Forest Ecology and Management 341 (2015) 93–109

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Modeling the direct effects of salvage logging on long-term temporal fuel dynamics in dry-mixed conifer forests

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ARTICLE INFO

Article history:
Received 8 August 2014
Received in revised form 1 January 2015
Accepted 4 January 2015
Available online 30 January 2015

Keywords:
Fuel succession
Re-burn
Salvage logging
Hazardous fuels
Snag dynamics
Decomposition

ABSTRACT

Salvage logging has been proposed to reduce post-fire hazardous fuels and mitigate re-burn effects, but debate remains about its effectiveness when considering fuel loadings are dynamic, and re-burn occurrence is stochastic, in time. Therefore, evaluating salvage loggings capacity to reduce hazardous fuels requires estimating fuel loadings in unmanipulated and salvaged stands over long time periods. We sampled for snag dynamics, decomposition rates, and fuel loadings within unmanipulated high-severity portions of 7 fires, spanning a 24-year chronosequence, in dry-mixed conifer forests of Oregon's eastern Cascades. We used these estimates to program an empirical model predicting temporal dynamics of fine and coarse woody fuels from sources directly targeted by salvage logging. We simulated 1000 unmanipulated and salvage logging scenarios, with variable snag dynamic rates, for three sample plots spanning a pre-fire biomass gradient. Total surface fine woody fuel loadings peaked 17–18 years post-fire (6.76–9.92 Mg ha^{-1}) in unmanipulated stands; thereafter decay losses exceeded input rates and loadings decreased. Salvage logging immediately increased surface fine woody fuel loadings by 160–237% above maximum loadings observed in unmanipulated stands, and were higher during the initial 18–22 years post-fire. 1000-h fuel loadings peaked 24–31 years post-fire in unmanipulated stands, but decomposition reduced total loadings by 34.8–49.6% of initial snag necromass by peak years. Our simulations suggest only 59.2% (34.3 Mg ha^{-1}), 47.8% (44.3 Mg ha^{-1}) and 22.3% (37.6 Mg ha^{-1}) of maximum 1000-h fuel loadings were available for combustion at this time. Available 1000-h fuel loadings in unmanipulated stands peaked 31, 34 and 82 years post-fire but were only 35.4% (40.7 Mg ha^{-1}), 30.8% (49.9 Mg ha^{-1}) and 27.3% (70.5 Mg ha^{-1}) of initial snag necromass. Salvage logging increased 1000-h fuel loadings for the initial 7 years post-fire, but 80–84% of initial snag necromass was removed or decayed when their maximum loadings were observed 17–22 years post-fire. Understory woody vegetation reestablished quickly following high-severity fire, creating another significant fuel layer and a source of post-fire fine woody fuels. Surface fuels accumulate quickly following high-severity fire, but our modeling results suggest salvage logging has mixed effects on reducing hazardous fuel conditions since it increases fine woody fuel loadings and decreases coarse woody fuel loadings. Reducing hazardous fuel loadings and their contribution to re-burn hazard requires manipulation of residual and future fuel sources, but treatment benefits should be evaluated against any negative effects to early seral forest structure and function if resilient forest ecosystems are the management goal.

1. Introduction

Stand-replacing fire can reduce forest resilience by inhibiting regeneration and facilitating a state-change, or by reestablishing a forest structure prone to stand-replacement when the next fire occurs (Savage and Mast, 2005). Forest ecosystems with a mixed-severity fire regime are typically resilient to stand-replacing fire, but a compounding disturbance (i.e., re-burn) could drive the system beyond a resiliency threshold. If an intense enough re-burn occurs prior to sexual maturity of establishing trees, an ecosystem state change to a persistent shrub dominated ecosystem could occur (Turner, 2010). This effect has been observed when a fire burned through a forest after a stand-replacing windthrow event (Buma and Wessman, 2011), and when re-burning occurred at higher frequencies than historical intervals (Diaz-Delgado et al.,

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http://dx.doi.org/10.1016/j.foreco.2015.01.002
0378-1127/

2002). It is probable that re-burning will be more common than recently observed as burned landscapes become more prevalent with climatically driven increases in fire extent and intensities (Lenihan et al., 2008; Littell et al., 2010; Westerling et al., 2011).

Salvage logging has been proposed as a way to mitigate re-burn effects following stand-replacing fire (Monsanto and Agee, 2008). Reducing post-fire fuels could mitigate re-burn fire hazard, although there remains a paucity of information regarding post-fire temporal fuel dynamics and the direct effect salvage logging has on post-fire hazardous fuels. Some research suggests salvage logging exacerbates fire risk and hazard (Donato et al., 2006, 2013), reduces hazardous conditions (Monsanto and Agee, 2008), or remains relatively neutral in its effect (McGinnis et al., 2010). Some of these disparate conclusions may result from the type of fuel being evaluated (e.g. fine woody fuels, coarse woody fuels, live fuels), as well as the particular point in time post-fire when fuel conditions were quantified because fuel inputs and losses are dynamic in time.

Models can expand our understanding of post-fire hazardous fuels by providing a quantitative method to test scenarios and evaluate fuel dynamics as a process rather than static condition in time. Snags are the dominant pool of surface fine and coarse woody fuels immediately following stand-replacing fire, so snag fall and fragmentation dominate surface fuel inputs (Dunn and Bailey, in press; Ritchie et al., 2013). Snag fall and fragmentation rates are primarily controlled by species and diameter-at-breast-height (DBH), although physical settings can influence these rates (Dunn and Bailey, 2012). In the absence of re-burn, fuel losses are dominated by decomposition. Decay rates within dry-forest environments vary by species, particle size, substrate quality (i.e., sapwood vs. heartwood), and whether the woody material is positioned on a snag or as surface fuel (Dunn and Bailey, 2012; Harmon et al., 2005). Additionally, only a portion of 1000-h fuels are available for combustion depending on their decay state, moisture conditions and interactions with other combustible material (Albini and Reinhardt, 1997; Hyde et al., 2011). This creates a dynamic input and loss system well estimated through modeling techniques.

Modeling can also overcome limitations in current fuel sampling techniques. Brown's planar intercept method (Brown, 1974) does not capture transfer or decay processes for fine woody fuels that are important for understanding long-term fuel dynamics (Fasth et al., 2010). Estimating fine woody fuel a loading using this method also requires extensive transect lengths to achieve accurate results (Sikkink and Keane, 2008), likely crossing variable forest conditions and increasing variance in estimates. The same limitations occur for 1000-h fuel loadings (Bate et al., 2004), although these estimates have been improved by accounting for their decay state (Harmon and Sexton, 1996). Integrating biophysical controls on inputs and losses into models would improve our understanding of temporal fuel dynamics and post-fire hazardous fuel conditions (Keane, 2008).

The objective of this study was to develop a model to compare temporal dynamics of fine (<7.62 cm diameter) and coarse (snags and surface woody fuels >7.62 cm) woody fuels from dead biological legacies following stand-replacing fire and salvage logging. We focus on dead biological legacies because they are the primary source of post-fire fuels targeted and directly altered by salvage logging. Specifically, we were interested in the following questions: (1) What are the temporal trajectories of fine and coarse woody fuels following stand-replacing fire? and (2) Is salvage logging an effective method for reducing hazardous fuels following stand-replacing fire? Answers to these questions are fundamental for understanding post-fire hazardous fuel conditions and potential strategies for mitigating compounding effects of re-burning.

2. Methods

2.1. Field sites

We focused on dry-mixed conifer forests in the Eastern Cascades Slopes and Foothills Ecoregion of Oregon, USA. This Ecoregion's climatic regime is dominated by warm dry summers and cold winters, with precipitation falling mostly as snow. Ponderosa pine (*Pinus ponderosa* subsp. *ponderosa*) was the dominant disturbance-mediated overstory species with co-dominant or sub-dominant grand and white fir (*Abies grandis* var. *idahoensis* and *Abies concolor* var. *lowiana*), Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), lodgepole pine (*Pinus contorta* subsp. *murrayana*) and incense-cedar (*Calocedrus decurrens*). All sampled plots were mixed ponderosa pine/true fir plant associations, with white fir substituting for grand fir in the southern portions of this ecoregion. Euro-American settlement altered fire regimes and increased shade-tolerant true fir and Douglas-fir abundance across this forest type (Weaver, 1943).

Thirty 0.25 ha (50 m $\times$ 50 m) plots were randomly selected with equal probability point sampling from unmanaged high-severity (>75% overstory mortality) fire areas within ponderosa pine/true fir plant associations to focus on dry-mixed conifer forests only. We evaluated ~100 years of fire history records on the Deschutes and Winema National Forest and Crater Lake National Park for potential fire sites on public lands. We constrained plots to dry-mixed conifer forests with a known high-severity fire and no recorded, or physical evidence of, pre- or post-fire manipulation (i.e. typically some sort of harvest treatment). We focused on unmanipulated stands because of increased high-severity fire in portions of this Ecoregion, and a lack of information regarding their future fuel conditions. Only seven fires up to 24 years post-fire (Fig. 1) met our criteria because salvage logging was common prior to implementation of the Northwest Forest Plan and new management guidelines in the mid-1990s. We constrained all plot locations so they were separated by a minimum of 200 m, resulting in 3–6 intensive fuels plots per fire distributed across multiple high-severity patches in larger fires (Table 1). Sampling intensity varied using this method because older, unmanipulated fire sites were rare and smaller in extent relative to more recent fires. Given our distance constraints and lack of fire scale replicates in older fires, we could only sample three intensive plots at the 15- and 24-year fire sites.

2.2. Field sampling

We systematically gridded each 50 $\times$ 50 m square plot to locate all snags in any of these conditions: (1) standing whole, (2) standing with a broken top or (3) fallen (Fig. 2). We recorded species, DBH, total height (except for fallen snags), decay class, and condition. Broken snags had fragmented tops along the main stem >2 m height, and fallen snags were either fragmented <2 m height or a tipped up root plate. Species was determined using characteristics described by Parks et al. (1997). Fire-created snags were separated from pre-fire killed snags when >5% of the sapwood was consumed or converted to char during the fire. These sapwood-charred snags or logs suggested to us bark was not present at the time of the fire, or sloughed off during the fire, and therefore was already a snag/log when the fire occurred. This data was also used for estimating the fall and fragmentation rates used in this model (Dunn and Bailey, 2012).

Decomposition loss-rate constants (k-constants) were estimated for standing and surface coarse woody detritus. We sampled snags 35–51 cm DBH (target was 41 cm) within randomly initiated 10 $\times$ 50 m belt transects located adjacent to snag inventory plots.