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Restoration thinning impacts surface and belowground wood decomposition

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ABSTRACT

Forest thinning to protect the soil and improve hydrologic function is used to alter stand structure and increase residual tree growth. However, little is known about how surface and belowground wood decomposition (*i.e.*, soil process changes) respond to aboveground vegetation manipulation. We determined mass loss of three species of wood stakes (loblolly pine (*Pinus taeda* L.), trembling aspen (*Populus tremuloides* Michx.), and Chinese pine (*Pinus tabuliformis* Carriére)) placed horizontally on the soil surface and vertically in the mineral soil after thinning a Chinese pine plantation in northern China. Restoration thinning treatments consisted of three levels of overstory removal (30%, 41% and 53% of the standing biomass) plus an unthinned control. Stakes were extracted every 12 months for 2years, and then at 6 month intervals until the end of the study (3.5 years). Surface stake mass loss was significantly greater (9.0%) in the 30% overstory removal treatment than the control, but overall mass loss at the soil surface was very low (< 10%) after 3.5 years. In the mineral soil, aspen stake mass loss was greater than either Chinese or loblolly pine stakes, which had similar mass loss. In addition, mass loss was greatest in the 41% overstory removal plots. Stakes of all species decomposed faster deeper in the mineral soil than near the soil surface, but they were not affected by changes in soil N, OM, and pH after thinning. Overall, thinning this Chinese pine stand had little impact on surface and belowground wood stake decomposition.

1. Introduction

Woody biomass contains a significant portion of the terrestrial ecosystem C pool (Houghton et al., 1999, McGill et al., 2006, Piao et al., 2009, Pan et al., 2011). It is also important for nutrient cycling by heterotrophic microbes (Vance, 2000), forest productivity (Jurgensen et al., 1997), and likely contributes to the surface soil organic matter (OM) pool. Many factors affect wood decomposition, which include stand nutrient dynamics (Ganjegunte et al., 2004, Laiho and Prescott, 2004, Titus et al., 2006), climatic conditions (Yatskov et al., 2003, Remsburg and Turner, 2006, Moroni, et al., 2009), and wood C and nutrient concentrations (Busse, 1994, Chambers et al., 2000, Palviainen et al., 2008, Weedon et al., 2009, Palviainen, et al., 2010). Wood nitrogen (N), C/N ratio, and lignin content also have a large influence on decomposition rates (Findlay, 1934, Fogel and Cromack Jr, 1977, Wang et al., 2018), as wood with low lignin concentrations and C/N ratios generally decompose faster than wood with higher levels (Cornwell et al., 2009, Strukelj et al., 2013, Wang et al., 2018), and have been used as predictors of wood decomposition in forest soils (Entry and Backman, 1995).

Forest management practices that alter forest structure can also influence soil environments (*e.g.,* temperature, moisture) and can change wood decomposition rates. Decomposition of surface coarse wood has been studied in undisturbed stands (Harmon et al., 1986, Woodall et al., 2008) and after clear-cut harvesting (Ruiz-Peinado et al., 2013, Finér et al., 2016), but the influence of the partial removal of trees on wood decomposition in different biomes is not fully understood (Campbell et al., 2009, Page-Dumroese et al., 2010).

Thinning is used to reduce forest stand stocking levels to increase tree-level wood production, reduce fire risk, mitigate drought (Elkin et al., 2015), and increase resistance to pests (Tian, 2005, Tappeiner et al., 2015). Reductions in stand canopy cover could alter wood decomposition rates by increasing the amount of sunlight reaching the forest floor, thereby changing the temperature and moisture contents in

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both the soil and woody residue (Thibodeau et al., 2000, Martin et al., 2001, Brischke and Rapp, 2008, Brooks and Kyker-Snowman, 2008) and influencing subsequent N mineralization rates (Covington, 1981, Sinclair, 1992). Thinning activities that open the canopy and reduce stand transpiration rates can also change soil C contents, nutrient pools, and acidity (Jurgensen et al., 2012, Baena et al., 2013, He et al., 2018), which can affect fungal communities associated with wood decomposition (Girvan et al., 2003, Fierer and Jackson, 2006, Lauber et al., 2008, Asplund et al., 2018).

There have been relatively few studies on wood decomposition responses to either commercial or precommercial thinning. Campbell et al. (2009) show that in the northern Sierra Nevada Mountains woody residue decomposition on the soil surface was not significantly affected by thinning (thinned from below, around 33.6%), but woody root decomposition was three times greater in the thinned stands where stumps were prevalent. In Western Australia, thinning reduced tree density from 4000 to 380 stems ha^{-1} and the resulting residues on the soil surface decayed in relation to their diameter (O'Connell, 1997). The impacts of thinning on wood decomposition have been used to model C dynamics or productivity changes, but the models use generally applied OM decomposition rates taken from litter bags or coarse woody residue studies in undisturbed stands (Blanco et al., 2011). Decomposition rates of surface wood or wood in the mineral soil (*e.g.,* roots) has been used as a predictor of *Pinus sylvestris* L tree growth in the Pyrenees Mountains of northern Spain (Gárate and Blanco, 2014) and for assessing soil processes (Harvey et al., 1987).

However, there have be no efforts to determine how wood on the soil surface or in the mineral soil may decompose in relation to various thinning regimes in northern China. Therefore, we conducted a study in northern China to assess the effects of three levels of thinning in a Chinese pine (*Pinus tabuliformis* Carriére) plantation on the decomposition (mass loss) of wood stakes placed on top of the litter layer (hereafter referred to as surface stakes) and in the mineral soil (hereafter referred to as mineral stakes). Stakes made from native Chinese pine, and non-native loblolly pine (*Pinus taeda* L.) and trembling aspen (*Populus tremuloides* Michx.) were used to comprise a range of wood properties with different lignin and cellulose content, which favor the development of both brown-rot (conifer) and white-rot (hardwood) wood-decomposing microbial communities (Blanchette, 1984). For example, white rot fungi can degrade all components of wood, including lignin; brown rot fungi attack the hemicellulose and cellulose components, leaving much of the lignin behind (Worrall et al., 1997). Both loblolly pine and trembling aspen stakes are also used as standard substrates in a global wood decomposition network (Finér et al., 2016; Jurgensen et al., 2006; Page-Dumroese et al., 2019; Risch et al., 2013; Wang et al., 2018). Wood stakes do not have bark and, therefore, they are not meant to simulate the decay of surface wood or coarse roots in the mineral soil, but are an index of litter and soil properties (physical, chemical, and microbiological) that affect the wood decomposition process. We hypothesized that: (1) wood stake mass loss in both surface and mineral soil would increase as the level of thinning increased, and (2) decomposition would be greater in mineral soil than on the surface of the litter layer.

2. Materials and methods

2.1. Site description

This study was conducted in a Chinese pine plantation located in Pingquan county, Hebei province (118°40′E, 41°13′N), China, at an elevation of 700–800 m. The area has a semi-humid, continental monsoon climate, with a mean annual temperature of 8.1 °C (min. -32.9 °C and max. 41.5 °C) and, during the wood decomposition study (May 2013-Oct 2015, Fig. 1), had an average frost-free period of 135 days. Precipitation per annum was 542 mm with the majority of rainfall occurring during the summer months of June, July, and August (data from Pingquan weather station). Unfortunately, we were unable to collect soil moisture and temperature in each plot due to equipment failure. Across the site, soil was a sandy loam derived from granitic parent material. Before thinning, the 0–15 cm depth was sampled by taking 24 random samples across the site. Soil within this depth had an average pH of 6.7, OM concentration of 1.66%, and total N concentration of 0.053% (unpublished data). The dominant understory vegetation species were *Elsholtzia stauntoni* L., *Spiraea salicifolia* L., *Rosa multiflora* L., *Carex lanceolata Boott* L., *Potentilla tanacetifolia* L. and *Caragana sinica* L.

The plantation is 1.44 ha in size, was established in 1976 from seed, and had an initial stand density of 5000 trees/ha before being thinned in 2011 when the stand was 35 years old. Thinning was conducted improve forest health conditions by reducing fire risk and the opportunity for insect or disease outbreaks. As such, the cutting was considered a restoration thinning in China. Because of the steep slope (≤40°), trees were hand-felled and all thinning residues were immediately removed by hand. The selection of trees to remove was done systematically. Each thinning treatment was replicated twice, but because 1 replication was shallow to bedrock (< 10 cm deep mineral soil), only 1 of the thinned replicates was used. Study plots of 20 m × 20 m (0.04 ha) were randomly assigned across the slope and separated from each other by a 5 m wide buffer. Two plots (replicates) were thinned to each of these stand densities: low (30% overstory removal, 3290 trees/ha), moderate (41% overstory removal, 2770 trees/ha), or heavy (53% overstory removal, 2200 trees/ha), and an adjacent portion of the plantation was left unthinned as a control (4700 trees/ha).

2.2. Wood stakes

Aspen, loblolly pine, and Chinese pine wood stakes were cut from kiln-dried, knot-free sapwood. Two aspen and loblolly pine surface stakes (2.5 × 2.5 × 15 cm) were cut from a 40 cm long stake, and two mineral stakes (2.5 × 2.5 × 20 cm) were cut from a 50 cm long stake. Since wood for making Chinese pine stakes was limited, both surface and mineral Chinese pine stakes were only 15 cm long. The top cut surface of each mineral stake was treated with a wood sealer to reduce moisture wicking through the stake after installation. A 10 cm section of each stake was used as a control (time = 0) to determine wood stake mass loss during the study (for details of this method see Jurgensen et al., 2006).

In May 2012, two subplots of twenty-five surface stakes of each species were placed on top of the litter layer (< 0.50 cm thick) in each plot, and secured with a stainless steel landscape staple. An additional 25 aspen and loblolly pine stakes were inserted vertically in the mineral soil to a depth of 20 cm in each subplot. As noted above, Chinese pine mineral stakes were only 15 cm long and, therefore, inserted to a soil depth of 15 cm. To minimize changing the soil physical properties surrounding the mineral stakes and limit damage to stakes during installation, the surface litter was pushed aside and a 2.5 cm^3 hole was made with a metal coring tool. Stakes were inserted into the hole so the top of each mineral stake was level with the top of the mineral soil, and the litter replaced. A total of 600 surface and 600 mineral stakes were installed (4 treatments × 2 replicate subplots × 3 wood species × 25 stakes). In May 2013 (1 year), May 2014 (2 years), October 2014 (2.5 years), May 2015 (3 years) and October 2015 (3.5 years), five surface and five mineral stakes of each species were randomly selected and removed from each plot, weighed in the field, air-dried, and sent to the School of Forest Resources and Environmental Science at Michigan Technological University (Houghton, MI, USA) for mass loss determination.

2.2.1. Determination of stake mass loss and moisture content

All stakes were dried at 105 °C for 72 h and weighed. A 2.5 cm long block was cut from the 3.8 and 16.2 cm depth of each loblolly pine and aspen stake and from the 3.8 and 11.2 cm depths of each Chinese pine

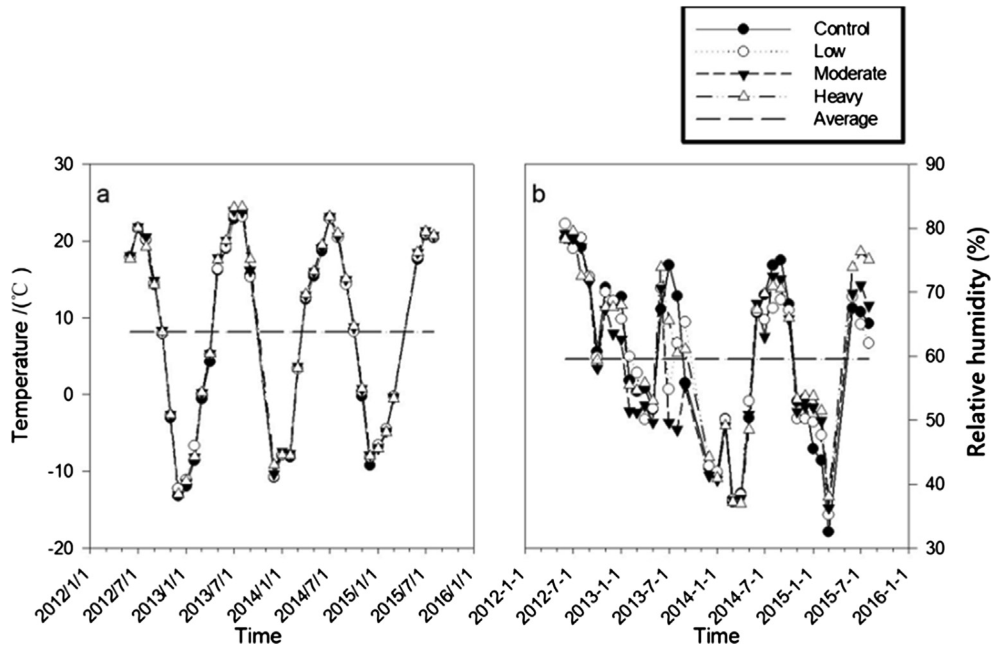

Fig. 1. Monthly (a) air temperature and (b) relative humidity in plots for the duration of the wood stake decomposition study (data from Oct-2013, Nov-2013, Apr-2015 and May-2015 were lost due to sensor failure).

mineral stake to assess the effect of soil depth on wood decomposition. Wood decomposition (mass loss) during each sample period was determined by comparing dry weight of each field stake to the weight of its corresponding control section (t_0). Mass loss averages for each plot were used as a treatment observation in the statistical analyses.

Stake moisture content was calculated using the field (wet) stake weight as an important factor for wood decay (Brischke and Rapp, 2008). Unfortunately, we were unable to measure soil moisture contents in the thinned treatments throughout the study period. Therefore, stake moisture content is used as a surrogate for soil moisture content and reflects soil conditions for the 2-4 weeks period prior to sampling.

2.3. Soil analysis

Six soil cores (50.6 mm [diameter] × 50 mm [height]) were collected from the 0–15 cm depth in each plot using an impact soil core sampler along an "S"- shaped transect immediately after thinning (July 2011) and at the end of the study (July 2015). Since the surface litter layer was shallow (< 0.50 cm), it was removed prior to sampling the mineral soil and not included in the analyses. Each composited soil sample was passed through a 2 mm screen to remove stones and root fragments, and stored at 4 °C until processing. Total soil N was determined by the Kjeldahl digestion method using H_2O_2 as the oxidant and a 0.5 g soil sample with 10 ml H_2SO_4 (William, 1980) followed by titration on a UDK 152 distillation and titration unit (VELP Scientifica, Usmate, Italy). Soil pH was determined in a 2:1 (water: soil) slurry (Vance, et al., 1987) and OM determined by the Walkley-Black method (Walkley and Black, 1934). The soil had very few rocks larger than 2 mm and, therefore, we did not correct N and OM concentrations for rock-fragment content (Page-Dumroese et al., 1999).

2.4. Statistical analyses

Stake mass loss, as a proportion of original weight, was the dependent variable in this factorial experiment, and was an average of 5 stakes/plot. An analysis of variance (ANOVA) was conducted with SAS (ver. 9.4; Cary, NC.) using a factorial design, and the factors in the ANOVA model were thinning treatment (low, moderate, heavy, and control), plot (2 plots within each treatment), extraction date (mass loss after 1, 2, 2.5, 3, and 3.5 years), and stake location (surface of soil litter layer and in mineral soil), and species of stakes (aspen, loblolly pine and Chinese pine). Within this model, plots were treated as nested effects within the thinning and control treatment. The nested effects were estimated by their own means instead of the mean across all plots. The initial model employed was the standard 'effects model' with factors and their interactions included.

When significant interactions were detected, the 'means model' was used to clarify the relationships (Page-Dumroese et al., 2019). All main effects and their interactions were included in the ANOVA model. Soil depth effect in the mineral soil was analyzed in a separate ANOVA. Due to high variability in the stake subplots, most likely due to micro-topographic difference, only one subplot for the May 2014 mineral soil stakes low thinning treatment was used in the ANOVA. Pair-wise differences in mass loss among thinning treatments and years were assessed post-hoc using Tukey's grouping test for multiple comparisons.

A simple T-test was used to compare soil total N, OM and pH between 2011 and 2015. Correlation (Pearson) analyses were used to study the relationships between stake mass loss and moisture content for each species. Data were not transformed, as the normality (Shapiro-Wilk test) and homogeneity (Levene's test) criteria were fulfilled. In all statistical analyses we assessed significance at $\alpha = 0.05$.

3. Results

3.1. Soil changes

Immediately after thinning (2011) there were no significant differences in soil N, OM, and pH in the 0–15 cm soil depth among the thinned treatments and unthinned control (Table 1), but by 2015, mineral soil OM had increased 27–96% in all thinned plots. Soil N concentrations increased by 40% in the heavily thinned treatment, and by approximately 20% in the low and moderate thinning treatments. Soil pH response to thinning varied, as it was greater in the moderately thinned plots, but less in the heavily thinned plot.

3.2. Wood stake mass loss

Preliminary analyses of wood stake mass loss showed that the

Table 1
Total nitrogen, organic matter, and pH in the 0–15 cm soil depth in the thinned and control plots immediately after thinning (2011) and after four years (2015).

Treatments	Total N (g/kg)		OM (g/kg)		pH	
	2011	2015	2011	2015	2011	2015
Control	0.49 ± 0.1	0.32 ± 0.07	16.6 ± 1.4	18.2 ± 0.5	6.66 ± 0.05	6.68 ± 0.02
Low	0.56 ± 0.04	0.67 ± 0.04*	16.5 ± 1.1	32.3 ± 0.3*	6.77 ± 0.06	6.81 ± 0.03
Moderate	0.42 ± 0.07	0.51 ± 0.03	17.0 ± 0.6	21.6 ± 0.5*	6.75 ± 0.06	6.99 ± 0.02*
Heavy	0.63 ± 0.09	0.88 ± 0.05*	16.4 ± 0.8	28.9 ± 0.9*	6.79 ± 0.04	6.53 ± 0.03*

* Indicate significant differences between sampling years ($p \le 0.05$) for soil N(g/kg), OM(g/kg), and pH.

Table 2
Results of the ANOVA identifying single factors and two- and three-way interactions for surface and mineral stakes.

Factor	Surface stakes			Mineral stakes		
	DF	F Value	*p*	DF	F Value	*p*
Time	4	17.99	**< 0.01**	4	46.93	**< 0.01**
Treatment	3	4.89	**< 0.01**	3	3.57	**0.02**
Species	2	16.94	**< 0.01**	2	16.38	**< 0.01**
Time × Treatment	12	0.49	0.91	12	1.194	0.31
Species × Time	8	2.06	0.06	8	1.003	0.44
Species × Treatment	6	0.92	0.48	6	1.558	0.19
Species × Time × Treatment	24	0.47	0.97	24	0.965	0.52

Bold fonts indicate significant values ($p < 0.05$).

explanatory power of stake location (surface or mineral) was the most important factor in the model ($F = 1132$; $p < 0.01$), so subsequent mass loss analyses were separated by stake location. Mass loss of both surface and mineral wood stakes was significantly affected by all three main effects of time, treatment, and stake species, but there were no significant two- or three-way interactions (Table 2).

3.2.1. Surface stakes

Only surface Chinese pine stakes in the unthinned plots had significant mass loss during the first year after installation, but by the 2nd year significant mass loss was generally found in all three species as the thinning level decreased, especially in the low thinning treatments (Table 3). Mass loss of all surface stakes averaged over 3.5 years was also greater in the low thinning than in the unthinned control (Fig. 2a). By the end of the study aspen and Chinese pine surface stakes had significantly greater mass loss than loblolly pine, but it was still less than 10% (Fig. 2b). Overall, conditions at the soil surface were not conducive for wood decay, as the average mass loss of all species across thinning treatments after 3.5 years was only 13.4% (Fig. 2c).

Table 3
Paired-*t* test of mass loss for three species of surface wood stakes among treatments sampled one year (May 2013) and two years (May 2014) after installation, as compared to stake control sections (time = 0).

Pairs	Treatment	Aspen		Loblolly pine		Chinese pine	
		t	p	t	p	t	p
Time 0 – May 2013	Control	−0.873	0.406	−0.013	0.990	2.571	**0.030**
	Low	1.809	0.104	0.601	0.563	0.807	0.440
	Moderate	1.421	0.189	−2.107	0.064	1.174	0.271
	Heavy	−0.026	0.980	1.079	0.309	1.642	0.135
Time 0 – May 2014	Control	1.079	0.309	−0.414	0.688	2.143	0.061
	Low	3.820	**0.004**	2.480	**0.035**	3.949	**0.003**
	Moderate	1.196	0.262	2.301	**0.047**	3.640	**0.005**
	Heavy	0.008	0.994	4.755	**0.001**	1.163	0.275

Bold fonts indicate significant values ($p < 0.05$).

3.2.2. Mineral stakes

In contrast to surface stakes, mineral soil stakes in the moderately-thinned plots had significantly greater mass loss than the other thinning treatments and the control (Fig. 3a; $p = 0.019$), with mass loss in aspen larger than either loblolly or Chinese pine ($p < 0.001$, Fig. 3b). Mass loss in the mineral soil was much greater than on the soil surface, averaging 61% at the end of the study (Fig. 3c). Soil depth was also a significant factor for Chinese and loblolly pine stake decomposition, as mass loss of both were significantly greater deeper in the soil than near the soil surface. However, soil depth had no effect on aspen stake decomposition (Fig. 4, $p = 0.254$).

3.3. Wood stake moisture content

There were no significant differences in surface stake moisture contents among thinning treatments within species, but Chinese pine surface stakes were moister than loblolly pine and aspen when averaged over the 3.5 year study (Table 4). Overall, mineral stakes were significantly wetter than the surface stakes, with both Chinese and loblolly pine stakes having greater moisture contents in the moderately-thinned plots than in the control. Surface stake mass loss for all three species was significantly correlated with stake moisture content, but only loblolly mineral stake mass loss showed a significant correlation with moisture content (Table 5).

4. Discussion

4.1. Surface stakes

In contrast to our hypothesis, the level of stand thinning had very little effect on surface wood stake decomposition. Any impact of thinning may have been muted by the small surface stake mass loss across all treatments at the end of 3.5 years. McColl and Powers (2003) found little effect on the decomposition of small diameter surface wood after thinning a California red fir stand (*Abies magnifica*). Similar results were found in a 19-year-old thinned Japanese larch (*Larix leptolepis)* stand (Son et al., 2004). While surface litter studies have shown that plant species can have different decomposition rates (O'Connell, 1997, Prescott et al., 2000, 2017), our surface stake mass losses were quite similar among the three species. Surprisingly, surface stake moisture contents were not significantly different among the three thinning treatments, as we expected that greater amounts of precipitation would reach the soil surface with increasing tree removal levels. This coupled with decreased transpiration from lower tree densities, would lead to greater soil and wood moisture contents (Goodell, 1952, Smith et al., 1997, Thibodeau et al., 2000, McJannet and Vertessy, 2001).

Surface wood is prone to drying during the hottest and driest times of the year, which limits fungal decay (Brischke and Rapp, 2008). July temperatures on our study site were extremely warm (> 20 °C), and summer precipitation was very low, particularly during the last year of our study, when most mass loss occurred. However, less canopy coverage from increasing levels of tree removal during thinning can also result in higher surface soil temperatures and lead to reduced surface soil moisture and decreased fungal biomass and enzyme production

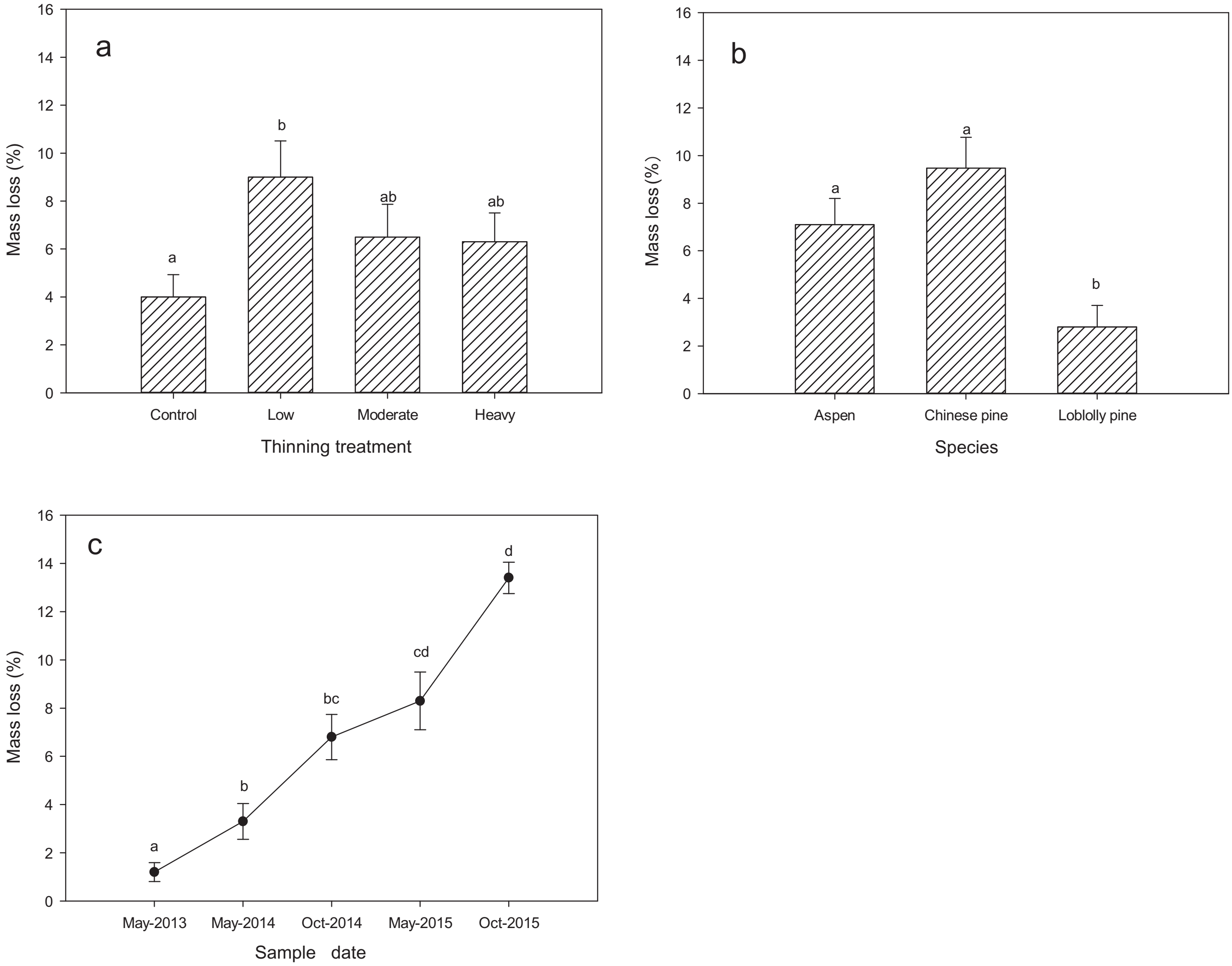

Fig. 2. Average surface stake mass loss after 3.5 years comparing (a) thinning treatments, (b) stake species, and (c) sample dates combined for all species and treatment. Different letters indicate significant differences (p = 0.05).

(Allison and Treseder, 2008). This change in surface conditions likely dictated the low rates of wood stake mass loss in moderate and heavy thinned plots as compared to stakes in low thinned plots. Our surface stake mass losses in northern China are much less (14% after 3.5 years) than the 30–45% mass loss after a clear-cut harvest in similar wood stakes reported by Finér et al. (2016) in Finland, which has a much cooler and wetter climate.

4.2. Mineral stakes

As hypothesized, stake mass loss would be much greater in the mineral soil than on the soil surface, but similar to the surface stakes, thinning had no consistent influence on decomposition. Roots in the mineral soil after thinning can decompose faster than in the unthinned control (Campbell et al., 2009), but Ma et al. (2004) found that mineral soil respiration (a surrogate for organic matter decomposition) was unaffected by thinning.

The greater wood stake mass loss with increasing mineral soil depth was likely caused by more available water and more consistent temperatures deeper in the soil (Thibodeau et al., 2000). Increased mineral soil water content usually leads to fewer fluctuations in soil temperature (Giardina and Ryan, 2000, Herrmann and Bauhus, 2013), which is more conducive to wood decomposition. Greater wood stake decomposition at deeper soil depth was also found by Page-Dumroese et al. (2019) after a wildfire in Montana, USA, but not in the cooler Swiss Alps (Risch et al., 2013). Wood decomposition and soil depth relationships appear to be implicitly tied to local site and soil climatic conditions, which govern wood and soil moisture contents, soil temperature fluctuations, fungal activity, and ultimately mass loss rates (Keeney, 1980, Sinclair, 1992, Thibodeau et al., 2000). Unfortunately, we did not have soil temperature or moisture data from the treatment plots, but generally soil temperature has been shown to increase after similar stands were thinned (Yang et al., 2017).

Aspen stakes had greater mass loss than either pine species, which is likely due to low lignin (20.6%) and high N concentration (0.11%) in aspen wood stakes, as compared to 31.1% lignin and 0.08% N in pine stakes (Wang et al., 2018). Similar aspen and pine stake results were also found by other authors using this method (*e.g.*, Risch et al., 2013, Finér et al., 2016). In addition to wood N concentrations, soil N contents can be an important variable for OM decomposition (McClaugherty et al., 1985), but it likely was not a factor limiting wood decomposition on our site. While all thinning levels increased soil N concentrations, soil N levels in the different thinning treatments had little relationship to stake mass losses.

Restoration thinnings can be an effective management tool where there is excessive stem density that pose a fire, insect, or disease risk. These thinnings are often done to selectively remove trees to return forest sites to more desirable ecological conditions and contributes to more desirable ecosystem structure and function (James et al., 2018; Brown et al., 2019). In this Chinese pine plantation, we found no

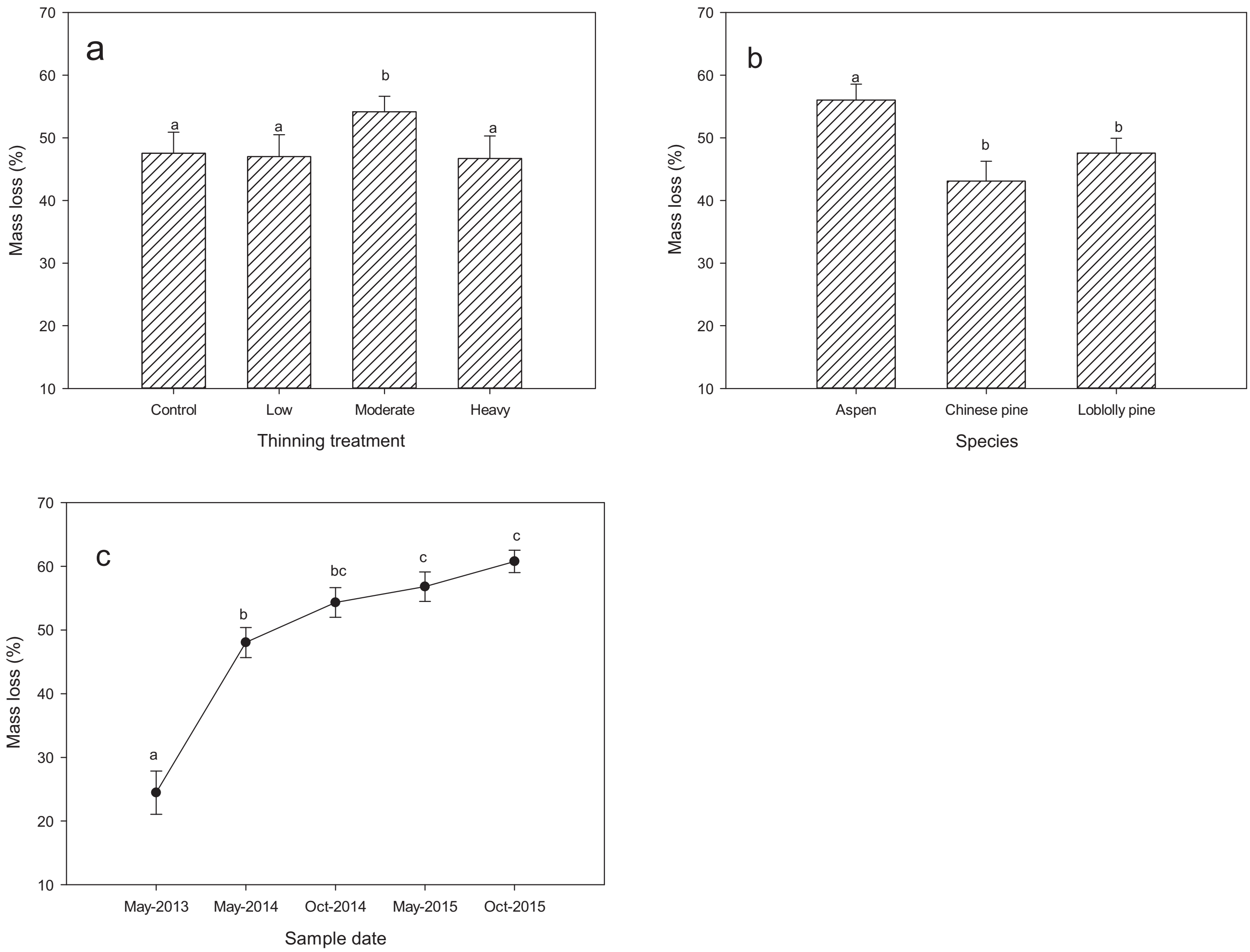

Fig. 3. Average mineral stake mass loss after 3.5 years comparing (a) thinning treatments, (b) stake species, and (c) sample dates combined for all species and treatment. Different letters indicate significant differences (p = 0.05) among treatments, wood species, and sample dates.

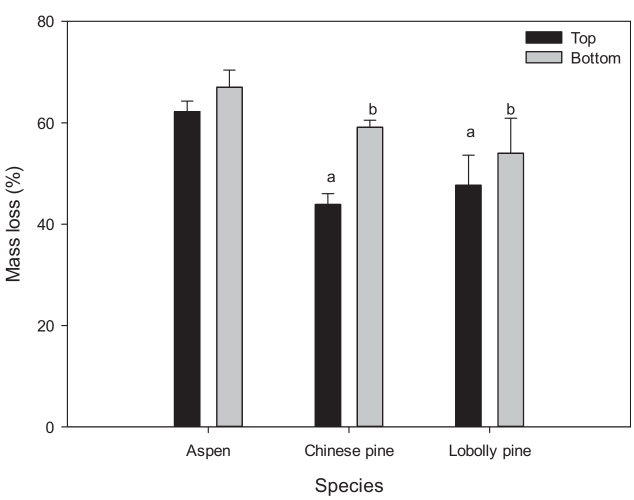

Fig. 4. Average mass loss of wood stakes at different soil depths after 3.5 years for the top (3.8 cm soil depth) and bottom (16.2 cm soil depth) for aspen and loblolly pine and 11.2 cm for Chinese pine. [Different letters indicate significant differences (p = 0.05) between soil depths.]

detrimental short-term (3.5 year) soil changes that would reduce stand or soil productivity. However, more time is likely required to detect how changes in forest stand structure may impact surface and

Table 4
Average stake gravimetric moisture content (mean ± standard error) of aspen, Chinese pine and loblolly pine stakes in three thinning treatments (low, moderate, and heavy) and the unthinned control for the 3.5 years' study period.

Stake location	Thinning treatment	Wood species		
		Aspen	Chinese pine	Loblolly pine
		Moisture content (%)		
Surface				
	Control	21.6 ± 8.1	46.8 ± 6.5	33.8 ± 5.1
	Low	24.7 ± 14.0	46.2 ± 6. 9	33.7 ± 5.0
	Moderate	20.0 ± 5.0	52.6 ± 10.3	37.9 ± 5.9
	Heavy	25.9 ± 13.6	48.0 ± 9.6	33.0 ± 4.3
	Average	23.1 ± 10.8C	48.4 ± 4.1A	34.5 ± 2.4B
Mineral				
	Control	48.7 ± 7.4	46.2 ± 4.3b	50.2 ± 6.8b
	Low	50.5 ± 4.8	59.6 ± 3.6ab	71.8 ± 8.3ab
	Moderate	69.7 ± 9.2	74.7 ± 8.9a	94.2 ± 9.8a
	Heavy	57.8 ± 7.7	70.3 ± 4.3ab	66.6 ± 7.0ab
	Average	56.7 ± 3.8*B	59.5 ± 3.2*AB	70.7 ± 5.2*A

Lowercase letters indicate significant differences among thinning treatment within the same species.
Capital letters indicate significant differences among species within the same stake location.
* Indicate significant (p ≤ 0.05) differences between stake locations (surface and mineral) within each species.

Table 5
Pearson correlation between mass loss and stake moisture content with all sample dates and treatments combined, N = 40.

Species	Moisture content	
	Pearson Correlation Coefficients	P
Surface aspen	0.538	**< 0.001**
Surface Chinese pine	0.626	**< 0.001**
Surface loblolly pine	0.354	**0.027**
Mineral aspen	−0.008	0.963
Mineral Chinese pine	−0.064	0.696
Mineral loblolly pine	0.518	**< 0.001**

Bold fonts indicate significant values ($p < 0.05$).

belowground processes. Coarse and fine woody residues are important for ecological functions (Jurgensen et al., 1997) and future thinning operations should consider leaving this material on the soil surface at levels that provide long-term C storage, but the amounts should also limit fire risk. In addition, it is likely this, and similar stands, will be thinned in successive years and additional work on the long- and short-term impacts of these successive thinnings should be assessed as part of adaptive management forest plans.

5. Conclusions

Although the results of our study are limited to this particular site and soil type, it provides needed baseline data on the impacts of thinning on wood decomposition. Understanding the impact of thinning on the decomposition of the various soil OM substrates is critical for maintaining long-term site sustainability, biodiversity, wildlife habitat, and mitigating climate change. Surprisingly, thinning this Chinese pine stand had very little impact on the decomposition of wood stakes both on the soil surface and in the mineral soil. Rather, it seems soil moisture became limiting near the soil surface in this ecosystem during the warm and dry summer that differences in tree removal had little effect on decomposition. While there were statistical differences in stake mass loss among thinned stands, especially for aspen, this was likely due to initial site and soil differences before the stands were thinned. Wood left on the soil surface after thinning operations in this stand type and climatic regime will likely decompose very slowly, and the choice of thinning regime has little impact on wood decomposition. Therefore, land managers should focus more strongly on treatments that influence C cycling and sequestration.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.117451.

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