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Soil amendments alter tree growth and wood decay after forest thinning

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Abstract

Forest soil amendments are increasingly used in western US forests to dispose of unmerchantable woody residues, reduce wildfire risk, and improve soil properties. Our objective was to determine the effect of fertilizer and organic amendments on tree growth and organic matter decomposition after thinning. Treatments were a control, three single soil amendments (wood chips, fertilizer, and biochar), and one combined soil amendment (biochar + fertilizer), each applied after thinning a ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws) stand. After 10 years, amendment treatments had no effect on tree diameter increment ($p = 0.600$), but the biochar + fertilizer and wood chip treatments significantly increased height growth ($p = 0.006$). To estimate belowground biological changes, we used wood stakes made from aspen (*Populus tremuloides* Michx.) and loblolly pine (*Pinus taeda* L.) as an index of microbial activity. Stakes were placed: (1) on top of the litter/amendments, (2) at the interface between the litter/amendments and mineral soil, and (3) vertically inserted into the mineral soil, and stake mass loss was measured over 5 years. Stake mass loss of each species was least on the soil surface and increased with increasing depth. Aspen stakes generally had greater mass loss at all three soil locations in the fertilizer and biochar treatments. In contrast, pine stake mass loss was lower than aspen and less affected by fertilizer. Using thinned tree biomass to create amendments can improve forest productivity by enhancing soil conditions and mitigating wildfire. However, the impact of amendments on tree growth may take decades to be detectable.

Plain Language Summary

After harvesting trees there is a great deal of woody biomass remaining on a forest site. This biomass can be converted into wood chips and biochar. In western Montana, we applied fertilizer, wood chips, and biochar as single treatments and a combined treatment of fertilizer + biochar. Amendments were placed around the stem of the tree. We measured tree growth and wood decay, on top of and within, the soil. The biochar + fertilizer and wood chips treatments had greater height growth, but it took 10 years to be able to detect this difference. Wood decay was slowest on top of the organic horizons and amendments and was greatest in the mineral soil. The mineral soil remained cooler and had greater moisture content throughout the year which helped to increase wood decay rates. Using wood chips or biochar, rather than burning piles, is a viable option for land managers seeking to reduce slash piles and limit the risk of wildfire. These amendments improve soil microbial conditions.

1 | INTRODUCTION

Ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws) forests cover about 3 million ha across the northern Rocky Mountains (Van Hooser & Keegan, 1988), and historic frequent fires at 5- to 25-year intervals maintained open and sustainable stands (Arno, 1988). As a result of reduced burning by indigenous peoples (Barrett & Arno, 1982) and active fire suppression (Savage & Swetnam, 1990), natural disturbance regimes have been interrupted (Naficy et al., 2010), and net forest volume has increased by 30% since 1953 (Oswalt et al., 2014). Therefore, thinning is routinely used in many forests to regulate stand structure, decrease wildfire risk, and increase forest resilience to drought (Sohn et al., 2016).

Thinning operations generate large volumes of woody biomass with nearly 8 million dry tonnes/year of logging residues produced across all forest types in the 15 western states of the United States (U.S. Department of Energy, 2011). This material is generally considered to be unmerchantable and is usually piled and burned. However, pile burning can create undesirable impacts on soil properties, and produce smoke and other air pollutants (Jang et al., 2017), and, therefore, other place-based options for reducing unmerchantable biomass are needed. Two of these options are mastication and place-based biochar production.

Wood chips from the mastication of excess woody residues are a common soil amendment that can be left on the soil surface or incorporated into the mineral soil. Although masticated wood incorporated into the mineral soil can increase mineral soil carbon (C) pools, it generally has little effect on forest floor or mineral soil C pools when left on top of the litter layer (Busse et al., 2008). Adding high-C masticated residues to the soil surface can increase microbial decomposition by increasing soil moisture retention but may result in less available nitrogen (N) for tree growth (Turner, 1977). Conversely, masticated wood on the soil surface can increase soil N content by stimulating nonsymbiotic N-fixation (Jurgensen, 1973).

Conversion of unmerchantable woody residues to biochar using on- or near-forest methods is also gaining popularity (Rodriguez Franco et al., 2022, 2024). Amending soil with biochar is an option that can increase soil water-holding capacity (Blanco-Canqui, 2017), decrease nutrient leaching (Ippolito et al., 2015), reduce compaction (Blanco-Canqui, 2021), promote fine-root production (Razaq et al., 2017), sequester C (Paustian et al., 2019), and increase tree growth (Thomas & Gale, 2015; Vannini et al., 2022). In addition, biochar can stimulate microbial activity (J. Wang et al., 2015), which accelerates the decomposition of soil organic matter (OM) (e.g., Gomez et al., 2014; Mitchell et al., 2015; Steinbeiss et al., 2009). Similar to adding masticated wood, biochar additions can also change nutrient availability (Rondon et al., 2007), which may have positive or negative effects on forest growth. Further, adding biochar to the soil after stand thinning may increase soil pH (Wrobel-Tobiszewska et al., 2016) and increase N mineralization rate and ammonium concentration (Gundale et al., 2016).

Ponderosa pine stands in the northern Rocky Mountains often have very low levels of inorganic N in the mineral soil because of slow decay rates and rapid plant uptake (DeLuca, 2000). In addition, many forest soils in this region are also considered nutrient deficient (Coleman et al., 2014; Mandzak & Moore, 1994; Moore et al., 2023). Low fertility soils, combined with a management focus on increasing environmental and ecosystem services, support the promotion of using place-based production systems to convert high-C biomass into biochar or masticated wood for soil application (Rodriguez-Franco et al., 2022). Yet, it remains unclear how additions of these high-C substrates may affect soil nutrient availability and wood decomposition rates, and if fertilization may be useful to compensate for any negative effects on nutrient pools.

Therefore, our objective was to assess the effects of masticated wood, biochar, and fertilizer (alone or combined) on tree growth and OM decomposition after thinning a ponderosa pine stand in the northern Rocky Mountains. We used wood stakes as an index of decomposition, in which wood quality is held constant and stake mass loss (decay) is a function of changes in soil properties from the treatments. Wood is a normal component of forest soils, and wood stakes have a long residence time, so longer term data can be collected. Stakes of two species, trembling aspen (*Populus tremuloides* Michx.) and loblolly pine (*Pinus taeda* L.), were used because they have differing properties (e.g., lignin–cellulose ratio, N content) and each could favor differing wood decay microbial communities (Blanchette, 1984). Further, non-native trembling aspen and loblolly pine were used because they are the species used in global study on wood decay (M. Jurgensen et al., 2006; Risch et al., 2013). Stakes were placed (1) on top of the surface OM (litter layer) or, where present, the amendment (e.g., masticated wood chips, biochar, fertilizer), (2) at the interface between the OM layers and, where present, the amendment and the mineral soil, and (3) in the mineral soil. We hypothesized that: (1) masticated wood and biochar would increase soil moisture; (2) masticated wood, biochar, and fertilization would increase tree growth; and (3) masticated wood, biochar, and fertilization would increase wood stake decomposition.

Core Ideas

- Amending forest sites with wood chips, biochar, or fertilizer is becoming more common.
- Wood stake decomposition can be used as an index of belowground changes in microbial activity.
- Aspen wood stake microbial decay was greater 5 years after soil amendment as compared to pine stakes.
- Tree growth was greater in the masticated wood chips and biochar + fertilizer treatments after 10 years.

2 | MATERIALS AND METHODS

2.1 | Study site

The Swift Creek harvest unit was established on the Bitterroot National Forest in western Montana near Sula, MT (45.8928° N, 113.7717° W) at an elevation of 1844 m. In 1965, the stand was clearcut-harvested; the soil surface was mechanically site-prepared in 1966 and planted with ponderosa pine seedlings. A pre-commercial thinning was conducted in 2009 (just prior to establishing this study). The site is dominated by ponderosa pine with an understory of Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass (*Pseudoroegneria spicata* Á. Löve), rosy pussytoes (*Antennaria rosea* Greene), and onespike oatgrass (*Danthonia unispicata* Monroe ex Macoun).

The soil on our study site was primarily the Macmeal series, which is a loamy-skeletal, mixed, superactive, frigid Typic Haplustalf (Soil Survey Staff, 2023). The soil texture of the surface 20 cm of mineral soil is gravelly loam, with a rock fragment content of 38% and a pH of 5.4 (Soil Survey Staff, 2023). Slopes range from 30% to 35% with a site index (SI_{100}) of 18 m (Milner, 1992). The site has a mean annual air temperature of 3.9°C and receives 620 mm of precipitation yearly with 80% falling as snow.

In 2009, two out of every three trees in the harvest unit were removed using ground-based logging operations. At the start of the experiment in 2010, trees ranged 23.1–30.0 cm in diameter and tree heights ranged 10.7–15.0 m (H. C. Anderson et al., 2017). A subset of residual trees was selected as experimental units based on uniformity of height and diameter (±10%). Trees were randomly assigned to one of five treatments in six replicates. In August 2010, a 4-m radius plot was established around each tree bole and these treatments were applied: (1) an untreated control, (2) a mineral fertilizer blend, (3) 112 Mg/ha masticated wood, (4) 25 Mg/ha biochar, and (5) 25 Mg/ha biochar + fertilizer for a total of 30 tree plots (six replicates × five treatments). Mastication was conducted operationally, which resulted in all trees having some masticated material on top of the surface litter layer. Therefore, to examine the effects of fertilizer or biochar amendments, the masticated wood chips were removed from the treatment area around those trees receiving other amendments.

2.2 | Soil amendments

2.2.1 | Fertilizer

A total of 517 kg/ha fertilizer was applied as 224 kg/ha N as urea, 190 kg/ha potassium chloride (KCl), 100 kg/ha ammonium sulfate (NH_4SO_4), and 3 kg/ha elemental boron (B) on top of the litter layer.

2.2.2 | Biochar

Biochar was created in equipment manufactured by Biochar Solutions, Incorporated (Carbondale, CO) using fast pyrolysis. The feedstock was a combination of green mixed conifer (90% ponderosa pine) and beetle-killed lodgepole pine (*Pinus contorta* Douglas ex Loud.) forest residues. The feedstock was ground, screened, and dried to 6%–8% moisture content before pyrolyzing. Biochar was created using a two-stage reactor. In the primary reactor, the feedstock is carbonized in a controlled aerobic environment with limited oxygen at a temperature between 700 and 750°C for less than 1 min. The material passed into a second reactor, where it was held in a sweep gas environment for approximately 10–15 min at a temperature between 400 and 550°C before being removed from the machine by a liquid-cooled auger with an air lock (N. Anderson et al., 2013). The biochar particle size classes ranged from 0.05 to 6 mm with an initial C content of 70.5% C:N of ∼200, and ash content was 94 mg/kg (N. Anderson et al., 2013; Sarauer et al., 2019). Biochar was applied to the top of the litter layer at a dry rate of 25 Mg/ha.

2.2.3 | Wood chips

Since this was pre-commercial thinning, removed ponderosa pine trees were generally less than ∼10 cm in diameter. All harvested material was masticated using a rotary mower and applied as a 3- to 5-cm deep layer (∼112 Mg/ha) on top of the surface organic horizons.

2.3 | Soil sampling

Immediately after treatments were applied, and at year 5 post treatment, the mineral soil was sampled at two depths (0–10 cm and 10–20 cm). Before collecting mineral soil samples, the surface litter, masticated wood, biochar, and any green vegetation were removed. Samples were collected from within 1 m of each tree base for a total of 30 samples (three replicates × five treatments × two depths). The surface OM was not collected in year 1 since the soil surface was highly disturbed. After drying at 60˚C for 48 h (to a constant weight), samples were ground to pass a 2-mm sieve and homogenized for C and N analyses on a TruSpec CN analyzer (Leco, Corp.).

At year 5, we collected the entire litter layer (inclusive of organic amendments, if applied) from within a 30-cm diameter hoop at a randomly selected location approximately 1 m from the tree stem, dried at 60˚C for 48 h, weighed, ground, and analyzed for C and N as shown above. Once the litter layer was removed, the mineral soil was sampled using an impact hammer with a core volume of 57.6 cm^3 (4.8 cm × 10 cm), placed into a zip-type bag, and transported to the Forestry Sciences Lab, Moscow, ID, for C, N, and pH analyses. Carbon and N were analyzed on the TruSpec CN analyzer (LECO Corp.), and pH was analyzed on a 2:1 water:soil paste. Soil OM was measured by weight loss after ignition at 375˚C for 6 h. Although this soil is classified as skeletal (>35% of rock fragments that are >2 mm), we had few rocks in our core samples, and our total and fine-fraction bulk density values were very similar (data not shown). Therefore, we used total bulk density to convert C and N concentrations to content.

We installed soil temperature probes (Onset Computers) and ECH_2O moisture probes (Meter Group) at the 5- and 10-cm mineral soil depths in one replicate of the control, wood chip, and 25 Mg/ha biochar treatments. These probes were attached to a datalogger (Onset Computers), which recorded data every 4 h, but sometimes were pulled from the soil or the wires destroyed by animals. This likely had an impact on the strength of our soil moisture results.

2.4 | Tree measurements

Tree heights were measured with a laser rangefinder, and diameter at breast height was measured with a diameter tape after the stand was thinned and 10 years after treatments were applied.

2.5 | Wood stakes

2.5.1 | Stake installation

For details on wood stake production, see M. Jurgensen et al. (2006). In general, aspen and pine stakes were cut from kiln-dried, knot-free sapwood. Stakes were cut to the desired length, and a non-deployed section of the original wood was kept as a laboratory control (time = 0) to determine mass loss of all field stakes (M. Jurgensen et al., 2006). The top of each mineral stake was treated with a wood sealer to reduce moisture loss.

In fall 2010, in each soil amendment treatment and the control, we placed 25 pine and 25 aspen wood stakes horizontally on the surface of the litter layer/soil amendment and another 25 stakes of each species at the interface between the litter layer/soil amendment and the mineral soil. Surface and interface stakes were placed ∼2.5 cm apart and were secured in place with a landscape staple. To install the mineral soil stakes, the litter layer and any organic amendments were removed, and a 2.5-cm square, 20-cm deep hole was created with an impact hammer to minimize soil compaction at the wood-stake interface and damage to the physical properties of the stake during installation. Mineral stakes were placed ∼30 cm apart and were inserted so top of the stake was level with top of the mineral soil. After mineral stake installation, the surface organic layers were replaced. A total of 2250 stakes were used in the study: three replicates × five treatments × two wood stake species × three stake locations × five yearly samples × five stakes.

For each of the next 5 years, five stakes of each species from each soil location were randomly removed from each treatment replicate ($n = 450$ stakes/year), weighed in the field for later determination of wood stake moisture content at extraction, and sent to the College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, MI, for processing.

2.5.2 | Wood stake analyses

All wood stakes were dried at 105˚C for 48 h and weighed to determine total stake mass loss. Wood decomposition (mass loss) during each year of the study was measured by comparing the dry weight of each field stake with the weight of the corresponding control section (t_0). Once total mass loss had been determined, a 2.5 cm long block was cut from the 5- and 15-cm stake depth of each mineral soil stake to assess the effect of soil depth on wood mass loss and used to calculate mass loss for the 0- to 5-cm and 10- to 15-cm depths. Mass loss averages for each treatment and replicate were used as treatment observations in the statistical analyses.

3 | STATISTICAL ANALYSES

3.1 | Trees and soil

Individual tree periodic annual height and tree diameter increment was analyzed using a paired *t*-test. Soil properties were analyzed using SAS version 9.4 after testing the assumptions of normality and equal variance. If there were significant differences, treatment means were separated using Tukey's range test ($\alpha = 0.05$).

3.2 | Wood stakes

Analyses were conducted using SAS version 9.4 and assessed at $\alpha = 0.05$ significance level. SAS PROC GLM was used in conducting an analysis of variance (ANOVA). Factors in this analysis were sampling date (2011, 2012, 2013, 2014, and 2015), treatment (biochar, biochar + fertilizer, fertilizer, wood chips, and control), stake location (surface, interface, or mineral), mineral soil depth (5 and 15 cm), and replicates (3). The response variable was stake mass loss as a proportion of original mass, and each factor and all possible interactions were considered in the model. The arcsine square root transformation was used to homogenize the mass loss error term, as described in Steel and Torrie (1980). Post hoc assessments of significant effects and interactions were conducted with SAS PROC MEANS utilizing Tukey's range test ($\alpha = 0.05$). Assessments of significant replication effects were conducted with the LSMEANS procedure. Results of these tests were considered for either pooled or un-pooled variances, as indicated by preliminary *F*-tests for homogeneity of variance. Stake mass loss was averaged by replicate and used for each treatment × sampling date combination.

4 | RESULTS

4.1 | Soil changes

Surprisingly, after 5 years, there were no significant soil amendment differences in surface organic horizon total C, N, and OM contents or horizon depth for any added soil amendments (Table 1). While there was a large increase in total C and OM after applying wood chips and biochar, the small sample size and spatial variability in applying organic amendments, especially wood chips, likely resulted in the lack of significance among treatments. In general, the biochar-only treatment had the highest litter layer C content, and the wood chip treatment had the highest N and OM contents and the greatest litter layer depth.

In the mineral soil, total bulk density immediately post treatment and after 5 years was unaffected by the amendments (data not shown); however, overall, the average total bulk density decreased approximately 30% at the surface (0–10 cm) and 15% in the subsurface (10–20 cm) from the initial post-thinning bulk densities. The overall ANOVA for mineral soil changes shows the lack of treatment effect on both total C and N contents (Table S1). Since all amendments were applied to the surface of the litter layer, it is not unexpected that our initial mineral soil sampling detected no differences in soil C and N in 2010 (data not shown). Generally, after 5 years, the surface mineral soil total C and total N were unchanged after thinning and applying amendments, and C and N contents were lower at the 10- to 20-cm sampling depth (Table 2). However, treatment C content differences were not significantly different ($p = 0.052$), but the wood chip and biochar treatments generally did have higher C levels than the other treatments.

Soil moisture sensors produced reliable data during four out of five growing seasons. Near the mineral soil surface (5-cm depth), there were few moisture differences during the first growing season, but by 2013, both wood chips and biochar resulted in significantly higher soil moisture contents compared to the untreated control soil (Figure S1A). Over the next 2 years, there were no significant treatment differences, although the biochar treatment tended to have slightly higher soil moisture contents. When averaged across all years, at the 10-cm soil depth, there were no significant treatment effects on soil moisture (Figure S1B) and no clear treatment trends. In general, immediate post-rainfall event soil moisture was retained longer in the biochar and masticated plots from 2013 to the end of our study.

4.2 | Tree growth

During the 5 years of our study, the average tree diameter increased 5.5% in the control, 10% in the fertilized plots, and 11% in both the masticated and biochar plots. In the combined biochar + fertilizer plots, diameter increased 10%. Similarly, average tree height growth increased 1.8% in the control and 2% in all the amended plots (H. C. Anderson et al., 2017). Height differences were not detectable until 10 years after applying the treatments. At 10 years, the wood chip and biochar+ fertilizer treatments had significantly greater tree height increment than the untreated control (Table 3). While

TABLE 1 Average litter layer properties including any organic amendments (±SE) 5 years post treatment at the Swift Creek study site on the Bitterroot National Forest in western Montana ($n = 3$).

Treatment	Total carbon (Mg/ha)	Organic matter (Mg/ha)	Total nitrogen (Mg/ha)	Depth (cm)	Coefficient of variation (%)
Control	102 (30)	186 (58)	2.8 (1.1)	1.4 (0.6)	103
Fertilizer	109 (14)	197 (24)	3.2 (0.3)	1.4 (0.4)	75
Wood chip retention	136 (35)	244 (65)	3.6 (1.5)	2.5 (0.7)	71
Biochar	162 (51)	224 (66)	2.3 (0.6)	1.6 (0.4)	68
Biochar + fertilizer	124 (14)	173 (20)	1.8 (0.3)	1.4 (0.3)	51
***p*-value**	**0.524**	**0.724**	**0.739**	**0.505**	

Note: Bolded *p*-values denote treatment differences within each measured variable.

TABLE 2 Average total carbon and nitrogen content (±SE) at the 0- to 10-cm and 10- to 20-cm soil depth after 5 years (2015) at the Swift Creek study site on the Bitterroot National Forest, Montana ($n = 3$ at each depth).

Treatment	Carbon (Mg/ha)	Nitrogen (Mg/ha)
0- to 10-cm depth		
Control	31 (5)	1.6 (0.2)
Fertilizer	23 (7)	1.3 (0.2)
Wood chips	28 (3)	1.4 (0.2)
Biochar	34 (10)	1.5 (0.2)
Biochar + fertilizer	30 (10)	1.5 (0.2)
***p*-value**	**0.403**	**0.816**
10- to 20-cm depth		
Control	9 (1)	0.7 (0.1)
Fertilizer	7 (1)	0.5 (0.1)
Wood chips	16 (2)	0.9 (0.1)
Biochar	16(4)	0.8 (0.2)
Biochar + fertilizer	12 (2)	0.7 (0.1)
***p*-value**	**0.052**	**0.093**

Note: The bolded *p*-values denote differences among treatments within each sampling depth.

TABLE 3 Average tree height and diameter increment (±SE) from pretreatment to 10 years after thinning and organic amendment application at the Swift Creek study site on the Bitterroot National Forest in western Montana.

Treatment	Height increment (m)	Diameter increment (cm)
Control	1.8 (0.3)a	4.5 (0.5)
Fertilizer	2.9 (0.7)ab	5.4 (0.6)
Wood chips	4.1 (0.3)b	5.9 (0.4)
Biochar	2.7 (0.6)ab	5.9 (0.6)
Biochar + fertilizer	4.3 (0.6)b	5.5 (0.6)

Note: Different letters for height increment indicate significant treatment differences ($p = 0.006$).

the diameter growth increment of all trees receiving soil amendments was greater than the control trees, the differences were not significant ($p = 0.473$).

4.3 | Wood stake decomposition

The full ANOVA model for wood stake mass loss indicated that extraction date, treatment, and stake location and the 2-way interactions were significant factors (Table S2). The explanatory power of extraction date and stake location were quite large (*F*-value), which likely confounded the other study variables in the model. Therefore, we analyzed the results of each wood stake species separately. Although this statistical model is still valid, it does reduce the overall power of the test but increases the effect of treatment. There were significant treatment replicate differences for aspen ($p = 0.0061$) and pine stakes ($p \leq 0.0001$), which will be discussed in more detail in Section 5.

4.3.1 | Aspen

The length of time for the soil amendments to significantly affect aspen stake decomposition varied from 1 year in the mineral soil to 3 years on the soil surface (Figure S2). Although year is a significant factor ($p \leq 0.0001$), it is helpful to evaluate the treatment effects by combining all the sample years. After 5 years, the aspen stakes in the fertilizer, biochar, and biochar + fertilizer treatments had greater mass loss than the wood chip treatment and the control at all three stake locations (Figure 1). As expected, surface aspen stakes had little decay after 5 years (Figure 1A). Both surface and interface (Figure 1B) aspen stakes had the lowest mass loss on and under the wood chip treatment. Averaged over 5 years, mineral aspen stakes had significantly greater mass loss in the biochar treatment as compared to the control and wood chip treatments (Figure 1C) and significantly greater mass loss than surface and interface stakes (Table S2). Across all

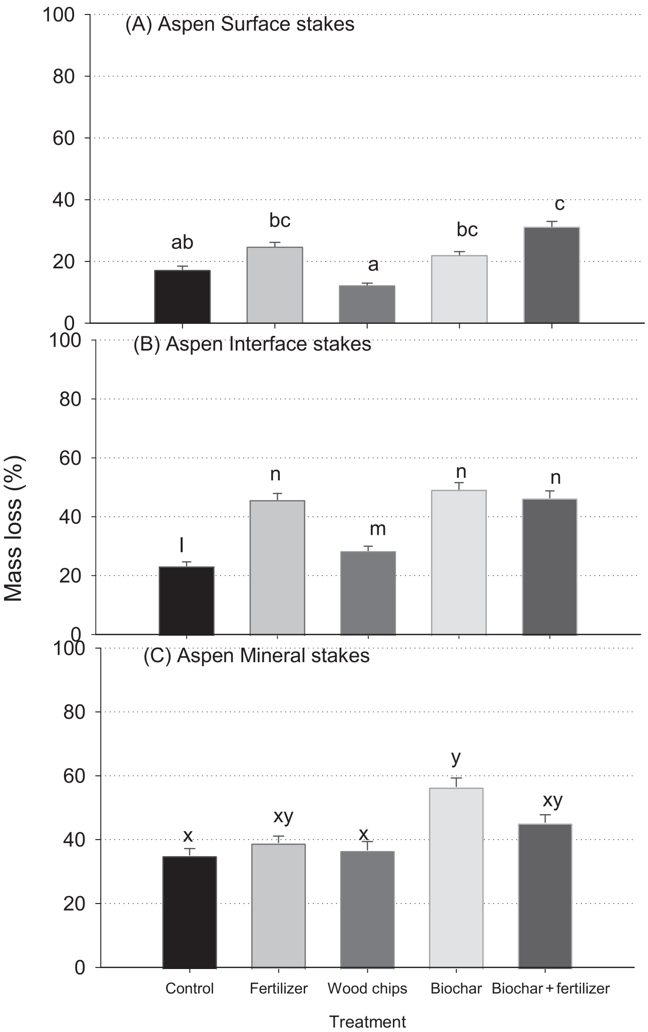

FIGURE 1 Mass loss of aspen stakes at the end of 5 years (A) on the surface of the litter layer and organic amendments, (B) at the interface of the litter layer/organic amendments and mineral soil, and (C) in the mineral soil at the Swift Creek study site on the Bitterroot National Forest in western Montana ($n = 225$ aspen stakes within each treatment and stake location). Within each stake location, bars with the same letter are not significantly ($\alpha = 0.05$) different.

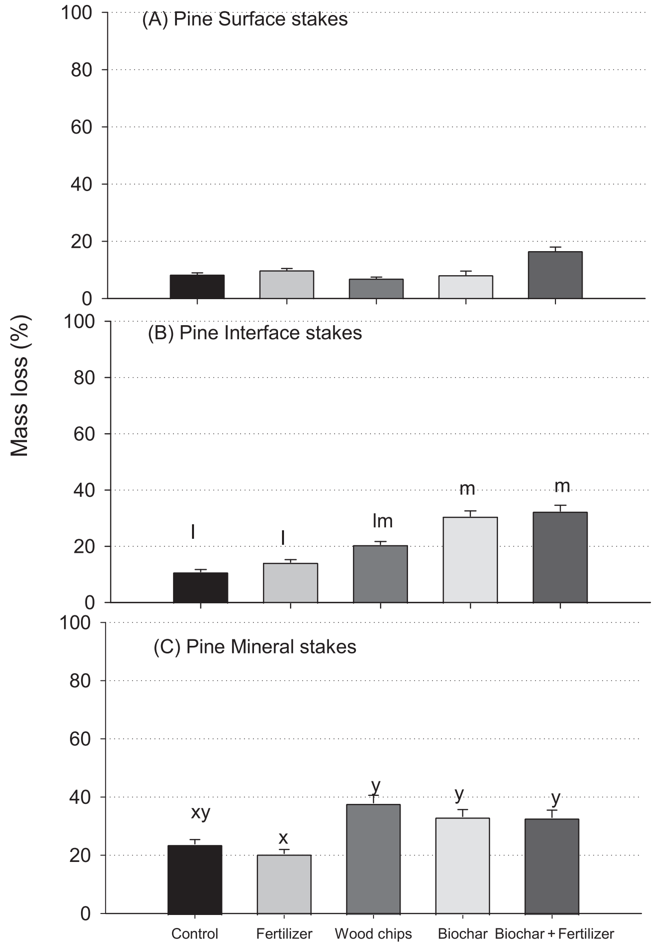

FIGURE 2 Mass loss of pine stakes at the end of 5 years (A) on the surface of the litter layer and organic amendments, (B) at the interface of the litter layer/organic amendments and mineral soil, and (C) in the mineral soil at the Swift Creek study site on the Bitterroot National Forest in western Montana ($n = 225$ pine stakes within each treatment and stake location). Within each stake location, bars with the same letter are not significantly ($\alpha = 0.05$) different.

sample dates and treatments, mineral aspen had significantly greater mass loss near the soil surface than at the 10- to 15-cm depth (Table S3).

4.3.2 | Pine

In contrast to aspen, none of the amendments affected surface pine stake decomposition (Figure S2), and overall mass loss was less than 20% across all treatments (Figure 2A). Further, it was not until the 4-year sampling that significant differences in Interface pine stake decomposition were found (Figure S3). After 5 years, Interface pine stake mass loss was significantly greater in the biochar and biochar + fertilizer treatments than in the control and fertilizer treatments (Figure 2B). Mineral pine stakes with wood chips, biochar, and biochar + fertilizer amendments had significantly greater mass loss than the fertilizer treatment ($p \leq 0.0001$; Figure 2C). Although mass loss was less for pine stakes than for aspen, a similar trend was found with greater mass loss near the soil surface (0–5 cm) than deeper in the soil profile (Table S3).

4.4 | Wood stake moisture content

Since it was difficult to get adequate soil moisture data, we also used wood stake moisture content as an index of soil moisture at each soil location when stakes were sampled annually in August. This provides an estimate of climatic conditions for approximately 2 weeks before sampling (Table S4). Similar to stake mass loss, there were significant moisture

TABLE 4 Aspen and pine moisture content for stakes placed on top of the litter layer and organic amendments, at the interface of the organic horizons and the mineral soil, and in the mineral soil averaged over 5 years for the Swift Creek site on the Bitterroot National Forest in western Montana ($n = 75$ stakes for each stake species, treatment, and location).

Species and treatment	Surface	Interface	Mineral soil
	Stake moisture content (%)		
Aspen			
Control	13.6a	17.3g	41.4l
Fertilizer	15.7a	22.8fg	38.9l
Wood chips	9.7a	24.5ef	41.9l
Biochar	13.4a	26.8ef	42.7l
Biochar + fertilizer	14.4a	32.4e	41.2l
Pine			
Control	17.7b	16.1e	31.9n
Fertilizer	23.7a	23.5f	32.0mn
Wood chips	17.5b	26.9f	35.9lm
Biochar	16.1b	22.8f	37.9l
Biochar + fertilizer	15.7b	24.6f	36.9lm

Note: For each species and stake location, different letters indicate significant differences among treatments ($p \leq 0.05$).

content differences among aspen ($p \leq 0.0019$) and pine ($p \leq 0.0001$) treatment replicates.

Averaged over the five sampling years, there were no significant differences in surface and mineral aspen stake moisture content (Table 4). Interface stakes did have a significantly higher moisture content in the biochar + fertilizer treatment as compared with the control and fertilizer treatments.

In contrast, surface pine stakes in the fertilizer treatment had a significantly greater moisture content than all other treatments. Although not always significant, Interface and Mineral pine stakes tended to have higher stake moisture contents in the organic amendment treatments.

5 | DISCUSSION

5.1 | Soil responses

Biochar tends to increase soil water retention and availability, with coarse-textured soils responding to a greater extent than fine-textured soils (e.g., Blanco-Canqui, 2017; Razzaghi et al., 2020). However, there are contradictory data that indicate biochar has no effects on soil moisture retention or availability (Streubel et al., 2011; Tyron, 1948) depending on soil texture, feedstock type, and biochar production method (Atkinson, 2018). Although our soil moisture data are fragmented, we did find a significant increase in soil moisture in the wood chip and biochar treatments beginning in year 2 at the 5-cm depth. This also tended to be the case for subsequent years. Similar to other work (Basso et al., 2012), we detected no significant moisture increases at the 10-cm depth, which is likely due to the length of time needed for the amendments to alter soil properties deeper in the soil profile.

Biochar and wood chip amendments have two distinct ways of changing soil moisture content. Masticating woody residues and leaving it on-site results in a mulch that changes evaporation rates from the mineral soil (Owen et al., 2009), but biochar is more effective at holding water once it moves into the mineral soil. The biochar we applied had a high Brunauer–Emmet–Teller (BET) surface area of 129 m^2/g and pore volume (N. Anderson et al., 2013), thus allowing for an increase in soil water holding capacity (Liu et al., 2017).

Soil C can also be altered by masticated fuel beds. In general, mastication increases O horizon depth and C content (Johnson et al., 2014). Although not significantly higher, the wood chip treatment had greater surface organic horizon C and N than the fertilizer treatment, indicating that mastication could be an effective strategy for short-term nutrient or C retention, especially with fresh residues (Johnson et al., 2014). A downside to adding masticated wood to forest soils is that it can result in N-immobilization (Scharenbroch, 2009). As decomposition proceeds, this N can be returned to the plant available N pool (Miller & Seastedt, 2009). However, the release of immobilized N can take more than a decade in some western forests (Keane et al., 2018). In addition, as masticated wood decays, it loses its ability to act as a mulch and retain soil moisture, and, in many cases, much of the C in the wood is lost to the atmosphere as it decomposes (Sikkink et al., 2017). There are few temperate forest studies that address changes in soil C after surface biochar additions. However, Sackett et al. (2015) found no change in total organic C and N concentrations 12 months after applying softwood and hardwood feedstock biochar in Ontario, Canada, indicating that movement of biochar through the litter layer(s) into the mineral soil can be slow. This is likely what happened on the Swift Creek site and why it took a decade to be able to detect any associated effects on tree growth. Furthermore, lack of significant differences in soil properties, particularly C, can be attributed to the surface variability among organic amendment applications and the time required for natural processes to move C and other nutrients into the soil. Soil disturbances associated with pre-commercial thinning and mastication may also mask early treatment responses.

Forest fertilization directly reduces nutrient deficiencies to increase microbial activity (Zhu et al., 2015). In addition to overstocking, many forests have soil nutrient limitations that can reduce plant growth (Gress et al., 2007), and ponderosa pine forests growing on low fertility soils respond favorably to fertilization (Garrison-Johnston et al., 2005). As an amendment, forest soil fertilization is designed to increase needle nutrition and ultimately tree volume growth (Powers et al., 1988). However, forest fertilization can result in nutrients being largely retained within the litter layers and may not affect tree growth (Tiedeman et al., 1998). We found that masticated wood and the biochar + fertilizer treatments were most effective at increasing tree height increment, but not diameter increment after 10 years, and the changes may be related to soil water or nutrient retention within the mineral soil. The combination of thinning and fertilization may also increase microbial activities by allowing greater solar radiation to reach the soil surface and increasing temperature and moisture near the soil surface (Mission et al., 2005; Vesterdal et al., 1995).

Mechanical thinning operations can have varying effects on soil bulk density, but use of a slash mat or thick organic horizons is effective at minimizing soil compaction (McIver et al., 2003). Where the soil is severely compacted (e.g., log landings, skid trails) to depths greater than 10 cm, recovery can be slow (D. S. Page-Dumroese et al., 2006), but the Swift Creek soil bulk density recovered approximately 20% within the first 5 years post harvest. This is a high recovery rate for this geographic region (D. Page-Dumroese et al., 2000), but it is likely due to the skeletal nature of the soil, freeze-thaw action, and the initial depth of the surface organic horizons (McNabb & Startsev, 2022). In addition, application of masticated wood to the soil surface can buffer trafficking impacts on the mineral soil (Fernández, 2022). Consequently, the Swift Creek soil appears to be on a trajectory of bulk density recovery within a decade, which will lead to maintenance of stand productivity and microbial populations (McIver et al., 2003).

5.2 | Tree responses

Studies in the Inland Northwest United States have found that biochar amendments did not affect tree diameter (Sarauer et al., 2019) or volume (H. C. Anderson et al., 2017; Sherman et al., 2018) growth when measured 2–5 years after site treatment. However, we found that after 10 years, the biochar + fertilizer and masticated wood chip treatments resulted in greater height increment as compared to the control. This indicates that the time needed to see changes in tree growth after applying amendments to the litter layer in a thinned forest stand is due to the amount of time for the additional nutrients and water to move into the rooting zone. Agricultural studies usually incorporate biochar (or other amendments) into the mineral soil, and they generally see rapid responses (e.g., Palansooriya et al., 2019; Schmidt et al., 2021). However, in forests where biochar, masticated wood, and fertilizer are generally not incorporated into the soil, managers must rely on water, freeze–thaw cycles, or soil fauna to move amendments deeper into the soil profile.

5.3 | Wood decomposition

The addition of surface amendments generally improves soil temperature, moisture, and physical and chemical properties (e.g., Berryman et al., 2014; Jourgholami et al., 2021; M. F. Jurgensen et al., 2020; Pavlů et al., 2020), leading us to hypothesize that mulches and the added nutrients from fertilization would increase wood stake decomposition. In general, this was true, but we also found individual mulch or fertilizer treatment responses were quite variable, depending on stake location and time since application. The reduced canopy after thinning was likely responsible for low decay rates on the soil surface, where soil surface temperature and moisture are generally more variable and extreme (Tang et al., 2005; W. Wang et al., 2019). Although wood decay fungi are most active when temperatures rise, this can be moderated by the lack of moisture in the wood (A'Bear et al., 2013), as we noted for the surface stakes.

Nitrogen availability can be another factor in wood decay (van der Wal et al., 2007), and this appears to have been true for aspen stakes, as decay rates were generally higher in the fertilizer treatment. However, pine stakes tended to be unaffected by the fertilizer treatment, which may be related to a low wood cellulose to lignin content (W. Wang et al., 2018). For masticated wood (Edmonds, 1991) and biochar (Clough et al., 2013), N could be tied up for long periods of time and then slowly released, resulting in greater mass loss several years after the amendments are applied. This is consistent with our interface and mineral pine and aspen stakes, where mass loss was greater after 2–5 years. Wood stake mass loss after various land management practices (e.g., M. F. Jurgensen et al., 2020; D. S. Page-Dumroese et al., 2021) provide an understanding of the rate of wood decay, which is important for calculating C storage from decaying wood on or in the mineral soil, and how soil amendments may affect woody root decay and slope stability (M. F. Jurgensen et al., 2020).

The variability in applying all three amendments, combined with the physical, chemical, and biological heterogeneity of forest organic and mineral soil horizons, was likely the reason for the significant treatment replicate differences in stake mass loss and moisture content. For example, there were no significant mass loss differences among replicates for pine stakes on the soil surface and at the interface for each sample date and averaged across the 5 years, but there were differences in the aspen stakes. Less mass loss of aspen on the wood chip treatment could indicate that the thickness of the amendment combined with dry summers limited decay (Reed et al., 2020). In addition, slight changes in slope position or aspect could alter soil moisture, C, and N contents and affect fungal populations and wood decay rates at all stake locations (Bardelli et al., 2018). For all dates and stake locations, there was no clear trend showing that a single replicate was responsible for the significant differences in aspen stake mass loss, but pine stakes located in more westerly facing replicates had lower mass loss in all treatments ($p \leq 0.0001$). Canopy coverage, shade duration and amount, closeness to other trees, microclimate, or small changes in slope or aspect could contribute to changes in wood decay, particularly on the soil surface. Forest soil amendments can address several ecosystem problems (e.g., soil physical properties, slash pile burning) on soils with low fertility (Liu et al., 2017), but specific site results will vary depending on soil type, biochar type, topography, and climatic regime.

6 | MANAGEMENT IMPLICATIONS

As forest managers look for opportunities to reduce slash pile volume to limit the risk of wildfire and protect or improve soil conditions, mastication and on-site biochar production will become more common. Each of these amendments has value in protecting the soil from erosion or other disturbances, holding water, and, in some cases, increasing the residual forest stand growth. Although not common on federal lands, the joint application of fertilizer with biochar has the potential to decrease nutrient losses while also promoting tree growth and altering wood decay. Patience is required for detecting amendment impacts on decay or soil properties, and especially for tree height increment growth. Unless the soil is already disturbed (e.g., log landings, skid trails), these amendment types are typically applied to the soil surface rather than mixing them into the soil, resulting in minimal risk for any adverse physical effects from the treatment application. The rate of applied biochar (25 Mg/ha) did not have any deleterious effects on tree growth or soil properties, and it is likely managers could use any rate up to this amount and obtain forest and soil health benefits. Although not detected in our study after 5 years, both wood chips and biochar are options for managers seeking to increase soil C pools. However, wood chips have a short duration on the soil surface and the amount of C input to the soil pools depends on climatic regime and decomposition rate (Sikkink et al., 2017). Biochar is a long-term, more durable C input similar to wildfire-produced charcoal that can last in the soil for hundreds of years (Gundale et al., 2016). In addition, masticated wood and biochar are increasingly being added to climate-smart forest activities and used to remediate soil disturbances, mitigate climate change, or reduce wildfire hazardous fuels near roads, trails, or communities (Rodriquez Franco et al., 2024).

AUTHOR CONTRIBUTIONS

Deborah S. Page-Dumroese: Funding acquisition; investigation; methodology; visualization; writing—original draft. **Martin F. Jurgensen**: Data curation; formal analysis; writing—review and editing. **Chris A. Miller**: Data curation; formal analysis; writing—review and editing. **Joanne M. Tirocke**: Data curation; investigation; resources; writing—review and editing. **Derek N. Pierson**: Investigation; writing—review and editing. **Cole Mayn**: Project administration; resources; writing—review and editing. **Mark J. Kimsey**: Conceptualization; data curation; methodology; writing—review and editing. **Haley C. Anderson**: Methodology; resources; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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