.9 (0.0-28.0)	52.1 (31.7-72.5)	82.9 (60.8-105)	<0.0001	0.0005	0.013
Live biomass total (Mg ha^{-1})	5.6 (3.4-7.8)	7.3 (5.1-9.5)	1.6 (0.0-3.8)	4.9 (3.5-6.3)	4.9 (3.4-6.4)	2.8 (1.2-4.4)	0.0008	0.385	0.170
Live biomass aerial (Mg ha^{-1})	0	0	0	0	0	0	na	na	na
Live biomass surface (Mg ha^{-1})	5.6 (3.4-7.8)	7.3 (5.1-9.5)	1.6 (0.0-3.8)	4.9 (3.5-6.3)	4.9 (3.4-6.4)	2.8 (1.2-4.4)	0.0008	0.385	0.170

[A] 95% CIs were derived from two-way ANOVA outputs. [B] Trt= treatment (*U, M, H*), Ftype= forest type (mesic, drier).

Table 4. Mean (SE) aboveground biomass pools [Mg ha^{-1}], separated by category, 3-4 years after stand-replacement wildfire and subject to three post-fire treatments: unlogged (*U*), moderate-intensity logged (*M*), and high-intensity logged (*H*). N= 8, 7, 6 for *U, M, H* in drier stands; and 3 each for *U, M, H* in mesic stands.

Biomass Category	Mesic stands			Drier stands		
	U	*M*	*H*	*U*	*M*	*H*
<u>DEAD MASS</u>						
Aerial stratum						
Branch	49.4 (11.1)	11.4 (7.4)	0.0 (0.0)	76.3 (10.4)	20.6 (6.0)	5.4 (1.8)
Stem	632 (130)	242 (84.8)	21.2 (16.8)	342 (44.6)	91.8 (18.5)	37.6 (14.3)
Surface stratum						
Stem + branch	0.9 (0.4)	3.8 (1.7)	0.4 (0.3)	4.7 (0.7)	3.3 (1.0)	0.5 (0.3)
Stumps	0.2 (0.2)	13.3 (4.2)	29.9 (7.5)	0.2 (0.1)	8.4 (1.9)	19.2 (1.9)
<0.62 cm fuels	0.2 (0.0)	0.6 (0.2)	0.8 (0.1)	0.3 (0.1)	0.4 (0.1)	0.6 (0.2)
0.62-2.54 cm fuels	0.6 (0.2)	2.6 (0.5)	3.6 (0.1)	0.9 (0.1)	1.5 (0.2)	4.1 (0.6)
2.55-7.62 cm fuels	0.6 (0.4)	9.7 (0.8)	14.6 (0.9)	1.3 (0.2)	3.8 (0.6)	10.9 (2.0)
7.63-20.32 cm fuels	2.8 (1.2)	13.1 (4.1)	15.6 (3.6)	1.1 (0.2)	5.4 (1.1)	13.8 (2.0)
>20.32 cm fuels	22.9 (21.2)	58.9 (13.4)	158 (8.8)	7.8 (1.8)	46.7 (13.4)	69.1 (9.3)
<u>LIVE MASS</u>						
Aerial stratum						
Stem + branch	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Surface stratum						
Foliage	1.0 (0.2)	2.5 (0.4)	0.2 (0.1)	1.6 (0.3)	1.7 (0.4)	0.6 (0.1)
Stem + branch	1.8 (0.2)	3.6 (0.5)	0.4 (0.2)	2.4 (0.5)	2.9 (0.5)	0.9 (0.1)
Forbs/low shrubs	2.9 (0.9)	1.2 (0.2)	1.0 (0.4)	0.9 (0.2)	0.3 (0.1)	1.3 (0.3)

Figure Captions

Figure 1. Study area and sampling locations for quantification of fire and post-fire logging effects. Dots correspond to post-fire timber sales and adjacent unburned areas in which sample stands were located (total n=38 stands: 30 in the Biscuit Fire and 8 unburned mature/old-growth stands). We sampled all large Biscuit Fire timber sales completed by late 2005, with one exception in the extreme west of the fire. Dashed line approximating transition zone between mesic westerly plant associations and drier easterly plant associations adapted from USDA (2004). Spatial data courtesy of Rogue River-Siskiyou National Forest.

Figure 2. Mean (±S.E.) live biomass in the surface layer (mid- and overstory trees excluded). See Table 3 for statistical comparisons. Data are aggregated across the drier to mesic forest types because treatments effects were similar in both types (Table 3). Small-case letters above bars denote statistical differences from the ANOVA at α=0.05; see Table 3 for full statistical outputs. Regenerating vegetation had already achieved similar biomass 3-4 years post-fire as in mature/old-growth stands, and was lower after high-intensity logging.

Figure 3. Mean (±S.E.) aerial (A-B) and surface (C-F) wood biomass in mature/old-growth stands, and following stand-replacement fire and post-fire logging. Small-case letters above bars denote statistical differences from the ANOVA at α=0.05; see Table 3 for full statistical outputs.

Figure 4. Surface mass of fine (A) and coarse (B) woody detritus after post-fire logging as a function of total basal area cut.

Figure 5. Mean (±S.E.) cover and spatial variation in surface fuels. Small-case letters above bars denote statistical differences at α=0.05 by one-way ANOVA across all stands. Areal coverages are percent of ground area of down wood (A) and live vegetation (B). Within-stand

spatial heterogeneity is estimated by computing the coefficient of variation among transects within each sample stand, for fine down wood (C) and coarse down wood (D).

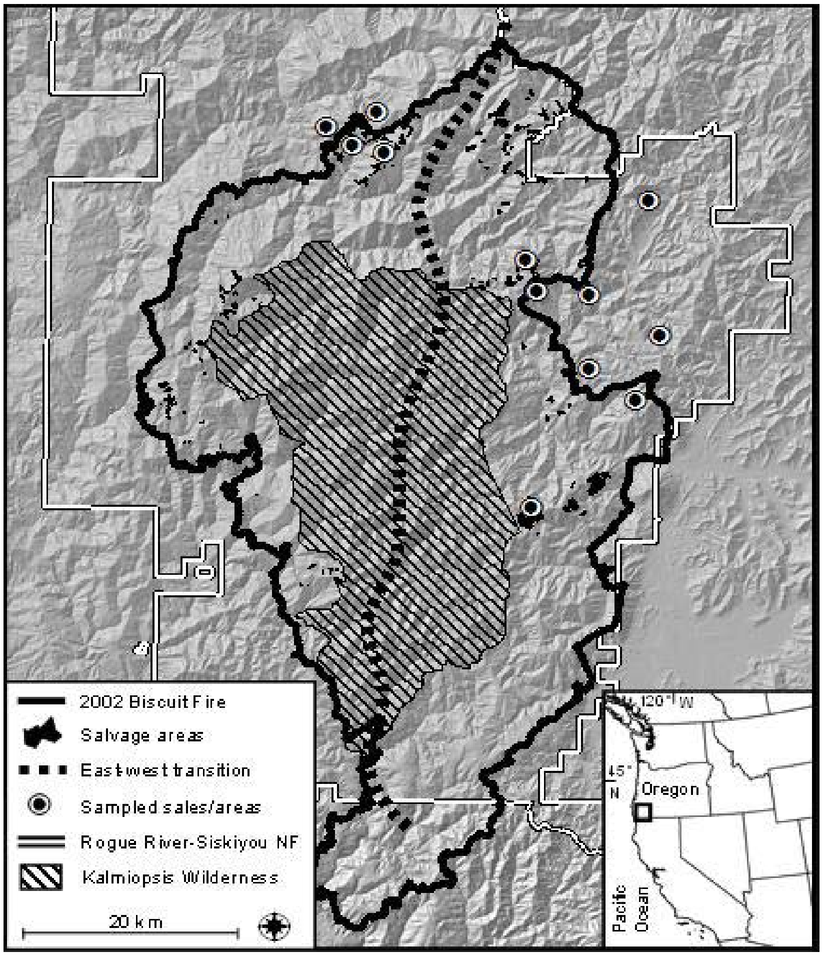

2002 Biscuit Fire
Salvage areas
East-west transition
Sampled sales/areas
Rogue River-Siskiyou NF
Kalmiopsis Wilderness
20 km
120° W
45° N
Oregon
Pacific Ocean

Figure 1.

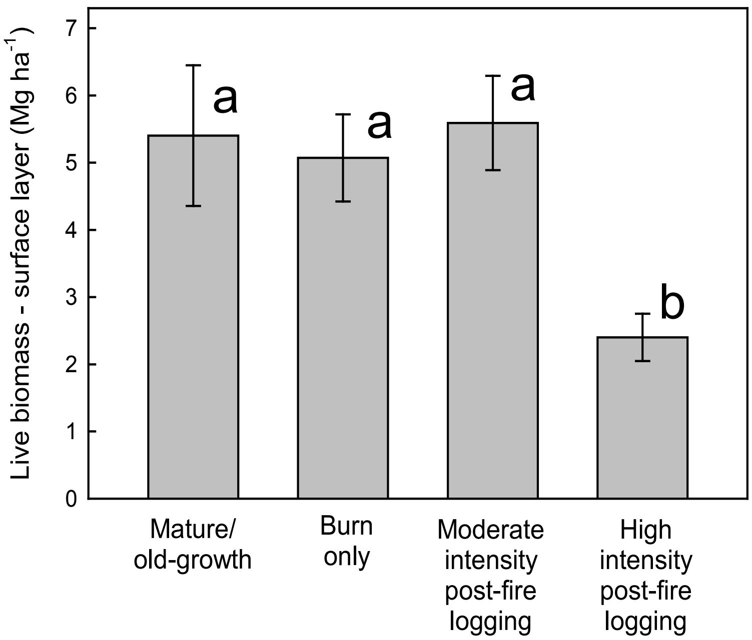
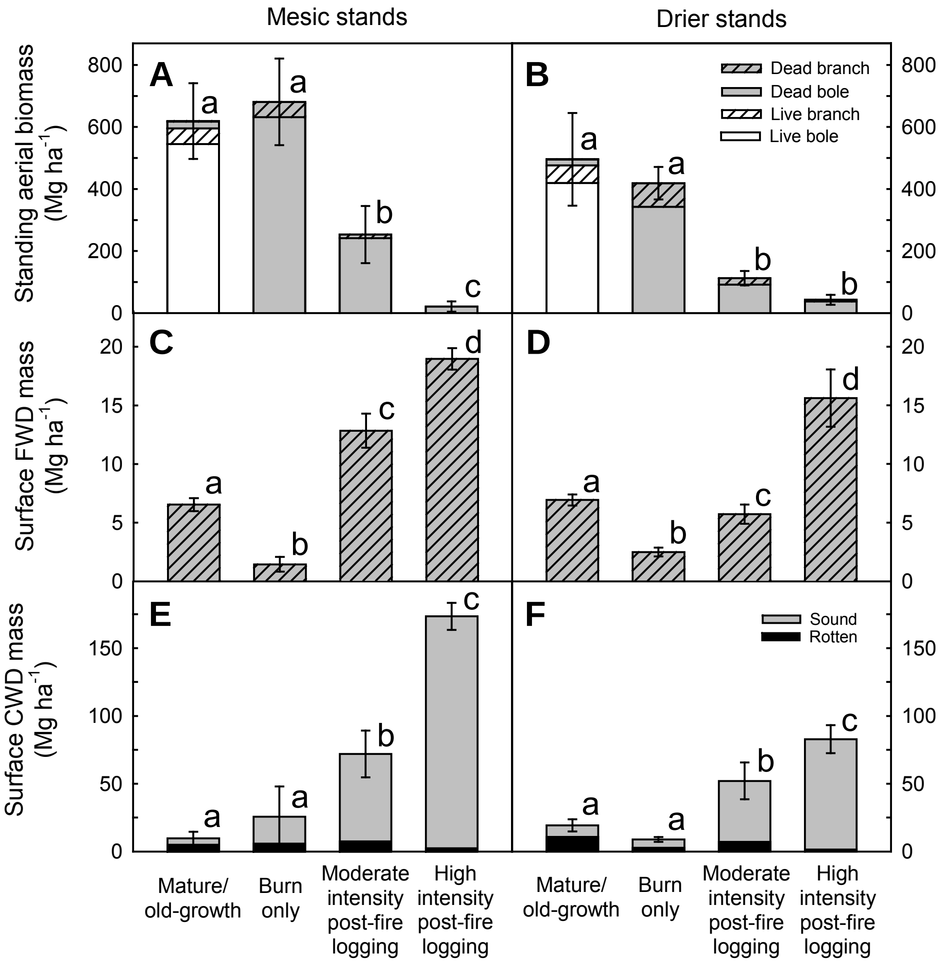

Live biomass - surface layer (Mg ha-1)
0
1
2
3
4
5
6
7
a
a
a
b
Mature/
old-growth
Burn
only
Moderate
intensity
post-fire
logging
High
intensity
post-fire
logging

Figure 2.



Mesic stands
Drier stands
Standing aerial biomass (Mg ha-1)
Surface FWD mass (Mg ha-1)
Surface CWD mass (Mg ha-1)
A
B
C
D
E
F
Dead branch
Dead bole
Live branch
Live bole
Sound
Rotten
Mature/ old-growth
Burn only
Moderate intensity post-fire logging
High intensity post-fire logging

Figure 3.

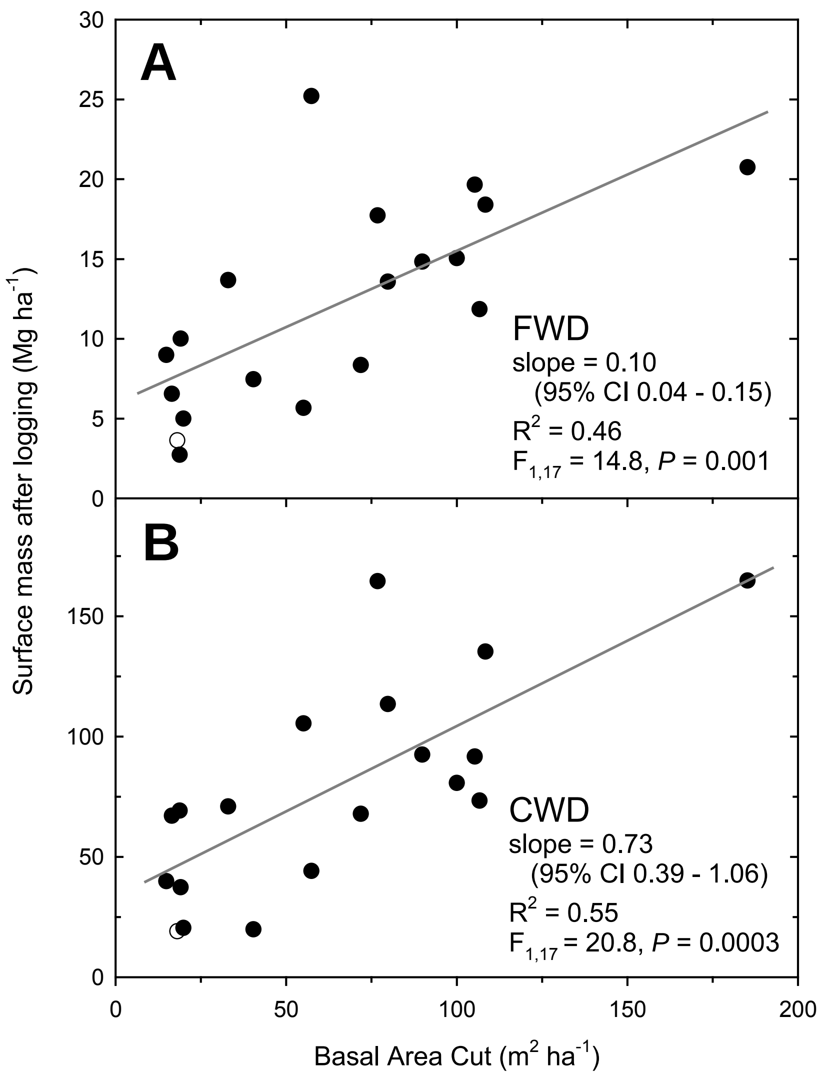
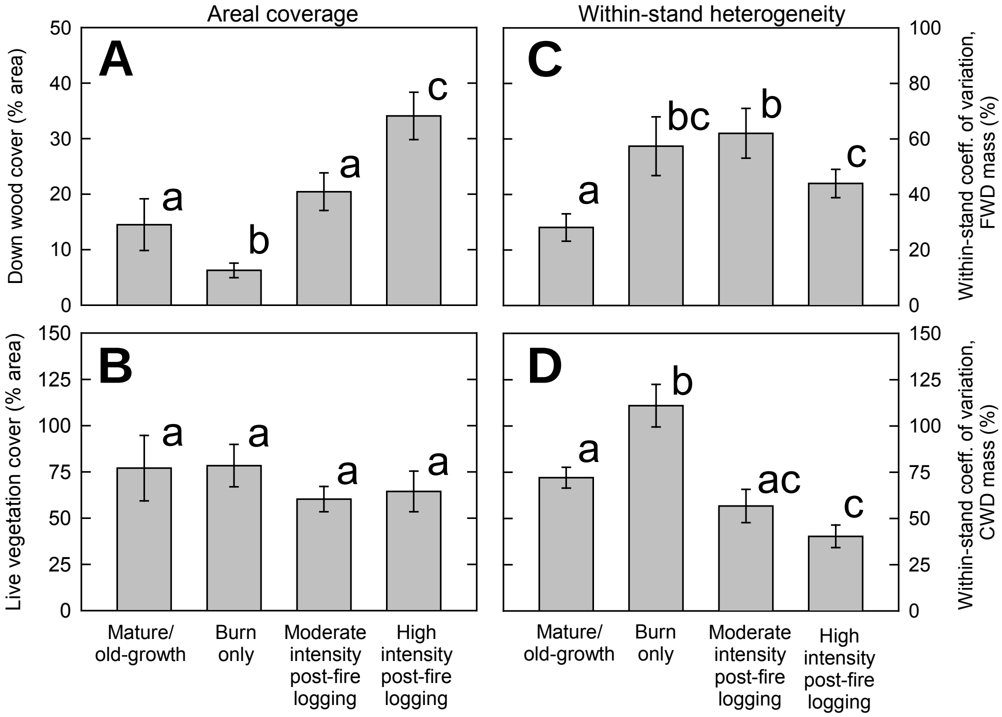

A
B
FWD
slope = 0.10
(95% CI 0.04 - 0.15)
R2 = 0.46
F1,17 = 14.8, P = 0.001
CWD
slope = 0.73
(95% CI 0.39 - 1.06)
R2 = 0.55
F1,17 = 20.8, P = 0.0003
Surface mass after logging (Mg ha-1)
Basal Area Cut (m2 ha-1)
0
5
10
15
20
25
30
0
50
100
150
200

Figure 4.



Areal coverage
Within-stand heterogeneity
A
B
C
D
Down wood cover (% area)
Live vegetation cover (% area)
Within-stand coeff. of variation, FWD mass (%)
Within-stand coeff. of variation, CWD mass (%)
a
b
a
c
a
a
a
a
a
bc
b
c
a
b
ac
c
Mature/ old-growth
Burn only
Moderate intensity post-fire logging
High intensity post-fire logging