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Post-fire logging reduces surface woody fuels up to four decades following wildfire

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ABSTRACT

Severe wildfires create pulses of dead trees that influence future fuel loads, fire behavior, and fire effects as they decay and deposit surface woody fuels. Harvesting fire-killed trees may reduce future surface woody fuels and related fire hazards, but the magnitude and timing of post-fire logging effects on woody fuels have not been fully assessed. To address this issue, we sampled surface woody fuels within 255 coniferous forest stands that burned with high fire severity in 68 wildfires between 1970 and 2007 in eastern Washington and Oregon, USA. Sampling included 96 stands that were logged after wildfire and 159 stands that were not logged. Most forest stands sampled were dominated by ponderosa pine (*Pinus ponderosa*) or Douglas-fir (*Pseudotsuga menziesii*) prior to wildfire and historically supported low and mixed-severity fire regimes. In unlogged stands, woody fuel loads were low initially, but then increased and peaked 10–20 years following wildfire. In logged stands, small and medium diameter woody fuel loads peaked immediately after logging, whereas large diameter woody fuel loads peaked 10–20 years after wildfire. Relative to unlogged stands, post-fire logging initially increased surface woody fuel loads, increasing small diameter fuel loads by up to 2.1 Mg/ha during the first 5 years after fire and increasing medium diameter fuel loads by up to 5.8 Mg/ha during the first 7 years after fire. Logging subsequently reduced surface woody fuel loads, reducing large diameter fuel loads by up to 53 Mg/ha between 6 and 39 years after wildfire, reducing medium diameter fuel loads by up to 2.4 Mg/ha between 12 and 23 years after wildfire, and reducing small diameter fuel loads by up to 1.4 Mg/ha between 10 and 28 years after wildfire. Logging also reduced rotten, large diameter fuel loads by up to 24 Mg/ha between 20 and 39 years after wildfire. Our study suggests that post-fire logging can significantly reduce future surface woody fuel levels in forests regenerating following wildfires. The magnitude of woody fuel reduction depends, however, on the volume and sizes of wood removed, logging methods, post-logging fuel treatments, and the amount of coarse woody debris left on-site to support wildlife habitat, erosion control, and other competing management objectives.

1. Introduction

Severe wildfires and insect outbreaks create pulses of dead trees and initiate a process of post-disturbance fuel succession that may affect future fire behavior and effects (Agee and Huff, 1987; Passovoy and Fulé, 2006; Kulakowski and Veblen, 2007; Monsanto and Agee, 2008). Surface dead and live fuels change over time as dead trees decompose and deposit needles, branches, tops, and boles on the forest floor; surface fuels decay; and recovering vegetation produces new fuels (Hall et al., 2006; Passovoy and Fulé, 2006). The influence of dead tree pulses and subsequent fuel succession processes on future wildfires depends on the magnitude of the pulse, the time to the next fire, and weather and fuel moisture conditions during the next fire.

Wildfires and insect outbreaks have caused widespread tree mortality in dry coniferous forests of western North America in recent decades, and anticipated climatic changes suggest even higher impacts in the future (e.g., Breshears et al., 2005; Westerling et al., 2006; Raffa et al., 2008; Flannigan et al., 2013; Luo et al., 2013). Fire exclusion, logging, grazing, and other management practices have increased tree densities, altered forest species composition, and allowed surface woody fuels to accumulate in modern forests, increasing the potential for high severity wildfires and insect outbreaks (Hessburg et al., 2005; Nacify

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et al., 2010; Marlon et al., 2012; Williams, 2013). Continuing wildfire suppression efforts also favor high fire intensity and severity by promoting continued fuel accumulations and by concentrating wildfire activity during periods of extreme fire weather when suppression is least effective (Reinhardt et al., 2008; North et al., 2012). The combination of high forest stand densities and high fire intensity can produce large pulses of dead trees that eventually generate high surface woody fuel loadings and the potential for subsequent high severity wildfires (sometimes called "re-burns") that impact both soils and vegetation (Brown et al., 2003).

Modifying forest fuels so that wildfires can burn within the natural range of variability for a particular fire regime and without creating unacceptable social–ecological hazards is an important ecological restoration objective for many fire-prone forests (Allen et al., 2002; Reinhardt et al., 2008). Forest restoration efforts in fire-prone forests often use mechanical thinning or prescribed fire to reduce surface and canopy fuels, reduce wildfire intensity and severity, and increase forest resiliency to fire (Brown et al., 2004; Stephens et al., 2009). However, funding and access limitations, conservation concerns, air quality regulations, and the increasing need to maintain treated areas have often limited treatments to forests surrounding populated areas and other high priority areas (North et al., 2012; Williams, 2013). Without dramatic increases in forest restoration and fuel reduction efforts, large wildfires are likely to continue burning dry coniferous forests at high intensity and severity, particularly during drought years (Miller et al., 2009; Marlon et al., 2012; Williams, 2013). Climate change may further exacerbate the problem by lengthening fire seasons, increasing drought frequency and intensity, altering fire weather, and lowering the fuels threshold required to restore low severity fire regimes (McKenzie et al., 2004; Westerling et al., 2006; Marlon et al., 2012; Luo et al., 2013).

Post-fire logging may provide an economical way to expand the scope of restoration-based fuel reduction treatments, reduce the threat of future high-severity wildfires, and improve future forest resiliency to fire in dry coniferous forests (Brown et al., 2003). By harvesting recently fire-killed trees and actively managing the amount and spatial distribution of residual woody debris (standing or fallen), post-fire logging may reduce future woody fuel loads, future wildfire intensity and severity, and associated hazards to vegetation, soils, watershed functions, and aquatic ecosystems (DeBano et al., 1998; Brown et al., 2003; Peterson et al., 2009; Johnson et al., 2013). However, post-fire logging is often controversial, with most proponents focused on recovering economic value from fire-killed trees and speeding forest regeneration (Sessions et al., 2004) and opponents focused on protecting burned ecosystems from further disturbance and on retaining standing dead trees (snags) and other woody debris for wildlife use (Beschta et al., 2004; Hutto, 2006).

Past studies of post-fire logging effects on surface woody fuels have produced mixed results, but suggest that time since fire and basal area logged are important factors influencing outcomes. Studies that examined woody fuels shortly after fire and logging (1–4 years) have found that post-fire logging increased surface woody fuels (Donato et al., 2006, 2013; McIver and Ottmar, 2007; Keyser et al., 2009; McGinnis et al., 2010; Monsanto and Agee, 2008), while studies conducted longer after fire (5–35 years) have found that post-fire logging reduced fuels (Monsanto and Agee, 2008; Keyser et al., 2009; Ritchie et al., 2013) or had no effect (McGinnis et al., 2010). Woody fuel loadings in logged stands are also correlated with stand basal area logged (Ritchie et al., 2013), suggesting that differences in stand basal area should be accounted for when studying post-fire logging effects on woody fuels.

The goal of this study was to improve our understanding of natural post-fire woody fuel dynamics and post-fire logging effects on woody fuels. We therefore studied post-fire logging effects on temporal patterns of surface woody fuel loadings through a retrospective study spanning broad temporal and spatial scales in eastern Oregon and Washington, U.S.A. We hypothesized that post-fire logging would initially increase woody fuels relative to unlogged stands by transferring non-merchantable woody debris from snag canopies to the forest floor, but would later reduce woody fuels by removing tree boles that would eventually become large diameter woody fuels. To test these hypotheses, we sampled surface woody fuels within 255 coniferous forest stands that burned in stand-replacing wildfires between 1970 and 2007, including 96 stands that were logged following wildfire. Our objectives were to (1) describe patterns of woody fuel succession following stand-replacing wildfires for logged and unlogged stands, (2) test the effects of post-fire logging on mean woody fuel loads up to 39 years after wildfire; and (3) assess the influence of pre-fire stand basal area on post-fire woody fuel loads.

2. Materials and methods

Our study examined fuel succession patterns by surveying downed woody fuels across a chronosequence of dry coniferous forest stands that burned with high fire severity (95–100% overstory tree mortality) within mixed- and high-severity wildfires in eastern Washington and Oregon, USA, between 1970 and 2007. We sampled forests in which ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are the dominant early-seral tree species, though such forests may also contain significant components of lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), or true firs (*Abies grandis*, *A. concolor*, or *A. magnifica*). These forests historically supported low- and mixed-severity fire regimes with mean fire return intervals often less than 35 years (Everett et al., 2000; Wright and Agee, 2004). Decay rates for downed wood are also relatively slow in ponderosa pine forests, as warm dry summers maintain low mean wood moisture content (Erickson et al., 1985), so surface woody fuels generated by wildfires can persist long enough to influence subsequent wildfire behavior and effects given continuation of the historical fire frequency (Monsanto and Agee, 2008). These forests have also experienced large, stand-replacing wildfires in recent decades and are now increasingly the subject of restoration-based management efforts to reduce fuels at a variety of spatial scales (Franklin and Johnson, 2012). Dry coniferous forests with comparable species composition, stand structural conditions, climatic conditions, and fire regimes are widespread throughout much of western North America.

From a population of large wildfires that burned with mixed and high severity on National Forest lands in eastern Washington and Oregon between 1970 and 2007, we selected 68 wildfires for study with the goal of providing a spatially and temporally balanced sample (geographical region and time since fire). This goal was largely met, despite some challenges in locating suitable unlogged stands in older wildfires and suitable logged stands in more recent wildfires.

Within each selected wildfire, we used fire perimeter maps and field visits to identify potential forest stands for sampling that burned with high severity (>95% tree mortality), contained significant numbers of ponderosa pine or Douglas-fir trees, contained at least some merchantable timber (e.g., trees >30 cm dbh), and were close enough to roads to allow easy access for field crews. From this pool of stands, we selected stands for sampling that represented a broad range of topographic settings (e.g., elevation, aspect) and pre-fire stand structural conditions (e.g., species composition and size structure). Similar to our selection of wildfires, we selected forest stands with the goal of sampling across a broad range of conditions; the selected stands do not represent a purely random sample of all suitable stands.

We selected a total of 255 forest stands for field sampling, including 96 stands that were logged following wildfire. We selected 1–16 forest stands for sampling within each wildfire, depending on wildfire size and severity, the range of topographic settings and pre-fire stand structural conditions found within high severity burn areas, and the availability of logged and unlogged stands. Sampled stands were distributed throughout the most fire-prone areas of eastern Washington and Oregon, USA (Fig. 1). Elevations ranged from 508 to 2030 m above sea level and spanned the full range of slope aspects (Fig. 2). Mean stand elevations increased from north to south within the study region, but did not differ significantly between logged and unlogged stands. Ranges of pre-fire stand basal area were also similar between logged and unlogged stands (mean ± SD was 30.1 ± 15.9 $m^2\ ha^{-1}$ for unlogged stands and 32.1 ± 14.3 $m^2\ ha^{-1}$ for logged stands).

For logged stands, we did not attempt to control logging methods, or post-logging treatments (fuel reduction and site preparation) – we simply selected stands with evidence of significant post-fire logging (not just a few scattered stumps, which could be due to firewood cutting). As a result, our results represent outcomes from post-fire logging practices commonly used in the interior Pacific Northwest between 1970 and 2008.

Within each selected stand, we established one study plot within which we sampled surface woody fuels and pre-fire stand structure. We determined plot locations within each stand by subjectively choosing a preliminary plot center within a representative area of the target stand that was at least 50 m from any roads or other stand boundaries. We established the final plot center by applying a random offset of 1–20 m in a random direction from the preliminary plot center.

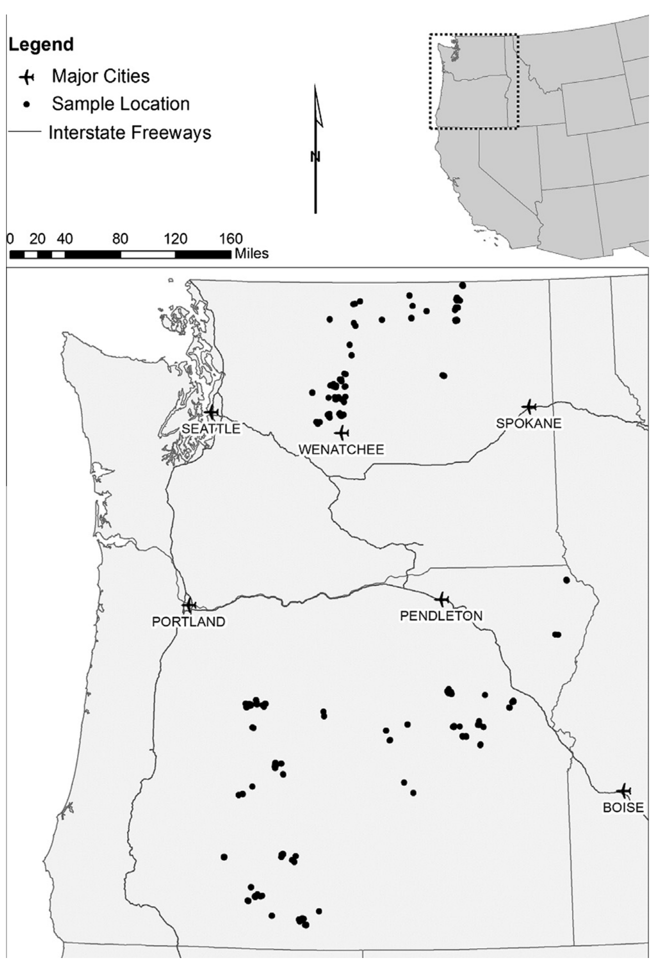

Fig. 1. Sample stand locations in eastern Washington and Oregon, USA.

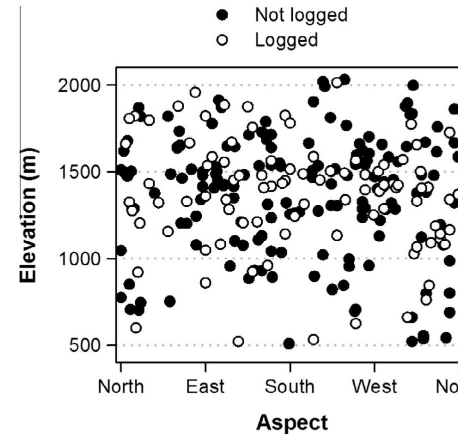

Fig. 2. Sampling distributions across elevation and aspect gradients for logged (open circles) and unlogged (closed circles) stands.

We measured surface woody fuels within each stand using the planar intercept method as described by Brown (1974). In 2007 and 2008, we measured fuels in 126 unlogged stands using three 20-m long fuel transects per stand, with transects radiating outward at random azimuths from the plot center and starting three meters from the plot center. In 2009, we measured fuels in 96 logged stands and in 33 additional unlogged stands using seven 20-m transects per stand (forming a hexagonal pattern around the plot center with one radial spoke). We changed the number and arrangement of fuel transects to increase the precision of the mean woody fuel mass estimates in each stand; however, both sampling intensities provide unbiased estimates of woody fuel mass.

We measured sound fuels in four diameter size categories in the field: fine (0–0.6 cm), small (0.7–2.5 cm), medium (2.6–7.6 cm), and large (⩾7.7 cm). These size classes correspond to the 1-h, 10-h, 100-h, 1000-h (and greater) fuel moisture classes that are commonly used for fire behavior and effects modeling. We estimated fuel mass for fine, small, and medium fuels from counts of woody fuel pieces along a small segment of each fuel transect (2 m for fine and small fuels, 3 m for medium fuels in 2007–2008, and 5 m for medium fuels in 2009) using formulae presented by Brown (1974). We then summed fuel mass estimates from the fine and small size categories to produce a combined "small fuels" category (0–2.5 cm diameter) for use in our analysis. We estimated fuel masses for large diameter fuels from measured diameters and field assessments of decay status (sound or rotten) for all large fuel pieces encountered along the full 20-m length of each transect. We estimated fuel masses for sound and rotten fuels separately, using different specific gravity estimates following Brown (1974), and then added the sound and rotten fuel mass estimates together to obtain total large fuel mass estimates. We first calculated fuel mass estimates (Mg ha^{-1}) in each size class for individual transects and then averaged the 3–7 transect estimates within each stand to obtain stand-level fuel mass estimates.

To reconstruct pre-fire stand structure, we surveyed all standing dead trees (snags) and fallen dead trees (logs) that were judged to have been living trees prior to wildfire within an 18–35 m radius of the plot center. In 2007 and 2008, plot radii for assessing stand structure ranged between 20 and 35 m. The standard plot radius was 25 m (69% of plots), but we allowed field crews to adjust plot radii down to 20 m (25% of plots) prior to beginning the survey to limit tree measurement time in dense stands. We also allowed crews to increase plot radii to 30 or 35 m prior to beginning the survey in low density stands to provide larger samples of dead trees for an associated snag dynamics study. In 2009, we used a constant plot radius of 18 m for assessing pre-fire stand structure on all sites. On plots in unlogged stands, we recorded species and measured the diameter of each fire-killed tree (standing or fallen snags with diameter ⩾15 cm) at a point corresponding to breast height (1.37 m) on a standing tree. On plots in logged stands, we recorded diameter and species for all stumps (diameter ⩾15 cm at top of stump) and estimated tree diameter at breast height from stump diameter using a correction factor of 0.9 (estimated based on field sampling in unlogged stands). We summarized these data to calculate pre-fire stand basal area and density for each stand.

3. Analysis

We modeled the effects of time since fire, post-fire logging, and pre-fire stand basal area on surface woody fuel loads using semi-parametric linear mixed models that combined elements of standard linear parametric models (e.g., regression) and additive models (e.g., splines). Response variables of interest included fuel mass estimates for small fuels (0.0–2.5 cm diameter); medium fuels (2.6–7.6 cm diameter); large fuels (⩾7.7 cm diameter, including both sound and rotten fuels); and large, rotten fuels. All models included a random effect for "wildfire" to account for potential correlations in responses among multiple sites within the same wildfire. The full statistical model for each response variable included predictor variables (fixed effects) for time since fire (years), post-fire logging treatment (yes or no), pre-fire stand basal area, and a two-way interaction between logging treatment and time since fire. We tested for significance of a potential interaction between logging treatment and pre-fire stand basal area, but this was not significant in any of the models. We also assessed the influence of additional stand and site variables (e.g., mean temperature, annual precipitation, and tree density) during preliminary data analysis, but found these variables to have little or no additional effect on woody fuel loadings and therefore dropped them from subsequent analyses.

Preliminary data analysis indicated that woody fuel responses to time since fire were non-linear and could not be described well using standard polynomial regression methods. We therefore modeled responses to time since fire using natural cubic smoothing splines with three internal knots based on data percentiles (quartiles at 6, 14, and 19 years after fire). Preliminary analyses also indicated that square-root transformations of the response variables were necessary and sufficient for all response variables to satisfy assumptions of normality in model residuals.

To account for the potential effects of using different sampling intensities (3 or 7 fuel transects per site) to assess woody fuels, we modeled separate error variances for three groups of sites: logged sites with high sampling intensity (7 transects/site), unlogged sites with high sampling intensity, and unlogged sites with low sampling intensity (3 transects/site).

We adopted a threshold Type I error rate of 5% for all statistical hypothesis testing and used SAS PROC GLIMMIX (SAS/STAT version 9.4, SAS Institute, 2012) to estimate model parameters and perform hypothesis tests for all fuel size classes.

4. Results

Our statistical analyses revealed significant interactive effects of logging treatment and time since fire on surface woody fuel loadings for all fuel diameter classes (Table 1), indicating that post-fire logging altered temporal patterns of surface woody fuel loadings. We also found significant effects of pre-fire stand basal area on mean post-fire surface woody fuels for all size classes except the small diameter fuels. We therefore describe post-fire woody fuel succession patterns separately for logged and unlogged stands in each fuel size category, including graphical displays of the effects of pre-fire stand basal area. We then describe post-fire logging effects on surface woody fuel loads for each fuel diameter class by comparing model least-square mean estimates from at different time periods (years since fire) for logged and unlogged stands with median pre-fire basal area.

Without post-fire logging, surface woody fuels were low in stands surveyed shortly after wildfire, reached maximum levels in stands surveyed 10–20 years after wildfire, and then declined gradually out to 39 years past wildfire (Fig. 3). The general pattern of woody fuel loads first increasing and then declining with time since fire was similar among fuel diameter classes (Fig. 3). Loadings of large, rotten fuels were very low in stands surveyed during the first 10 years after wildfire, but then increased steadily with increasing time since fire in stands surveyed 10–39 years after fire (Fig. 3).

With logging, small and medium fuels were highest in stands surveyed shortly after fire (and logging) and declined with increasing time since fire (Fig. 3). Large fuels peaked 10–20 years after wildfire, but changed relatively little across the chronosequence of logged stands (Fig. 3). As in unlogged stands, rotten, large fuels were very low in stands surveyed during the first 10 years after wildfire, but then increased steadily with increasing time since fire (Fig. 3).

Woody fuel loads were highly variable across the chronosequence in both logged and unlogged stands (Fig. 3). Some of this variability was due to differences in pre-fire stand basal area, which was positively correlated with woody fuel loadings at any given time since fire. Pre-fire basal area accounted for much of the variability in medium, large, and very large woody fuels, but did not significantly influence small woody fuels (Table 1, Fig. 3).

Statistical tests of differences in model least square means estimates for logged and unlogged stands (at the median pre-fire stand basal area of 27-m^2/ha) show that post-fire logging effects on the relative abundance of surface woody fuels varied among woody fuel size classes and through time (Fig. 4). Logging significantly reduced predicted fuel loads of large fuels (⩾7.7 cm diameter, sound and rotten combined) between 6 and 39 years after wildfire (Fig. 4). Logging also significantly reduced predicted fuel loads for large, rotten fuels between 20 and 39 years after wildfire (Fig. 4). Logging significantly increased predicted fuel loads for small diameter fuels (up to 2.1 Mg/ha) during the first 5 years after wildfire and for medium diameter fuels (up to 5.8 Mg/ha) during the first 7 years after wildfire. However, logging subsequently significantly reduced predicted fuel loads for small diameter fuels (up to 1.4 Mg/ha) between 10 and 28 years after wildfire and for medium diameter fuels (up to 2.4 Mg/ha) between 12 and 23 years after wildfire (Fig. 4).

5. Discussion

5.1. Post-fire fuel succession

Our results support a conceptual model of woody fuel succession following wildfire beginning with a "fuel accumulation" stage, during which woody fuel deposition by decaying snags exceeds woody fuel decay, followed by a "fuel decay" stage, during which decay of surface woody fuels exceeds woody fuel deposition. The basic pattern we found of fuel accumulation followed by declining fuels is consistent with previous chronosequence and longitudinal studies of downed dead wood dynamics in ponderosa pine forests (Hall et al., 2006; Monsanto and Agee, 2008; Ritchie et al., 2013). The fuel accumulation period we observed for large diameter fuels was very similar to that described for ponderosa pine forests in

Table 1
Type III tests of fixed effects from additive models of surface fuel responses to time since fire (TSF), post-fire logging (logging), and pre-fire stand basal area (basal area).

Response	Effect	Num. d.f.	Den. d.f.	*F* value	Prob.> *F*
Small fuels,	Time since fire (TSF)	2	36.4	3.30	0.048
1- to 10-h	Logging	1	167.7	10.13	0.002
(diameter ⩽ 2.5 cm)	Logging × TSF	2	180.8	8.47	<0.001
	Basal area	1	194.9	2.72	0.101
Medium fuels,	Time since fire (TSF)	2	33.4	1.84	0.175
100-h	Logging	1	171.6	18.37	<0.001
(2.6–7.6 cm diam.)	Logging × TSF	2	168.4	10.31	<0.001
	Basal area	1	188.4	25.44	<0.001
Large fuels,	Time since fire (TSF)	2	20.4	21.20	<0.001
⩾1000-h	Logging	1	137.9	1.51	0.221
(⩾7.7 cm diam.)	Logging × TSF	2	179.5	10.54	<0.001
	Basal area	1	152.0	45.35	<0.001
Large, rotten fuels	Time since fire (TSF)	2	45.2	51.57	<0.001
⩾1000-h	Logging	1	168.1	0.55	0.459
(⩾7.7 cm diam.)	Logging × TSF	2	214.4	3.90	0.022
	Basal area	1	196.4	11.39	<0.001

Colorado (Hall et al., 2006), with modeled maximum fuel accumulations occurring within the first 20 years after wildfire, but with some sites having very high large diameter fuel (dead wood) loads up to 40 years after wildfire.

Surface woody fuel deposition is particularly rapid during the first decade after wildfire, as fire-killed trees shed branches and a high percentage of ponderosa pine and Douglas-fir snags fall or have tops broken off during this period (Keen, 1929; Dahms, 1949; Everett et al., 1999; Dunn and Bailey, 2012; Ritchie et al., 2013; Peterson, unpublished data). Loadings of small and medium diameter fuels begin to decline, on average, in subsequent decades as most snags have shed branches and tops and decay of surface woody fuels exceeds deposition. Deposition of large diameter fuels can continue to exceed losses to decay for up to three decades, particularly in stands with large diameter snags and more slowly decaying species like Douglas-fir (Dunn and Bailey, 2012).

5.2. Post-fire logging effects

We found that post-fire logging altered post-fire fuel succession by (1) greatly accelerating the deposition of surface woody fuels from logged snags (logging residue), (2) reducing peak loadings of large diameter woody fuels, and (3) initiating the woody fuel decay stage earlier (at least for small and medium diameter fuels). As a result, post-fire logging produced a transient pulse of elevated surface woody fuel loadings followed by a much longer period of reduced surface woody fuel loadings, relative to burned stands that were not logged.

The initial pulse of elevated surface fuels in logged stands was expected under our first hypothesis. Post-fire logging transfers woody debris in tree branches and tops from the canopies of fire-killed trees to the forest floor, producing well-documented conditions of higher surface woody fuels in logged stands than in unlogged stands in the first 1–4 years following logging (Donato et al., 2006, 2013; McIver and Ottmar, 2007; Monsanto and Agee, 2008; Keyser et al., 2009). Higher amounts of surface woody fuels – especially small and medium diameter woody fuels – can increase short-term fire hazards in logged stands by increasing potential rate of spread and fire-line intensity (Donato et al., 2006), but actual fire risks are low unless there are enough fine fuels (e.g., litter, grass, and shrub fuels) to carry fire through the logged stand and there are sufficient fuels in surrounding stands to allow wildfires to spread into or away from the logged stand. The period of elevated hazards is also relatively short-lived, as deposition and accumulation of surface fuels from decaying snags causes mean surface fuel loadings in unlogged stands to exceed those in logged stands within 5–10 years after wildfire (Monsanto and Agee, 2008; Keyser et al., 2009; Ritchie et al., 2013; this study).

Post-fire logging was most effective for reducing large diameter surface fuels, consistent with our second hypothesis. By removing tree boles, post-fire logging reduced maximum large diameter fuel loadings and produced a long period of reduced large diameter fuels, including both sound and rotten fuels. Although large diameter fuels may contribute little to fire spread rates (Hyde et al., 2011) and are typically disregarded in fire behavior modeling (e.g., BEHAVE, Andrews, 1986), they can influence fire residence times and total heat release during fire (Brown et al., 2003; Monsanto and Agee, 2008) and can contribute to large fire growth by promoting greater torching, crowning, and spotting behavior (Brown et al., 2003). Reducing amounts of large, rotten woody fuels may be especially useful, as rotten fuels ignite more easily than sound fuels and smoldering combustion of large diameter rotten fuels can lengthen fire residence times, increase soil heating, increase tree mortality, and produce large amounts of smoke (DeBano et al., 1998; Brown et al., 2003; Monsanto and Agee, 2008). Large rotten woody fuels may also contribute more to surface fire intensities than large sound woody fuels because their greater surface area allows them to function more like smaller diameter fuels (Brown et al., 2003).

Future potential fuel loadings and the effects of post-fire logging on fuels depend, in part, on the mass or volume of trees killed by fire and the amount of material removed during logging. Basal area of fire-killed trees, or of snags retained after logging, appears to be a useful scaling factor for predicting fuel loadings through post-fire fuel succession and reductions in fuel loadings from post-fire logging (Ritchie et al., 2013; this study), assuming that tree diameter distributions do not vary radically. Measuring basal area of fire-killed trees could also assist in predicting future fuel loadings in forest stands where wildfires cause only partial overstory mortality.

Surface woody fuel loadings varied considerably among stands in both the logged and unlogged treatment groups beyond what could be explained by time since fire, differences in pre-fire stand basal area, and stand environmental factors such as climate. In some stands without post-fire logging, windstorms or heavy snow loads may have accelerated fuel deposition from decaying snags, producing pulses of surface fuels across a wide range of diameter and decay classes (Ritchie et al., 2013). Variability in species composition and tree size distributions among stands may also have

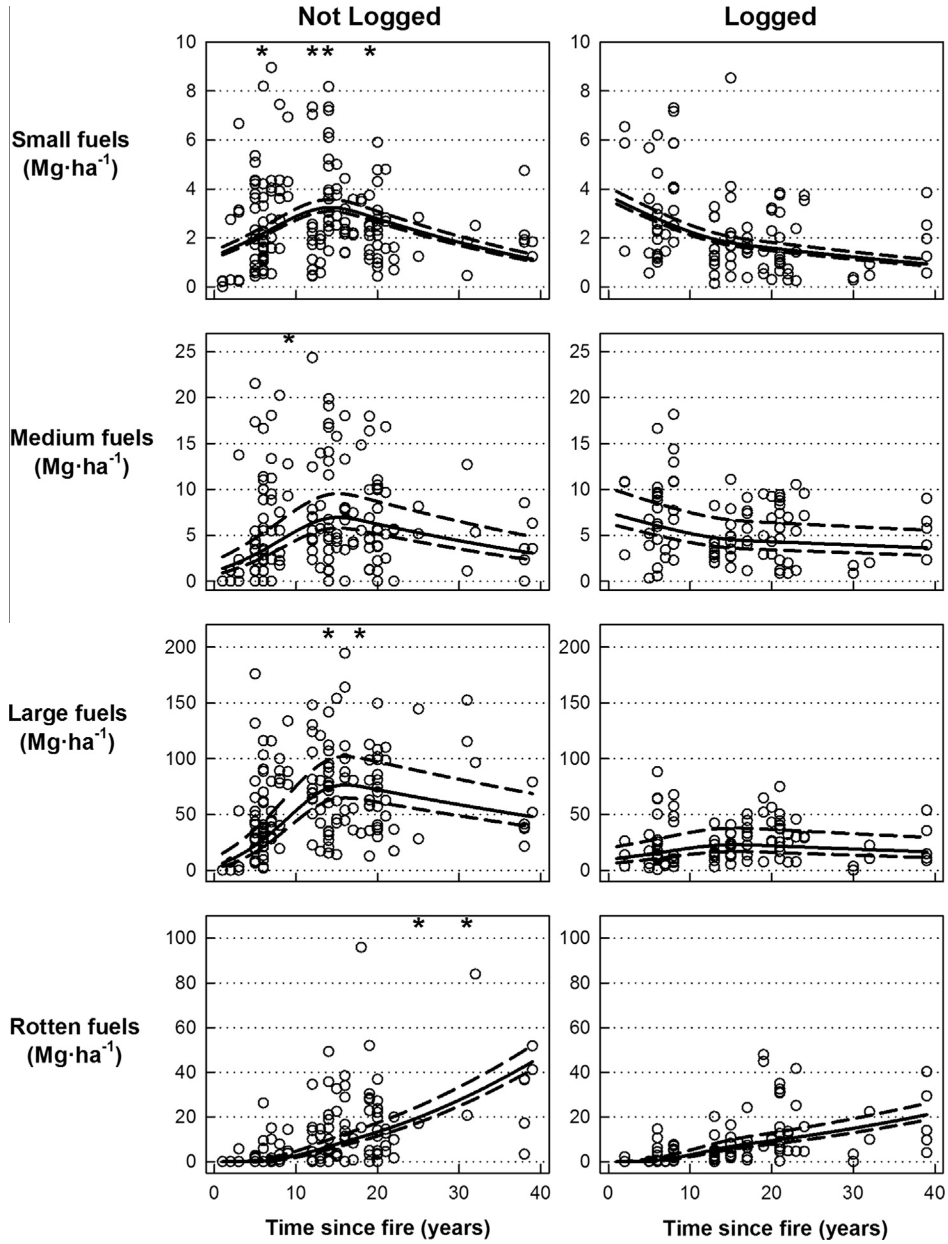

Fig. 3. Changes in mean surface fuel levels with increasing time since fire, with and without post-fire logging. Individual graphs show temporal changes for small, medium, and large (sound and rotten) diameter fuels and for large diameter rotten fuels (rows), in stands without post-fire logging (left column) and with post-fire logging (right column). Curves on each graph show model predictions for three levels (10th, 50th, and 90th percentiles) of pre-fire stand basal area: 15 m^2 ha^{-1} (lower dashed line), 27 m^2 ha^{-1} (solid line), and 51 m^2 ha^{-1} (upper dashed line). Asterisks indicate the presence of an outlier observation that exceeded plot axis limits at a given time since fire.

influenced fuel deposition rates, as small diameter and ponderosa pine snags tend to fall earlier than large diameter and Douglas-fir snags (Dunn and Bailey, 2012). Some unexplained variability could also be attributed to sampling error, as we found that model residual error variances were lower in all fuel diameter classes for stands surveyed using seven fuel transects than for stands surveyed using only three fuel transects.

In logged stands, variability in management objectives, logging practices, and post-logging fuel treatments could have influenced amounts and spatial heterogeneity of residual surface woody fuels. Logging fire-killed trees primarily for fuel reduction and restoration of low severity fire regimes would likely call for different logging methods and treatment of logging residues than logging trees primarily to recover economic value. Management requirements for retaining adequate standing and downed dead trees for wildlife use or soil erosion control could also alter amounts, sizes, and spatial distributions of residual fuels (Brown et al., 2003). These considerations could be incorporated into post-fire logging prescriptions, just as they are with thinning and logging prescriptions in green forests.

As a fuel reduction treatment, post-fire logging could contribute to long-term restoration objectives in dry coniferous forests by restoring surface fuels to levels more consistent with low and mixed-severity fire regimes. At the stand scale, post-fire logging reduces surface fuels over the longer term, particularly in the large diameter size classes, which should increase management options for applying prescribed fire treatments or allowing future wildfires to burn without causing excessive damage to forest vegetation and soils. Post-fire logging prescriptions could also be designed to generate spatial variability in snag densities and fuels within stands,

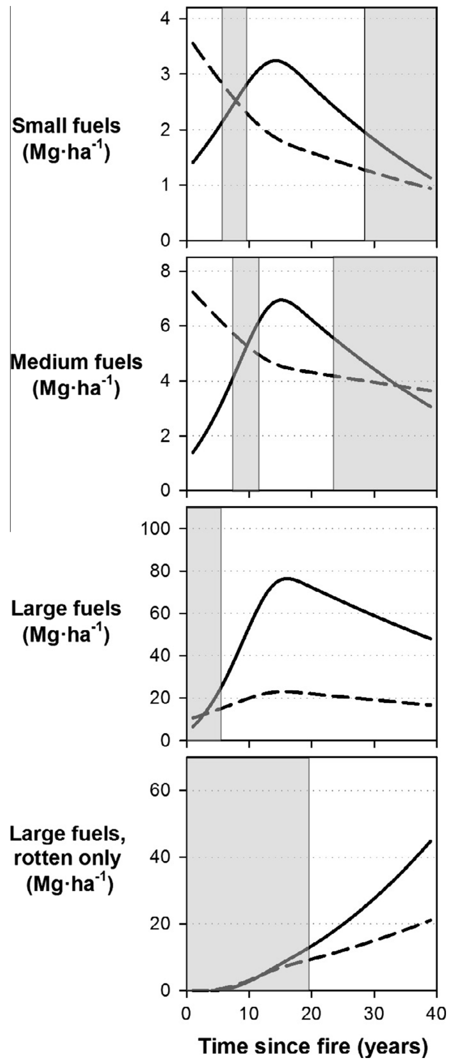

Fig. 4. Predicted surface fuel levels as a function of time since fire for stands with post-fire logging (dashed lines) and without post-fire logging (solid lines), standardized for the median stand basal area of 27 m^2 ha^{-1}. Shaded areas indicate periods after wildfire when fuel loadings are not significantly different between treatments (logged or not logged) based on least-square means estimates.

retaining some snags for wildlife habitat while also creating zones with low fuel loadings to limit the extent of future severe fire behavior. At the landscape scale, post-fire logging could be used to increase heterogeneity in maximum potential fuel loadings, reduce synchrony in fuel succession stages among stands, and influence the relative frequency and spatial distribution of future low, moderate, and high severity fire effects in future fires.

Post-fire logging decisions on public lands should ideally be made within a landscape restoration framework. Like most forest management activities, decisions about the suitability of post-fire logging for achieving management objectives are context-dependent and must balance multiple resource objectives at a variety of spatial scales. Planning tools are available or being developed to inform decisions about prioritization of restoration treatments in unburned forests, and these may also be useful for planning post-fire fuel treatments as well (e.g., Ager et al., 2012; Hessburg et al., 2013). Candidate areas for post-fire logging treatments could be identified during forest restoration or other planning efforts as part of a wildfire contingency plan. Doing so would promote aligning post-fire logging objectives with broader forest management objectives; increase opportunities for stakeholder input on objectives, methods, and proposed locations; and facilitate rapid, responsible decision-making in the wake of severe wildfires.

6. Conclusions

Our study shows that post-fire logging can serve as an effective tool for managing fuel loadings in forests regenerating after high severity wildfires. By strategically applying and varying post-fire logging treatments within landscapes, post-fire logging could reduce woody fuels and help reduce threats to human health, property, and ecosystem services from unacceptable future wildfire behavior and effects. If applied using best management practices and with consideration for possible environmental impacts and meeting other management objectives, post-fire logging could serve as an effective option – along with mechanical thinning, prescribed fire, and managed low to mixed severity wildfires – for reducing fuels and restoring low and mixed severity fire regimes in dry coniferous forests of western North America and other fire-prone forest types.

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