2017

LONGEVITY OF PONDEROSA PINE FUEL REDUCTION TREATMENTS: A LEGACY OF RESEARCH AT LICK CREEK DEMONSTRATION/RESEARCH FOREST IN WESTERN MONTANA

Katelynn J. Bowen
University of Montana

LONGEVITY OF PONDEROSA PINE FUEL REDUCTION TREATMENTS: A LEGACY OF RESEARCH AT LICK CREEK DEMONSTRATION/RESEARCH FOREST IN WESTERN MONTANA

By

KATELYNN JENKINS BOWEN

Bachelor of Science in Forestry, Northern Arizona University, Flagstaff, Arizona, 2013

Thesis

presented in partial fulfillment of the requirements
for the degree of

Master of Science
in Forestry
The University of Montana
Missoula, MT

December 2017

Approved by:

Scott Whittenburg, Dean of The Graduate School
Graduate School

Christopher R. Keyes, Research Professor, Chair
Department of Forest Management

Sharon M. Hood, Research Ecologist
RMRS Missoula Fire Sciences Laboratory
USDA Forest Service

Carl Seielstad, Associate Professor,
Department of Forest Management
National Center for Landscape Fire Analysis

ABSTRACT

Bowen, Katelynn J., M.S., Fall 2017 Forestry

Longevity of ponderosa pine fuel reduction treatments: a legacy of research at Lick Creek Demonstration/Research Forest in western Montana.

Chairperson: Christopher R. Keyes

In ponderosa pine ecosystems of the interior western United States, fuels reduction treatments are common, but the persistence of their effectiveness in mitigating fire behavior is poorly understood. We addressed this problem by analyzing ponderosa pine – Douglas-fir stands during more than two decades of response following fuel reduction treatments. An experiment at the Lick Creek Demonstration/Research Forest in western Montana was initiated in 1991 as a partnership between the USDA Forest Service and the University of Montana to evaluate tradeoffs among alternative cutting and burning strategies to reduce fuels and forest fire behavior while restoring historical stand structures and species compositions. One portion of the experiment tested a commercial thinning strategy, while a second tested a retention shelterwood strategy. Harvesting was performed in all treated units in 1992. Units were burned one-to-two years after harvesting, using different broadcast prescribed fire treatments to simulate a range of burning conditions. The units were measured prior to initiation of treatments in 1991, immediately following the completion of treatments in 1993-4, and in 2005 and 2015. Analysis included differences in 2015 canopy and surface fuel loads by treatment with fire behavior predictions using BehavePlus. Canopy fuel loading remained ~30% lower in all cut units in the thinning and 55-60% lower in cut and burned units in the retention shelterwood site. Canopy bulk density was 30% lower in cut units in the thinning but no different by treatment in the shelterwood and canopy base height was no different by treatment in either installation. Various surface fuel components exhibited differences by treatment in 2015 including 1-hr fuels, litter, and duff. The shelterwood site experienced much higher Douglas-fir regeneration, increasing canopy bulk density and reducing canopy base height. Under extreme weather scenarios, all sites were susceptible to passive or active crown fire behavior.

A second study utilized the 2015 fuels datasets to compare and contrast two common methods for sampling coarse woody debris fuel loads: fixed-area plot sampling and planar intersect transects. Both methods are commonly used in research and management but have tradeoffs in execution and accuracy that managers must consider. Our findings indicated that neither method provided a significantly different estimate at the stand level. However, plot-by-plot, fixed-area plot sampling was more likely to capture CWD presence; transects estimated zero load on 23-47% of plots. Results of this study will provide forest managers with guidance for measuring coarse woody debris in this forest type.

ACKNOWLEDGEMENTS

Thank you to my advisor, Dr. Christopher Keyes, for taking me on for this project and providing his ever patient guidance and support. I hope one day to match his wit and understand his pop culture references. Thank you also to my committee members, Dr. Sharon Hood and Dr. Carl Seielstad, for their feedback and support. Further gratitude goes to Dr. Duncan Lutes at the Missoula Fire Lab for his contributions to all of my fuel loading and modeling questions, Dr. Dave Affleck and Mr. Theodore Owen for their statistical guidance, Dr. Justin Crotteau for keeping his door open whenever I needed help with statistics or writing, and my office mates and cohort that all pushed through grad school successfully. Thank you to my parents, Patrick and Patricia Jenkins, for having faith in me, and thank you especially to my husband, Samuel Bowen, for never doubting me even when I would.

TABLE OF CONTENTS

LIST OF FIGURES

Burn “WB” (Shelterwood only), and Cut+Dry Burn “DB” (Shelterwood only). Uppercase letters denote statistical differences between groups at α=0.05 while lowercase letters denote differences at α=0.1. Only significant differences are shown.

Figure 1.6. Surface fuel load in Thinning (a-c) and Retention Shelterwood (d-f), broken down by Pre-Burn (post-harvest; 1993), Post-Treatment (1993-4 in thinning and 1993 in shelterwood), and 2015. Bars denote mean fuel loading per particle type per treatment with +/- 1 standard error (n=3). Treatments are Control “CO”, No Burn “NB”, Cut+Spring Burn “SB” (Thinning only), Cut+Fall Burn “FB” (Thinning only), Cut+Wet Burn “WB” (Shelterwood only), and Cut+Dry Burn “DB” (Shelterwood only). Significant differences are shown in Figure 1.7.

Figure 1.7 Significant surface fuel differences by treatment in 2015 for Thinning one-hour fuels, litter, and duff (a-b) and Retention Shelterwood one-hour fuels, duff, and rotten coarse woody debris (c-e). Bars denote mean fuel loading per particle type per treatment with +/- 1 standard error (n=3). Treatments are Control “CO”, No Burn “NB”, Cut+Spring Burn “SB” (Thinning only), Cut+Fall Burn “FB” (Thinning only), Cut+Wet Burn “WB” (Shelterwood only), and Cut+Dry Burn “DB” (Shelterwood only). Statistical significance is given for 2015 differences by treatment. Uppercase letters denote significance at α= 0.05 while lowercase letters denote significance at α= 0.10.

Figure 1.8. Predicted surface fire behavior metrics (rate of spread, fireline intensity, and flame length) by treatment for each wind/moisture scenario in the Thinning installation. Dots represent unit estimates. Treatments are Control “CO”, No Burn “NB”, Cut+Spring Burn “SB”, and Cut+Fall Burn “FB”.

Figure 1.9. Predicted surface fire behavior metrics (rate of spread, fireline intensity, and flame length) by treatment for each wind/moisture scenario in the retention Shelterwood installation. Dots represent unit estimates. Treatments are Control "CO", No Burn "NB", Cut+Wet burn "WB", and Cut+Dry Burn "DB".

Figure 1.10. Predicted fire type for the thinning (left) and retention shelterwood (right) with transition ratio above and active ratio below in each treatment replicate (a-c) for each fuel moisture/wind scenario. Transition ratio (surface fireline intensity/critical surface fireline intensity) is the required surface fireline intensity to initiate crown fire and active ratio (crown fire rate of spread/critical crown fire rate of spread) is the required rate of spread to maintain active crown fire. Scenarios are as follows: "Low-Mod" for low wind speed, moderate fuel moisture; "Low-Dry" for low wind speed, dry fuel moisture; "High-Mod" for high wind speed, moderate fuel moisture; and "High-Dry" for high wind speed, dry fuel moisture.

SECTION 2.

Figure 2.1. Stand-level (n=24) coarse woody debris load (kg m^{-2}) distribution by method. Methods included fixed-area plot ("FAP") sampling, a single planar intersect transect per plot ("PIT – One Transect"), and two planar intersect transects per plot ("PIT – Two Transects").

Figure 2.2. Distribution of plot-level (n=142) coarse woody debris estimates by the three compared methods: fixed area plot sampling (FAP), one planar intersect (PIT) ("PIT – One Transect"), and two PIT ("PIT – Two Transects"). Note: at the plot-level, the lowest FAP estimate was 0.039 kg m^{-2}, whereas 61 plots estimated zero load using one PIT, and 33 plots estimated zero load using two PIT.

LIST OF TABLES

SECTION 1.

Table 1.5. Changes in fuel loads (kg m^{-2}) from 1993-4 (Post-treatment) to 2015 for (a) Thinning and (b) Retention Shelterwood installations. Percent change is based on treatment-level averages. Bold values represent significance at $\alpha = 0.10$ on a one-sample t-test of mean difference between post-treatment and 2015.

University of Montana

SECTION 1:

Longevity of ponderosa pine fuel reduction treatments: a legacy of research at Lick Creek Demonstration/Research Forest in western Montana

Katelynn J. Bowen

Chair of the Supervisory Committee:
Christopher Keyes, Research Professor
Department of Forest Management
College of Forestry and Conservation

Abstract

In ponderosa pine ecosystems of the interior western United States, fuels reduction treatments are common, but the persistence of their effectiveness in mitigating fire behavior is poorly understood. We addressed this problem by analyzing ponderosa pine – Douglas-fir stands during more than two decades of response following fuel reduction treatments. An experiment at the Lick Creek Demonstration/Research Forest in western Montana was initiated in 1991 as a partnership between the USDA Forest Service and the University of Montana to evaluate tradeoffs among alternative cutting and burning strategies to reduce fuels and forest fire behavior while restoring historical stand structures and species compositions. One portion of the experiment tested a commercial thinning strategy, while a second tested a retention shelterwood strategy. Harvesting was performed in all treated units in 1992. Units were burned one-to-two years after harvesting, using different broadcast prescribed fire treatments to simulate a range of

burning conditions. The units were measured prior to initiation of treatments in 1991, immediately following the completion of treatments in 1993-4, and in 2005 and 2015. Analysis included differences in 2015 canopy and surface fuel loadings by treatment with fire behavior predictions using BehavePlus. Results included:

- ~30% lower canopy fuel loading in all treated Thinning units
- 55-60% lower canopy fuel loading in cut and burned Retention Shelterwood units
- 30% lower canopy bulk density in treated Thinning units
- 67% lower 1-hr fuels in cut and burned Thinning units and 62-87% lower 1-hr fuels in all treated Retention Shelterwood units
- 19-25% lower litter in all treated Thinning units
- 78% lower duff in Thinning spring burn treatment
- 30-55% lower duff in cut and burned Thinning units
- 62% lower rotten coarse woody debris in Retention Shelterwood

The shelterwood site experienced much higher Douglas-fir regeneration, increasing canopy bulk density and reducing canopy base height. Under extreme weather scenarios, all sites were susceptible to passive or active crown fire behavior but only the cut but unburned retention shelterwood sites exhibited potential crown fire behavior in moderate fuel moisture and high winds. Ultimately, the longevity of the fuel reduction treatments was dictated by the initial silvicultural prescription.

1. INTRODUCTION

In the northern Rocky Mountains of the United States, ponderosa pine (*Pinus ponderosa*)/Douglas-fir (*Pseudotsuga menziesii*) forests cover over eight million hectares (Ryker and Losensky 1983). A century of fire suppression policies has converted many open, seral ponderosa pine forests to dense stands with abundant Douglas-fir regeneration (Covington and Moore 1994, Hartwell et al. 2000, Hanberry 2014), resulting in reduced vigor, susceptibility to insect infestations, and increased fire hazard (Hood et al. 2016, Hessburg et al 2015, Schoennagel et al. 2004). For managers interested in moderating fire behavior, the fuel complex remains the factor most amenable to manipulation (Keane 2015). Forest managers in the West routinely implement fuel reduction projects designed to reduce wildfire hazard, but the aims of those projects can also include ecological restoration, wildlife habitat enhancement, and forest health improvement (Covington et al. 1997, Agee and Skinner 2005, Russell et al. 2009, Kalies et al. 2010, Hood et al. 2016,).

Two common approaches to fuels reduction exist – cutting and burning – plus their many permutations. Fuel treatments affect fire behavior by altering both surface and aerial fuel complexes. Surface fuels (both type and quantity), along with weather and topography, influence surface fire intensity (heat output of the fire) and fire severity (ecological impact of the fire). The aerial canopy fuel structure and composition can affect whether a fire transitions from surface fire to crown fire. Fuel treatments affect these two fuel elements both directly – by reducing (or inadvertently increasing) fuel quantities and their contiguity, and indirectly – by altering trajectories of fuel decay, aggradation, and distribution (Jain et al. 2012). Furthermore, because fuel reduction treatments alter the physical environment which in turn alters wind and moisture regimes, future fire behavior may prove more intense (e.g. higher surface fire rates of spread driven by increased wind penetration in open forests) or severe (e.g. higher surface fuel loading from mechanical treatments can increase soil heating) (Agee 1996, Battaglia et al. 2008, Stephens et al. 2009, Fulé et al. 2012, Swim et al. 2014, Kalies and Yocom Kent 2016). Seemingly minor differences in fuel treatment prescriptions may manifest differences in fuel loading and distribution that become significant with the passage of time.

In order to adequately evaluate fuel treatment alternatives, managers require a better understanding of fuel treatment longevity, or the persistence of fuel treatment effectiveness, over years following treatment (Reinhardt et al. 2008, Jain et al. 2012, Keane 2015). While the near-term effects of fuel treatments on fire behavior in the northern Rockies have been well documented (Smith and Arno 1999, Stephens et el. 2009, Schwilk et al. 2009, McIver et al. 2012), the persistence of those effects remains poorly understood (Fulé et al. 2012, Jain et al. 2012). In the short term (<10 years), fuel reduction treatments may reduce surface and canopy fuels, increasing forest resilience to wildfire (Reinhardt et al. 2008, Fulé et al. 2012, Stephens et al. 2012). Over time, however, vegetation can respond to canopy openings and soil scarification resulting from mechanical treatments, increasing surface and ladder fuels. Greater surface and canopy fuel loading increases forest susceptibility to severe wildfire and decreases fuel treatment longevity (Battaglia et al. 2008, Stephens et al. 2009, Stephens et al. 2012, Swim et al. 2014). Few studies have analyzed treatment effects for longer than a decade and there are no studies to date in the northern Rockies that claim a 20+ year treatment response period.

We aimed to compare the long-term effectiveness of fuel reduction treatments in a ponderosa pine forest typical of many across the northern Rocky Mountains. For this we used an experiment established in 1991 at the Lick Creek Demonstration/Research Forest in western Montana. A partnership between the USDA Forest Service and the University of Montana, the experiment was established to enable the evaluation of tradeoffs among alternative cutting and burning strategies to reduce fuels and moderate forest fire behavior while restoring historical stand structures and species compositions (Carlson et al. 1994, Carlson and Floch 1996, Smith and Arno 1999). The experiment consisted of thinning and retention shelterwood cuttings followed by various post-harvest burning treatments.

Our main objective of this study was to compare surface and canopy fuel loadings twenty-three years after treatment initiation. Namely, we aimed to (1) determine how fuel loading differed among treatments twenty-three years following implementation, (2) characterize the associated potential temporal changes in fire behavior among the treatments, and (3) analyze the fuels for which historical data exist. We considered treatments effective if treated units maintained lower surface and canopy fuel levels than control units after twenty-three years, and were resistant to active crown fire based on fire behavior modeling under various wind and fuel moisture scenarios. We intend this information to inform managers' actions and future planning when considering two particular silvicultural strategies (thinning and retention shelterwood) for reducing fuel loading and wildfire hazard in dry montane forests of the northern Rocky Mountains.

2. METHODS

2.1 Study site

The Lick Creek Demonstration/Research Forest (Lick Creek) lies on south-facing slopes in the Lick Creek drainage of the Darby Ranger District on the Bitterroot National Forest in southwestern Montana (46°5'N, 114°15'W) (Figure 1.1). The elevation varies between 1300 to 1500 meters AMSL with largely 10-30% slopes except in microsite conditions where slopes range up to 70% (Gruell et al. 1982). Lick Creek has an average winter temperature of -4 degrees C (range -21 to 10 degrees C) and an average summer temperature of 17 degrees C (range 4 to 32 degrees C). The area receives 400 mm of precipitation per year, about half of which occurs as snowfall (RAWS data for Little Rock Creek LRCM8 site near Lick Creek; elevation: 1678 m, PRISM Climate Group). Soils are typified by Elkner Gravelly Loam, coarse-loamy, mixed, frigid Typic Cryochrepts derived from highly weathered granitic parent material (DeLuca and Zouhar 2000, Gruell et al. 1982).

Lick Creek is characterized as a ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *ponderosa* C. Lawson)/Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.)) forest. Other tree species include grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt. var. *lasiocarpa*), and lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson). On the upper slopes, the habitat types (Pfister et al. 1977) are *Pseudotsuga menziesii/Calamagrostis rubescens, Pinus ponderosa* phase, and *Pseudotsuga menziesii/Symphoricarpos albos*, *Calamagrostics rubescens* phase (Gruell et al. 1982). On the lower slopes, the habitat types are *Pseudotsuga menziesii/Vaccinium* caespitosum, and *Pseudotsuga menziesii/Vaccinium globulare, Arctostaphylos uva-ursi* phase (Gruell et al. 1982). Similar to other ponderosa pine/Douglas-fir forests in the northern Rockies (Heyerdahl et al. 2008), the historic, pre-settlement fire return interval across the Lick Creek drainage averaged seven years (ranging five to fifteen years) (Gruell et al. 1982) and was characterized by low-intensity surface fires (Arno 1976, Arno and Fiedler 2005).

Lick Creek was the site of the first ponderosa pine commercial timber sale by the newly fledged Northern Region of the US Forest Service, which occurred in 1906. Further cuttings occurred throughout the Lick Creek area in the 1950s, 1960s, and 1980 (Menakis 1994).

2.2 Treatments

Ecosystem-based fuels treatments were designed to reintroduce low-intensity fire and restore ponderosa pine-dominated forests at Lick Creek (Figure 1.2) (Arno et al. 1995, Arno 1999a), largely based on historical reconstructions of fire frequency in the area (Gruell et al. 1982). The treatments were intended to maintain and increase large ponderosa pine in the overstory, improve wildlife habitat, and reduce severe wildfire or insect and disease hazard (Arno 1999a). Cutting and burning treatment combinations were tested within each of three separate installations, each representing a silvicultural restoration strategy considered appropriate to the existing forest condition (Arno 1999a). One installation utilized a (commercial) thinning restoration strategy to reduce fuels while favoring ponderosa pine in the overstory, boosting tree vigor and growth, and maintaining an even-aged stand structure. The intent of the thinning was to maximize annual increment growth for future yield but not to promote pine regeneration until future cuttings, though regeneration might be achieved (Arno 1999a). A second unit focused on retention shelterwood cutting as a restoration strategy to reduce fuels while favoring ponderosa pine in the overstory, removing Douglas-fir regeneration, encouraging ponderosa pine recruitment, and promoting a two-aged stand structure. The intent of the shelterwood cutting was to initiate an uneven-aged stand structure with residual large, old ponderosa pine in the overstory and conditions favorable to pine recruitment in the understory. In both installations, tree tops >15.24 cm in diameter were left on site to provide foliar nutrient input and trees yarded and delimbed at road-side landings (Arno 1999a). A third unit that utilized an uneven-aged single tree selection strategy was not included in the present study.

Prior to the treatment initiation in 1992, the area designated for thinning had been selectively cut starting in 1907 and partially cut in 1955, 1967, and 1979-80. In 1991, it supported a 70 year-old second-growth stand of ponderosa pine and Douglas-fir with 370 trees ha^{-1}, a quadratic mean diameter of 27.0 cm, and 21 m^2 ha^{-1} basal area (Table 1.1a). Ponderosa pine made up 93% of the trees ha^{-1} and basal area, and was dominant across all size classes (Figure 1.3a).

The area designated for shelterwood cutting was an 80-85-year-old second-growth stand of ponderosa pine and Douglas-fir. In 1991, it had 434 trees ha^{-1}, a quadratic mean diameter of 28.2 cm, and 26.9 m^2 ha^{-1} basal area (Table 1.1b, Figure 1.3g). Less than 1% of the overstory was composed of lodgepole pine, with 13% Douglas-fir and 86% ponderosa pine. Saplings were abundant in the understory, with Douglas-fir making up 67% (the remainder were ponderosa pine, plus one *Abies lasiocarpa*).

In the thinning installation, two burn treatments – fall burn and spring burn – were conducted in addition to a no-burn treatment to examine the influence of burning season on fuel consumption. In the shelterwood, two burn treatments – wet duff burn (50% moisture) and dry duff burn (16% moisture) – were tested in addition to a no-burn treatment to examine the effect of duff moisture content on fuel consumption and effects. The thinning and shelterwood installations were each divided into nine units of 1-2 ha each. Control units were not originally included in the experimental design but were later added. Three replicates of each treatment were randomly assigned to a unit: cut-only/no burn ("NB"), cut and spring/wet burn ("SB"/"WB"), and cut and fall/dry burn ("FB"/"DB"). In the shelterwood, the WB and DB prescribed fires both occurred in May of 1993; in the thinning, the FB occurred in fall of 1993 and SB in the spring of 1994. Three unthinned and unburned control units ("CO") were installed and measured in each installation in 1993 (following the cutting treatments) (Figure 1.4).

Fuels were not measured at the outset of the study (i.e. 1991) but were measured in cut-burn units following harvesting and prior to burning (i.e. 1992-3). Data from that post-harvest/pre-burning measurement indicate surface fuel loadings as follows for the thinning treatment: fine woody debris averaged 0.81 kg m^{-2} in the SB and 0.69 kg m^{-2} in the FB, coarse woody debris averaged 1.34 kg m^{-2} in the SB and 0.90 kg m^{-2} in the FB, litter was 0.27 kg m^{-2} in both treatments, and duff depth was 2.29 cm in the SB and 3.05 cm in the FB (Harrington 1999). In the shelterwood, fine woody debris averaged 1.01 kg m^{-2} in the WB and 1.19 kg m^{-2} in the DB, coarse woody debris averaged 0.38 kg m^{-2} in the WB and 0.72 kg m^{-2} in the DB, litter averaged 0.31 kg m^{-2} in the WB and 0.43 kg m^{-2} in the DB, and duff depth was 2.79 cm in the WB and 3.56 cm in in the DB (Harrington 1999).

2.3 Data collection & processing

A permanent plot network was established in 1991 prior to initiation of treatments and expanded in 1993 to incorporate control units. Within each unit (treated and control), a grid of 12 systematically-placed plot centers was installed on 15-40 m spacing, for a total of 144 plots per installation. In the fall of 2014, a natural-ignition wildfire burned approximately 0.5 ha of a NB treatment unit in the shelterwood installation, eliminating 4 plots.

Trees and saplings were measured in 0.04-ha circular plots centered at each plot center. All trees ≥15.24 cm DBH were measured in 1991 prior to harvest (treated units only), in 1993-4 after prescribed burning, and again in 2005 and 2015. Each tree's species, diameter, height, crown base height (post-harvest only), and condition (live/healthy, unhealthy, dead) were recorded. Saplings (≥2.50 cm and <15.24 cm in the thinning and >0.10 and <15.24 cm in the shelterwood) were measured in 1991, and saplings >0.10 and <15.24 cm were measured in all following visits in both installations (1993-4, 2005, and 2015). Sapling species and diameter were recorded. A subsample of systematically selected saplings was measured for height, crown base height, and crown ratio, for a minimum of 10% complete sampling. Seedlings were tallied by species in 0.004-ha nested circular subplots centered on each plot center. We summarized overstory structure metrics – stem density, quadratic mean diameter, and basal area – with mean and standard error by installation and treatment.

Following cutting, woody surface fuels in cut-burn treatment units (thinning SB/FB and shelterwood WB/DB) were quantified via one Brown's (1974) planar intersect transect per plot prior to the burn treatments (spring 1993 in both installations) and following them (spring/summer 1993 in the shelterwood, fall 1993 in the thinning FB and spring 1994 in the thinning SB). Woody surface fuels were distinguished by size-based time-lag diameter classes of 1-hr (<0.64 cm), 10-hr (≥0.64 and <2.54 cm), 100-hr (≥2.54 and <7.62 cm) fuels, and sound or rotten 1000-hr fuels (≥7.62 cm). Along each transect, 1-hr fuels were measured from 0-0.30 m, 10-hr fuels were measured from 0-1.80 m, 100-hr fuels were measured from 0-3.70 m, and 1000-hr fuels were measured from 0-15.24 m. These transects were permanently monumented with metal duff spikes at the start (plot center) and end points (15.24 m). In 2005, transects were remeasured and expanded to all units, with two additional live and dead surface fuels measured at two points (4.60 m and 9.10 m) on each transect: (1) litter and duff depth and (2) live/dead herb and shrub height and percent canopy cover. In 2015, all transects were relocated using metal detectors and fuels were remeasured, with the addition of overall average fuel bed depth (m) taken at two points (4.60 m and 9.10 m) on each transect.

Surface fuel loadings (kg ha^{-1}) were calculated from the raw data using the FEAT/Firemon Integrated (FFI) software program (Lutes et al. 2006), which utilizes Brown's (1974) and Brown et al.'s (1982) formulas. Surface fuels were categorized by particle type: fine woody debris (FWD) consisted of 1-, 10-, and 100-hr fuels, and coarse woody debris (CWD) consisted of sound and rotten 1000-hr fuels.

To estimate canopy fuels, we used FuelCalc (Lutes et al. 2016), a software program designed to compute surface and canopy fuel loading at the plot level from measured tree data (species, diameter, height, crown ratio and/or crown base height, and crown class). Because we had a subset of sapling data from 2015, we established height-diameter equations for each predominant species (PIPO and PSME) by installation. These models were then applied to generate fitted heights for all remaining sapling records lacking measured heights. Saplings were arbitrarily categorized as "intermediate" crown class and assigned 50% crown ratio. In the thinning, about 5% of the saplings required an estimated height (45 PSME and 1 PIPO) while in the shelterwood, about 20% (1192 PSME and 2 PIPO) required an estimated height. Combined with overstory tree characteristics, saplings, surface fuels, and vegetation were used by FuelCalc to calculate canopy fuel loading, canopy bulk density, and canopy base height.

2.4 Fire behavior modeling

Average unit-level fuel loading data were used in conjunction with BehavePlus (v. 5.0.5; Heinsch and Andrews 2010) to model the potential surface and crown fire behavior for each unit individually within each installation. We developed custom models founded on Fire Behavior Fuel Model 9 (FBFM 9, Anderson 1982) using the calculated live and dead surface and canopy fuel variables from Lick Creek. FBFM 9 was selected because it was the most ubiquitous (modal) fuel model calculated for all plots in both treatment installations by FuelCalc and validated by LANDFIRE (LANDFIRE 2008). Our custom fuel loading inputs included surface fuel loadings for 1-hr, 10-hr, 100-hr, and 1000-hr fuels; live herbaceous and woody fuel loadings; fuel bed depth, canopy base height, canopy bulk density, and slope steepness. Slopes ranged 0-60% across both studies but was held constant at the average 15% for fire modelling. We retained FBFM 9 default input values for surface area to volume ratio for 1-hr fuels and live herbaceous and woody fuels, dead fuel moisture of extinction, and dead and live fuel heat content (Anderson 1982).

Live fuel loadings (herbaceous biomass and shrub biomass) were derived from FFI, which calculated biomass from the measured heights and percent covers taken along each Brown's transect. Plot-level canopy bulk density (CBD) and canopy base height (CBH) were calculated from stand data by FuelCalc and summarized to the unit level for our inputs. FuelCalc defines CBH as the lowest height above ground where CBD reaches a threshold value: the maximum stand-level CBD x 0.1 up to 0.12 kg m^{-3}, after which 0.012 kg m^{-3} is used. Canopy bulk density, the mass of canopy fuel loading per unit volume (Scott and Reinhardt 2001), is estimated at the plot-level as the maximum 1.52-m running average in the fuel profile (Lutes et al. 2016).

We developed four fire weather scenarios consisting of factorial combinations of two dead surface fuel moisture contents and two windspeeds for comparison (Table 1.3). To standardize comparisons across forest types, we selected moderate and very dry fuel moistures with moderate and high windspeeds (Scott and Burgan 2005). In both installations, windspeed adjustment factor was set to 0.2 for treated units and 0.1 for control units (Rothermel 1983). Slope was standardized across each installation to 15% for all simulations.

Model outputs included the following surface fire behavior metrics: rate of spread (ROS), fireline intensity (FLI), and flame length (FL). Crown fire behavior metrics consisted of critical fireline intensity (critical heat release per unit time to transition fire from surface to crown fire) and critical spread rate (rate of spread necessary for a fire to sustain an active crown fire) (Van Wagner 1977). From those two sets, transition ratio (surface FLI/critical surface FLI; or, the intensity needed to initiate crown fire), active ratio (crown fire ROS/critical crown fire ROS; or, the ROS required to maintain crown fire), and modeled fire type were determined.

2.5 Data analysis

Each installation (thinning, shelterwood) was examined separately. We evaluated differences in fuels among treatments by the following: canopy fuel loading (CFL), canopy bulk density (CBD), and canopy base height (CBH); surface fuel loadings separately by particle type (1-hr, 10-hr, 100-hr, and 1000-hr sound and rotten), categorized by particle size (FWD, CWD), and in total. Surface and canopy plot (subsample) fuel loading were averaged to the unit (replicate) level for our analyses.

Similarly, we evaluated differences in potential fire behavior among treatments for the surface fuel loadings alone (surface fire rate of spread (ROS), fireline intensity (FLI), and flame length (FL), and together with crown fuel loadings (critical surface FLI, critical crown ROS and predicted fire type). We assessed predicted potential fire type by unit using the combination of modelled transition ratio and active ratio. BehavePlus categorizes surface fire as any fire with transition ratio and active ratio below 1.0, conditional crowning ("CONDCROWN") as fire that has potential to sustain to crown fire if fire transitions to the overstory (transition ratio <1.0 and active ratio ≥ 1.0), and crowning fire as both transition and active ratio ≥ 1.0.

We analyzed 2015 treatment effects using one-way analysis of variance (ANOVA) models (α = 0.1) to test for differences by treatment for each dead surface fuel particle and category (FWD and CWD), canopy fuels (CFL, CBH, CBD), and fire behavior (surface ROS, surface FLI, surface FL, critical crown ROS, and critical surface FLI). The model took the form:

$$y_{ij} = \mu + T_j + \varepsilon_{ij}$$

where y_{ij} is the loading at a given fuel class (1-hr, 10-hr,100-hr, 1000-hr, litter, or duff), canopy fuel measurement (CFL, CBD, or CBH), or fire behavior (ROS, FLI, or FL) for each i^{th} unit (replicate); μ is the overall grand mean; T_j is the fixed effect of the j^{th} treatment level (j = three treatments plus control in each installation, or CO, NB, SB/WB, FB/DB); and ε_{ij} is the within-subject experimental error. If treatment differences existed, we followed up with Tukey's test for Honest Significant Difference (hereafter Tukey's HSD) (Tukey 1949) to determine which treatments were significantly different.

In the burned units, we evaluated the net aggradation/degradation of those woody surface fuel elements that had been remeasured on multiple occasions: 1993 (post-harvest, pre-burn in both installations & post-treatment in shelterwood only), 1994 (post-treatment (thinning only)), and 2005 and 2015. For all woody fuels (FWD and CWD), we tested for a difference in 2015 – post-treatment mean fuel loading at the unit level within each treatment using one-sample *t*-tests (α = 0.1). Because litter and duff were not measured in 2015 using the same methods as in the initial pre-burn and post-treatment sampling events, they were not analyzed for comparison to post-treatment levels.

Previous analysis (Harrington 1999) revealed no apparent effect of either seasonality (thinning installation) or duff moisture content (shelterwood installation) on prescribed fire fuel consumption immediately post-treatment in 1993-4. Because surface fuels were not measured prior to plot installation and cuttings in 1991-2, it is impossible to determine if the differences in surface fuels before and after treatment completion can be attributed to site differences between installations or if it is a relic of the harvesting activities. Additionally, fuels were only measured in units slated for prescribed fire in the initial study.

Prior to analysis, all variables were tested for homogeneity of variance using Levene's Test ($\alpha = 0.1$; Levene 1960) and their residuals visually were inspected for violations of normality on quantile-quantile plots. All metrics passed homogeneity of variance and normality assumptions. All statistical analyses were performed using the R software program (R Core Team 2016).

3. RESULTS

3.1 Stand structure

In the thinning, the cutting reduced stem density by 37-46% with an average of 220 trees ha^{-1} across treated units (Table 1.1a, Figure 1.3b). Quadratic mean diameter increased by 2-8% at an average of 28.5 cm, and basal area ranged 13.2-14.6 m^2 ha^{-1}. Sapling density was variable across treatments at an average 54 saplings ha^{-1} and was composed of 97% ponderosa pine and 3% Douglas-fir. Following the completion of treatments in 1993, the spring and fall burns reduced litter by 92-95%, duff depth by 42-69%, fine woody debris by 43-51%, and coarse woody debris by 66-87% (Figure 1.6a-c). As described earlier, surface fuel loadings were only collected in units slated for burning and are not available for control or cut-only treatments in either installation.

In the shelterwood, the cutting reduced stem density by 61-68% across treated units with an average stem density of 159 trees ha^{-1} (NB, WB, and DB) (Table 1.1b, Figure 1.3h). Quadratic mean diameter increased by 7-10% to an average of 30.6 cm. Basal area varied among treatments: in the NB, basal area was 13% lower overall at 23.3 m^2 ha^{-1}, but was 55-62% lower in burned units at 10.3 m^2 ha^{-1} (WB) and 12.0 m^2 ha^{-1} (DB). Sapling density was reduced by 53-99% across the treated areas with the fewest residual saplings in the burned units (WB and DB). The wet and dry burns reduced surface fuels by 79-82% in litter, 17-38% in duff depth, 60-75% in fine woody debris, and 75-80% in coarse woody debris (Figure 1.6d-f).

By 2015 in the thinning, stem densities in treated units had not increased, but QMD had increased by an average of 25-29%, and basal area had increased by 50-60% (compared to 18% QMD and 22% BA increase in the CO). Unlike most of the treated area which had no change in stem density after twenty-three years, stocking decreased 9% in the FB from 232 trees ha^{-1} to 211 trees ha^{-1}. This mortality was a result of a recent mountain pine beetle (*Dendroctonus ponderosae*) outbreak in two of the FB units. The mountain pine beetle also affected CO units, which had an 11% decrease in stem density from 378 trees ha^{-1} post-treatment to 335 trees ha^{-1} in 2015. Despite the mortality, the FB also had the highest QMD and BA and the lowest sapling density of the treated units (Table 1.1a). Tree size distributions were similar across treatments but there were more trees in smaller size classes in the CO units (Figure 1.3c-f). Sapling composition was made up of 68% ponderosa pine and 32% Douglas-fir overall but Douglas-fir were more prevalent in the NB (Table 1.1a). Ponderosa pine seedlings were more abundant than Douglas-fir in all treated units except NB, and averaged 377.5-1393.4 seedlings ha^{-1} (Table 1.2a).

In the shelterwood in 2015, there was a substantial increase of Douglas-fir trees in the lower diameter classes, especially in the NB treatment (Table 1.1b, Figure 1.3i-l). Tree density declined 14% in CO units, to 319 trees ha^{-1}, due to recent mountain pine beetle mortality. Though tree densities were 9% and 11% lower in 2015 in both the WB and DB, to 129 trees ha^{-1} and 149 trees ha^{-1} respectively, this was due to fire-induced mortality from intense burning conditions during treatment implementation (Harrington 1999) and was not an effect of recent insect or disease. In contrast, stem density increased 7% in the NB. QMD increased by 23-28% in burned units compared to 17% in the NB and 14% in CO. Interestingly, basal area decreased in the NB treatment by 22% to 18.2 m^2 ha^{-1} compared to the CO, which increased by 13% to 29.5 m^2 ha^{-1}.

Sapling density increased substantially and was highest in the NB treatment at 2125 saplings ha^{-1}, a 28-fold increase from post-treatment. Saplings increased in all units two-fold in the CO, 362-fold in the WB, and 27-fold in the DB (Table 1.1b). Douglas-fir saplings made up 79% of saplings across the shelterwood site with less than one percent composed of grand fir (*Abies grandis*), subalpine fir (*Abies lasiocarpa*), western larch (*Larix occidentalis*), and lodgepole pine (*Pinus contorta*). The remainder were ponderosa pine. Douglas-fir saplings dominated the regeneration composition in the CO (95%), NB (88%), and DB (70%). Similarly, seedling density was highest in the CO unit with 6565.2 seedlings ha^{-1}, 90% of which were Douglas-fir (Table 1.2b). Other species present in CO units were ponderosa pine, grand fir, and Engelmann spruce (*Picea engelmannii).* Seedling density was similar in NB and WB units but the proportion of ponderosa pine to Douglas-fir differed dramatically between treatments: the NB (74% Douglas-fir) had 1.5 times more Douglas-fir than WB (only 36% Douglas-fir) but the WB had the most ponderosa pine seedlings of any treatment at 2265.1 ha^{-1}.

3.2 Ladder & canopy fuels

In the thinning, the model for PSME saplings (Eq. 1) explained 91% of the variation while the model for PIPO saplings (Eq. 2) explained 85% of the variation. In the shelterwood, the model for PSME saplings (Eq. 3) explained 92% of the variation and the model for PIPO (Eq. 4) explained 82% of the variation in height by diameter.

$$Ht = 3.28269 + (4.817458 * DBH) \tag{1}$$

$$Ht = 3.9139 + (5.035291 * DBH) \tag{2}$$

$$Ht = 3.921119 + (5.442178 * DBH) \tag{3}$$

$$Ht = 3.062883 + (4.918217 * DBH) \tag{4}$$

where “Ht” is calculated height and DBH is measured diameter at breast height.

There was a strong difference in the effect of cutting treatment on canopy fuel between the two installations. In the thinning installation, there was a clear difference between control and cut units (NB, SB, & FB) on canopy fuel loading and canopy bulk density, but there was no additional effect of burning. Canopy fuel loading was 28-30% lower in the NB (p-value = 0.037), SB (p-value = 0.017), and FB (p-value = 0.007) than CO, at about 0.467-0.480 kg m^{-2} in treated units compared to 0.669 kg m^{-2} in CO. This demonstrates a lasting effect of the thinning but not of the burning (Figure 1.5a, Table 1.4a). Those results were mirrored in canopy bulk density which had over 30% lower CBD in NB (p-value = 0.048), WB (p-value = 0.075), and FB (p-value = 0.066). CBD values in treated units were all about 0.04 kg m^{-3} compared to 0.06 kg m^{-3} in the CO (Figure 1.5b, Table 1.4a.). Canopy base height was not different between treatments and averaged from 3.0-4.1 m across units (Figure 1.5c, Table 1.4a).

In the shelterwood, both the WB and DB maintained 60% and 55% lower CFL (p-value=0.009 and 0.014, respectively) than CO, at average loadings of 0.375 kg m^{-2} and 0.420 kg

m^{-2} in burned units compared to 0.931 kg m^{-2} in CO. CFL in the NB was 0.746 kg m^{-2} on average. There was no significant difference by treatment for CBD and CBH but we did see variability within the treatment replicates indicating there may once have been an effect of treatment on these variables (Figures 1.5e-f). Mean CBD was 58% higher in NB units than CO and 241-280% than the WB and DB. CBH ranged from 0-11 m but two out of three units within each treatment (CO, NB, WB, & DB) had median CBH values at or near 0 m, indicating dense ladder fuels at the surface level. On average, CBH was lowest in the NB at 1.0 m compared to 1.9 m in the CO, 2.8 m in WB, and 2.4 m in DB (Table 1.4b).

3.3 Surface fuels

Few surface fuel categories exhibited significant differences between treatments in 2015. In the thinning, 1-hr fuels in the SB were 67% lower than CO (p-value=0.060) at 0.002 kg m^{-2} compared to 0.006 kg m^{-2} but there were no other strong relationships (Figure 1.6a, Figure 1.7a). No other woody particle type (FWD or CWD) was significantly different by treatment (Figure 1.6a, b). Litter in the treated units was lower than CO by 19% (p-value=0.037), 22% (p-value=0.017), and 25% (p-value=0.007) in the NB, SB, and FB. Duff loading in the SB was 78% lower than in the CO (p-value=0.061) at 0.196 kg m^{-2} in the SB compared to 0.981 kg m^{-2} in the CO (Figure 1.6c, Figure 1.7b).

In the retention shelterwood, 1-hr fuels in the NB, WB, and DB were 62% (p-value=0.022), 76% (p-value=0.007), and 90% (p-value=0.003) lower, respectively, at 0.009, 0.006, and 0.003 kg m^{-2} compared to 0.024 kg m^{-2} in the CO (Figure 1.7c). Neither 10-hr, 100-hr, nor FWD particles showed any evidence of difference by treatment. Rotten CWD was 62% (p-value = 0.082) lower in the WB than the NB at 0.459 kg m^{-2} compared to 1.195 kg m^{-2} (Figure 1.7e). No other fine or coarse woody debris loading were statistically different despite average CWD loadings being 45% lower in burned units than the CO and 35-36% lower than the NB (Table 1.4b, Figure 1.6d, e). Litter loading was relatively similar between shelterwood treatments ranging 0.835-0.940 kg m^{-2}. However, duff was significantly lower by 55% in both the WB (p-value=0.011) and DB (p-value=0.010) at 0.485 and 0.475 kg m^{-2} compared to 1.067 kg m^{-2} in CO (Figure 1.6f, Figure 1.7d).

3.4 Woody surface fuels over time

Despite twenty-three years of potential fuel aggradation, surface fuels were generally lower in 2015. The only appreciable difference in fuel loading between 2015 and post-treatment (1993-4) occurred in some fine woody debris size classes in each installation, with lower 1-hr and 10-hr fuels. In the thinning installation, considered as a whole, fine woody debris loading in the burned units (SB and FB) showed little difference in 2015 compared to post-treatment values from 1993-4 (Figure 1.6a). By particle size, 1-hr fuels were lower by 79% in the SB (p-value = 0.058) and 65% lower in FB (p-value = 0.019) and 10-hr fuels by 61% the SB (p-value = 0.014) (Table 1.5a). This decrease in 1- and 10-hr fuels may be correlated with the decomposition of branches from smaller trees (2.54-17.78 cm DBH) that died in the prescribed burns or activity fuels left onsite that partially burned in the prescribed burns and/or decomposed. CWD loading was mostly composed of rotten logs and was not significantly higher or lower in 2015 (Table 1.5a & Figure 1.6b).

In the shelterwood, 10-hr fuels in the WB were 50% lower in 2015 than post-treatment in 1993 (p-value = 0.022) (Table 1.5b). CWD levels were almost four times higher in both burn treatments in 2015 at 0.574 kg m^{-2} in the WB (p-value = 0.098) and 0.674 kg m^{-2} in the DB (p-value = 0.062) and while mostly composed of rotten logs, indicated net aggradation over twenty-three years (Figure 1.6e).

3.5 Modeled fire behavior

Regardless of treatment, predicted fire behavior was most heavily influenced by the combination of high winds and dry fuel moistures (Figures 1.8 and 1.9). When we compared modeled fire behavior from unit-level summaries, there were no detectable differences between surface fire rate of spread, fireline intensity, or flame length between any treatments by modelling scenario in either the thinning or shelterwood installation 23-years post-treatment. No unit presented a torching potential without active crowning fire (transition $\geq$1.0 but active <1.0).

In the three most moderate scenarios, predicted fire type was consistently surface fire across both installations and treatments, except for three units in the shelterwood that had potential for crown fire in moderate moisture, high wind (Figure 1.10). In our high wind/dry moisture scenario, however, both conditional crown fire and active crowning were predicted. In the thinning, at least one unit in every treatment had high enough canopy bulk density to support conditional crowning under dry and windy conditions, and in the CO, all units had the potential for crown fire. Surface fuel loading and sapling density in the thinning were low but units that exhibited conditional crown fire potential all had tree densities ranging 214-416 trees ha^{-1}. No unit with fewer than 200 trees ha^{-1} demonstrated crown fire potential in our modeling.

In the shelterwood, two out of three units in both the CO and NB had enough surface and canopy fuels to maintain active crowning and all CO and NB units had potential for crown fire. One unit in each the WB and DB had some potential for either conditional or active crowning because of high CBD. Surface fuels were generally higher in the shelterwood but mostly in CWD, not FWD, and were therefore not the cause for increased fire behavior. Similarly, overstory tree density was not the driving factor increasing CBD treated units in the shelterwood; saplings had the greatest effect on CBD. For example, NB Unit 2 only had 138 trees ha^{-1} but had

3525 saplings ha^{-1} in for 0.201 kg m^{-3} CBD, generating a transition ratio of 1.69 and active ratio of 5.02 (shown as replicate "c" in Figure 1.10). In our most extreme modelling scenario, all units susceptible to crown fire had a combination of high surface fuels and high canopy bulk density, driven by the dense Douglas-fir ladder fuels in the understory.

Unlike the thinning, which only demonstrated conditional crown fire under the most extreme scenario (high wind/dry fuel moisture), the shelterwood had three treated units (two NB and one DB unit) with adequate CBD for an active ratio >1.0. Worth noting are the three control units that had active ratios 0.95-0.98. These units all had 50% or more CBD compared to most SB or FB units, affected by both dense overstory and understory trees, but were just under the active ratio threshold of 1.0.

4. DISCUSSION

What elements contribute to the persistence of a fuel treatment's effectiveness, or its longevity? Jain et al. (2012) outlined three characteristics that determine fuel treatment longevity: (1) fuel decay, the degradation of dead surface fuels; (2) fuel growth, the response of residual vegetation (especially advance regeneration) to the treated environment; and (3) fuel recruitment, the establishment of new vegetation (typically tree seedlings) which ultimately becomes dead surface fuel. Because forests are dynamic and responsive, treatment longevity depends on how heavily and where cuttings occur as well as site quality and time (Jain et al. 2012). It is important to quantify surface, ladder, and canopy fuel loadings to help inform management decisions (Stephens et al. 2009). Our research questions focused on determining long-term differences in fuel loading and how these fuels contributed to fire behavior.

4.1 Ladder & canopy fuels

By 2015, the thinning, which had few saplings to begin with, experienced 1.5-4 times the amount of saplings since post-treatment while the treated units in the shelterwood had increases of 28 to 362 times the post-treatment levels (Table 1.1). In both installations, the larger residual trees increased in size but only the thinning maintained a unimodal distribution of diameter classes (Figure 1.3).

In the shelterwood, the smallest diameter classes saw an increase of small trees, mostly Douglas-fir. This highlights the importance of silvicultural prescriptions for setting the stage for future conditions. Retention shelterwood cuttings are intended to facilitate regeneration while retaining large trees of the desired species. While the original 1990s study intended the treatments to recruit ponderosa pine, sufficient Douglas-fir overstory existed on site as mature trees or advance regeneration in the form of seedlings and saplings, especially in cut but unburned units. Arno (1999b) previously reported at Lick Creek that five-years post-treatment, Douglas-fir advance regeneration (seedlings and saplings >5 years old) averaged over 3200 trees ha^{-1} in the NB units compared to 0 advance regeneration stems in either cut-and-burn (WB and DB) treatment. Even post-treatment (seedlings <5 years old) Douglas-fir regeneration exceeded 760 trees ha^{-1} in the cut-only units, more than 3-5x higher than cut-burn units. In all treated units, post-treatment ponderosa pine regeneration averaged 770 trees ha^{-1}. Whereas in the shelterwood, prescribed burning eliminated seedlings and saplings, in the NB units, they were not eliminated by the harvesting alone. In this instance, a shelterwood system without additional surface fuel treatments undermined the objectives.

The emergent ladder fuel levels translated directly to canopy fuel metrics and fire behavior. In the thinning, canopy fuel loading and canopy bulk density were consistently ~30%

lower in treated units, regardless of prescribed burning. In the shelterwood, burned units (WB and DB) maintained lower Douglas-fir sapling regeneration compared to NB units, which translated directly to lower canopy base height and higher canopy bulk density in this lower stratum.

4.2 Surface fuels

In 2015, there were few differences in the surface fuel components between treatments in either installation. In the thinning, the only consistent and lasting effect of the treatments was on some fine fuels. One-hour fuels and duff were 67% and 78% lower in the SB relative to CO, respectively, while litter was 19-28% lower in all treated units relative to control. This could be explained by the fact that there are fewer trees in the thinned units to drop needles compared to the controls. In the shelterwood, the WB and DB units had 55% lower duff loading but there were no differences in litter layer by treatment. One-hour fuels were 62-87% lower in treated units in the shelterwood. Such a difference could be due to the fact that stands opened by harvesting exhibit less self-pruning. Additionally, increased sunlight exposure and precipitation through-fall to the forest floor in cut units may have increased surface fuel decomposition rates (Keane 2008).

Harvesting operations inevitably generate some residual slash that may affect surface fuel loading and fire behavior (Prichard et al. 2010; Schwilk et al. 2009; Stephens et al. 2009; Agee and Skinner 2005). When whole-tree harvesting is utilized, thinning operations can have negligible effect on surface fuels. However, when limbs and tree tops are left on site, whether masticated or scattered, the residual slash has in some cases increased fire intensity in wildfires (Stephens et al. 2009; Pollet and Omi 2002; Graham et al. 1999). In our case, whole trees were harvested with the exception of tree tops which remained at the cutting site. Tree limbs were removed and pile-burned near roadsides, reducing the potential amount of activity fuels (Arno 1999a).

There were few long-term responses of surface fuel loading between immediately post-treatment and 2015. Across installations, FWD surface fuels were lower or had returned to post-treatment levels (Figure 1.6a, d, Table 1.5). CWD was 3-4 times higher in the shelterwood installation in both prescribed fire treatments but the majority of that CWD was made up of rotten material, likely from post-treatment slash development, e.g. tree tops left on site that did not burn, and mortality caused by the prescribed fires (Figure 1.6b). Litter and duff values appeared to have stabilized but could not be analyzed. The composition of the litter/duff layer changed from mostly duff pre-and post-burning to mostly litter in 2015 (Figure 1.6c, f). However, because we have so few repeated measures of the fuel profile since the treatments, it is not possible to determine whether the high and low responses of surface fuel loading over time were captured. Additionally, since there was no pre-harvest measurement of all the fuel components, it is impossible to distinguish between the impacts of harvesting versus prescribed burning.

This is not an especially productive site, nor one that is experiencing heavy mortality. Prior to treatment initiation in 1991, Harrington (1999) described the surface fuel loading as not “excessive” and our data indicate that except for CWD in the shelterwood installation, surface fuels are lower after twenty-three years. Indeed, surface fuels levels are low at Lick Creek compared to most Rocky Mountain forested ecosystems (Ottmar et al. 2007, Keane 2008, Baker 2009). Therefore, surface fuel loading is unlikely to be a major driver of fire behavior. Rather, ladder fuel abundance and canopy continuity are the main factors of concern.

4.3 Modeled fire behavior

Anderson's Fire Behavior Fuel Model 9 (Anderson 1982) was the most represented fuel model estimated at the plot level from FuelCalc's fuel model selector, representing 69% of plots in the thinning unit and 64% of plots in the shelterwood. Other represented fuel models included FBFM 8 and 13. FBFM 9 is exemplified by closed-canopy long-needle pine stands with fire spread primarily through abundant needle litter and tree torching from concentrated coarse woody debris. One of the biggest limitations in selecting a single fuel model is that the spatial variability of fuel loadings within a stand is lost: not every point in a stand will burn similar to the predicted unit-level fire behavior (Scott and Reinhardt 2001, Contreras et al. 2012). Additionally, fire behavior fuel model classifications do not account for overstory fuel composition quantitatively but rather with a qualitative assessment of the primary fire-carrying fuel (Scott and Burgan 2005). Crown fire modeling addresses this by including canopy bulk density and canopy base height (Scott and Reinhardt 2001) but stand-level estimates of these values are only appropriate in a homogenous, even-aged stand. Nevertheless, fire behavior fuel models are the most efficient way to integrate all the fuel variables from our site into one output.

Potential for crown fire initiation (high transition ratio) is driven by low canopy base heights, in addition to higher surface fire rate of spread and flame length (which are driven by greater fuel loadings and windspeeds). Increased potential for active crown fire (high active ratio) is influenced by greater canopy bulk density, as well as high crown fire ROS (from increased wind) and low fuel moistures (Andrews 2009).

High winds and dry fuels were the dominant drivers of conditional and active crown fire behavior. In the thinning, surface and ladder fuels were low enough to prevent active torching but the canopy bulk density was great enough in at least one unit in every treatment to allow for conditional crown fire. All replicates of the control were susceptible to conditional crowning due to greater CBD.

The shelterwood, which generally had higher surface fuel bed depths, lower canopy base height, and higher canopy bulk density, was more susceptible to crown fire in the most extreme conditions (Figure 1.10). In the CO and NB units, surface and ladder fuels were abundant enough to contribute to active crown fire. The WB and DB treatments were less likely to experience conditional or crown fire but were not wholly immune. Even though our modeling did not produce isolated torching (transition ≥ 1.0 and active < 1.0), this is likely an artefact of using mean CBH per unit instead of another estimate such as median or first quantile, which may have been more representative of the continuous canopy in lower strata.

Thinning and burning in combination have been found by others (e.g. Fulé et al. 2012, Martinson and Omi 2013) to reduce surface and canopy fuels to greater effect than either treatment alone. At least one replicate of each treatment showed some level of susceptibility to conditional or active crown fire under the most extreme fuel moisture and wind scenarios. While it is encouraging that our stands did not demonstrate high torching potential, they may be susceptible to active crown fire initiated elsewhere (Scott and Reinhardt 2001).

As a local point of comparison, we evaluated our modeled fire behavior against a recent nearby wildfire on the Bitterroot National Forest that was reported on July 31, 2016, about 12 km north of our site. The Roaring Lion Fire started as an abandoned illegal campfire that grew nearly 200 ha on the first day it was reported and by the end of August 1, 2016, had grown to almost 1800 ha. By August 3rd, the fire was over 3100 ha and by the time it was fully controlled months later, had burned over 3500 ha. Local RAWS data 17 km south of the fire site recorded twenty-foot winds 32-35 km hr-1 on three of the four first days of large fire growth, with fine dead fuel moistures as low as 2% in exposed fuels (RAWS data for Little Rock Creek LRCM8, elevation 1678 m, accessed 11/22/17 MesoWest 2017)). On July 31, the high temperature was 25 degrees C and the minimum relative humidity was 13%. High temperatures reached 31 degrees C during the first few days of fire growth. Temperatures fluctuated in the days following the fire's initial growth but conditions were both windy and dry enough to facilitate favorable conditions for active fire behavior.

Fuel reduction treatments are increasingly being tested by wildfires. In the northern Cascades, several 5-20 year-old fuel reduction treatments were tested by the Tripod Complex of 2006 and in most cases, previous prescribed fires (with and without prior mechanical treatments) reduced wildfire severity (Prichard and Kennedy 2014). In northern Arizona, the Wallow Fire of 2002 burned through 10-year-old fuel treatments with much lower severity than in untreated stands, as measured by overstory mortality and herbaceous community response (Strom and Fulé, 2007; Waltz et al. 2014). These cases highlight the advantages of fuel reduction treatments for breaking aerial fuel continuity and mitigating fire severity, especially in the wildland-urban interface.

In our modeling scenarios, we used generalized fuel moistures and typical low and high windspeeds that were more extreme than those observed near the Roaring Lion fire. We intended our modeling to be broadly applicable to wildfire conditions, but it is important to note RAWS data may not encompass the range of windspeeds and fuel moisture fluctuations that occurred near the flaming front on the Roaring Lion fire. Such extreme conditions would result in higher intensity fire than we predicted with our scenarios. Additionally, while fire behavior at Lick Creek is predicted to be surface fire under favorable conditions, our high active ratios indicate that a crown fire entering from outside the site might carry through the stands in extreme circumstances.

4.4 Treatment longevity

In order to select from alternative fuel treatment options, managers need to know the expected longevity and plan for repeated entries, which requires an understanding of silvics for the forest type. For our study, treatments were effective if (1) treated units maintained lower canopy and surface fuel loadings than control ("CO") units and (2) the treatments were resistant to active crown fire. We saw shifts in ladder fuels generated by the initial silvicultural prescriptions and influenced to some degree by subsequent burning. Surface fuels across the site were low for a northern Rockies ponderosa pine/Douglas-fir stand (Ottmar et al. 2007, Baker 2009). Consequently, potential extreme fire behavior was only produced in units with high ladder fuel presence combined with extreme wind and fuel moisture scenarios.

At Lick Creek, treatment longevity is dictated by fuel growth and recruitment. The treatments are still maintaining lower fine surface fuel loading and overstory canopy fuels relative to control units but the silvicultural prescriptions affected understory and ladder fuels in contrasting ways. In the thinning, prescribed burning did not further reduce canopy fuel loading or bulk density but burning in the shelterwood significantly reduced residual sapling densities. In this way, the retention shelterwood treatment longevity was undermined by high ladder fuel development. Ultimately, cutting levels and species composition (i.e. silvicultural prescription) had a direct impact on treatment longevity in both sites. In the thinning, the treatments are still effective but the retention shelterwood is overdue for additional treatments.

Similar results have been found elsewhere. In the Black Hills, prescribed fire within ten to fifteen years of mechanical treatments is necessary to ensure fuel treatment longevity by reducing ladder fuel development from pine regeneration resulting from mechanical activities (Battaglia et al. 2008). Long-term monitoring plots in ponderosa pine forests of the southern Sierras of California showed 63-84% surface fuel recovery within ten years of prescribed fire treatments, with fuel loading exceeding pre-treatment levels after thirty years (Keifer et al. 2006). Treatment longevity may vary by ecosystem productivity but in existing studies, fuels have recovered to near pre-treatment levels within ten years (Martinson and Omi, 2013). However, the lack of available long-term data makes it difficult to determine treatment longevity beyond a decade (Fulé et al 2012). Our results corroborate the growing emphasis on the need to understand fuel treatment lifespan as well as effectiveness, and to plan for repeated fuel treatments before longevity expires (Reinhardt et al. 2008, Fulé et al 2012, Stephens et al. 2012).

4.5 Management implications

While our sites demonstrate lasting effects of fuel reduction treatments in the overstory after 23 years, managers should be cautious when considering these treatments effective. The thinning treatments were conducted on a dry south-facing slope with low understory vegetation loading and modest ponderosa pine and Douglas-fir regeneration. In contrast, the retention shelterwood study occurred near the bottom of the Lick Creek drainage, a much more productive site with a cutting treatment intended to facilitate regeneration. The cutting treatments reduced Douglas-fir in the overstory but did not eliminate the species from the site. As a result, post-treatment and advance regeneration grew dense enough over 23 years for the shelterwood site to be vulnerable to severe wildfire. Across the literature, fuel reduction treatments are most successful with a combination of cutting and burning strategies (Reinhardt et al. 2008, Fulé et al 2012 Stephens et al. 2012, Kalies and Yocom Kent 2016). Because the shelterwood NB treatment did not receive prescribed fire, residual slash (now rotten CWD) was not reduced and now poses a potential torching hazard in conjunction with regeneration pockets.

Previous work by Arno and Peterson (1983) demonstrated that the Lick Creek area experienced regular surface fires prior to 1900 but that fire frequency declined significantly after 1900. That interruption in regular surface fires allowed shade-tolerant conifers to establish over decades and shift the composition of the understory to continuous ladder fuels. Under extreme weather scenarios, the Lick Creek sites exhibited moderate to high potential for active crown fire, which would result in severe degradation of the forest condition. Fuel reduction treatments, when implemented correctly, are effective at reducing canopy continuity and maintaining lower crown fire hazard. However, it is critical to maintain treatment effectiveness by repeated entries of mechanical and prescribed fire treatments (Reinhardt et al. 2008, Fulé et al 2012). As evidenced by the 2015 fire season in the northern Rockies, it is only a matter of time before treated areas are tested by wildfire.

5. CONCLUSIONS

One challenge to hazard fuel treatment decision support is the diversity of fuel types and their unique fire ecologies. Agee and Skinner (2005) identified several “fire safe” principles for improving ecological resilience that are applicable to forest ecosystems across the West. These principles, along with site quality, can help guide treatment designs and inform the expected outcomes. While the treatments at our sites maintained lower canopy fuel loadings, the silvicultural strategy (thinning or retention shelterwood) had a significant effect on stand development over two decades. Where a thinning was used, treated stands maintained lower canopy fuel levels and were overall more resistant to active crown fire. However, when a retention shelterwood was used and shade tolerant species were left on site, regeneration was dominated by Douglas-fir thickets that translated to higher susceptibility to active crown fire in extreme weather scenarios and shortened periods of fuel treatment effectiveness.

At least one replicate of each treatment showed some level of susceptibility to conditional or active crown fire under the most extreme fuel moisture and wind scenarios. While it is encouraging that our stands did not demonstrate high torching potential, several units were susceptible to active crown fire if initiated elsewhere (Scott and Reinhardt 2001). Fuels treatments can be effective in moderating fire behavior which is important not only ecologically, but socially, financially, and managerially. Our stands were resilient to crown fire in all but the most extreme scenarios.

As this study indicates, timely removal of shade tolerant species and maintenance treatments are needed. One treatment alone will not return either installation to historic or sustainable conditions but creating stands with larger, fire resistant species improves forest resiliency to climate change and wildfire (Agee and Skinner 2005, Youngblood 2010, Fulé et al. 2012).

REFERENCES

Agee JK. 1996. The influence of forest structure on fire behavior. Pages 52-68 in: proceedings of the 17th annual forest vegetation management conference, January 16-18, 1996; Redding, California. [Place of publication unknown]. [Publisher unknown].

Agee JK, Skinner CN. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211: 83-96.

Anderson HE. 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report INT-GTR-122. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 28 p.

Andrews PL. 2009. BehavePlus fire modeling system, version 5.0: variables. General Technical Report RMRS-GTR-213WWW Revised. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 111 p.

Arno SF. 1976. The historical role of fire on the Bitterroot National Forest. Research Paper INT-RP-187. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 29 p.

Arno SF, Peterson TD. 1983. Variation in estimates of fire intervals: a closer look at fire history on the Bitterroot National Forest. Research Paper INT-301. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 8 p.

Arno SF. 1999a. Ecosystem-based management treatments. Pages 22-26 in: Smith HY and Arno SF, editors. Eighty-eight years of change in a managed ponderosa pine forest. General Technical Report RMRS-GTR-23. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55 p.

Arno SF. 1999b. Tree regeneration. Page 35 in: Smith HY and Arno SF, editors. Eighty-eight years of change in a managed ponderosa pine forest. General Technical Report RMRS-GTR-23. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55 p.

Arno SF, Harrington MG, Fiedler CE, Carlson CE. 1995. Restoring fire-dependent ponderosa pine forests in western Montana. Restoration & Management Notes. 13(1): 32-36.

Arno SF, Fiedler CE. 2005. Mimicking Nature's Fire Restoring Fire-Prone Forests in the West. Island Press: Washington, D.C.

Baker WL. 2009. Fire Ecology in Rocky Mountain Landscapes. Island Press: Washington, DC.

Battaglia MA, Smith FW, Shepperd WD. 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? Forest Ecology and Management. 256(12): 2029-2038.

Brown JK. 1974. Handbook for inventorying downed woody material. General Technical Report INT-GTR-16. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Brown JK, Oberhau RD, Johnston CM. 1982. Handbook for inventorying surface fuels and biomass in the Interior West. General Technical Report INT-GTR-129. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 52 p.

Carlson CE, Floch RF, Fiedler C. 1994. Research and demonstration of ecosystem management principles in ponderosa pine/Douglas-fir forests: Lick Creek, Bitterroot National Forest. Pages 201-206 in: Foley, L., compiler. Proceedings – silviculture: from the cradle of forestry to ecosystem management. National Silviculture Workshop, Hendersonville, North Carolina; November 1-4, 1993. General Technical Report SE-GTR-88. Asheville, North Carolina: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 268 p.

Carlson CE, Flock RF. 1996. Lick Creek ecosystem management/research demonstration area. Pages 81-86 in: Schmidt, W.C., and J.L. Friede, compilers. Experimental forests, ranges, and watersheds in the northern rocky mountains: a compendium of outdoor laboratories in Utah, Idaho, and Montana. General Technical Report INT-GTR-334. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 128 p.

Contreras MA, Parsons RA, Chung W. 2012. Modeling tree-level fuel connectivity to evaluate the effectiveness of thinning treatments for reducing crown fire potential. Forest Ecology and Management. 264: 134-149.

Covington WW, Moore MM. 1994. Post-settlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. Journal of Sustainable Forestry. 2:153-181.

Covington WW, Fulé PZ, Moore MM, Hart SC, Kolb TE, Mast JN, Sackett SS, Wagner MR. 1997. Restoring ecosystem health in ponderosa pine forests of the Southwest. Journal of Forestry. 95(4): 23-29.

DeLuca TH, Zouhar KL. 2000. Effects of selection harvest and prescribed fire on the soil nitrogen status of ponderosa pine forests. Forest Ecology and Management. 138: 263-271.

Fulé PZ, Crouse JE, Roccaforte JP, Kalies EL. 2012. Do thinning and/or burning treatments in western USA ponderosa pine or Jeffrey pine-dominated forests help restore natural fire behavior? Forest Ecology and Management. 269: 68-81.

Graham RT, Harvey AE, Jain TB, Tonn JR. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. General Technical Report PNW-GTR-463. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

Gruell GE, Wyman CS, Arno SF, Reich WJ. 1982. Seventy years of vegetative change in a managed ponderosa pine forest in western Montana - implications for resource management. General Technical Report INT-GTR-130. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 42 p.

Hanberry BB. 2014. Compositional changes in selected forest ecosystems of the western United States. Applied Geography. 52: 90-98.

Harrington MG. 1999. Effects of ecosystem-based management treatments. Pages 27-31 in: Smith HY and Arno SF, editors. Eighty-eight years of change in a managed ponderosa pine forest. General Technical Report RMRS-GTR-23. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55p.

Hartwell MG, Alaback P, Arno SF. 2000. Comparing historic and modern forests on the Bitterroot Front. Pages 11-16 in: Smith HY, editor: The Bitterroot Ecosystem Management Research Project: What We Have Learned. Symposium Proceedings; Missoula, Montana, May 18-20, 1999. General Technical Report RMRS-GTR-17. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 154 p.

Heinsch FA, Andrews PL. 2010. BehavePlus fire modeling system, version 5.0: design and features. General Technical Report RMRS-GTR-249. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 111 p.

Hessburg PF, Churchill DJ, Larson AJ, Haugo AD, Miller C, Spies TA, North MP, Povak NA, Belote RT, Singleton PH. 2015. Restoring fire-prone Inland Pacific landscapes: seven core principles. Landscape Ecology. 30: 1805-1835.

Heyerdahl EK, Morgan P, Riser II JP. 2008. Crossdated fire histories (1650 to 1900) from ponderosa pine-dominated forests of Idaho and western Montana. General Technical Report RMRS-GTR-214WWW. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 89 p.

Hood SM, Baker S, Sala A. 2016. Fortifying the forest: thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience. Ecological Applications. 26(7): 1984-2000.

Kalies EL, Chambers CL, Covington WW. 2010. Wildlife responses to thinning and burning treatments in southwestern conifer forests: A meta-analysis. Forest Ecology and Management. 259(3): 333-342.

Kalies EL, Yocom Kent LL. 2016. Tamm Review: are fuel treatments effective at achieving ecological and social objectives? A systematic review. Forest Ecology and Management. 275: 84-95.

Keane RE. 2008. Surface fuel litterfall and decomposition in the northern Rocky Mountains, U.S.A. Research Paper RMRS-RP-70. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 22 p.

Keane RE. 2015. Wildland Fuel Fundamentals and Application. Springer: New York, New York.

Keifer M, van Wagtendonk JW, Buhler M. 2006. Long-term surface fuel accumulation in burned and unburned mixed-conifer forests of the central and southern Sierra Nevada, CA (USA). Fire Ecology. 2(1): 53-72.

LANDFIRE, 2008, Existing Fuel Type Layer, LANDFIRE 1.1.0, U.S. Department of the Interior, Geological Survey. Accessed December 12, 2017. online: https://landfire.cr.usgs.gov/viewer/.

Levene H. 1960. Robust tests for equality of variance. Pages 278-292 in: Contributions to probability and statistics. Editors Olkin I, Ghurye SG, Hoeefeling W, Madow WG, and Mann HB. Stanford University Press: Stanford, CA.

Lutes DC, Keane RE, Caratti JF, Key CH, Benson NC, Sutherland S, Gangi LJ. 2006. FIREMON: The fire effects monitoring and inventory system. General Technical Report RMRS-GTR-164-CD. Fort Collins, Colorado
: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 400 p.

Lutes DC, Reinhardt ED, Keane RE, Scott JH, Gangi LJ. 2016. FuelCalc (version 1.4.0). Accessed May 21, 2017. Available at: https://www.firelab.org/project/fuelcalc.

Martinson EJ, Omi PN. 2013. Fuel treatments and fire severity: A meta-analysis. Research Paper RMRS-RP-103WWW. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 38 p.

McIver J, Erickson K, Youngblood A. 2012. Principal short-term findings of the National Fire and Fire Surrogate study. General Technical Report PNW-GTR-860. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 210 p.

Menakis JP. 1994. A summary of ponderosa pine (*Pinus ponderosa*) management activities in the Lick Creek drainage of the Bitterroot National Forest. Thesis. Missoula, Montana: University of Montana. 79 p.

MesoWest. 2017. University of Utah Department of Atmospheric Sciences, SynopticLabs. Downloading LRCM8 Data. <ttp://mesowest.utah.edu/cgi-

bin/droman/downloading_api2.cgi?stn=LRCM8&year1=2017&day1=13&month1=12&hour1=22&timetype=GMT&unit=0>. Accessed November 22, 2017.

Ottmar RD, Sandberg DV, Riccardi CL, Prichard SJ. 2007. An overview of the Fuel Characteristic Classification System – quantifying, classifying and creating fuelbeds for resource planning. Canadian Journal of Forest Research. 37: 2383-2393.

Pfister RD, Kovalchik BL, Arno, SF, Presby RC, editors. 1977. Forest habitat types of Montana. General Technical Report INT-GTR-34. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Pollet J, Omi PN. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire. 11(1): 1-10.

Prichard SJ, Peterson DL, Jacobson K. 2010. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest. Washington, USA. Canadian Journal of Forest Research. 40(8): 1615-1626.

Prichard SJ, Kennedy MC. 2014. Fuel treatments and landform modify landscape patterns of burn severity in an extreme fire event. Ecological Applications. 24(3): 571-590.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. online: <https://www.R-project.org/.>

Reinhardt ED, Keane RE, Calkin DE, Cohen JD. 2008. Objectives and considerations for wildland fuel treatments in forested ecosystems of the interior western United States. Forest Ecology and Management. 256: 1997-2006.

Russell RE, Royle JA, Saab VA, Lehmkuhl JF, Block WM, Sauer JR. 2009. Modeling the effects of environmental disturbance on wildlife communities: avian responses to prescribed fire. Ecological Applications. 19(5): 1253-1263.

Ryer RA, Losensky J. 1983. Ponderosa pine and rocky mountain Douglas-fir. Pages 53-55 in: Burns RM, tech. comp. Silvicultural systems for the major forest types of the United States. Agriculture Handbook No. 445. Washington, D.C.: U.S. Department of Agriculture, Forest Service. 196 p.

Schoennagel T, Veblen TT, Romme WH. 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. BioScience. 54(7): 661-676.

Schwilk DW, Keeley JE, Knapp EE, McIver J, Bailey JD, Fettig CJ, Fielder CE, Harrod RJ, Moghaddas JJ, Outcalt CW, Skinner CN, Stephens SL, Waldrop TA, Yaussy DA, Youngblood A. 2009. The National Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecological Applications. 19(2): 285-304.

Scott JH, Reinhardt ED. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Research Paper RMRS-RP-29. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 59 p.

Scott JH, Burgan RE. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153. Fort Collins, Colorado: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

Smith HY, Arno SF, editors. 1999. Eighty-eight years of change in a managed ponderosa pine forest. General Technical Report RMRS-GTR-23. Ogden, Utah: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55 p.

Stephens SL, Moghaddas JJ, Edminster C, Fiedler CE, Haase S, Harrington M, Keeley JE, Knapp EE, Mciver JD, Metlen K, Skinner CN, Youngblood A. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecological Applications. 19(2): 305-320.

Stephens SL, McIver JD, Boerner REJ, Fettig CJ, Fontaine JB, Hartsough BR, Kennedy PL, Schwilk DW. 2012 The effects of forest fuel-reduction treatments in the United States. BioScience. 62: 549-560.

Strom BA, Fulé PZ. 2007. Pre- wildfire fuel treatments affect long-term ponderosa pine forest dynamics. International Journal of Wildland Fire. 16(1): 128-138.

Swim SL, Walker RF, Johnson DW, Fecko RM, Miller WW. 2014. Evaluation of mechanized thinning and prescribed fire effects on long-term fuels accumulations in uneven-aged Jeffrey pine. Journal of Sustainable Forestry. 33(8): 827-59.

Tukey JW. 1949. Comparing individual means in the analysis of variance. Biometrics. 5(2): 99-114.

Van Wagner CE. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7: 23-34.

Waltz AEM, Stoddard MT, Kalies EL, Springer JD, Huffman DW, Meador AS. 2014. Effectiveness of fuel reduction treatments: assessing metrics of forest resiliency and wildfire severity after the Wallow Fire, AZ. Forest Ecology and Management. 334: 43-52.

Youngblood A. 2010. Thinning and burning in dry coniferous forests of the western United States: effectiveness in altering diameter distributions. Forest Science. 56(1): 46-59.

Table 1.1 Overstory stand structure in 1991 (pre-treatment), 1993/4 (post-treatment) and 2015 for (a) Thinning and (b) Retention Shelterwood. 1991 values are stand averages with min- and max- range in parentheses. 1993/4 and 2015 mean and standard error (in parentheses) are given for treatments within each installation. Sapling species composition (% ponderosa pine "PP"/% Douglas-fir "DF"/% other "OT" (where applicable)) is provided for 2015.

(a) THINNING

	Stand Average	**Control**		**No Burn**		**Spring Burn**		**Fall Burn**	
	1991	1993/4	2015	1993/4	2015	1993/4	2015	1993/4	2015
Trees ha^{-1}	369 (313-443)	378 (50)	335 (41)	199 (22)	200 (20)	230 (29)	230 (39)	232 (20)	211 (26)
QMD cm	27.0 (24.4-29.2)	28.6 (1.0)	33.6 (1.1)	29.4 (1.5)	36.7 (0.7)	27.5 (1.5)	34.9 (2.3)	28.5 (1.5)	36.7 (2.0)
BA m^2 ha^{-1}	21.0 (18.4-26.0)	24.0 (2.2)	29.3 (2.2)	13.2 (0.2)	21.1 (1.3)	13.4 (0.1)	21.2 (1.2)	14.6 (0.4)	21.9 (0.6)
Saplings ha^{-1}	N/A	80 (17)	231 (82)	41 (6)	178 (56)	96 (79)	132 (40)	24 (5)	34 (9)
% spp			(79 PP/21 DF)		(44 PP/56 DF)		(82 PP/18 DF)		(63 PP/37 DF)

(b) RETENTION SHELTERWOOD

	Stand Average	**Control**		**No Burn**		**Wet Burn**		**Dry Burn**	
	1991	1993/4	2015	1993/4	2015	1993/4	2015	1993/4	2015
Trees ha^{-1}	438 (336-608)	369 (58)	319 (42)	168 (23)	179 (22)	141 (11)	129 (16)	167 (6)	149 (2)
QMD	28.2 (23.7-32.0)	30.4 (1.5)	34.6 (1.6)	31.0 (2.9)	36.4 (1.8)	30.7 (0.9)	39.2 (1.5)	30.2 (0.4)	37.2 (0.5)
BA	26.9 (21.3-33.2)	26.1 (2.1)	29.5 (1.9)	23.3 (0.6)	18.2 (0.7)	10.3 (0.5)	15.5 (1.8)	12.0 (0.7)	16.2 (0.6)
Saplings ha^{-1}	160 (76-453)	360 (134)	717 (276)	75 (9)	2125 (919)	2 (1)	724 (390)	25 (7)	676 (408)
% spp			(3 PP/95 DF/ 2 OT)		(12 PP/88 DF/ <1 OT)		(53 PP/47 DF)		(30 PP/70 DF/ <1 OT

Table 1.2. Seedling density in 2015 for Thinning (a) and Retention Shelterwood (b). Species are ponderosa pine (*Pinus ponderosa*, "PIPO"), Douglas-fir (*Pseudotsuga menziesii*, "PSME"), grand fir (*Abies grandis*, "ABGR"), and Engelmann spruce (*Picea engelmannii* "PIEN"). No grand fir or Engelmann spruce seedlings were observed in the Thinning units. Units are seedlings ha^{-1}.

(a) THINNING

	Control	No Burn	Spring Burn	Fall Burn
PIPO	212.8 (79.2)	377.5 (86.0)	954.1 (473.2)	1393.4 (291.8)
PSME	103.0 (23.8)	418.7 (101.1)	823.7 (327.1)	556.0 (226.8)

(b) RETENTION SHELTERWOOD

	Control	No Burn	Wet Burn	Dry Burn
PIPO	521.7 (161.9)	1036.5 (174.1)	2265.1 (645.4)	1098.2 (203.3)
PSME	5896.2 (2493.3)	2560.3 (1287.6)	1743.5 (1193.3)	1448.3 (1263.9)
ABGR	116.7 (106.6)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
PIEN	20.6 (11.9)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

Table 1.3. Four fire behavior modeling scenarios used with Fire Behavior Fuel Model 9 in BehavePlus.

	Moisture Content (%)						
Scenario	1-hr	10-hr	100-hr	Live Herb	Live Woody	Canopy Foliar[C]	6.1-m windspeed (km h^{-1})
Very Dry-low wind	3	4[A]	5	30	60	100	16.1
Very Dry-high wind	3	4	5	30	60	100	64.4
Moderate-low wind	9	10[B]	11	90	120	100	16.1
Moderate-high wind	9	10	11	90	120	100	64.4

[A]Based on Scott and Burgan (2005) dead fuel moisture scenario D1 and live fuel moisture scenario L1.
[B]Based on Scott and Burgan (2005) dead fuel moisture scenario D3 and live fuel moisture scenario L3.
[C]Based on Nexus (Scott 1999) recommended value.

Table 1.4 Canopy and surface fuels by treatment in 2015 for (a) Thinning and (b) Retention Shelterwood installations. Standard errors are in parentheses. CFL = canopy fuel loading, CBD = canopy bulk density, and CBH = canopy base height. Treatments are Control “CO”, No Burn “NB”, Cut+Spring burn “SB” (Thinning only), Cut+Fall burn “FB” (Thinning only), Cut+Wet burn “WB” (Shelterwood only), and Cut+Dry burn “DB” (Shelterwood only). Uppercase letters denote statistical differences between groups at α=0.05 while lowercase letters denote differences at α=0.10.

(a) THINNING

Treatment	CFL kg m^{-2}	CBD kg m^{-3}	CBH m	1-hr kg m^{-2}	10-hr kg m^{-2}	100-hr kg m^{-2}	1000-hr kg m^{-2}	Litter kg m^{-2}	Duff kg m^{-2}
CO	0.669^{A}	0.058^{A}	3.4	0.006^{A}	0.145	0.198	0.431	1.239^{a}	0.892^{a}
	(0.190)	(0.005)	(0.5)	(0.002)	(0.027)	(0.008)	(0.113)	(0.055)	(0.286)
NB	0.473^{B}	0.038^{B}	3.1	0.003^{AB}	0.116	0.223	0.441	1.009^{b}	0.634^{ab}
	(0.231)	(0.005)	(0.3)	(0.0)	(0.032)	(0.081)	(0.051)	(0.064)	(0.122)
SB	0.480^{B}	0.040^{B}	3.0	0.002^{B}	0.069	0.196	0.377	0.969^{b}	0.195^{b}
	(0.188)	(0.005)	(0.2)	(0.001)	(0.018)	(0.021)	(0.070)	(0.028)	(0.043)
FB	0.467^{B}	0.040^{B}	4.1	0.002^{AB}	0.097	0.108	0.614	0.929^{b}	0.311^{ab}
	(0.096)	(0.002)	(1.0)	(0.001)	(0.012)	(0.050)	(0.225)	(0.034)	(0.069)

(b) RETENTION SHELTERWOOD

Treatment	CFL kg m^{-2}	CBD kg m^{-3}	CBH m	1-hr kg m^{-2}	10-hr kg m^{-2}	100-hr kg m^{-2}	1000-hr kg m^{-2}	Litter kg m^{-2}	Duff kg m^{-2}
CO	0.931^{A}	0.078	1.9	0.024^{A}	0.222	0.191	1.579	0.837	1.067^{A}
	(0.056)	(0.002)	(1.4)	(0.003)	(0.060)	(0.076)	(0.674)	(0.073)	(0.048)
NB	0.746^{AB}	0.123	1.0	0.009^{B}	0.158	0.314	1.284	0.940	0.744^{AB}
	(0.152)	(0.046)	(0.4)	(0.003)	(0.026)	(0.044)	(0.143)	(0.050)	(0.070)
WB	0.375^{B}	0.044	2.8	0.006^{B}	0.122	0.183	0.574	0.914	0.485^{B}
	(0.010)	(0.009)	(1.2)	(0.003)	(0.018)	(0.057)	(0.151)	(0.311)	(0.121)
DB	0.420^{B}	0.051	2.4	0.003^{B}	0.131	0.260	0.674	0.901	0.475^{B}
	(0.067)	(0.019)	(0.8)	(0.001)	(0.013)	(0.076)	(0.157)	(0.049)	(0.119)

Table 1.5. Changes in fuel loadings (kg m^{-2}) from 1993-4 (Post-treatment) to 2015 for (a) Thinning and (b) Retention Shelterwood installations. Percent change is based on treatment-level averages. Bold values represent significance at $\alpha = 0.10$ on a one-sample *t*-test of mean difference between post-treatment and 2015.

(a) THINNING

Treatment	Particle Type	Mean diff	% change	p-value
Spring Burn	**1-hr**	**-0.007**	**-79**	**0.05806**
	10-hr	**-0.107**	**-61**	**0.01437**
	100-hr	-0.078	-29	0.4116
	FWD	-0.192	-42	0.1355
	CWD – Sound	-0.138	-92	0.2398
	CWD – Rotten	0.057	19	0.6941
	CWD combined	-0.081	-18	0.2156
Fall Burn	**1-hr**	**-0.006**	**-66**	**0.01849**
	10-hr	-0.038	-28	0.2974
	100-hr	-0.086	-44	0.3044
	FWD	-0.130	-39	0.1587
	CWD – Sound	0.086	156	0.6338
	CWD – Rotten	0.410	664	0.252
	CWD combined	0.496	424	0.1334

(b) RETENTION SHELTERWOOD

Treatment	Particle Type	Mean diff	% change	p-value
Wet Burn	1-hr	-0.003	-30	0.3444
	10-hr	**-0.122**	**-50**	**0.0221**
	100-hr	0.001	0	0.9894
	FWD	-0.124	-29	0.1107
	CWD – Sound	0.028	33	0.7133
	CWD – Rotten	0.425	1261	0.1767
	CWD combined	**0.453**	**375**	**0.0981**
Dry Burn	1-hr	-0.023	-90	0.1545
	10-hr	-0.154	-54	0.2202
	100-hr	-0.038	-13	0.6634
	FWD	-0.215	-35	0.2436
	CWD – Sound	0.038	61	0.6629
	CWD – Rotten	**0.496**	**638**	**0.0556**
	CWD combined	**0.534**	**382**	**0.0624**

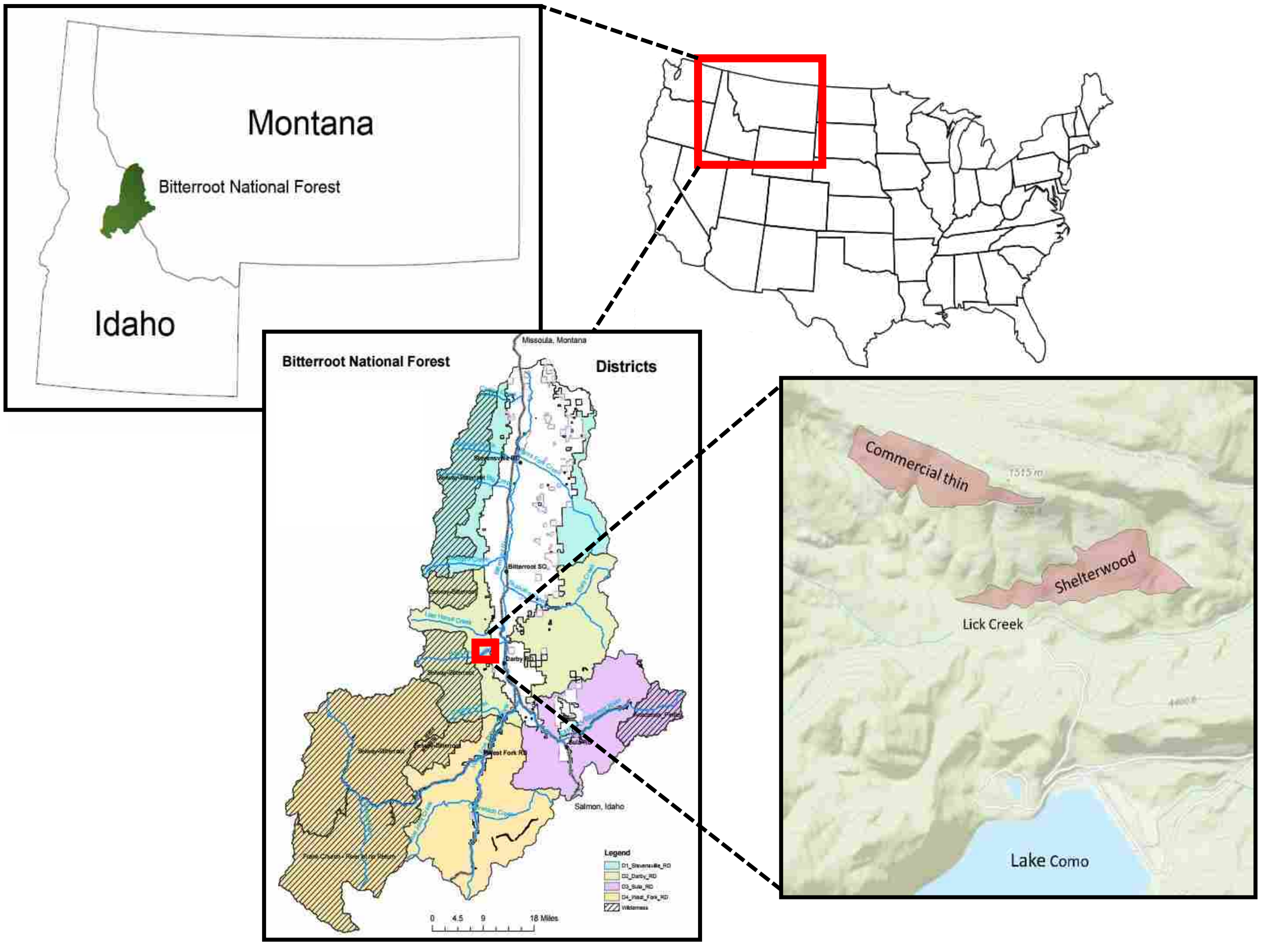

Figure 1.1 Location of Lick Creek Demonstration/Research Forest on the Bitterroot National Forest in western Montana.

THINNING

Pre-harvest

2015

RETENTION SHELTERWOOD

Pre-harvest

2016

Figure 1.2. Examples of Thinning Cut and Spring Burn treatment (left) and Retention Shelterwood Cut and Wet Burn treatment (right) for pre-harvest (1991) (top) and 2015/16 (bottom). Note: Photos were taken in the fall of 2015 in the Thinning and fall of 2016 in the Retention Shelterwood.

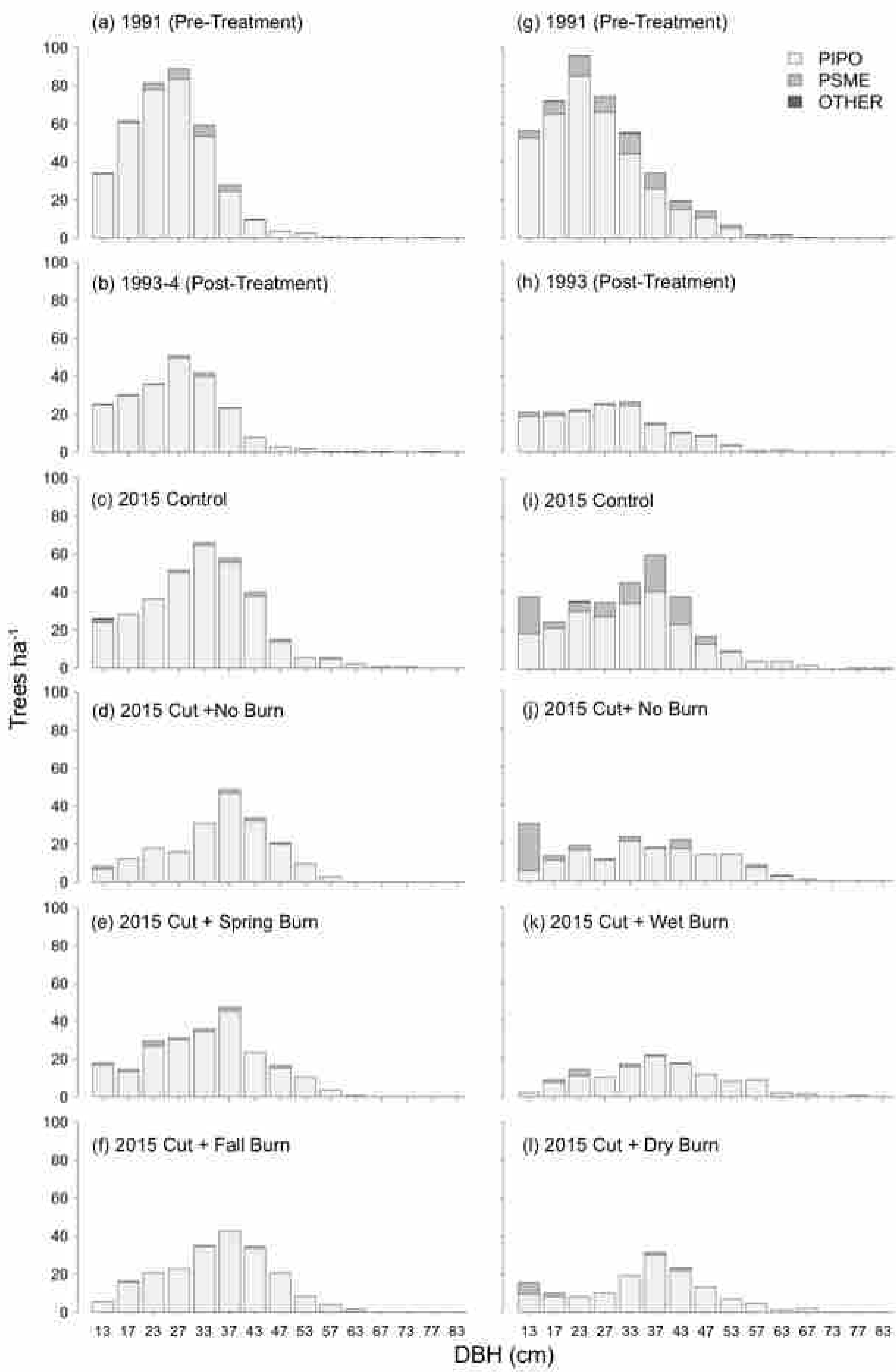

Figure 1.3. Diameter distributions of treated units in the Thinning (a-f) and Retention Shelterwood (g-l) in 1991 (pre-treatment), 1993-4 (post-treatment), and in 2015. Post-treatment figures (b & h) are after the completion of both cutting and burning treatments. “Other” trees included *Pinus contorta* and *Abies spp.*, which made up less than 1% of the overstory.

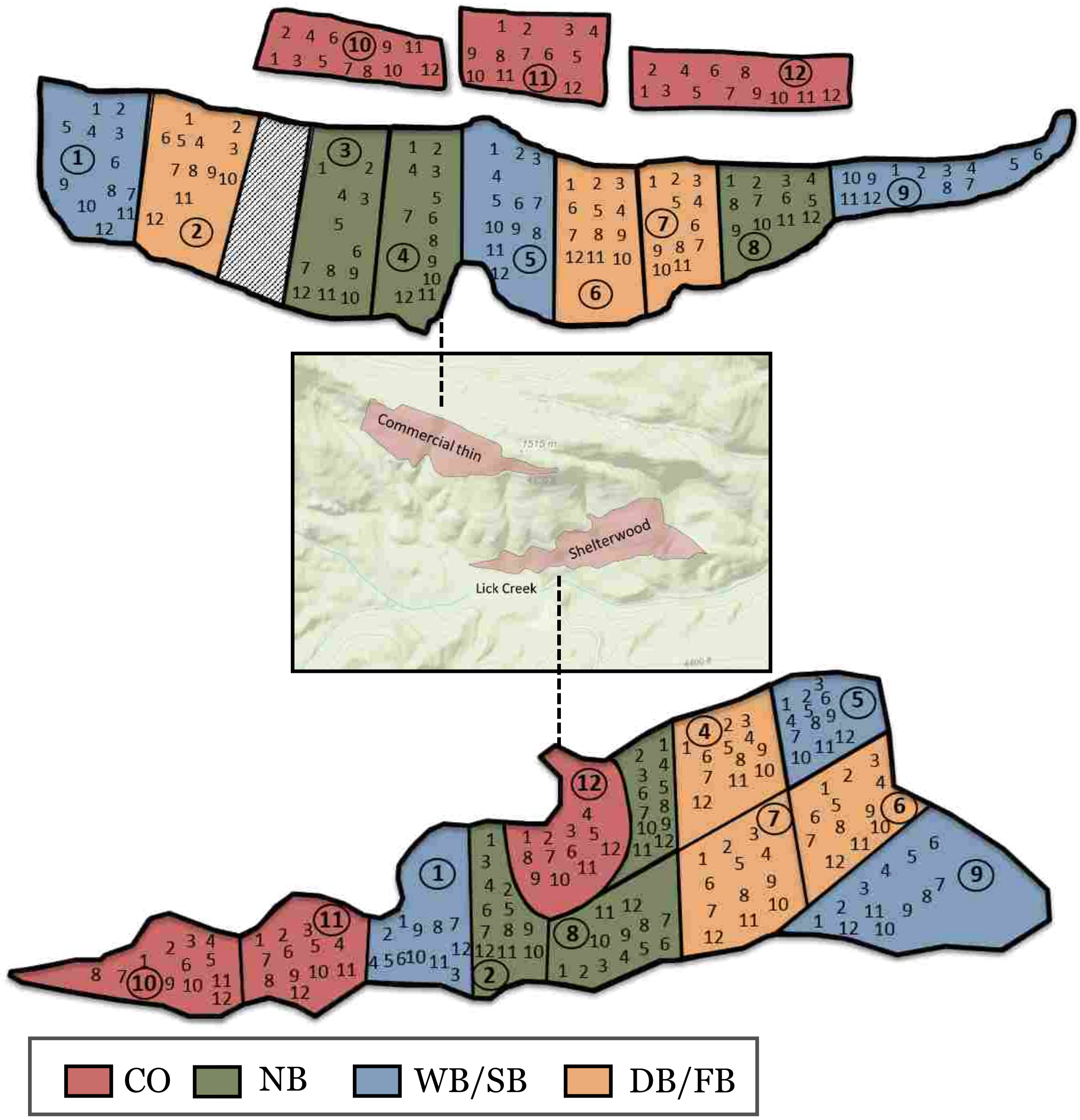

Figure 1.4. Thinning (top) and Retention Shelterwood (bottom) with treatment units color coded as follows: "CO" for control, "NB" for cut but unburned units, "SB/WB" for Cut and Spring Burn (Thinning)/Cut and Wet Burn (Retention Shelterwood), and "FB/DB" for Cut and Fall Burn (Thinning)/Cut and Dry Burn (Retention Shelterwood).

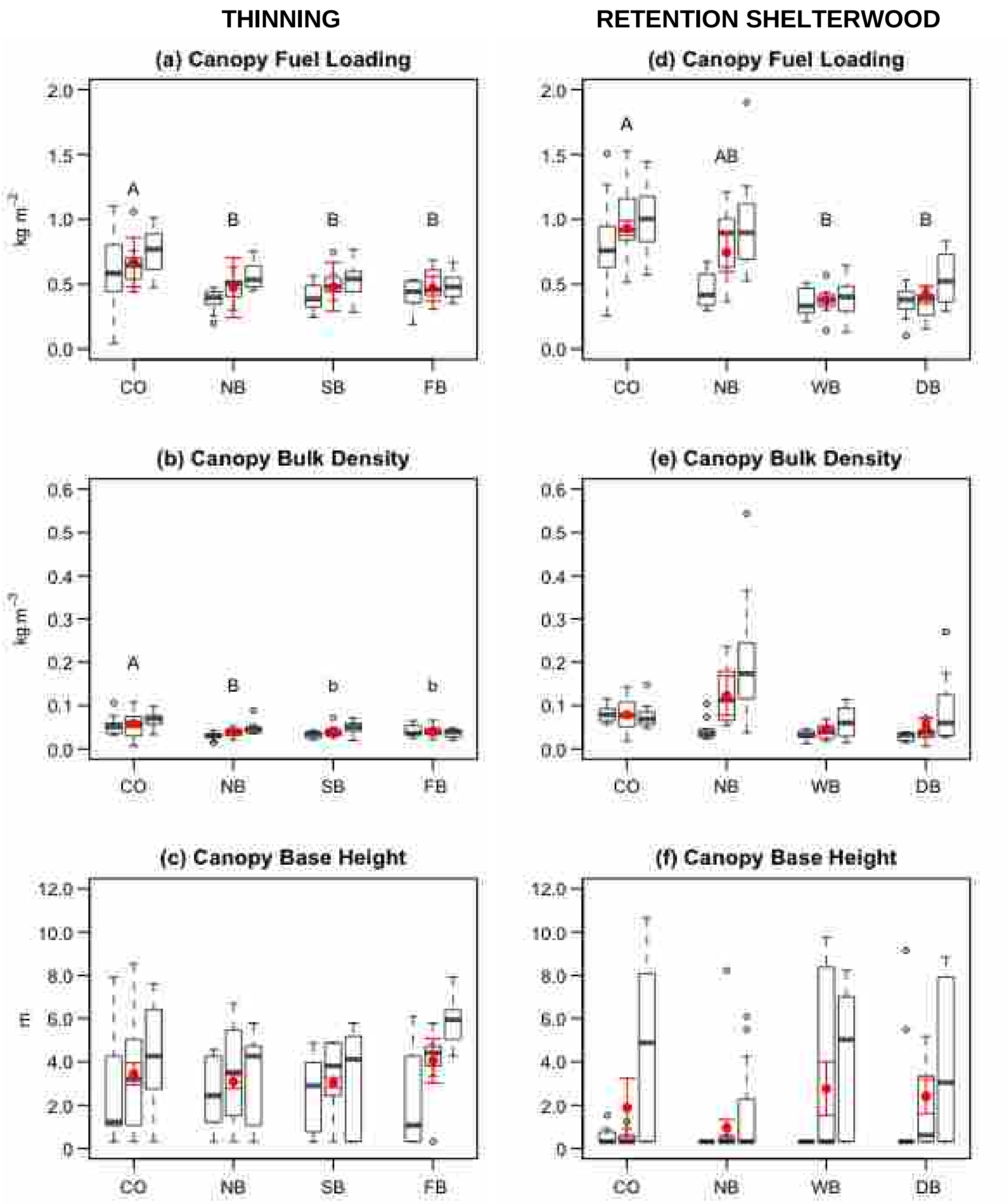

Figure 1.5. Side-by-side box-and-whisker plots for canopy fuel variables in the Thinning (a-c) and Shelterwood (d-f). Each box-and-whisker plot represents one unit replicate of each treatment to show within-unit variation. Boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range (IQR). Red points and error bars represent treatment mean and standard error to show treatment-level comparisons. Treatments are Control "CO", No Burn "NB", Cut+Spring Burn "SB" (Thinning only), Cut+Fall Burn "FB" (Thinning only), Cut+Wet Burn "WB" (Shelterwood only), and Cut+Dry Burn "DB" (Shelterwood only). Uppercase letters denote statistical differences between groups at α=0.05, while lowercase letters denote differences at α=0.10.

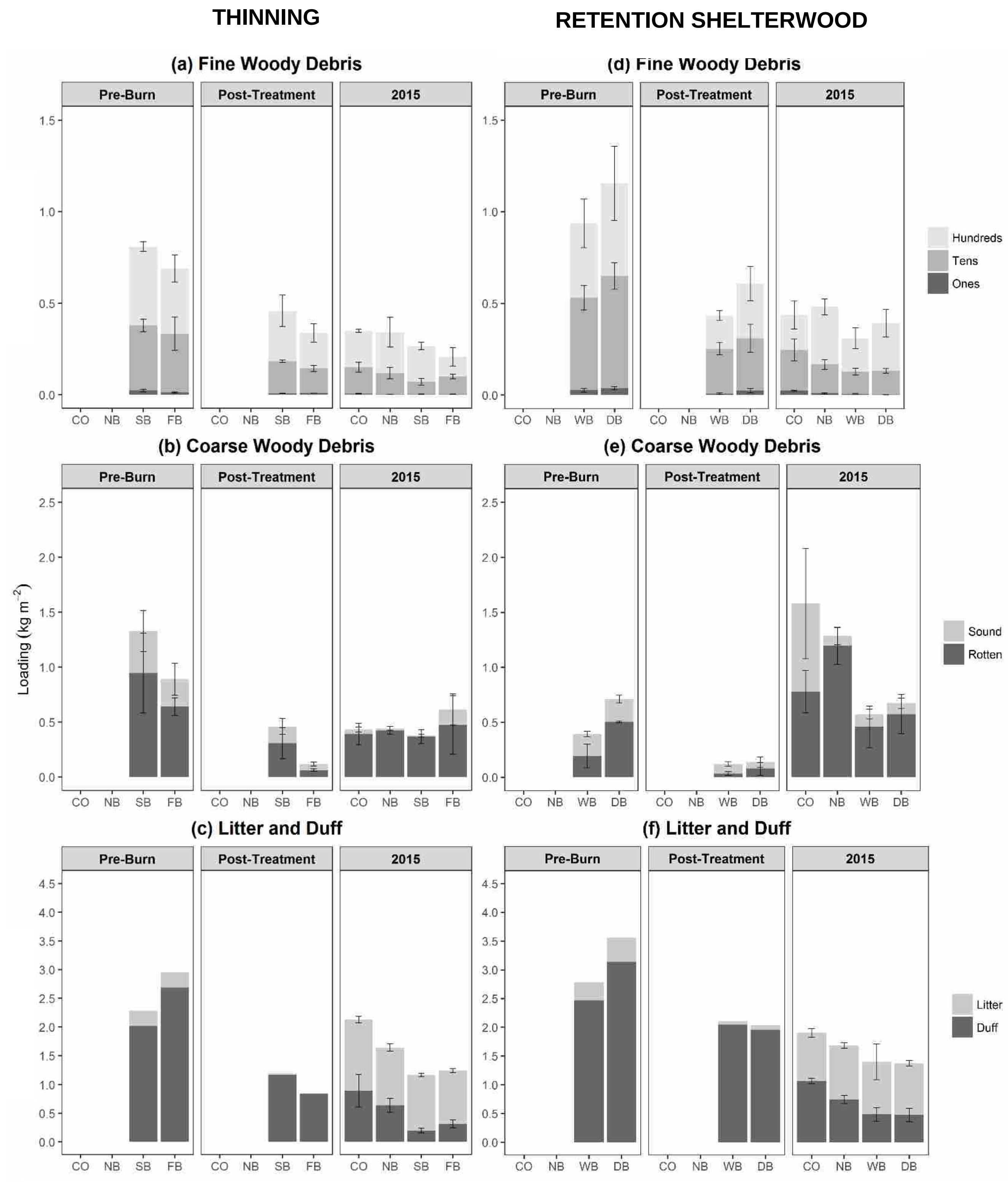

Figure 1.6. Surface fuel load in Thinning (a-c) and Retention Shelterwood (d-f), broken down by Pre-Burn (post-harvest; 1993), Post-Treatment (1993-4 in thinning and 1993 in shelterwood), and 2015. Bars denote mean fuel loading per particle type per treatment with +/- 1 standard error (n=3). Treatments are Control "CO", No Burn "NB", Cut+Spring Burn "SB" (Thinning only), Cut+Fall Burn "FB" (Thinning only), Cut+Wet Burn "WB" (Shelterwood only), and Cut+Dry Burn "DB" (Shelterwood only). Significant differences are shown in Figure 1.7.

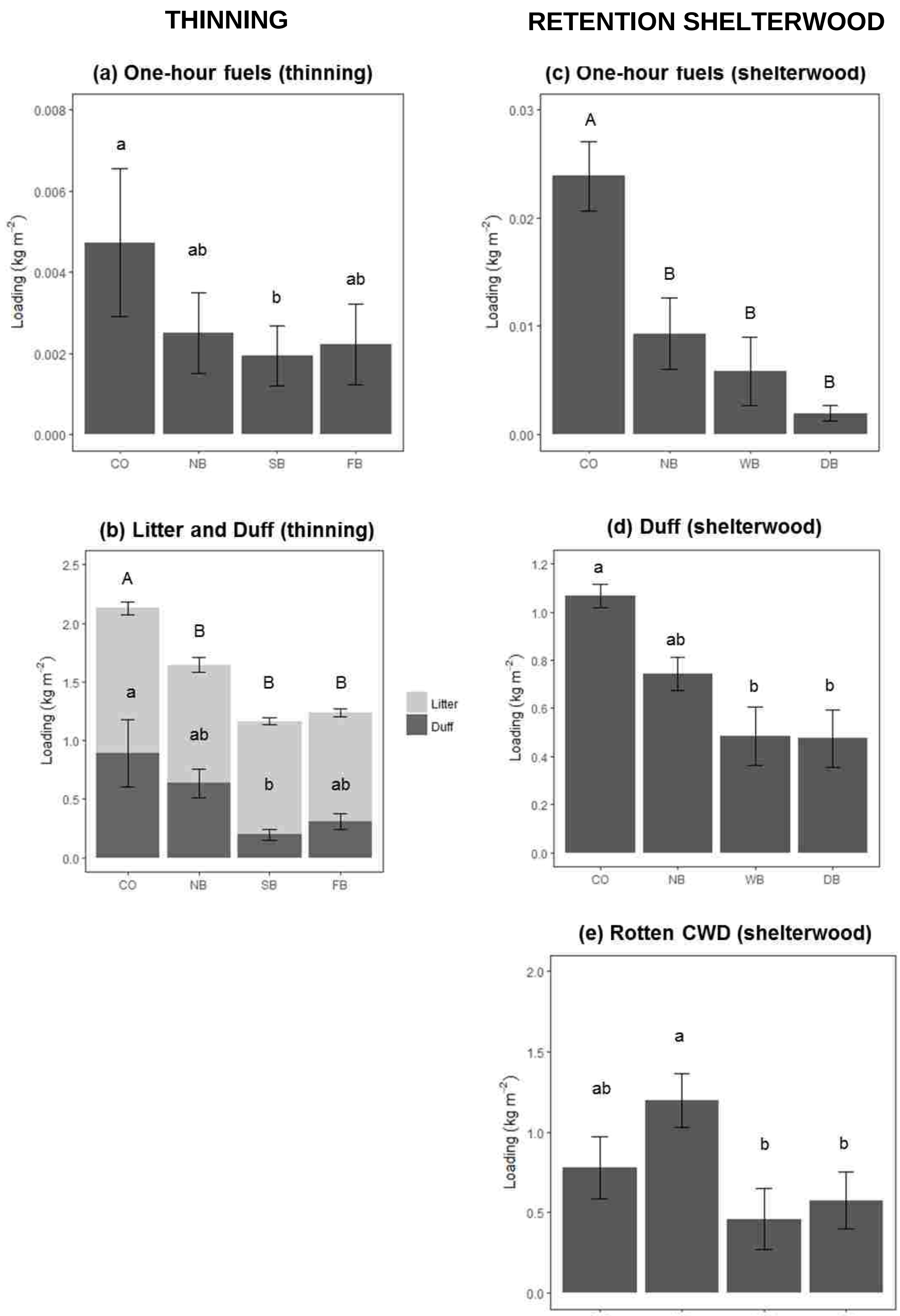

Figure 1.7. Significant surface fuel differences by treatment in 2015 for Thinning one-hour fuels, litter, and duff (a-b) and Retention Shelterwood one-hour fuels, duff, and rotten coarse woody debris (c-e). Bars denote mean fuel loading per particle type per treatment with +/- 1 standard error (n=3). Treatments are Control "CO", No Burn "NB", Cut+Spring Burn "SB" (Thinning only), Cut+Fall Burn "FB" (Thinning only), Cut+Wet Burn "WB" (Shelterwood only), and Cut+Dry Burn "DB" (Shelterwood only). Statistical significance is given for 2015 differences by treatment. Uppercase letters denote significance at α= 0.05 while lowercase letters denote significance at α= 0.10.

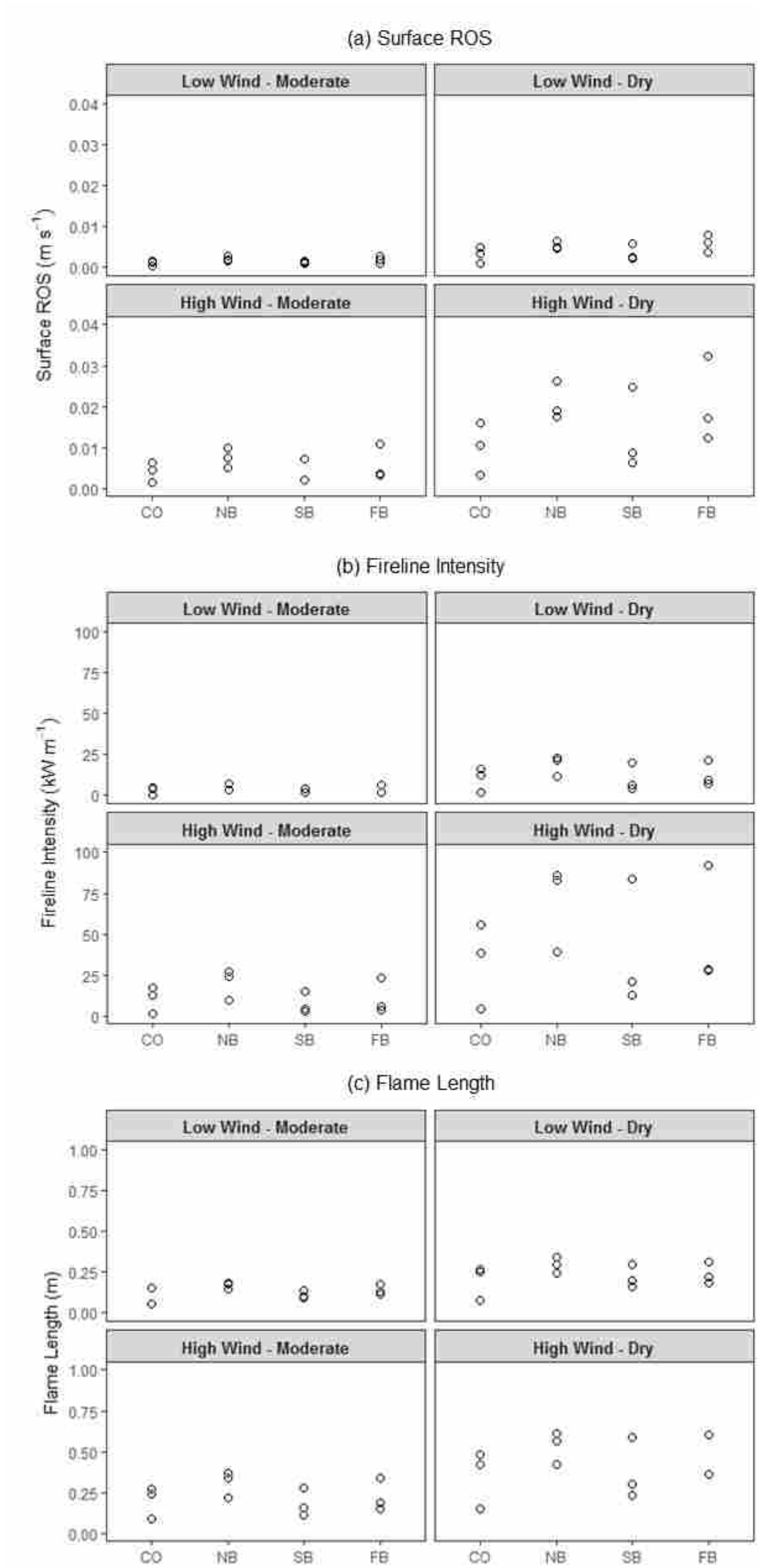

Figure 1.8. Predicted surface fire behavior metrics (surface rate of spread "ROS", fireline intensity, and flame length) by treatment for each wind/moisture scenario in the Thinning installation. Dots represent unit estimates. Treatments are Control "CO", No Burn "NB", Cut+Spring Burn "SB", and Cut+Fall Burn "FB".

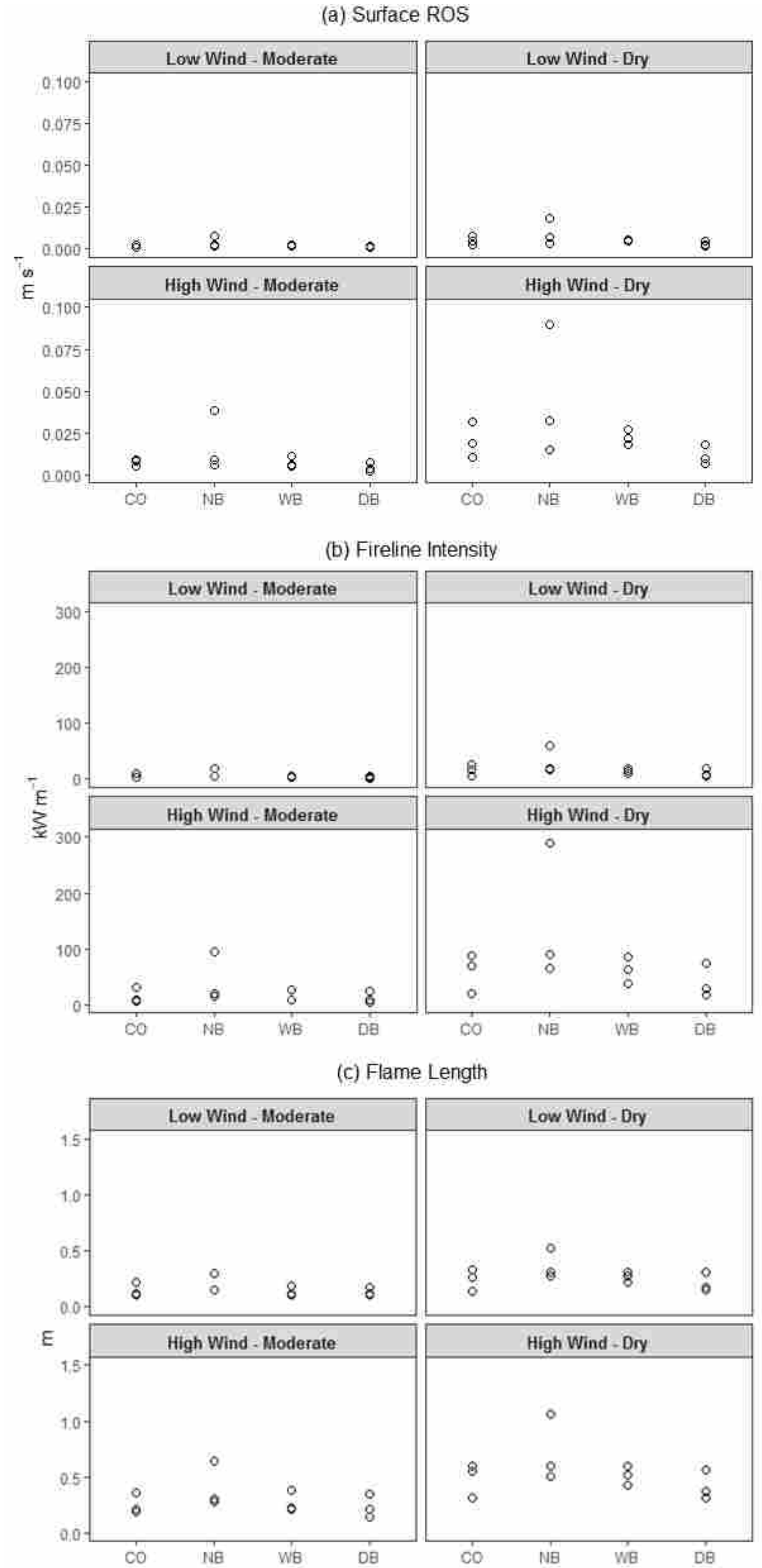

Figure 1.9. Predicted surface fire behavior metrics (surface rate of spread "ROS", fireline intensity, and flame length) by treatment for each wind/moisture scenario in the retention Shelterwood installation. Dots represent unit estimates. Treatments are Control "CO", No Burn "NB", Cut+Wet burn "WB", and Cut+Dry Burn "DB".

			Low-Mod	Low-Dry	High-Mod	High-Dry
THINNING	CONTROL	a	0	0.02	0.2	0.05
			0.1	0.21	0.66	1.34
		b	0.01	0.02	0.02	0.05
			0.01	0.2	0.65	1.32
		c	0	0	0	0
			0.13	0.26	0.82	1.68
	NO BURN	a	0.01	0.02	0.03	0.08
			0.06	0.11	0.36	0.73
		b	0	0.01	0.01	0.04
			0.07	0.15	0.47	0.96
		c	0.01	0.03	0.04	0.13
			0.09	0.18	0.57	1.17
	SPRING BURN	a	0	0.01	0.01	0.03
			0.06	0.12	0.39	0.8
		b	0	0	0	0.01
			0.07	0.15	0.47	1
		c	0	0.02	0.01	0.08
			0.09	0.19	0.6	1.23
	FALL BURN	a	0	0.01	0.01	0.04
			0.07	0.14	0.44	0.89
		b	0	0.01	0	0.02
			0.08	0.16	0.51	1.03
		c	0	0.02	0.01	0.05
			0.08	0.16	0.51	1.04

			Low-Mod	Low-Dry	High-Mod	High-Dry
RETENTION SHELTERWOOD	CONTROL	a	0	0	0	0.01
			0.15	0.3	0.95	1.94
		b	0.04	0.28	0.15	1.16
			0.15	0.31	0.98	2
		c	0.14	0.4	0.47	1.35
			0.14	0.29	0.92	1.88
	NO BURN	a	0.01	0.06	0.05	0.28
			0.08	0.17	0.53	1.08
		b	0.17	0.57	0.71	2.3
			0.24	0.48	1.53	3.12
		c	0.11	0.34	0.55	1.69
			0.38	0.77	2.46	5.02
	WET BURN	a	0	0.01	0.01	0.05
			0.07	0.15	0.47	0.96
		b	0	0.01	0.01	0.03
			0.06	0.12	0.39	0.8
		c	0.21	0.67	0.96	3.04
			0.11	0.23	0.75	1.52
	DRY BURN	a	0	0	0	0.01
			0.07	0.15	0.46	0.94
		b	0.01	0.02	0.02	0.07
			0.05	0.11	0.34	0.69
		c	0.02	0.06	0.08	0.25
			0.17	0.34	1.07	2.19

- SURFACE
- CONDCROWN
- CROWNING

Figure 1.10. Predicted fire type for the thinning (left) and retention shelterwood (right). For each treatment replicate (a-c), transition ratio (uppermost value) and active ratio (lowermost value) are provided for each fuel moisture/wind scenario. Transition ratio (surface fireline intensity/critical surface fireline intensity) is the capacity for crown fire initiation. Active ratio (crown fire rate of spread/critical crown fire rate of spread) is the capacity for maintained crown fire spread. Green represents predicted surface fire ("SURFACE"; transition and active ratios <1.0), yellow represents conditional crowning ("CONDCROWN"; transition ratio < 1.0, active ratio ≥ 1.0), and red represents active crown fire ("CROWNING"; transition and active ratio ≥ 1.0). Scenarios are as follows: "Low-Mod" for low windspeed, moderate fuel moisture; "Low-Dry" for low windspeed, dry fuel moisture; "High-Mod" for high windspeed, moderate fuel moisture; and "High-Dry" for high windspeed, dry fuel moisture.

University of Montana

SECTION 2:

Comparative case study of two methods for quantifying coarse woody debris in a northern Rocky Mountain ponderosa pine/Douglas-fir forest

Katelynn J. Bowen

Chair of the Supervisory Committee:
Christopher Keyes, Research Professor
Department of Forest Management
College of Forestry and Conservation

Abstract

Using 2015 fuel sampling datasets from a northern Rockies ponderosa pine/Douglas-fir stand, we compared two methods for sampling coarse woody debris (CWD) fuel loads: fixed-area plot sampling and planar intersect transect sampling. Both methods are commonly used in research and management but have tradeoffs in execution and accuracy that managers must consider. Our findings indicated that neither method provided a significantly different estimate at the stand level. However, plot-by-plot, fixed-area plot sampling was more likely to capture CWD occurrence; transects estimated zero load on 23-47% of plots. Results of this study will provide forest managers with guidance for measuring coarse woody debris in this forest type.

INTRODUCTION

Fuel reduction treatments are frequently applied in forested ecosystems as a means to mitigate wildfire behavior. Evaluating the impacts and effectiveness of fuel treatments commonly includes monitoring of surface woody debris (Waddell 2002, Brown *et al.* 2003, Strom and Fulé, 2007, Crotteau *et al.* 2016). Of particular interest in many forested ecosystems is coarse woody debris (CWD), or dead and down logs >7.62 cm in diameter (Lutes 1999, Robertson and Bowser 1999). Although photo series are sometimes employed to measure forest fuels, other more intensive fuel sampling protocols are more common (Keane 2015). These include planar intersect transects and fixed-area plot sampling protocols.

Planar intersect transect (PIT) sampling was developed and refined by Brown (1971, 1974) as a two-dimensional modification of Van Wagner's (1968) line intersect sampling for forest fuels, which allowed only for one-dimensional sampling using a probability-proportional-to-size framework. In PIT sampling, woody debris that crosses a vertical plane along a linear transect is measured for diameter and decay class at the point of crossing (Brown 1974). From those intersect recordings, fuel loads are calculated on a mass per unit area basis. Planar intersect transects are adjustable to length and orientation and are generally quick to measure. As such, they have become standard to many forest and fuel monitoring programs for measuring both fine and coarse woody debris as well as other live and dead fuels (Busing *et al.* 1999, Waddell 2002, USDI National Park Service 2003, Woodall 2003, Lutes *et al.* 2006).

While planar intersect transects are easily taught and learned, they have some disadvantages. If transect orientation is not adjusted throughout a stand, PIT sampling may produce biased estimates of CWD load if fuels are similarly oriented or evenly distributed (Van Wagner 1968, Brown 1971). Additionally, stands with highly variable CWD loads may require very large sample sizes or transect lengths to attain accurate estimates (Woldendorp *et al.* 2004, Keane 2015). However, the PIT sampling technique is adaptable to both management and research requirements and can incorporate metrics of other fuel components.

Fixed area plot (FAP) sampling is an equal probability sampling technique that uses a fixed sample area to estimate CWD. Fuel can be removed for weighing in the lab or fuel dimensions can be measured on site (and loads later calculated from log volume and wood density). The FAP method may capture site variability more accurately than the PI method (Woldendorp *et al.* 2004) depending on plot size, size class of woody debris, and distribution of fuels (Sikkink and Keane 2008, Keane 2015), but FAP plots are time-intensive and are not always practical for resource-limited monitoring programs. For CWD, FAP sampling may require plots as large as 0.04-ha (Keane 2015).

In this study, we aimed to compare planar intersect transect and fixed-area plot sampling methods for quantifying CWD. Our sampling location was an established monitoring network from a 23-yr old forest restoration and hazardous fuels treatment experiment at the Lick Creek Demonstration/Research Area (Bitterroot National Forest, Montana, USA). First, we aimed to determine if there was a stand-level difference in estimated coarse woody debris load between FAP sampling and PI transects. Second, we wanted to assess how these methods compare at the plot level. Fuels are intrinsically variable in distribution and abundance; at a plot-by-plot level, either sampling method may produce significantly different results. Greater sampling intensity as a rule should reduce error, but sampling costs are always a concern; balancing these two factors is key. The study's findings will help fire and fuels managers evaluate the tradeoffs associated with these sampling methods, and choose the method most informative for their project.

METHODS

Study Site

We sampled coarse woody debris at the Lick Creek Demonstration/Research Forest (Lick Creek), part of the Bitterroot National Forest in southwestern Montana (46°5'N, 114°15'W). Lick Creek is predominantly on 10-30% south-facing slopes at an elevation of 1300 to 1500 meters AMSL (Gruell *et al.*, 1982). This study occurred in two mixed stands of ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson var. *ponderosa* C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.)). Other tree species present include grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt. var. *lasiocarpa*), and lodgepole pine (*Pinus contorta* Douglas ex Loudon var. *latifolia* Engelm. ex S. Watson). On the upper slopes, the habitat types (Pfister *et al.* 1977) are *Pseudotsuga menziesii/Calamagrostis rubescens* h.t. *Pinus ponderosa* (Douglas-fir/pinegrass h.t. ponderosa pine) phase and *Pseudotsuga menziesii/Symphoricarpos albos* h.t. *Calamagrostics rubescens* (Douglas-fir/snowberry h.t., pinegrass) (Gruell *et al.*, 1982). On the lower slopes, the habitat types are *Pseudotsuga menziesii/Vaccinium caespitosum* (Douglas-fir/dwarf huckleberry) and *Pseudotsuga menziesii/Vaccinium globulare* h.t. *Arctostaphylos uva-ursi* (Douglas-fir/blue huckleberry h.t., kinnikinnick) phase (Gruell *et al.* 1982).

The sites selected for this study included the treated and control units of a 1992 long-term fuels reduction experiment that tested combinations of restoration-focused cutting and burning strategies (Carlson *et al.* 1994, Carlson and Floch 1996; Smith and Arno 1999). They were selected to represent stands of this common cover type, and for the diverse range of fuel loads that they contain in one compact space. One site had been treated with a thinning, followed by broadcast burn and no-burn treatments; the second site had been treated with a retention shelterwood cutting, followed by similar broadcast burn and no-burn treatments. No management had been conducted at either site since 1994. We emphasize that the purpose of this study was simply to utilize this study area to compare sampling methods within these known contexts, and not compare sampling methods among specific treatments within this set.

Data Collection & Analysis

Each of the two sites contained a network of 0.04-ha fixed-area circular plots across 12 stands, with 6 plots per stand, yielding 144 plots. In the fall of 2014, a natural-ignition wildfire burned approximately 0.5 ha of the shelterwood site, eliminating 2 plots from one stand and reducing the sample size to 142.

Measurements were conducted in the summer of 2015. At each plot, we remeasured the original (established 1993) planar intersect transect (Brown 1974). Transects originated at plot center and extended 15.24 m, alternating either upslope or side-hill in orientation. To test if doubling sampling intensity affected CWD estimate, we added a second 15.24 m planar intersect transect 90 degrees clockwise from the original (producing two estimates of load per plot: one estimate using just the first transect and a second estimate based on the average of both transects). Data from the planar intersect transects were compiled using the FEAT/Firemon Integrated (FFI) software program (Lutes *et al.* 2006), which uses Brown's (1974) and Brown *et al.*'s (1982) formulas to calculate loads.

Using the original 0.04-ha circular fixed-area plots from the preexisting study, we also measured the total log volume per plot. For every log >7.62 cm in diameter within the plot area, we measured small-end diameter, large-end diameter, and log length and recorded whether the log was sound or rotten. Only the portion of the log occurring within the plot boundary was measured. The log measurements were used to calculate coarse woody debris volume (m^3) at the plot level using Smalian's formula (Avery and Burkhart, 2002):

$$Cubic\ volume: \frac{(B + b)}{2} L$$

Where *B* and *b* are the cross-sectional areas of the log at the large and small ends, respectively, and *L* is the log length.

Each log's volume was adjusted for density based on its soundness using Brown's (1974) density values. The sum of log load per plot was expressed on a per unit area basis.

Coarse woody debris loads were compiled across each of the 24 stands. We used analysis of variance (ANOVA) to test for differences in CWD load estimates between the three sampling methods at the stand level (α=0.05). Because the stand-level estimates were right-skewed in all sampling methods, we log-transformed the data for the ANOVA test to satisfy normality. Next, we wanted to determine how the estimates compared on a plot level. Using the plot mean CWD load from the FAP sampling method as the predictor variable, we applied separate simple linear regression models to compare plot-level CWD estimates from both one and two PI transects per plot. As the most thorough sampling method, we used FAP as the reference fuel load but did not test if it was the true estimate at the unit level. Finally, we compared the predicted values of these two models against the FAP estimates to determine how well the models predicted CWD load.

Normality was assessed with quantile-quantile plots and histograms of the residuals. All tests were conducted using the R software program (R Core Team, 2016).

RESULTS & DISCUSSION

Using one planar intersect transect produced the lowest overall estimate with FAP and two PIT producing nearly equal means and standard errors. The overall estimate of CWD load from our model was 0.645 ± 0.104 kg m^{-2} for fixed-area sampling, 0.581± 0.093 kg m^{-2} using one planar intersect transect per plot, and 0.653 ± 0.105 kg m^{-2} using two planar intersect transects per plot. CWD estimates were similarly distributed among measurement methods (Figures 2.1 and 2.2). We found no evidence ($F_{2, 69}$ = 0.161, p = 0.852) of a difference in CWD load estimates between the three methods at the stand level. Indeed, side-by-side comparisons of each method by stand demonstrated a lack of patterns or bias but there were some cases where either one or two transects estimated much higher loading (Figure 2.3). Across all stands, there was a great deal of overlap between each method's estimates, indicating that at the stand level and a 6-plot average, the three methods produced equivalent results.

At the plot level, we generated two simple linear regression models to predict CWD load from the PIT sampling estimates, using the FAP estimate as the predictor variable. The models for CWD estimated from one PIT (1) and two PIT (2) are:

$$CWD = 0.541 + 0.275 * PIT \qquad (1)$$

$$CWD = 0.485 + 0.329 * PIT \qquad (2)$$

Compared to fixed-area plot sampling at the plot level, planar intersect transects only captured 33.8% (model 1) and 34.2% (model 2) of the variability in CWD load. At low CWD load, PIT sampling tended to over-predict load, whereas at high loads, PIT sampling under-predicted (Figure 2.4).

Assuming FAP sampling provides the most accurate CWD estimate, PIT was a poor predictor of CWD load on a plot-by-plot basis. Every FAP captured at least some CWD (range: 0.039-5.561 kg m^{-2}) but out of 142 plots, 47% of plots measured with one PIT and 23% measured with two PIT estimated zero load (range: 0-15.640 kg m^{-2} using one transect and 0-13.049 kg m^{-2} using two transects). If only one plot was to be measured in a stand, our results indicate there is a strong chance of not only incorrectly estimating CWD load but estimating zero load.

In general, our CWD fuel loads were low for a northern Rocky Mountain ponderosa pine/Douglas-fir forest. Baker's (2009) text, *Fire Ecology in Rocky Mountain Landscapes*, reports 2.34 kg m^{-2} (10.44 ton ac^{-1}) of CWD (of which 30% is rotten wood) in a typical Interior ponderosa pine/Douglas forest, which is 358-403% greater than our observed estimates. This value is based on early Fuel Characteristics Classification System (FCCS) fuelbed loadings. The most recent FCCS estimates are 1.93 kg m^{-2} (8.6 ton ac^{-1}) of CWD (also 30% rotten wood), which is 296-332% greater than our observed estimates (Ottmar *et al.* 2007). That implies our results may be applicable for stands of this forest type that have been subjected to fuel reduction treatments, but may not apply to unmanaged stands of the same forest type.

Accurate CWD inventorying is critical to monitor wildlife habitat, soil health, and fuel treatment effectiveness (Bull *et al.* 1997, Busing *et al.* 2000, Waddell 2002, Keane 2015). While not typically a driver of surface fire behavior modelling (Anderson 1969), CWD is nevertheless an important component of fire severity: larger logs smolder longer, leading to greater soil heating and higher severity (Albini and Reinhardt 1995). Therefore, having a good understanding of the advantages of CWD measurement techniques is important for managers and researchers alike. Our goal with this study was to determine if there was a stand-level difference in estimated CWD load between FAP and PIT sampling and which method, given limited resources, should be used to generate an accurate estimate. Based on our study, we conclude that each sampling technique produces similar results at the stand level, but that FAP sampling is more likely to capture the more rare occurrences of CWD. At any given plot, PIT sampling may over- or underestimate CWD. Additionally, doubling the number of transects per plot does not seem to avoid any sampling bias at either low or high CWD load.

REFERENCES

Albini, F.A., and E.D. Reinhardt. 1995. Modeling ignition and burning rate of large woody natural fuels. International Journal of Wildland Fire 5(2): 81-91.

Anderson, H.E. 1969. Heat transfer and fire spread. USDA Forest Service Research Paper INT-RP-69, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Avery, T.E., and H.E. Burkhart. 2002. Forest measurements. Fifth edition. McGraw-Hill, New York, New York, USA.

Baker, W.L. 2009. Fire ecology in rocky mountain landscapes. Island Press, Washington, D.C., USA.

Brown, J.K. 1971. A planar intersect method for sampling fuel volume and surface area. Forest Science (17)1: 96-102.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service Technical Report INT-GTR-16, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Brown, J.K., R.D. Oberheu, and C.M. Johnston. 1982. Handbook for inventorying surface fuels and biomass in the interior west. USDA Forest Service General Technical Report INT-GTR-129, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Bull, E.L, C.G. Parks, and T.R. Torgerson. 1997. Trees and logs important to wildlife habitat in the Interior Columbia River Basin. USDA Forest Service General Technical Report PNW-GTR-391, Pacific Northwest Research Station, Portland, Oregon, USA.

Busing R., K. Rimar, K.W. Stolte, T.J. Stohlgren, and K. Waddell. 2000. Forest health monitoring: vegetation pilot field methods guide. Vegetation diversity and structure down woody debris fuel loading. USDA Forest Service, National Forest Health Monitoring Program, Washington, D.C., USA.

Carlson, C.E., R.F. Floch, and C. Fiedler. 1994. Research and demonstration of ecosystem management principles in ponderosa pine/Douglas-fir forests: Lick Creek, Bitterroot National Forest. Pages 201-206 in: Foley, L., compiler. Proceedings – silviculture: from the cradle of forestry to ecosystem management. National Silviculture Workshop, Hendersonville, NC; November 1-4, 1993. USDA Forest Service General Technical Report SE-GTR-88, Southeastern Forest Experiment Station, Asheville, North Carolina, USA.

Carlson, C.E., and R.F. Flock. 1996. Lick Creek ecosystem management/research demonstration area. Pages 81-86 in: Schmidt, W.C., and J.L. Friede, compilers. Experimental forests, ranges, and watersheds in the northern rocky mountains: a compendium of outdoor laboratories in Utah, Idaho, and Montana. USDA Forest Service General Technical Report INT-GTR-334, Intermountain Research Station, Ogden, Utah, USA.

Crotteau, J.S., C.R. Keyes, E.K. Sutherland, D.K. Wright, and J.M. Egan. 2016. Forest fuels and potential fire behaviour 12 years after variable-harvest in lodgepole pine. International Journal of Wildland Fire 25: 633-345.

Gruell, G.E., C.S. Wyman, S.F. Arno, and W.J. Reich. 1982. Seventy years of vegetative change in a managed ponderosa pine forest in western Montana - implications for resource management. USDA Forest Service General Technical Report INT-GTR-130, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Keane, R.E. 2015. Wildland fuel fundamentals and applications. Springer, New York, New York, USA.

Lutes, D.C. 1999. Comparison of methods for the quantification of coarse woody debris and identification of its spatial scale: a study from the Tenderfoot Creek Experimental Forest, Montana. M.S. Thesis, University of Montana, Missoula, USA.

Lutes, D.C., R.E. Keane, J.F. Caratti, C.H. Key, N.C. Benson, S. Sutherland, and L.J. Gangi. 2006. FIREMON: fire effects monitoring and inventory system. USDA Forest Service General Technical Report RMRS-GTR-164CD, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Ottmar, R.D., D.V. Sandberg, C.L. Riccardi, and S.J. Prichard. 2007. An overview of the Fuel Characteristic Classification System – quantifying, classifying and creating fuelbeds for resource planning. Canadian Journal of Forest Research 37: 2383-2393.

Pfister, R.D., B.L. Kovalchik, S.F. Arno, and R.C. Presby, editors. 1977. Forest habitat types of Montana. USDA Forest Service General Technical Report INT-GTR-34. Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

Robertson, P.A., and Y.H. Bowser. 1999. Coarse woody debris in mature *Pinus ponderosa* stands in Colorado. Journal of the Torrey Botanical Society 126(3): 225-267.

Sikkink, P.G., and R.E. Keane. 2008. A comparison of five sampling techniques to estimate surface fuel loading in montane forests. International Journal of Wildland Fire 17: 363-379.

Smith, H.Y., and S.F. Arno, editors. 1999. Eighty-eight years of change in a managed ponderosa pine forest. USDA Forest Service General Technical Report RMRS-GTR-23, Rocky Mountain Research Station, Ogden, Utah, USA.

Strom, B.A., and P.Z. Fulé. 2007. Pre-wildfire treatments affect long-term ponderosa pine forest dynamics. International Journal of Wildland Fire 16: 128-138.

USDI National Park Service. 2003. Fire monitoring handbook. National Interagency Fire Center, Fire Management Program Center, Boise, Idaho, USA.

Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. Forest Science 14(1): 20-26.

Waddell, K.L. 2002. Sampling coarse woody debris for multiple attributes in extensive resource inventories. Ecological Indicators 1: 139-153.

Woodall, C.W. 2003. The national inventory of down woody materials: methods, outputs, and future directions. Pages 87-91 in: Proceedings of the Society of American Foresters 2002 National Convention, Winston-Salem, North Carolina; October 5-9, 2002. Society of American Foresters Publication 03-01, Bethesda, Maryland, USA.

Woldendorp, G., R.J. Keenan, S. Barry, and R.D. Spencer. 2004. Analysis of sampling methods for coarse woody debris. Forest Ecology and Management 198: 133-148.

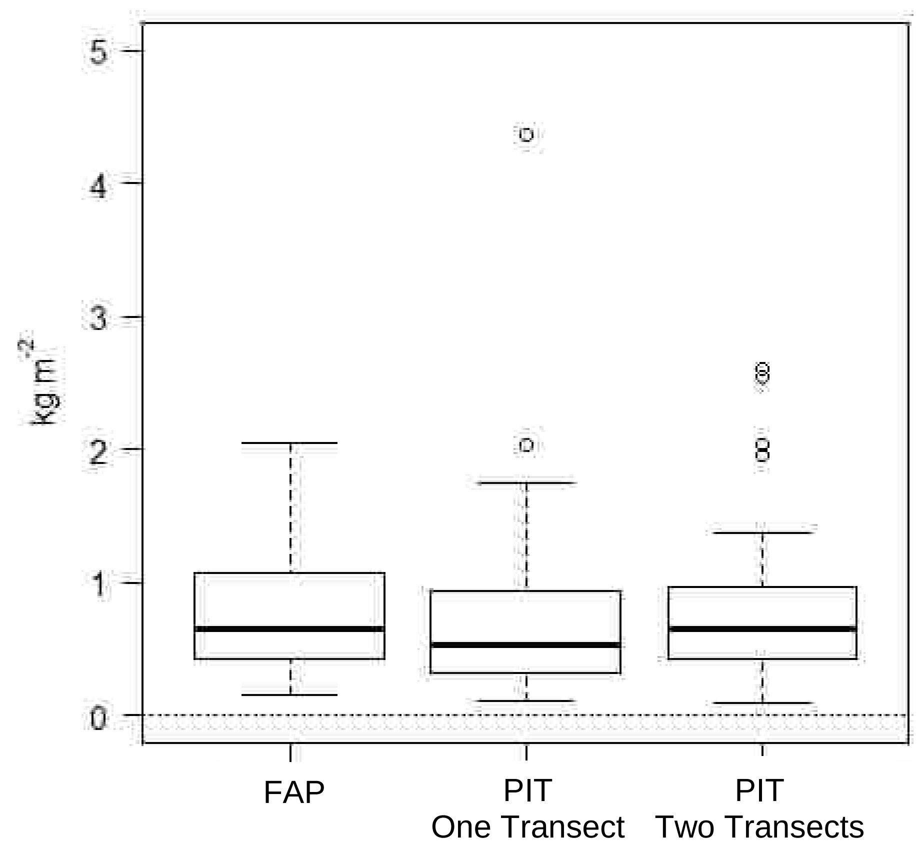

Figure 2.1. Stand-level (n=24) coarse woody debris load (kg m^{-2}) distribution by method. Methods included fixed-area plot ("FAP") sampling, a single planar intersect transect per plot ("PIT – One Transect"), and two planar intersect transects per plot ("PIT – Two Transects").

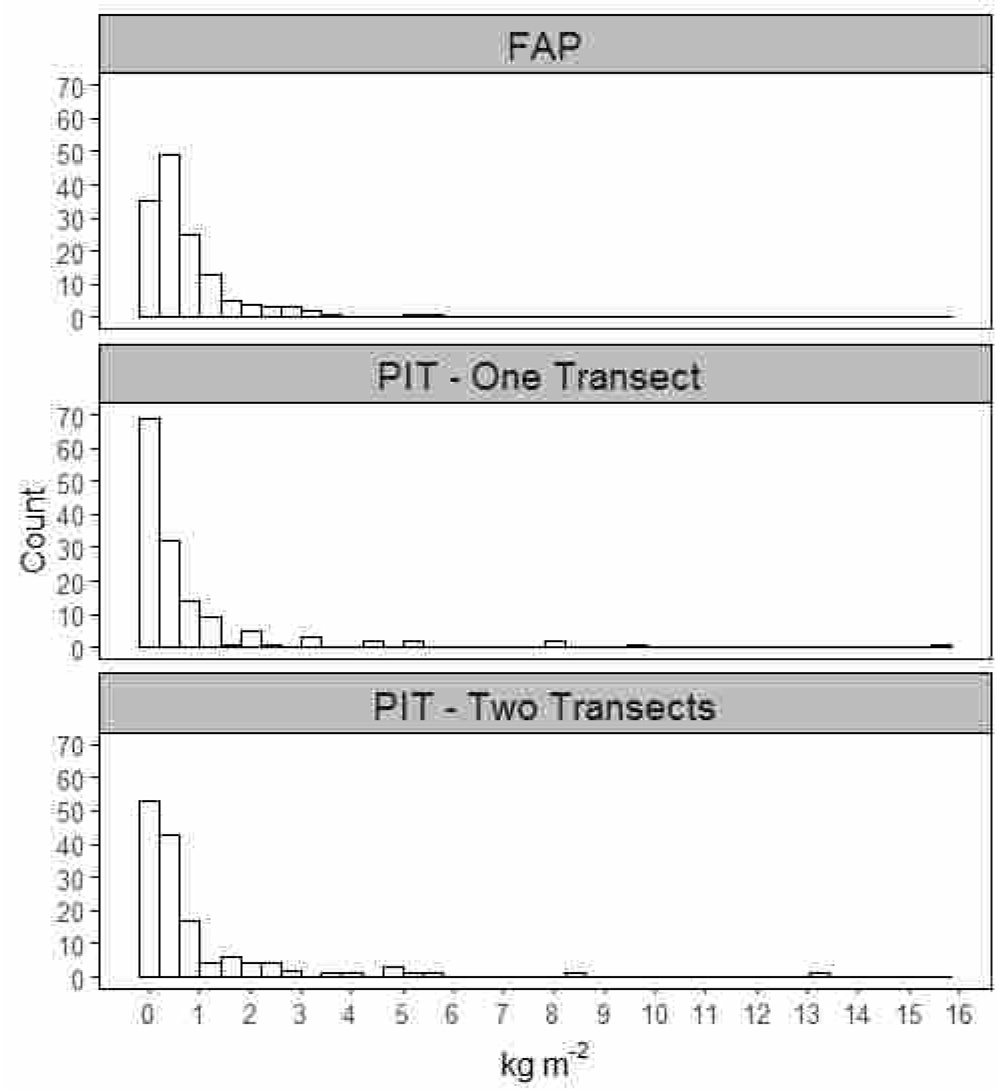

Figure 2.2. Distribution of plot-level (n=142) coarse woody debris estimates by the three compared methods: fixed area plot sampling (FAP), one planar intersect (PIT) (“PIT – One Transect”), and two PIT (“PIT – Two Transects”). Note: at the plot-level, the lowest FAP estimate was 0.039 kg m^{-2}, whereas 61 plots estimated zero load using one PIT, and 33 plots estimated zero load using two PIT.

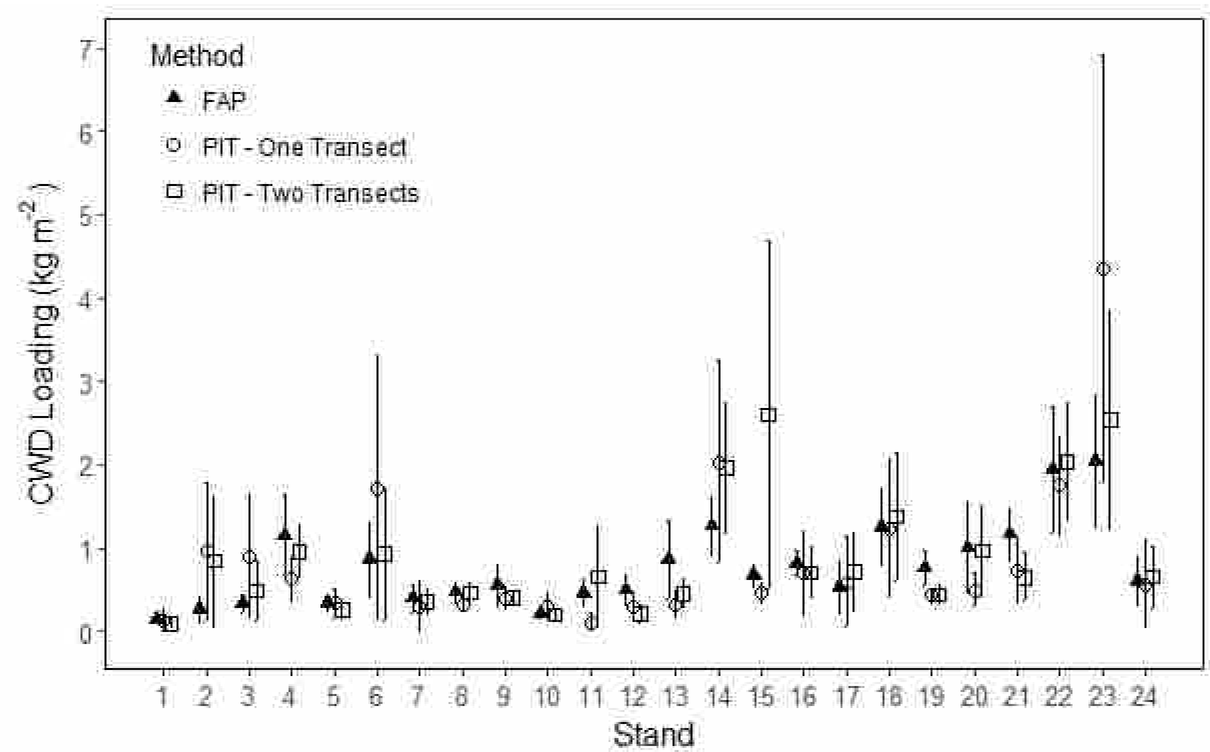

Figure 2.3. Comparison of mean and standard error at each stand by method. Methods included fixed-area plot ("FAP") sampling, a single planar intersect transect per plot ("PIT – One Transect"), and two planar intersect transects per plot ("PIT – Two Transects").

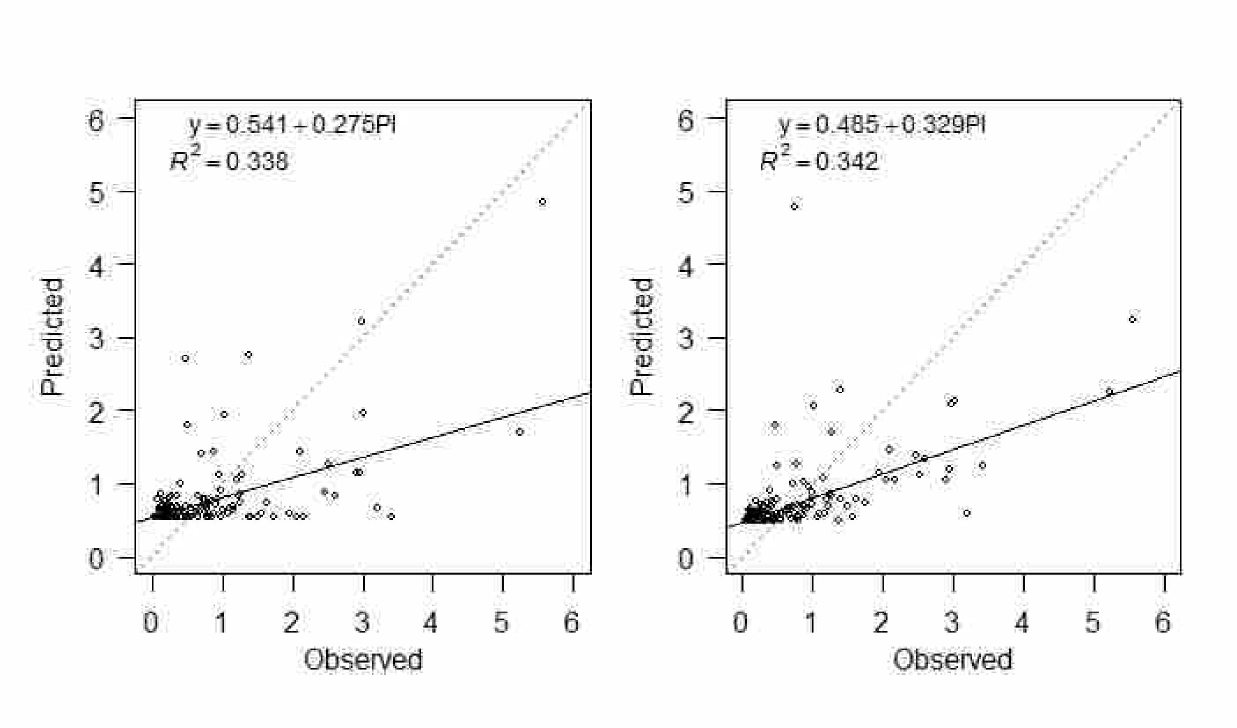

Figure 2.4. Predicted versus observed plot-level estimates of CWD (kg m^{-2}) for planar intersect transects (PIT) against fixed-area plot (FAP) sampling for one PIT (left) and two PIT (right), with 1:1 line (dotted gray) and linear model line (black). At low levels of coarse woody debris load (as estimated by FAP), transects over-predict load but at high levels of CWD, transects under-predict load.