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Thinning and Burning Effects on Long-Term Litter Accumulation and Function in Young Ponderosa Pine Forests

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We measured forest-floor accumulation in ponderosa pine forests of central Oregon and asked whether selected ecological functions of the organic layer were altered by thinning and repeated burning. Experimental treatments included three thinning methods applied in 1989 (stem only, whole tree, no thin—control) in factorial combination with prescribed burning (spring 1991 and repeated in 2002; no burn—control). Forest-floor depth and mass were measured every 4–6 years from 1991 to 2015. Without fire, there was little temporal change in depth or mass for thinned (270 trees ha^{-1}) and control (560–615 trees ha^{-1}) treatments, indicating balanced litterfall and decay rates across these stand densities. Each burn consumed 50–70 percent of the forest floor, yet unlike thinning, postfire accumulation rates were fairly rapid, with forest-floor depth matching preburn levels within 15–20 years. Few differences in forest-floor function (litter decay, carbon storage, physical barrier restricting plant emergence, erosion protection) resulted from thinning or burning after 25 years. An exception was the loss of approximately 300 kg N ha^{-1} because of repeated burning, or approximately 13 percent of the total site N. This study documents long-term forest-floor development and suggests that common silvicultural practices pose few risks to organic layer functions in these forests.

Study Implications: Mechanical thinning and prescribed fire are among the most widespread management practices used to restore forests in the western US to healthy, firewise conditions. We evaluated their effects on the long-term development of litter and duff layers, which serve dual roles as essential components of soil health and as fuel for potential wildfire. Our study showed that thinning and burning provided effective fuel reduction and resulted in no adverse effects to soil quality in dry ponderosa pine forests of central Oregon. Repeated burning reduced the site carbon and nitrogen pools approximately 9–13 percent, which is small compared to C located in tree biomass and N in mineral soil. Litter accumulation after burning was rapid, and we recommend burning on at least a 15–20-year cycle to limit its build-up.

Keywords: forest floor, fuel hazard, prescribed fire, soil quality

Forest-floor (litter and duff, O horizon) content and function were altered in the last century as wildfire frequency declined in many pine and dry mixed-conifer forests in the western United States. Frequent natural fires once led to thin or patchy duff layers that presumably contributed little to total ecosystem nutrient pools or fuel hazard (Currie et al. 2003, Miller et al. 2010). Nutrient turnover was ephemeral, fire driven, and less dependent on microbial decomposition processes than present-day forest-floor organics. With fire exclusion, however, thicker forest-floor layers developed, providing a small but continuous supply of available nutrients (Jorgensen et al. 1980, Monleon and Cromack 1996) along with increased fuel loads (Agee and Skinner 2005). As a result, predictive fire behavior models today include the forest-floor litter layer (Oi) as a fundamental constituent of the fuel load, acknowledging its role in providing surface fuel continuity and mass to the flaming front of surface fires (Rothermel 1972). Duff, composed of partially decomposed needles (Oe) and humus (Oa), can account for the bulk of forest-floor mass in conifer forests (Vaillant et al. 2009), yet is omitted in fire-spread models because it is not necessarily consumed by the flaming front. Still, duff layers typically smolder and produce a downward heat pulse that results in the release of plant-available nutrients and, if consumption is

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sufficiently high, tree mortality and physiochemical damage to mineral soil (Neary et al. 1999).

The forest floor serves multiple and, at times, diverging roles in fire-adapted forests. As a soil constituent, the forest floor helps regulate mineral soil temperature and moisture extremes, supplements soil nutrient availability and nutrient pools, reduces surface water runoff, helps limit erosion, provides habitat for soil biota, and offers a short-term sink for soil-carbon sequestration (Schlesinger and Lichter 2001, Harrison et al. 2016, Binkley and Fisher 2019, Thompson et al. 2019). If sufficiently deep, however, the forest floor may act as a physical barrier, inhibiting seedling emergence and plant diversity (Hiers et al. 2007), and serve as a fuel source for smoldering ground fires (Ottmar et al. 2007).

The list of site factors that influence forest-floor development is long. This ranges from forest vegetation conditions that affect litter input (tree density, stand age, tree species, understory plant diversity and cover, litterfall rate, litter chemistry), soil properties affecting litter decay (microbial activity, organic matter content, pH), and site temperature and moisture regimes affecting both litter input and decay (Ovington 1954, van Wagtendonk et al. 1998, Garten 2011, Marty et al. 2015, Senior et al. 2019). Collectively, these factors help explain the high spatial and temporal variability of forest-floor layers common at stand and landscape scales (Currie et al. 2003). Forest-management practices, particularly prescribed burning and harvesting, add additional complexity to forest-floor development (Waldrop et al. 2016). For example, prescribed fire effects can vary from near-complete forest-floor consumption (Parsons 1978, Moghaddas and Stephens 2007) to minimal change (Youngblood et al. 2008), depending on burn objectives, preburn forest-floor mass, weather conditions during burning, and lighting techniques used by burn crews. Like fire, harvesting effects vary as a function of the prescription objectives (harvest intensity) along with the extent of forest-floor disturbance by harvest equipment (Moghaddas and Stephens 2007).

Scientific understanding of forest-floor development and function remains incomplete. How thinning and burning disrupt the trajectory of long-term litter accumulation and whether this matters to soil quality is unclear. Some of this uncertainty can be traced to the lack of long-term datasets and, instead, a reliance on chronosequence or modeling studies (Yanai et al. 2000, Chiono et al. 2012), although long-term studies of thinning and burning are becoming more common, as are their early results (McIver et al. 2013, James et al. 2018). Here, we report results from a long-term study whose aim was to establish the relation between restoration practices and forest-floor accumulation and function.

Our objective was to quantify long-term changes in forest-floor depth, mass, and function following thinning and repeated burning. Replicate study sites were installed in 1989 in 45–60-year-old ponderosa pine (*Pinus ponderosa* C. Lawson) forests on the dry, infertile pumice plateau of central Oregon. We hypothesized that repeated burning would limit the accumulation of surface litter and duff, particularly in thinned plots, and result in measurable changes in soil-quality indices (e.g., C and N pools, litter decay, and herbaceous plant emergence and production as affected by litter depth). We also tested whether litter and duff depth accumulates unchecked in the absence of disturbance (using control plots), or if litter input and litter decomposition rates are largely balanced in these pine stands.

Materials and Methods

Study Location

The study was conducted on the pumice plateau of the Deschutes National Forest, along the eastern toe slope of the Cascade Range in central Oregon (Figure 1). The landscape is gently rolling and dominated by ponderosa pine and lodgepole pine (*Pinus contorta* Dougl. ex Loud.) forests. The climate is continental with cold winters (3° C mean January temperature) and warm summers (17° C mean July temperature). Annual precipitation between 1990 and 2015 averaged 60 cm (39 cm minimum, 100 cm maximum), primarily as winter snow and rain with infrequent summer thunderstorms (Prism Climate Group, Oregon State University 2015).

We selected three ponderosa pine sites within young "black bark" forests that regenerated naturally following railroad logging in the 1930s: East Fort Rock, the eastern-most site (45-year-old stand in 1991); Sugar Cast (55-year-old stand in 1991); and Swede Ridge (62-year-old stand in 1991) to the north. Slopes were gentle (<10 percent), site elevation ranged from 1,400 to 1,554 m, and site productivity was low (site index of 25–35 m at 100 years) owing to limited soil moisture, nutrients, and length of growing season. The soil (loamy sand texture) was a cryic Vitrand that developed from wind-blown deposits of pumice and ash following the eruption of Mt. Mazama approximately 7,700 years before present. Soil fertility was low, with an organic matter content of 42 g kg^{-1} and total nitrogen content of 1.4 g kg^{-1} in the surface 10 cm depth (Busse et al. 2009). Common understory plants included bitterbrush (*Purshia tridentate* [Pursh] DC.), snowbrush (*Ceanothus velutinus* Douglas ex Hook), greenleaf manzanita (*Arctostaphylos patula* Greene), Idaho fescue (*Festuca idahoensis* Elmer), squirreltail (*Elymus elymoides* [Raf.] Swezey), and Ross's sedge (*Carex rossii* Boott).

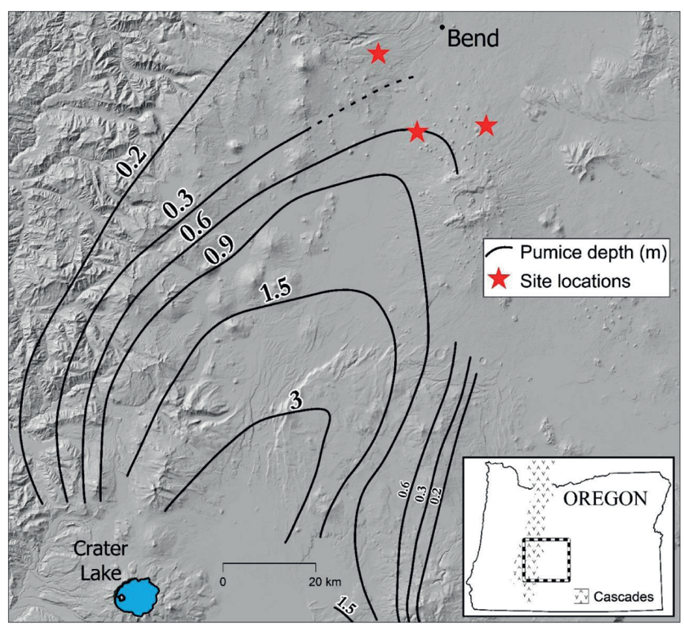

Figure 1. Study-site locations on the central Oregon pumice plateau. Isolines (Williams 1942) depict pumice fall from the eruption of Mount Mazama (now Crater Lake). Dashed line is an extrapolation of William's 0.3 m isopach.

Study Design

The experiment was a randomized complete block with three replications (sites) of six treatments arranged in a 3 × 2 factorial design (3 thinning treatments × 2 burn treatments). The thinning treatments included: (1) thin, stem-only removal (SO); (2) thin, whole-removal removal (WT); and (3) no thin (NT). Each thinning treatment was combined with two prescribed fire treatments (burn; no burn). The plot size was 0.4 hectares (61 × 61 m) with ≥20 m between adjacent plots.

Prior to treatment (1988), stands averaged 609 trees ha^{-1}, 30 m^2 ha^{-1} basal area, and 24 cm quadratic mean diameter (Busse et al. 2009). The thinning prescription targeted a retention basal area of 13.7 m^2 ha^{-1} and an even tree spacing of approximately 5 × 6 m that favored the removal of smaller or damaged trees. Trees were cut by chainsaw and removed by grapple skidder between November 1988 and October 1989. All harvest material was removed from WT plots. Stem wood only was removed from SO plots, with tree crowns and branches lopped and scattered.

Prescribed burning was conducted by Deschutes National Forest and Oregon Department of Forestry personnel in early June 1991 and repeated in June 2002 using a strip head-fire technique (Martin and Dell 1978). Burns were of low to moderate intensity, with average flame lengths of 0.5–1.2 m during the 1991 burns and 0.3–0.7 m during the 2002 burns.

Forest-Floor Measurements

We measured forest-floor depth at 60 points per plot in 1991 (pre- and postburn), 1996, 2002 (pre- and postburn), 2006, 2011, and 2015 using 12 systematically located transect lines that each had five equally spaced points. Litter and duff layers were difficult to separate visually and thus were measured as a combined layer on all sample dates. Forest-floor depths were converted to mass using plot-specific bulk density values (weight per unit volume). Bulk density was determined by collecting, drying (65° C for a minimum of 72 h), and weighing all forest-floor organics within 30 × 23 cm frames. The forest-floor depth above mineral soil was measured on four sides of the frames to calculate the volume of each sample. A minimum of six bulk density samples were collected from each plot and on each sampling date.

Functional attributes of the forest floor were measured periodically between 1992 and 2015, as specified in the following paragraphs. These included C and N content, litter decay, herbaceous biomass as an indirect test of forest-floor constraints on plant emergence, and erosion potential (estimated by the percentage of bare soil from forest-floor depth measurements).

Forest-floor C and N concentrations were analyzed by dry combustion by Oregon State University Central Analytical Laboratory, Corvallis, OR (1991 samples) and University of Idaho Analytical Sciences Laboratory, Moscow, ID (2015 samples). Carbon and N concentrations were converted to total content basis (kg ha^{-1}) by multiplying by the mean forest-floor mass of each plot. These data were also used to develop an estimate of C and N volatilization losses during the 1991 and 2002 fires. Loss was estimated by multiplying C and N contents by percent forest-floor consumption for each burn (e.g., 300 kg N ha^{-1} forest-floor content × 50 percent consumption = 150 kg N ha^{-1} volatilized). We considered this a semiquantitative measure of the upper limit of C and N loss.

Litter decay rate was measured as an index of biological activity on the forest-floor surface using the litterbag technique (Berg and Ekbohm 1991). Eight litterbags per plot (10 × 20 cm, 0.2 cm-mesh) containing 5 g (dry weight equivalent) of recent ponderosa pine litterfall were placed on the forest-floor surface. Duplicate litterbag samples were collected from each plot every 6 months during a 2-year period (1992–1994), the litter was dried and weighed, and the percentage mass loss was determined relative to the initial weight. Microbial biomass, as a complementary index of decomposition potential, was measured using the substrate-induced respiration method (Jenkinson and Powlson 1976) on litter samples collected at the end of the 2-year field incubation.

Herbaceous biomass production was measured during the peak growing season (late June to mid-July) in 1992, 1994, 1997, 1998, and 2003. All plants within eight systematically located subplots (0.25 m^2) per plot were clipped, dried, and weighed.

Stand Conditions

Stand measurements were taken periodically to document the relation between overstory conditions and forest-floor accumulation. Diameter at breast height (dbh) and tree condition (living, dead, damaged) were measured on all trees within each plot every 5 years beginning in 1990 and were used to calculate stand basal area and tree mortality rates. Canopy cover was estimated using regression equations developed for our sites that predicted tree cover as a function of dbh (Busse et al. 2009). Total canopy cover was determined by summing the canopy area of all living trees within a plot. Foliage mass was estimated using site equations developed by Cochran et al. (1984), which calculate live mass as a function of dbh.

Statistical Analyses

The effects of thinning and burning combinations on forest-floor depth and mass were analyzed by repeated-measures analysis using PROC MIXED (SAS Institute version 9.4). Treatment combinations were considered fixed effects; sites and plots within sites were random effects. Plots were the experimental unit for all analyses ("subject = plot" in PROC MIXED). Our goal was to determine whether forest-floor accumulation differed among treatments following each burn. To do this, we tested for differences in predicted slope estimates (increase in depth or mass with time) between the initial burn interval (1991–2002) and the repeated burn interval (2002–15) using contrast comparisons. Both burn intervals were within the mean historic fire-return length for central Oregon pine forests of 4–24 years (Bork 1984). The difference in burn-interval length (11 versus 13 years) was considered a minor source of error in comparing slope estimates given the linear response of litter accumulation with time. Treatment effects on litterbag decay, herbaceous biomass, and percentage bare soil were also analyzed by repeated-measures analysis in PROC MIXED but without separating the data by burn interval. Differences among treatments were identified using Tukey's post-hoc test. All data were evaluated for normality by visual inspection of normal quantile plots and residual histograms; no transformations were required. Treatment differences were considered significant at $\alpha = 0.05$. Mean values were combined for the SO and WT treatments for all measures except forest-floor depth and mass because no statistically significant differences were detected between these two thinning methods.

Results

Stand Conditions

Thinning reduced tree density by 55 percent and canopy cover by 30 percent (Table 1). Repeated burning without prior thinning resulted in 24 percent tree mortality, with most mortality found in small openings about 10–15 m in diameter following the initial burn. Thinning, with or without followup burning, resulted in limited tree mortality during the study. Live foliage mass was about 55 percent greater for control plots than the other treatments (Table 1) because of greater tree densities.

Forest-Floor Accumulation

No significant differences in accumulation rate were found because of thinning method for depth (P = .77) or mass (P = .95) in the repeated-measures analysis. Without burning, the average forest-floor depth between 1991 and 2015 was 4.9 ± 0.4 cm for NT—control, 3.8 ± 0.4 cm for SO thinning and 3.5 ± 0.4 for WT thinning (Figure 2). The average mass was 33 ± 4 Mg ha^{-1} for NT—control, 29 ± 4 Mg ha^{-1} for SO thinning, and 31 ± 4 for WT thinning. Net forest-floor accumulation for the three thinning methods (without fire) was minor during the 25-year period, with rates averaging 0.03 cm year^{-1} for depth and 0.4 Mg ha^{-1} year^{-1} for mass.

With burning, the average depth and mass remained lower than that of the unburned plots for the length of the study (P < .001). Forest-floor depth was reduced 60–70 percent by burning in 1991 and 50–60 percent by burning in 2002 (Figure 2). A steady increase in both depth and mass was observed following each burn. By 2015, forest-floor depth on burned plots was near its preburn (1991) depth of 3.7 cm and its preburn mass of 23 Mg ha^{-1}. Postfire accumulation rates were similar between the first (1991–2002) and second (2002–2015) burn intervals. Slopes estimates were 0.14–0.16 cm year^{-1}. Thus, 10 years after burning would yield 1.4–1.6 cm of additional forest floor at the estimated rates, or five times greater than net accumulation for unburned treatments. Accumulation of forest-floor mass was also considerably greater for burned than for no-burn treatments (P < .01), averaging 1.0 Mg ha^{-1} yr^{-1} and 0.4 Mg ha^{-1} year^{-1}, respectively. No difference in the rate of mass accumulation was detected between the first and second burn intervals (P = .74).

Forest-Floor Attributes

Forest-floor C and N contents in 2015 were 42 and 44 percent lower, respectively, on burned than on unburned treatments (Figure 3). In comparison, thinning alone had little effect on C content (P = .83) or N content (P = .63). Estimated C and N volatilization losses from burning in 1991 and 2002 were 12 Mg C ha^{-1} and 275 kg N ha^{-1}, respectively, for the burn-only treatment and 14 Mg C ha^{-1} and 320 kg N ha^{-1} for the thin and burn treatment.

Table 1. Effects of thinning and burning in central Oregon ponderosa pine forests on tree density, canopy cover, and foliage mass.

Treatment	Tree density (trees ha^{-1})		Canopy cover (percent)	Live foliage mass (Mg ha^{-1})
	1990	2007		
Control	615 (75)	561 (41)	60 (6)	14.2 (1.9)
Burn	603 (77)	458 (13)	50 (8)	8.9 (0.9)
Thin	279 (28)	269 (27)	42 (5)	9.0 (1.4)
Thin + burn	279 (33)	262 (32)	39 (5)	7.8 (1.2)

Note: Thinning was completed in 1989, and burning was conducted in spring 1991 and 2002. Canopy cover and live foliage mass were based on 2001 tree-diameter and crown-width measurements. Values are means plus standard errors in parentheses (n = 3).

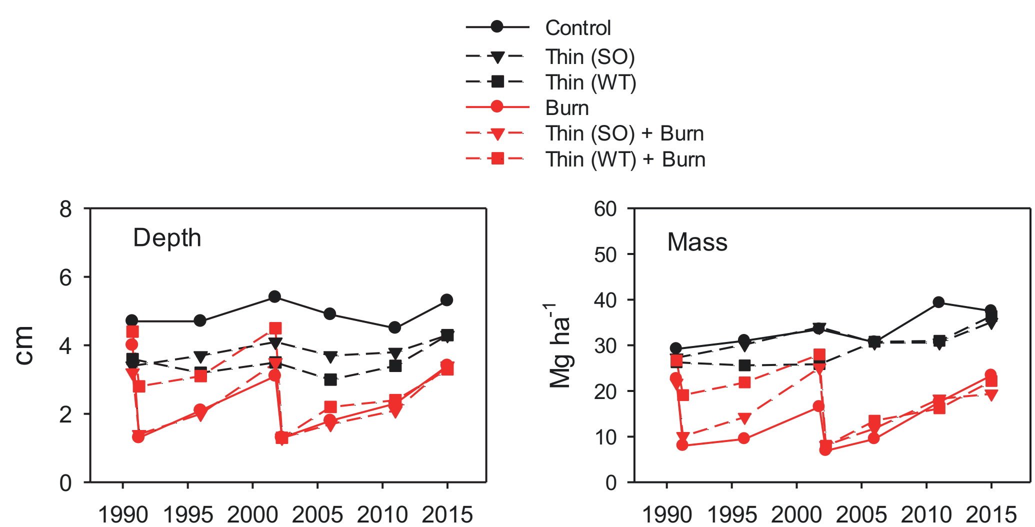

Figure 2. Twenty-five-year changes in forest-floor depth and mass following thinning and burning. Plots were thinned in 1989 and burned in the spring of 1991 and 2002. Data points are means. Standard error of the mean for all treatments and dates = 0.4 cm for depth and 4.0 Mg ha^{-1} for mass. SO = stem-only thin; WT = whole-tree thin.

These losses represent approximately 9 percent of the site C pool and 13 percent of the site N pool found on control plots (Figure 4). Interestingly, the majority of C (80–86 percent) was contained in tree biomass plus mineral soil, whereas the majority of N (73–83 percent) was found in mineral soil.

Results from the litterbag study showed an average decay (mass loss) across all treatments of 39 percent by the end of the second year (Figure 3). No statistically significant differences were detected for thinning method ($P = .41$), burning ($P = .34$), or their interactions ($P = .45$). Similarly, there were no statistically significant effects of thinning ($P = .78$), burning ($P = .67$), or their interactions ($P = .11$) on litter microbial biomass.

Herbaceous biomass was low for all treatments, averaging 14 ± 3 kg ha^{-1} across six growing seasons. No differences in biomass were detected due for burning ($P = .37$), thinning method ($P = .25$), or the burning × time interaction ($P = .38$). In addition, the relation between forest-floor depth and herbaceous biomass was weak ($r^2 = .01$; Figure 5) across a range of litter depths from 0.5 to 6.7 cm.

An ephemeral increase in percent bare soil was noted after the 2002 burns, as 22–25 percent of the ground surface area had exposed mineral soil at 2 months after burning (Table 2). Bare soil declined to <5 percent by four growing seasons after burning and remained comparable to unburned treatments for the remainder of the study, resulting in a significant time × burning interaction in repeated measures ($P < .001$).

Discussion

Forest-floor organics contribute to soil quality, site nutrient content, and erosion protection (Tiedemann et al. 2000, Binkley and Fisher 2019), but typically forest management recommendations favor reducing forest-floor mass in order to increase plant diversity and decrease wildfire hazard (Craigg et al. 2015). We addressed this conundrum by examining the trajectory of forest-floor development and evaluating changes in forest-floor functions associated with traditional forest practices. During the 25-year study period, thinning without subsequent burning resulted in only minor changes in forest-floor depth, mass, or ecological function. In comparison, repeated burning alone or in combination with thinning resulted in reduced forest-floor depth and mass, moderately rapid forest-floor recovery rates, and short-lived changes in forest-floor function. An exception to this was a fire-volatilized reduction in the total N pool, which arguably has the potential to reduce the long-term productivity of these low-fertility sites. Nevertheless, most evidence pointed to a modest response by the forest floor to the

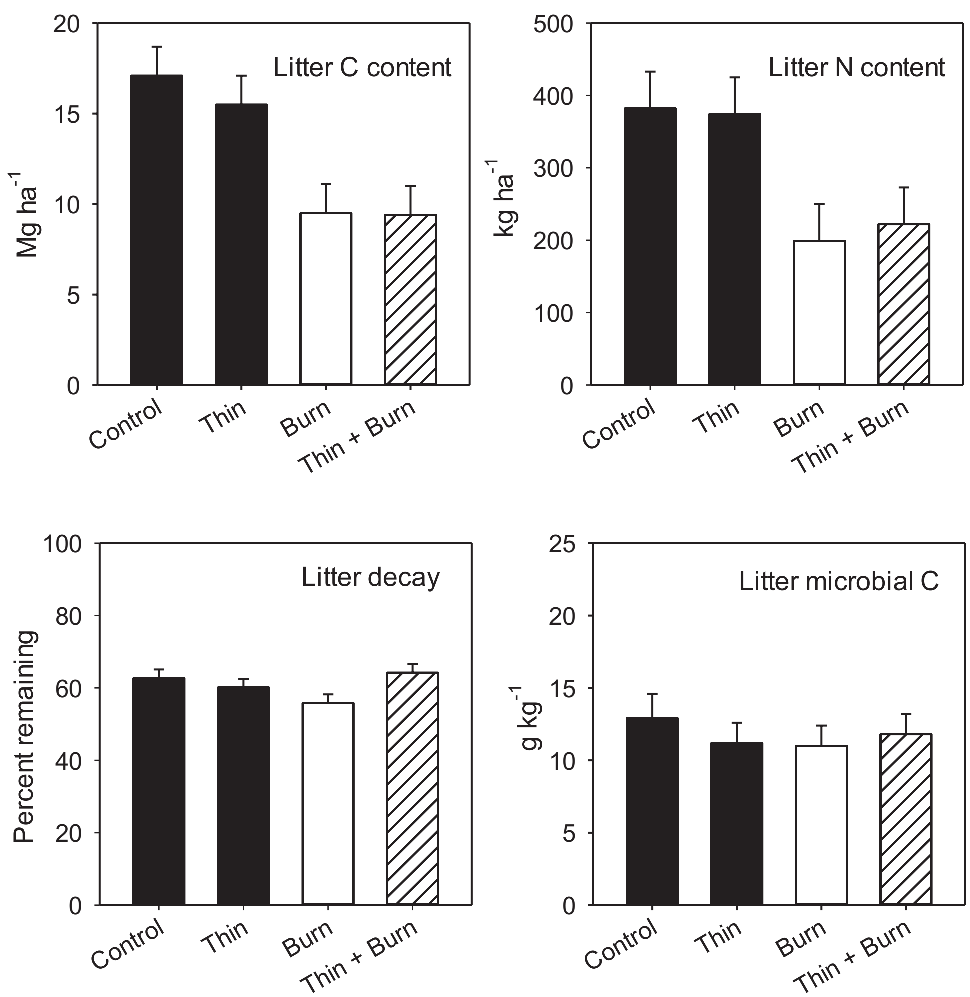

Figure 3. Effect of thinning and burning on litter C and N content, litterbag decay, and litter microbial C. Carbon and N content values are from samples collected at year 25 (2015). Litter decay and microbial C are from a litterbag study conducted between 1992 and 1994. Bars are means plus SE.

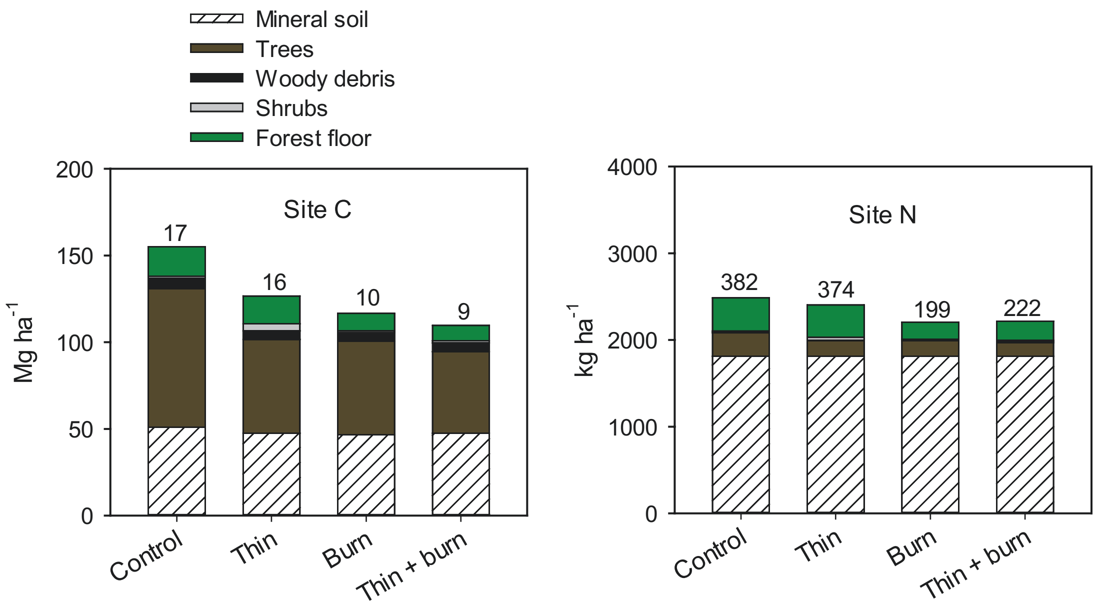

Figure 4. Site C and N pools. Mineral soil C and N content are from Little and Shainsky (1995); tree data were calculated as the product of stand volume (Busse et al. 2009) times wood C and N concentrations from Little and Shainsky (1995); woody debris and shrub C and N content were calculated as the product of their mass (Busse et al. 2009) times their respective C and N concentrations (Little and Shainsky 1995); and forest-floor C and N content are from Figure 3. Values above each green bar are the respective forest-floor C or N content for a given treatment.

thinning and burning prescriptions. Thus, maintaining forest-floor soil quality while also meeting fuel reduction needs is an obtainable objective in these forests.

Forest-floor accumulation on burned plots was rapid, such that the projected forest-floor depth approached preburn levels in 15–20 years, which is within the historic fire-return interval for these forests of 4–24 years (Bork 1984). Moderately rapid recovery rates also were found after prescribed burning in pine and mixed-conifer forests in the Sierra Nevada of California (Parsons 1978, Keifer et al. 2006, Vaillant et al. 2015). These collective results are likely explained by input of burned needle cast and, more importantly, slower decay of thin, dry surface layers that develop following fire (Raison et al. 1986, Köster et al. 2016), and have relevance for managers considering repeated burn options and frequencies. From strictly a forest-floor perspective, reburning every 15–20 years would balance both soil quality and fuel hazard concerns while of course recognizing that numerous operational, budget, ecological, and societal factors also weigh into prescribed fire decisionmaking (Agee and Skinner 2005). Interestingly, results from the litterbag study did not reflect the 25-year trends at our sites, as no differences in decay were found between treatments during the 2-year incubation. This supports the suggestion of Prescott (2005), who questioned the validity of short-term litterbag studies to accurately predict long-term spatial dynamics of complex forest-floor organics. In our case, we placed the litterbags on the forest-floor surface, and hence they were not exposed to possible variations in moisture conditions within the duff layer.

An additional study objective was to determine whether forest-floor organics accumulate unchecked in dense pine forests without fire. Results from other studies have shown that, to the contrary, forest-floor depth and mass often reach an equilibrium within a given climatic region as litterfall and decomposition rates eventually equalize after disturbance (Birk and Simpson 1980, Keifer et al. 2006). Sizable duff accumulation at the base of large-diameter conifers in more mature, fire-suppressed stands is an important exception to this concept (Hood 2010, Kreye et al. 2014). Still, we found only small changes in forest-floor content for untreated plots between 1991 and 2015, leading us to agree with earlier studies that an upper limit to forest-floor accumulation is common in young stands.

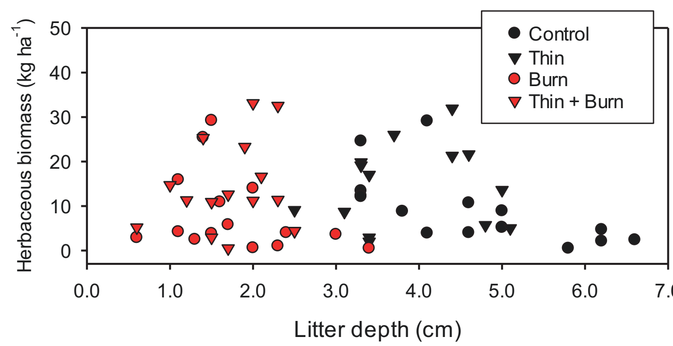

Figure 5. Relation between forest-floor depth and herbaceous biomass measured during peak-season growth (late June to mid-July) between 1992 and 2003. Values are plot averages.

Similarities in forest-floor accumulation between control (615 trees ha^{-1}) and thinned (279 trees ha^{-1}) treatments were also noteworthy. Control plots had on average 55 percent greater foliage mass than thinned plots, but this did not lead to greater forest-floor accumulation as might be expected (van Wagtendonk and Moore 2010). Agee and Lolley (2006) also found minor differences in forest-floor mass between unthinned and thinned conifer forests in central Washington within a year of treatment, and Busse et al. (1996) found no differences in forest-floor mass among treatments ranging from 154 to 1,235 trees ha^{-1} after

Table 2. Effect of thinning and burning on soil erosion potential (percentage bare soil).

Sampling date	Control	Thin	Burn	Thin + burn
2002—preburn	1 (1)	4 (3)	2 (2)	2 (1)
2002—3 months postburn	1 (1)b	4 (3)b	25 (9)a	22 (7)a
2006	1(1)	1 (1)	4 (3)	2 (1)
2015	1 (1)	1 (1)	1 (1)	1 (1)

Note: Mean values (standard errors in parentheses) within rows followed by different letters are significantly different at $\alpha = 0.05$.

several decades of stand development. This suggests that bioclimatic control of litter decomposition is a primary determinant of forest-floor development in dry systems without fire, and that greater litter input in unthinned stands leads to greater duff moisture content and, consequently, faster decomposition rates than thinned stands (Marty et al. 2015).

How thinning and burning affect forest-floor functions was a key aspect of our study. If surface organic layers were thin and patchy prior to the fire-suppression era, is there an ecological benefit in retaining a thicker layer in present-day forests? Are soil quality, plant community growth, or fire hazard jeopardized or, alternatively, improved by a more robust forest floor? The attributes we examined (herbaceous plant production, litter decay, exposed bare soil, and C and N content), although not a comprehensive set, offer a starting-point to answer these questions.

Thinning and burning had little effect on herbaceous plant production or erosion potential. We had hypothesized that plant biomass would decline as forest-floor thickness increased and became a physical barrier to seedling emergence. Instead, herbaceous biomass was exceedingly low regardless of treatment across a range in depths from 1 to 7 cm. Two factors likely contributed to this observation. First, herbaceous production and diversity are generally low in central Oregon pine forests, even after moderate disturbance, and require substantial nutrient additions for plant establishment and growth, additions that far exceed the amount of nutrients released from low to moderate prescribed fire (Busse et al. 2009). Second, the range of forest-floor depths at the study sites may have been inadequate (too shallow) to properly test our hypothesis. In the case of potential erosion, the burn treatments produced an ephemeral increase in bare soil (22–25 percent), which is well below the range of 50–75 percent bare soil required for accelerated surface erosion (Robichaud et al. 2013, Harrison et al. 2016), and thus was considered of minor consequence.

Finally, forest-floor total C and N were approximately 40 percent lower in burned than unburned plots at the end of the study, a direct reflection of 25 years of forest-floor mass loss by burning. Loss of soil N to the atmosphere, in particular, is a well-documented consequence of prescribed burning (Neary et al. 1999). Most N is volatilized from forest-floor organics, not mineral soil, with the amount of N lost proportional to the mass of organic matter consumed. Studies from a variety of forested ecosystems document N losses between 50 and 700 kg ha^{-1} depending on site and burn conditions (see Busse et al. 2014). Our N loss estimate of 275–320 kg ha^{-1} from the two burns is within this range and is similar to findings for interior pine and mixed-conifer forests (Johnson et al. 1998). As a point of reference, the thinning prescription resulted in N removal of 50 kg ha^{-1} for SO harvesting and 90 kg ha^{-1} for whole-tree harvesting (unpublished data).

Whether N losses from prescribed burning influence long-term soil quality depends largely on site fertility. Fertile soils are well buffered to withstand N losses from even severe prescribed burning with little consequence. However, infertile sites with low total N content, like those in central Oregon, are at greater risk. In our case, the estimated loss of 300 kg ha^{-1} represented only 13 percent of the total site N and may not be considered a serious consequence. Some concern is noted, however, because this N loss will not be replaced for 150–300 years given the estimated N input rate of 1–2 kg ha^{-1} year^{-1} from atmospheric deposition and N fixation in these forests (Busse 2000). Thus, awareness of forest-floor consumption targets and fire frequency cycles that minimize forest-floor N loss is suggested for nutrient-poor sites when full N retention is considered important. In this regard, Johnson et al. (1998) predicted that N losses in dry pine systems would be greatest for frequent fires (5–10-year cycle) and minimized if return intervals exceed 20–30 years.

Conclusion

Forest-floor organics were monitored for 25 years in moisture- and nutrient-limited pine forests, and the effects of thinning and burning on their mass, depth, rate of recovery, and selected functions determined. Use of long-term research plots and repeated measures was invaluable for tracking both instantaneous (fire consumption) and subtle, decade-long changes in litter and duff. Thinning alone produced few changes in forest-floor characteristics compared to control plots, indicative of a long-term balance between litterfall and decay processes in the absence of fire. By comparison, prescribed burning—with or without thinning—consumed 50–70 percent of the forest floor and was followed by a fairly rapid recovery to preburn levels within 15–20 years. Postfire erosion potential (exposed mineral soil), however, was low, as was herbaceous biomass across multiple growing seasons after burning. Repeated burning resulted in approximately 300 kg ha^{-1} N loss, or approximately 13 percent of the site N pool. The results showed that forest-floor characteristics were not strongly influenced by thinning or burning, and that maintaining soil quality while providing effective fuel reduction is a compatible objective in central Oregon pine forests.

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