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Mechanical thinning without prescribed fire moderates wildfire behavior in an Eastern Oregon, USA ponderosa pine forest

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ABSTRACT

Reducing fuels to better manage risk of high severity wildfire in seasonally dry, fire-prone forests of the western U.S. is an important goal of forest managers, including private landowners, non-governmental organizations, tribal, state, and local governments, and federal agencies. Managing fire risk is a critical objective of the U.S. Forest Service, which emphasizes the use of thinning to reduce tree density and ladder fuels followed by prescribed fire to reduce surface fuel. But the area of Forest Service land treated with thinning and prescribed fire is lagging far behind the area treated only with mechanical thinning due to regulatory and logistical challenges in prescribed fire implementation. Determining if mechanical thinning alone (without prescribed fire) can achieve adequate fire risk reduction has important implications for addressing the fire and fuel management goals set by Congress and the Administration, as well as the management objectives set by non-federal actors. In this study, we report on the effects of mechanical thinning and standard post-thinning fuels management but without prescribed fire on modeled fire behavior and changes in fuel loading over time in a ponderosa pine forest in Eastern Oregon. Thinning without prescribed fire significantly reduced potential crown fire immediately following thinning and also moderated surface modeled fire behavior beginning 2–3 years following thinning. Although small (<7.6 cm diameter) woody surface fuel loading increased following thinning, other ground and surface fuels (i.e., litter and duff) declined substantially, which we attribute to surface disturbance from ground-based logging, decreased deposition of litter, and increased decomposition. These results suggest that fuel reduction and fire risk management objectives can be met with mechanical thinning alone for a number of years. Prescribed fire is likely necessary to extend the effectiveness of mechanical thinning after significant tree or shrub regeneration. Continued monitoring will allow managers to use prescribed fire most efficiently to achieve fire and fuel management objectives.

1. Introduction

The natural fire regime of seasonally dry forests across western North America was historically characterized by frequent, low intensity surface fire that maintained open stands of older trees (Hagmann et al., 2021; Heyerdahl et al., 2001). Beginning in the late 1800s, logging that removed old fire-resistant trees, unregulated grazing that removed herbaceous fuel, and organized fire suppression and exclusion have resulted in significantly increased tree density, fuel continuity, and surface fuel loading (Abella et al., 2007; Hessburg and Agee, 2003). These changes to dry forests, along with a warming climate, have resulted in increasingly large, fast-moving fires with stand replacing fire effects that have significant negative impacts to old-growth habitat, water quality, and human infrastructure (e.g., Jones et al., 2019; Sankey et al., 2017; Williams, 2013). A variety of actors, including non-governmental organizations, tribal governments, state and local governments, and private landowners are adapting to climate change by reducing fuels across the seasonally dry forests that they manage (Charnley et al., 2017). The federal government is making significant investments in thinning to reduce fuels across lands managed by the U.S.

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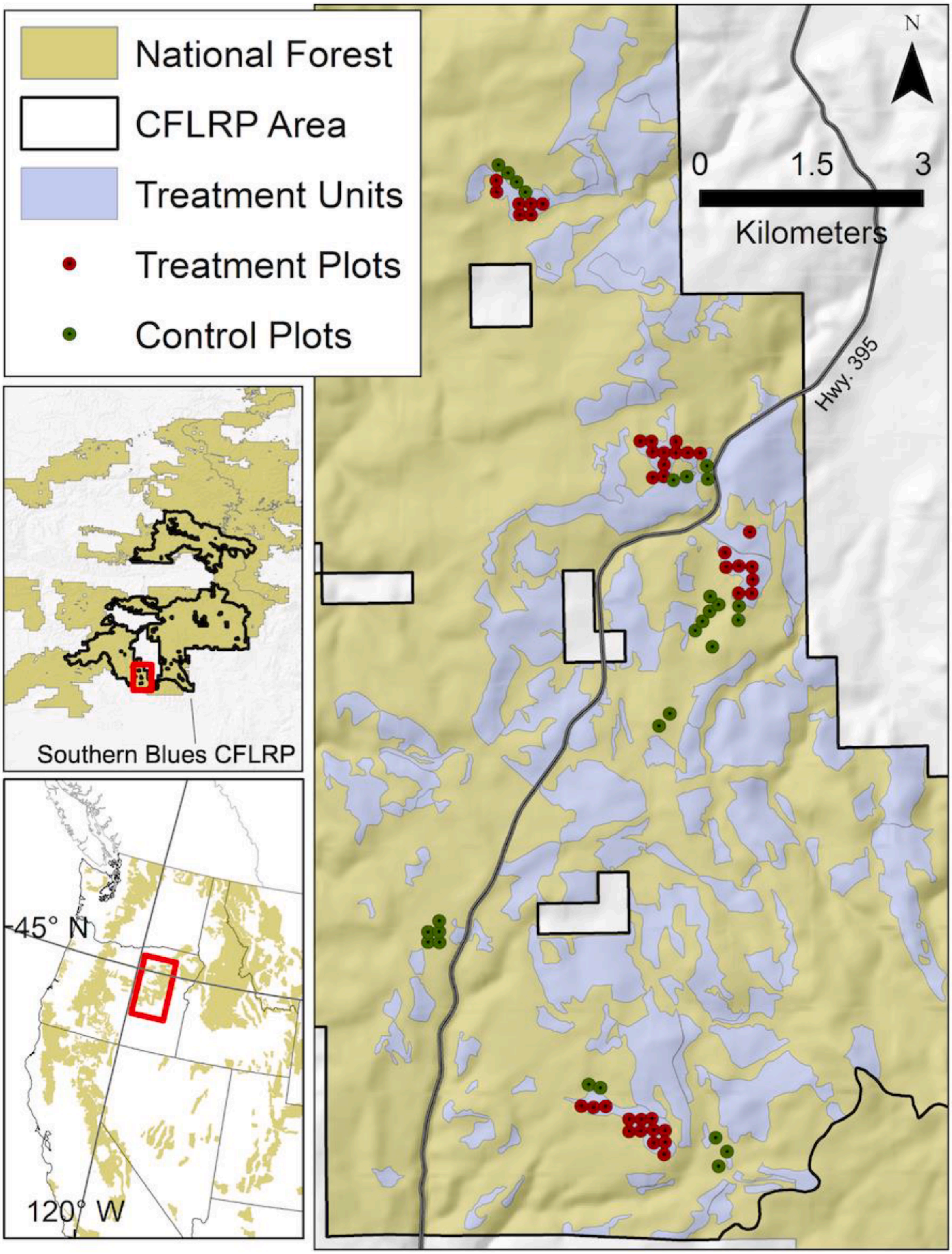

Fig. 1. The Marshall Devine planning area (right panel) in the southern Blue Mountains (middle left panel) in Eastern Oregon (bottom left panel). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Forest Service (USFS), which manages the majority of seasonally dry forests in the western U.S. (Chapin et al., 2021; Prichard et al., 2021; Stephens et al., 2020).

Evaluating the effectiveness of fuel reduction treatments is important for targeting future investments and designing treatments in an adaptive management framework (Stephens and Ruth, 2005). A large number of studies have evaluated the influence of fuel reduction thinning on fire behavior in seasonally dry forests of the western U.S. Past research has drawn conclusions about the effects of thinning by statistical analyses of forest structural and compositional elements known to influence fire (e.g., Knapp et al., 2017), modeling of fire behavior in thinned stands (e.g., Parsons et al., 2018), or by evaluating effects of wildfire that burned thinned stands (e.g., Lydersen et al., 2017). Results from individual studies, as well as metanalyses and syntheses (e.g., Willms et al., 2017; Kalies and Yocom Kent, 2016; Martinson and Omi, 2013; Fulé et al., 2012; Stephens et al., 2009) demonstrate that mechanical thinning followed by prescribed fire is generally effective at moderating wildfire severity. A few studies (e.g., Cram et al., 2015) report little difference in fire effects across a variety of treatments including thinning only and thinning followed by prescribed fire. But the majority of published studies suggest thinning that is not followed by prescribed fire is less effective at moderating fire severity than thinning combined with prescribed fire (e.g., Prichard and Kennedy, 2012; Schwilk et al., 2009). Some studies suggest that thinning without prescribed fire can increase wildfire severity by adding fine fuels to the forest floor (e.g., Raymond and Peterson, 2005).

One of the most extensive studies of fuel management was the U.S. national Fire and Fire Surrogate study (FFS). The FFS involved a total of twelve treatment sites, seven located in western U.S. states and five located in eastern states. At each site, treatments were designed to thin stands so that 80% of the residual dominant and co-dominant trees would survive a wildfire under 80th-percentile fire weather conditions. Three different treatments—included mechanical thinning only, prescribed fire only, and mechanical thinning plus prescribed fire—were replicated within at least three randomly assigned treatment units that measured at least 15 ha in size. The overarching goal of the FFS study was to evaluate the effectiveness and ecological consequences of commonly used fuel reduction treatments (McIver et al., 2013). Results across these twelve diverse study sites were somewhat mixed. One study that summarized results of treatments across sites found that the mechanical thinning plus fire treatment was best suited for the creation of stands with fewer and larger trees, reduced surface fuel mass, and greater herbaceous species richness, but that the mechanical thinning plus fire treatment sometimes resulted in invasion of sites by invasive species (Schwilk et al., 2009). Another comprehensive summary of FFS results suggested that all treatments were relatively effective at moderating modeled fire behavior (Stephens et al., 2009).

Congress has taken several steps to increase the pace and scale of fuel reduction thinning treatments on lands managed by the USFS across the western U.S. The Healthy Forest Restoration Act passed by Congress in 2003 streamlined planning processes (Pub. L. 108–148; Radmall, 2004). In 2009, Congress authorized the Collaborative Forest Landscape Restoration Program (CFLRP), which provides augmented funding for thinning to reduce fuels and restore forest resiliency to high priority national forest landscapes managed by the USFS (CFLRP; Pub. L. 111–11; Butler et al., 2015). Although the area of western U.S. national forest land treated by mechanical thinning has increased in recent decades, prescribed fire applied to national forests has remained flat over the last 20 years due to shortfalls in agency capacity, regulatory constraints on smoke production, and risk-averse agency culture (Kolden, 2019; Engebretson et al., 2016; Quinn-Davidson and Varner, 2012). If both thinning and prescribed fire are necessary to moderate future wildfire behavior, it may be difficult if not impossible for fuel treatments to influence fire behavior at the landscape scales envisioned by Congress (Vaillant and Reinhardt, 2017; North et al., 2015; North et al., 2012).

In this paper, we report results from long-term monitoring of a typical dry forest fuel reduction project on USFS lands in the southern Blue Mountains of Eastern Oregon. The southern Blue Mountains is one of 23 high-priority CFLRP areas that receives augmented funding from Congress to accelerate the pace and scale of forest restoration. Between 2012 and 2020, over $17 million has been invested to mechanically thin ~87,000 ha across the 220,000 ha CFLRP area. Less than one-fifth of the area treated with mechanical thinning in the southern Blues has also been treated with prescribed fire. Treating mechanically thinned areas with prescribed fire has been significantly slowed by budget constraints, regulatory restrictions on smoke production, local opposition to fire use, and restrictions on burning imposed by COVID-19 response measures (Zhou et al., 2021; Engebretson et al., 2016; Quinn-Davidson and Varner, 2012).

The objective of this study was to determine if mechanical thinning without a followup prescribed fire treatment moderated modeled wildfire behavior. Like most stands that have been thinned in the southern Blue Mountains, the thinned stands we studied had experienced post-thinning fuel treatments that are typical of forest restoration activities, including hand or machine piling of activity fuels and burning of piles. But follow-up prescribed fire that is planned to occur across treated stands had not yet been applied at the time of this writing. To determine if typical thinning treatments in the absence of prescribed fire were still effective at moderating fire, we used a well-tested fire behavior model to simulate wildfire effects in these stands under different weather and fuel moisture scenarios. Ground and surface fuel loadings play a critical role in wildfire behavior in ponderosa pine forests (Keane, 2013), and so we also created statistical models of changes in individual ground and surface fuel components (hereafter surface fuels for simplicity) in thinned stands in order to better understand drivers of modeled changes in fire behavior.

2. Methods

2.1. Study area

We collected and analyzed data from the Marshall Devine planning area, the first fuel reduction thinning project completed in the southern Blue Mountains using CFLRP funds (Fig. 1). The 13,841 ha Marshall Devine planning area is one of 28 different planning areas within the southern Blues CFLRP area where thinning activities are analyzed in environmental assessments or environmental impact statements prepared pursuant to the National Environmental Policy Act (NEPA). The Marshall Devine planning area is located on the northern edge of the Great Basin and climate is semi-arid continental. Thirty-year average precipitation was 612 mm, 80% of which fell between November and May, mostly as snow. December and January are the coldest months with an average temperature of −3.3°C. The hottest months are July and August, with an average temperature of 17.4° C (PRISM, 2020). Lightning ignitions associated with summer convective storms are common (Rorig and Ferguson, 1999). Before the adoption of fire exclusion policies in the late 1800s, mean fire return intervals within the Marshall Devine planning area were approximately 11 years (Johnston et al., 2017).

The Marshall Devine planning area is characterized by gently rolling hills. Elevations range from 1,433 to 2,012 m. The area is dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) with scattered western juniper (*Juniperus occidentalis* Hook.) in the understory. Common understory shrubs include mountain mahogany (*Cercocarpus ledifolius*), bitterbrush (*Purshia tridentata*), sagebrush (*Artemisia tridentata*), and snowberry (*Symphoricarpos albus*), along with dozens of species of native perennial grasses and forbs. The entire area was heavily logged as part of the Bear Valley Timber Sale, which removed >2x10^6 m^3 of old-growth ponderosa pine timber between 1928 and 1968 (Cox, 2010; Langston, 1995). USFS records indicate limited cutting occurred between 1983 and 1997 in many of the stands we studied (USDA, 2012).

As a result of fire exclusion and past logging that primarily targeted older trees, prior to thinning most forested stands in the Marshall Devine planning area were characterized by dense stands of 90- to 130-year-old ponderosa pine, with scattered older (>250 year old) trees. Before thinning, stand basal area ranged from 35 to 46 m^2 ha^{-1}. Mechanical thinning treatments completed between late summer of 2014 and spring of 2015 removed 85,000 m^3 of sawlogs across 2,900 ha. In all stands we studied, trees up to 53 cm diameter at breast height (DBH) were removed until residual stand basal area was reduced to between 11.5 and 16 m^2 ha^{-1} (USDA, 2012). Thinning was accomplished using cut to length or whole tree yarding systems. Trees smaller than commercial size were removed by hand crews following commercial thinning. Some non-commercial material was removed and sold for fuel. As in the case

Table 1
Number of Forest Vegetation and Fuels (FVF) plots measured from 2014 to 2019 in ponderosa pine forests in the Marshall Devine planning area.

Stand ID	Treatment	2014	2015	2016	2017	2018	2019
MDE006	Thin	8	7	7	7	7	8
MDE018	Thin	11	11	11	11	11	11
MDE049	Thin	7	7	7	7	7	7
MDE094	Thin	13	–	13	–	13	13
MDE992	Control	–	–	–	–	4	–
MDE993	Control	–	–	–	–	2	–
MDE994	Control	–	–	–	–	3	–
MDE995	Control	5	–	–	–	5	–
MDE997	Control	3	–	–	–	2	2
MDE998	Control	15	–	–	–	9	5
MDE999	Control	–	–	–	–	4	4
	Total Thin	39	25	38	25	38	39
	Total Control	23	0	0	0	29	11
	Total	62	25	38	25	67	50

with almost all similar restoration projects, much of the remaining non-commercial material was hand or machine piled and the piles burned a year or two after thinning. Prescribed broadcast burning across the entire surface of treatments units was planned for all Marshall Devine treatments units, but as of this writing, no prescribed fire has been completed in the stands we studied.

2.2. Field data collection

Data were collected as part of the Southern Blues CFLRP Forest Vegetation and Fuels (FVF) multi-party monitoring program (Johnston et al., 2021). Between 2014 and 2018, the FVF program established 511 long-term monitoring plots throughout the Southern Blues CFLRP area. Monitoring plots were established by randomly selecting thinned stands within different NEPA planning areas. Circular plots 0.1 ha in size were systematically located approximately 150–250 m apart within thinned stands. Control plots were also located in untreated stands that are 1) within the same NEPA planning area as treated stands; 2) keyed to the same plant association as treated stands; 3) have similar stand density index (SDI) as treated stands before thinning (±15 SDI); and 4) were of similar slope, elevation, and aspect. Plots in treated stands are measured once before thinning, and both treatment and control plots are remeasured following thinning as funding, monitoring priorities, and other exigencies (e.g., large wildfires) allow.

A total of 62 FVF plots—39 plots in thinned stands and 23 plots in control stands outside of thinned stands—were located in the Marshall Devine planning area in the summer of 2014 immediately before thinning began. Distance between plots in these treatment areas was 150 m apart, and resulted in a similar sampling intensity as the FFS sampling design. Most treatment plots were remeasured in the summer of 2015 after thinning was completed and in subsequent years until 2019. Most control plots were remeasured in 2018. A total of 7 control plots could not be relocated or were judged unsuitable for remeasurement in 2018 because of damage from off-highway vehicle use or grazing activities. To compensate for the loss of these control plots, we located an additional 13 control plots in nearby unthinned stands (Table 1). We were unable to establish more than 13 additional control plots to match the number of thinned plots because of a lack of extensive unthinned stands similar in characteristics to thinned stands. All plots were measured within 20 days of the time of the initial measurement in the summer so that time of year did not significantly influence fuel characteristics (for instance, the height of live herbaceous fuel).

Within each plot, FVF monitoring crews recorded the species of trees and took a number of measurements of trees within plots (e.g., diameter, height, and height to fine aerial fuels) as well as plot-scale overstory tree characteristics (e.g., plot canopy closure and stand structure). We tallied 1-, 10-, 100-, and 1,000-hour (<0.6 cm, 0.6 to 2.5 cm, 2.5 to 7.6 cm, >7.6 cm) woody fuel particles along two 18.3 m transects extending from plot center (Brown, 1974). We measured the depth of litter and the depth of duff at three points along each transect. Litter consisted of all detached and dead leaves, cones and bark scales (the vast majority of litter was ponderosa pine needles). Duff consisted of partially decomposed litter found between the lower layer of litter and mineral soil. We estimated live understory vegetation fuels using the photoload sampling technique in two 1-m^2 microplots located along each transect (Keane and Dickinson, 2007). Finally, we recorded understory species composition and ground cover (bare dirt, litter, etc.) at 25 points along each transect (Herrick et al., 2005). Our surface fuel data collection along transects represents approximately half the transect length per area of treatment unit as the FFS (see Section 1). Test plots undertaken prior to field data collection indicated that doubling the length of transects did not significantly reduce confidence intervals for estimates of surface fuels, and also resulted in significant trampling of vegetation within plots that hampered collection of detailed understory vegetation, which was also of interest as part of the broader study.

Woody fuels were converted to surface fuel loading using the equations found in Brown (1974). Litter and duff measurements were converted to surface fuel loading using depth-to-weight coefficients for ponderosa pine litter from the Sierra Nevadas found in van Wagtendonk et al. (1998). We confirmed these coefficients produced accurate depth-to-weight conversions for our study area by measuring the depths of litter and duff at 11 randomly selected sites outside of plots, removing that material from the field, kiln drying these samples to remove moisture, and weighing samples.

2.3. Fire behavior modeling

The timing and location of plot measurements permitted several different comparisons of modeled fire behavior over time in response to thinning. First, we compared modeled fire behavior between thinned stands and unthinned control stands in 2018, the year when all FVF thinning and control monitoring plots in the Marshall Devine planning area were measured. Second, we compared modeled fire behavior within thinned stands in 2014 before thinning occurred and in every subsequent year between 2015 and 2019 after thinning was completed. For the purposes of fire modeling, we averaged all plot measurements within each stand where we collected data, reasoning that fire spread, crown fire potential, and other modeled fire behavior outputs were most interpretable at a stand scale.

We modeled fire behavior using the Fuel Characteristic Classification System (FCCS) version 3.0, part of the Fuel and Fire Tools software application (FERA, 2020; Ottmar et al. 2007). At the time of our analysis, the FCCS modeling environment contained 216 fuelbeds representative of vegetation conditions across the U.S. We modified the ponderosa pine–high density (fuelbed #211) and ponderosa pine–post thin (fuelbed #212) with field-collected surface fuel loading and canopy and understory characteristics to create custom fuelbeds for each Marshall Devine treatment and control stand in each year plots within each stand were measured. To characterize potential differences in fuel moisture, we developed custom environmental moisture scenarios from historical weather data covering the length of the study period (2014–2019). We calculated 80th, 90th, 95th and 99th percentile historical fuel moisture characteristics for each fuel component. We also ran FCCS using sustained wind speed scenarios of 8, 16, and 24 kph, which wildland fire reports we examined suggested were moderate, high, and very high sustained wind speeds typically encountered in the course of recent (last 12 years) wildfire suppression operations in the southern Blue Mountains. For each combination of fuel moisture and wind speed, we calculated the following surface fire behavior outputs for each stand in each year: Fire rate of spread (m per minute), flame length (m), and reaction intensity (watts m^2).

FCCS also output "crown fire initiation" and "crown-to-crown transmissivity," which estimate the potential for torching of the canopy and fire spread through the forest canopy respectively. At the time of this

Table 2
Percent difference in FCCS fire behavior outputs between thinned stands and control stands in 2014 and in 2018.

	2014			2018		
	Thin	Control	Difference thin-control	Thin	Control	Difference thin-control
Rate of spread (m/min)	5.02	4.97	−1%	4.24	6.07	43%
Flame length (m)	1.39	1.46	5%	1.32	1.66	26%
Reaction intensity (W m^2)	9978	9249	−7%	8277	9423	14%

writing, FCCS does not support customization of environmental conditions (fuel moisture and windspeed) for crown fire potential outputs as it does for surface fire behavior. Both crown fire initiation and crown-to-crown transmissivity are reported as a relative index from 0 to 9, with 0 indicating no potential for crown fire and 9 indicating total consumption of overstory tree canopies.

Supplementary materials summarize total surface fuel loading data (S.1) provide detail about FCCS inputs and FCCS model runs (S.2), and development of moisture scenarios (S.3).

2.4. Statistical models of surface fuel loading

We created models to evaluate change in the surface fuel loading response over time in thinned stands using a linear mixed model with measurement year as a fixed effect, forest stand where plots were located as a random effect, and a first-order auto-correlation term to account for repeated measurements. While FCCS fire behavior modeling results were evaluated at the scale of forest stands (model inputs were averaged across plots), in statistical models we used individual 0.1 ha circular plots as sample units to increase power to detect change in individual fuel components. We modeled six different surface fuel responses: 1) Fine down wood, which included woody fuel particles from 0 to 7.6 cm in diameter (1-, 10-, and 100-hour fuels); 2) litter; 3) live surface fuels; 4) all fine surface fuels, which combined fine down wood, litter, and live surface fuels; 5) duff; and, 6) all surface fuels including woody fuel particles of any size, litter, live surface vegetation, and duff. Surface fuel responses 1, 2, 3, and 4 represent changes in flashy fuel components with low heat residence times that combust rapidly and contribute to fire spread. Surface fuel responses 5 and 6 represent change both to flashy fuel components that contribute to fire spread and duff and large woody particles (>7.6 cm diameter) that release energy over time periods ranging from seconds to days (Prichard et al., 2017; Battaglia et al., 2008).

All models were implemented using the *nlme* package in R (Pinheiro et al., 2020; R Core Team, 2020). During preliminary analyses, we tested a variety of biophysical (e.g., elevation and heat load) and vegetation (e.g., plant association group) variables as potential predictor variables. However, none of these terms had any meaningful predictive power, probably because plots were quite similar with respect to vegetation (all ponderosa pine plant associations), elevation (min = 1,530 m, max = 1,678 m, mean = 1,599 m), slope (min = 0%, max = 15%, mean = 4%), and aspect (generally flat or situated on a gently sloping hill). We examined diagnostic plots and log transformed the woody fuel particle response to stabilize variance in model residuals.

The stakeholders and managers with whom we developed this research are interested in the magnitude of the effect of treatment vs. no treatment and/or time since treatment. To ensure the relevance of our results to end users (Keeler et al., 2017), we considered time since thinning to have a significant effect when 95% confidence intervals for the estimated mean surface fuel response between years did not overlap. This approach ensures that managers and stakeholders have confidence that there is large and meaningful change in fuel loading and not simply that there is weak evidence against a null hypothesis, although we also provide traditional measures of statistical significant (i.e., *p*-values) in model results (Wasserstein et al., 2019).

3. Results

3.1. Fire behavior modeling

There was little difference between modeled fire rate of spread, flame length, and reaction intensity in thinned stands and control stands in 2014 before thinning was completed. By 2018, four years after thinning was completed, rate of spread, flame length, and reaction intensity were 43%, 26%, and 14% greater respectively in unthinned controls than in thinned stands (Table 2). FCCS model runs of thinned stands under different fuel moisture and wind scenarios from 2014 to

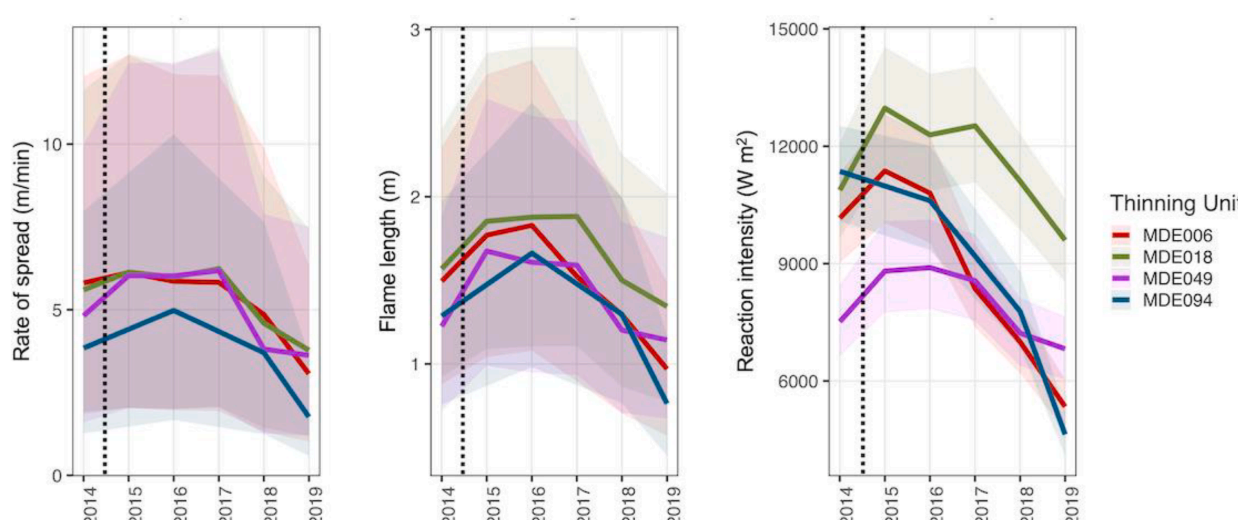

Fig. 2. Modeled fire behavior in thinned Marshall Devine stands in 2014 (prior to thinning) and for five years after thinning was completed (2015–2019; thinning is indicated by the dotted line). Solid lines indicate mean values for each thinned stand for each fire behavior metric over all modeled wind speeds (8–24 kph) and fuel moisture scenarios (80th to 99th percentile fuel conditions). Transparent ribbons indicate the full range of values for each metric for all wind speed and moisture scenarios.

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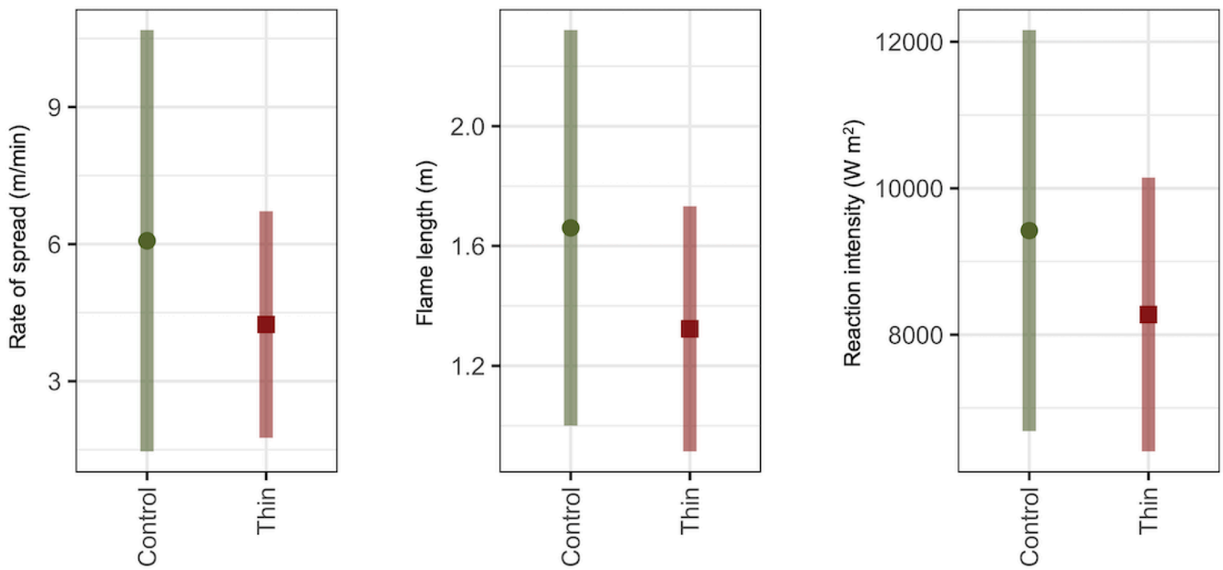

Fig. 3. Modeled fire behavior for control stands and thinned stands in 2018, the year where all plots were measured. Points indicate mean values over all wind speed and moisture scenarios. Lines indicate the full range of values for each metric for all wind speed and moisture scenarios.

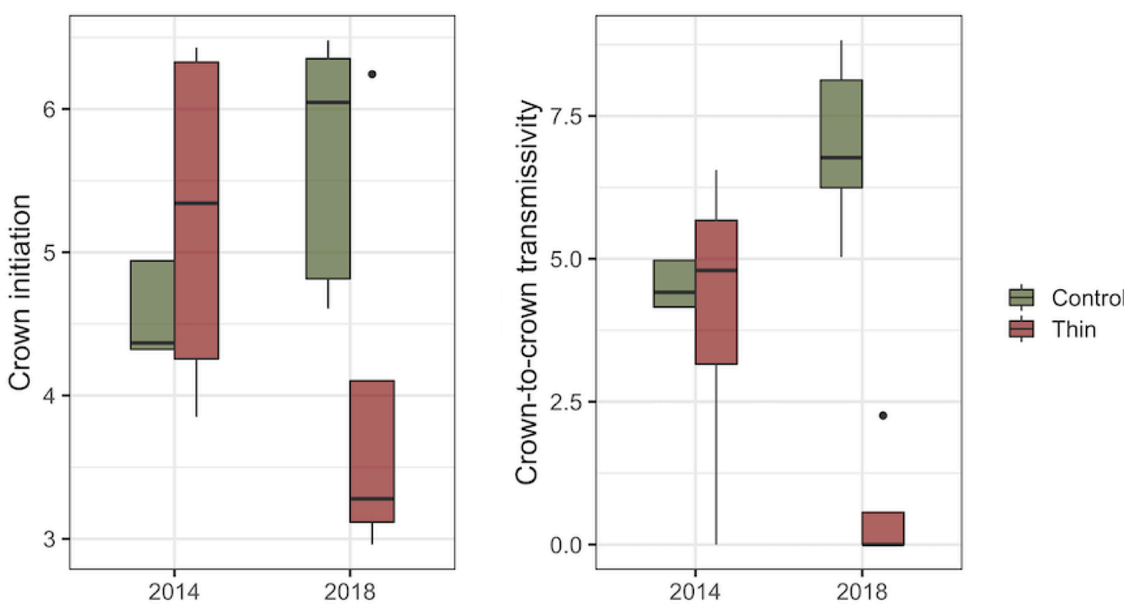

Fig. 4. Crown fire potential modeled in FCCS in thinned stands and unthinned controls in 2014 before thinning began and in 2018 four years after thinning had been completed. FCCS outputs crown fire potential (the y-axis) as a dimensionless index from 0 to 9.

2019 showed an increase in modeled fire behavior outputs for 2 to 3 years following thinning followed by sharp declines (Fig. 2). Mean surface fire rate of spread in thinned stands across wind/moisture scenarios increased by 23% immediately following thinning and did not decline to below the pre-thinning rate until 2018. By 2019, the mean rate of spread across moisture/wind scenarios was 39% lower than the pre-thinning rate. Mean flame length across thinned stands and wind/moisture scenarios increased by 27% immediately following thinning and did not decline to below pre-thinning flame length until 2018. By 2019, average flame length was 24% lower than the pre-thinning flame length. Mean reaction intensity across thinned stands and wind/moisture scenarios increased by 11% immediately following thinning but declined to below the pre-thinning rate by 2017 and was 34% lower than pre-thinning levels by 2019. In 2018, when all control and thinning plots were measured, mean rate of spread, flame length, and reaction intensity were all higher in control stands than in thinned stands (Fig. 3).

There was little difference between modeled crown fire potential indexes in thinned stands and unthinned controls in 2014 before thinning began. In 2015, immediately following thinning, crown initiation potential increased by 30%. By 2016, crown initiation potential was 16% less than before thinning began and remained 16–20% lower than pre-thinning crown initiation potential from 2017 to 2019. The crown-to-crown transmissivity index declined to nearly zero immediately following thinning and remained near zero over the time period analyzed. There was little difference in crown fire potential between thinned stands and unthinned stands before thinning began in 2014, but by 2018 there was far less potential for crown fire in thinned stands (Fig. 4).

3.2. Statistical models of surface fuel loading

Mean total fine surface fuel loading was estimated to be 10.3 Mg

Table 3
Results of statistical models of surface fuel loading over time.

Fine surface fuel loading					
Year	Fuel loading (Mg ha^{-1})	SE	Lower CI	Upper CI	*p*
2014	10.3	1.0	7.3	13.4	<0.01
2015	15.7	1.6	10.6	20.8	<0.01
2016	16.2	1.5	11.3	21.0	0.01
2017	13.3	1.4	9.0	17.7	<0.01
2018	11.4	1.1	8.0	14.9	<0.01
2019	9.8	0.9	6.9	12.8	<0.01
Total surface fuel loading					
Year	**Fuel loading (Mg ha^{-1})**	**SE**	**Lower CI**	**Upper CI**	***p***
2014	67.1	8.6	39.8	94.4	<0.01
2015	33.1	4.6	18.5	47.8	0.01
2016	40.2	5.2	23.7	56.7	<0.01
2017	32.7	4.6	18.2	47.3	0.01
2018	27.6	3.5	16.3	38.9	<0.01
2019	17.6	2.2	10.4	24.7	<0.01

ha^{-1} in 2014 before thinning began and increased to a mean of 16.2 Mg ha^{-1} in 2016 before declining to 9.8 Mg ha^{-1} in 2019. The increase in the two years following thinning was marginally significant, although 95% confidence intervals for total fine surface loading estimates overlapped in other years and thus provide no evidence of a significant change in fine surface fuel loading between stands before they were thinned and in the last several years of our study. There was evidence of a significant decline in total surface fuel loading over time. Total mean surface fuel loading was estimated to be 67.1 Mg ha^{-1} in 2014 before thinning but had dropped to 17.6 Mg ha^{-1} by 2019. This large decline was mostly attributable to significant declines in litter and duff fuel loading, which constituted a large proportion of total surface fuel loading. Fine surface fuels (small woody particles, litter, and live vegetation) increased immediately following thinning in 2015 due to an increase in fine woody particles from logging and declined to pre-thinning levels by 2019 as litter and duff fuel loading declined. Live surface vegetation was a minor component of total surface fuel loading that exhibited little change over time (Table 3 and Fig. 5).

4. Discussion

4.1. Fire and fuel loading dynamics following thinning

Significant declines in modeled surface fire behavior in thinned stands after 2–3 years following thinning provide strong evidence that mechanical thinning followed by typical post thinning fuel treatments including pile burning but without prescribed fire can moderate fire behavior. Modeled crown fire potential declined immediately following thinning, undoubtedly due to significant reductions of ladder fuels that carry fire into the crown and crown density that facilitates spread between crowns. Fig. 6 illustrates the dramatic reduction in amount and continuity of aerial fuels in our study area following thinning. Contrasts between thinned and unthinned controls also provide evidence that thinning in the absence of prescribed fire moderates modeled fire behavior. Thinned and unthinned stands were very similar with respect to modeled fire behavior in 2014 before thinning began. Four years after thinning, all modeled indexes of fire behavior had declined markedly in

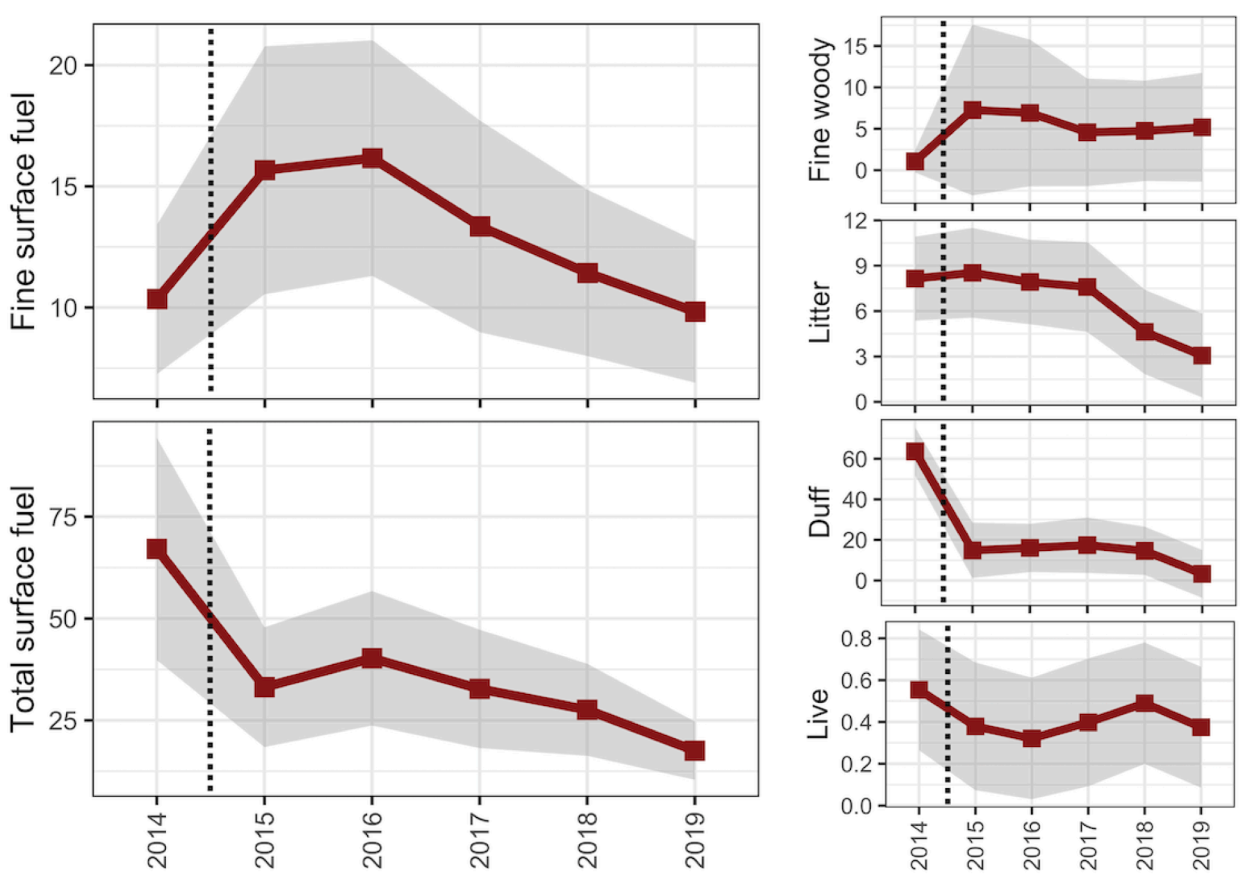

Fig. 5. Changes to surface fuel loading following thinning (indicated by dotted black line). Solid lines and points indicate estimates of mean surface fuel loading from statistical models. Transparent ribbons indicate confidence intervals (alpha = 0.05) for estimates. Fine surface fuel = 1-, 10-, and 100- hour woody particles (0–7.6 cm diameter), litter, and live surface vegetation. Total surface fuel = 1-, 10-, 100-, and 1000-hour woody particles, litter, duff, and live surface vegetation. Fine woody = 1-, 10-, and 100-hour woody particles (0–7.6 cm diameter) (fine woody fuel loading is back-transformed from the log scale). Live = live rooted understory vegetation (shrubs, forbs and herbaceous plants). Unit of measurement for all panels = Mg ha^{-1}.

Fig. 6. Changes to overstory structure as a result of thinning. Marshall Devine thinning unit prior to thinning in 2014 (Panel A). The same view in 2019 five years after thinning (Panel B).

thinned stands but remained high in unthinned stands. In fact, modeled fire behavior was typically higher in unthinned controls in 2018 than in 2014. This may reflect inconsistency in measurements of control stands—we did not remeasure 7 plots in 2018 that were measured in 2014 and we established 13 new control plots that had not previously been measured. However, there was mortality of ponderosa pine from western pine beetle (*Dendroctonus brevicomis*) in many unthinned controls between 2014 and 2018 that often exceeded 25% and was sometimes in excess of 50%, which added fine fuels to the forest floor and left many trees that were alive in 2014 with red needles highly conducive to crown fire (Schoennagel et al., 2012). Although we did not explicitly test for the effects of pine beetle, we noted <5% mortality (mean < 1%) in all thinned stands. It is possible that increased tree vigor associated with thinning has the added benefit of moderating fire behavior relative to unthinned stands. Previous studies have shown that mechanical thinning is associated with increased radial growth, which in turn confers resistance to fire damage and insect attack (Tepley et al., 2020; Van Mantgem et al., 2020; Vernon et al., 2018).

Changes in individual surface fuel components in response to thinning varied among fuel components. As should be expected from felling trees, thinning operations increased the amount of woody fuel particles on the forest floor. Although confidence intervals for estimates of fine woody fuel particles mostly overlapped because of variability in fuel loading among plots, the four-fold increase in mean 1-, 10-, and 100-hour surface fuel loading that we measured likely had a meaningful effect on modeled and actual fire behavior. But this increase in surface fuel and modeled fire behavior was offset by a steady decline in litter and a dramatic decline in duff over time (Fig. 5). Litter fuel, composed almost entirely of ponderosa pine needles in our study area, is highly flammable and a major contributor to fire spread, particularly in hot and dry conditions (Varner et al., 2015).

It is possible that observed declines in litter and duff are due to measurement error. Consistent and accurate estimates of litter and duff fuel loading are often difficult because of inconsistent delineation of litter and duff layers and imprecisions inherent in measurement of a shallow (0–60 cm) surface strata (Westfall and Woodall, 2007). However, we do not believe that observed declines in litter and duff are due to measurement error for three reasons: First, although we used different crews in different years, the same personnel applied the same training techniques for measuring litter and duff to each crew. Second, the same crews working in the same year observed significant differences in litter and duff fuel depths between thinned and unthinned stands consistent with our observations of a decline in litter and duff in thinned stands over time. Third, different crews working in different years in FVF plots outside of Marshall Devine stands, but in similar forest types, made observations of litter and duff fuel depths in thinned and unthinned stands that were consistent with our observations in Marshall Devine stands. Finally, we note that although our statistical models estimated changes in total litter and duff fuel loading, FCCS takes litter and duff inputs of depth and percent cover. While entering a total loading was optional, we chose to use the FCCS internal calculations in order to maintain consistency with other FCCS calculations. Although there may be error associated with measuring depth, our measurements of percent cover of litter along transects were straightforward and unlikely to be consistently biased.

We believe that the decline in duff fuel loading we observed following thinning is attributable to surface disturbance associated with ground-based logging which resulted in mixing of the duff layer with

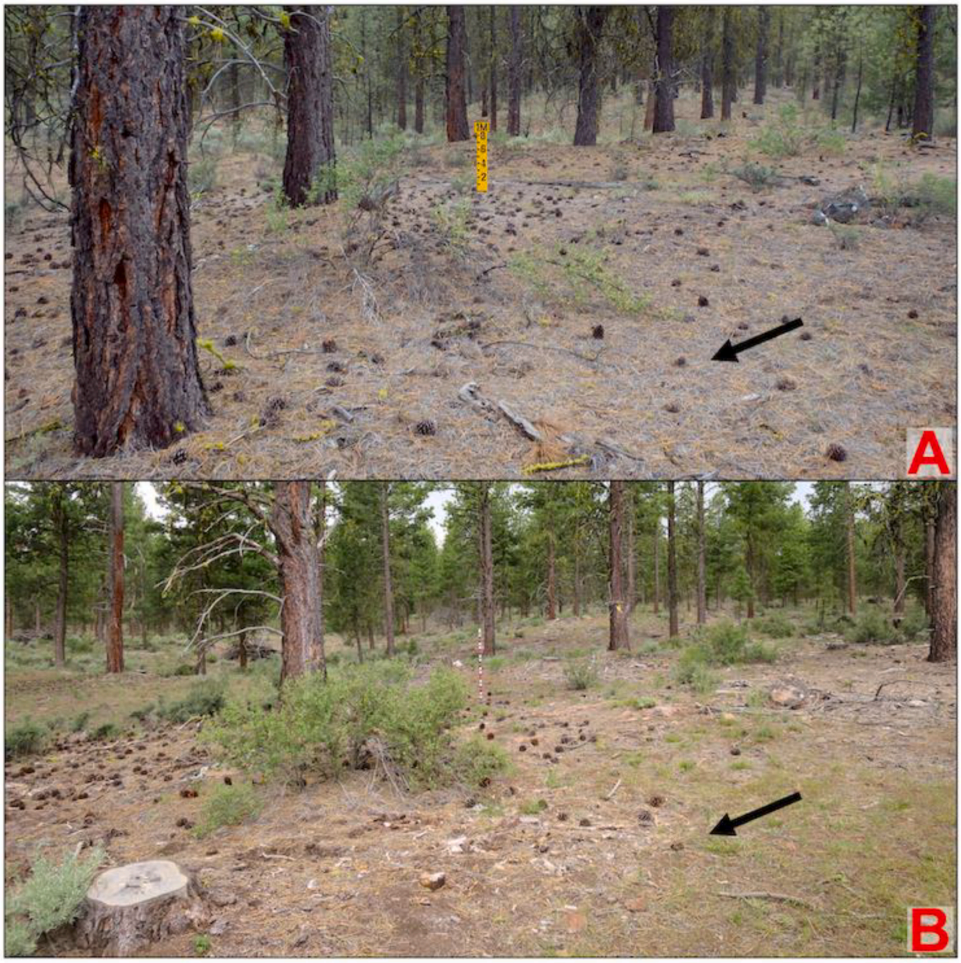

Fig. 7. Changes to litter and duff fuel loading following thinning. Marshall Devine thinning unit prior to thinning in 2014 (Panel A). The same view in 2019 five years after thinning (Panel B). Arrows point to examples of significant changes in litter and duff structure. Litter depth across Marshall Devine treatment units averaged 2.9 cm in 2014 and 1.6 cm in 2019. Duff depth across Marshall Devine treatment units averaged 4.7 cm in 2014 and 0.4 cm in 2019. Duff and litter layers were continuous across Marshall Devine treatment units prior to thinning, but patchy and less continuous following thinning.

mineral soil sufficient to make it less combustible. Our direct observations in the field also suggested that surface disturbance aerated duff and exposed it to increased solar radiation sufficient to accelerate decomposition (Zhang et al., 2010). We attribute the steady decline in litter over time to these same factors as well as decreased deposition of needles after overstory removal (Keane, 2008). These hypotheses are consistent with previous research that demonstrates that litter accumulation is correlated with canopy cover and sensitive to solar radiation and temperature (Nunes Biral et al., 2019, Hall et al., 2006). Examination of repeat photographs of plots lends support for our theory that significant reductions in litter cover were associated with canopy removal (Fig. 7).

4.2. Management implications

This study demonstrates that thinning in the absence of prescribed fire is effective at moderating modeled crown fire potential immediately following thinning and can moderate modeled surface fire behavior for a number of years after a relatively short period (1–3 years) of elevated surface fire behavior. We found no difference in modeled fire behavior or a difference in surface fuel loading between stands thinned using a cut to length logging system versus stands thinned using whole tree logging systems. Different logging systems have the potential to produce different quantities of woody fuels, but post-thinning fuel management treatments (piling and burning of slash) likely helped to reduce woody fuel loading across thinned stands within one to two years following thinning. We observed an increase in woody fuel loading following treatment followed by a slight decline in woody fuel within two years, which is consistent with piling and burning of woody fuels (Fig. 8). But the majority of surface fuel loading decline that we observed following thinning was attributable to declines in litter and duff loading (Fig. 5).

It is likely that the observed trend of significantly declining surface fuel loading and significantly moderated modeled fire behavior will continue for a number of years as fine woody fuel particles decompose. Although we show that thinning in the absence of prescribed fire moderates modeled fire behavior for a number of years, prescribed fire is still an important tool for accomplishing fuel reduction and fire management objectives in ponderosa pine forests of the southern Blue Mountains and elsewhere (Mitchell et al., 2009). Prescribed fire is likely to be effective at extending the longevity of treatments in thinned stands at some point in the future when the trend towards decreasing surface fuel loading is reversed and surface fuel loading begins to exceed desired thresholds (Kalies and Yocom Kent, 2016).

Previous research suggests that conifer regeneration is a primary driver of increased fuel loading and fire hazard following thinning in ponderosa pine and Douglas-fir forests (Hood et al., 2020; Battaglia et al., 2008). We observed very little regeneration in Marshall Devine stands following thinning until 2019 (following a mast year in 2018) when we recorded an average of 8,700 seedlings ha^{-1}. In the course of previous studies in the area we observed significant seedling mortality following drought from 2012 to 2015 and it remains to be seen if trees established in 2019 thrive. Our observations of recent Marshall Devine regeneration patterns and past growth and establishment research in the area suggest that there will be irregularly distributed patches of $\geq$ 1 m tall ponderosa pine within thinned stands across the Marshall Devine area in approximately 12–20 years following thinning. It may be

Fig. 8. Post-thinning fuel treatment (piling and burning) resulted in reductions in woody fuels. Marshall Devine thinning unit prior to thinning in the summer of 2014 (Panel A). The same view after thinning with activity fuels piled in the summer of 2015 following thinning (Panel B). The same view in 2019 (Panel C). Piles were burned in winter or spring of 2015–2016.

difficult to reliably kill seedlings taller than this height with flame lengths typical of prescribed fire operations (Battaglia et al., 2008). This suggests that prescribed fire 10–18 years after thinning may be the most efficient way to accomplish fuel reduction objectives in our study area. This hypothesis should be validated by continued monitoring of thinning treatments and experimentation with different prescribed fire management regimes (Stephens et al., 2012).

We do not assume that mechanical thinning in the absence of prescribed fire will moderate fire behavior for many years following thinning across the southern Blue Mountains or at other sites across the western U.S. Our study area was a relatively low productivity site near the edge of the range of ponderosa pine with significant evapotranspirative demands on trees, particularly seedlings. As noted above, regeneration of conifers in the stands we studied lagged ground-based logging disturbance by many years and we anticipate that conifer regeneration will not be well established for at least another five years (Kolb et al., 2020). We observed little shrub response to overstory removal and logging disturbance in the stands we studied. In moister and more productive sites we would anticipate significant regeneration of fast-growing grand fir in response to thinning. Other sites may see significant growth of shrubby species following thinning, which would contribute to live surface fuel loading in a relatively short amount of time following thinning. It is likely that the results we report here are applicable to other low productivity ponderosa pine sites across western North America, but are likely to be less applicable to more productive sites or sites with a significant shrub response to mechanical disturbance. We urge decisions about the timing of prescribed fire to be based on careful consideration of site conditions informed by ongoing monitoring.

5. Conclusion

Previous research (e.g., Raymond and Peterson, 2005; Waltz et al., 2003) indicates that reintroduction of fire following thinning is necessary to reduce fine surface fuel loading. But in dry ponderosa pine forests of the southern Blue Mountains of Eastern Oregon, we show that overstory tree removal followed by typical post-thinning fuel treatments without prescribed fire is associated with significant reductions in total surface fuel loading and moderates modeled surface fire behavior after an initial 1- to 3-year period of increased fire hazard. These findings provide important validation for investments in mechanical thinning by Congress through the CFLRP and other federal initiatives, and will also inform private and non-governmental landowners as well as tribal, state and local governments. Broad-scale evaluations of the effect of different fuel treatments (e.g., FFS) indicate that fire behavior outcomes may vary as function of site characteristics as well as specific treatment types, i.e., thinning vs. thinning and prescribed fire. The trends we observed over six years also suggests that treatment effects may vary significantly over time. We urge continued monitoring of our study area and other sites across western North America in order to adapt thinning treatments to lessons learned and optimize the restoration value of prescribed fire.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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