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Wood stake decomposition twenty years after organic matter removal at the Lake States LTSP sites

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ABSTRACT

Organic matter (OM) is an integral part of site productivity for a forest, and understanding the effects of OM removal on various forms of carbon (C) cycling is important for land managers and for policy makers. In this study, we utilized the Lake States Long-Term Soil Productivity (LTSP) study sites, located along a gradient in soil texture (clay, silt loam and sand) and high to low productivity, to evaluate the impacts of two OM removal treatments on belowground wood decomposition. In 2013, approximately 20 years after the LTSP treatments had been installed, we placed standardized aspen and loblolly pine wood stakes in the mineral soil of plots receiving the bole only harvesting treatment (BO) and the whole tree harvesting with forest floor removal treatment (WT + FF), and in plots in an adjacent unharvested reference area (1350 wood stakes total). Soil was also sampled to characterize the microbial community composition in the various treatments. From 2014 to 2018, wood stakes were removed from each treatment, and mass loss determined. We found significant differences in wood stake decomposition among the three sites, and between the two wood species, but little impact of timber harvesting and surface OM removals on decomposition. Soil microbial composition also reflected site differences in stake decomposition. We conclude that clearcut harvest and surface OM removal had little effect on stake mass loss in the mineral soil 20 years after the treatments were initiated, and the inherent soil factors are now controlling decomposition.

1. Introduction

Soil organic matter (OM) is key to maintaining forest site productivity by moderating soil water availability, nutrient supply, soil aggregation, and soil microbial function (Harvey et al., 1987; Van Cleve and Powers, 1995; Laiho and Prescott, 2004; Schmidt et al., 2011). Therefore, understanding the processes and variability associated with OM dynamics is important to forest managers and to policy makers. Considerable research has addressed the effects of harvesting on soil carbon (C) cycling, and generally, forest harvesting has led to reduced soil C stocks (Thiffault et al., 2011; Achat et al., 2015; James and Harrison, 2016; Mayer et al., 2020). Subsequent site preparation can further increase the loss of soil C (Walmsey and Godbold, 2010), which varies with disturbance intensity and soil texture (Carlyle, 1993; Mallik and Hu, 1997).

The loss of soil C after harvesting and site preparation results from reduced tree litter and fine root inputs in the cut stand, but the dominant process is increased decomposition of surface and mineral soil OM (Grigal, 2000; Powers et al., 2005; Nave et al., 2010). The loss of tree overstory generally increases soil temperatures and also often increases mineral soil water availability (Gray et al., 2002), both of which will likely by affected by projected climate changes. However, the majority of OM decomposition studies have been conducted within several years after harvesting/site preparation or before crown closure of the regenerating stand ((Prescott, 2005). In contrast, very little information is available on how long these management operations can affect soil OM decomposition in the new stand.

Most decomposition studies use OM from a particular location and provide site-specific information on C and nutrient turnover rates, but differences in OM quality (lignin content, C:N ratio, etc.) can make it

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difficult to generalize results across sites (e.g., Trofymow et al., 2002). To overcome this problem, the use of standardized organic substrates of consistent quality allows the decomposition process to more closely reflect "local" biotic and abiotic conditions, and would be especially suited for cross-site comparisons of forest management practices on OM decomposition across a wide range of climatic regimes and soil types (Berg, 2000).

While there have been many studies on the decomposition of standardized OM substrates in forest soils, most have focused on leaf litter on or in forest floor layers (e.g. Berg et al., 1996). Comparably little research has looked at OM decomposition in mineral soil, especially in relation to forest management practices (Smyth et al., 2016). Of the various types of organic substrates used, wood seems best suited for mineral soil OM decomposition studies. Wood is a normal component of mineral soil (e.g. coarse roots, coarse woody debris), is considered an important terrestrial C sink (Woodall et al., 2008), and its slow decomposition rate reflects changes in soil conditions over longer time periods (Harmon et al., 1986; Wang et al., 2021).

The Long-Term Soil Productivity (LTSP) study was initiated to advance the understanding of soil factors which control forest productivity over a forest rotation (Powers et al., 1990). Two soil properties – site OM and soil porosity – were identified as most likely to influence long-term productivity because they regulate water and gas exchange, nutrient availability and microbial activity (Powers et al., 2005). The experimental design for this national (now international) long-term cooperative research effort consisted of three levels of two soil treatments (compaction, OM removal) for a total of nine core study combinations (Stone, 2001; Slesak et al., 2017). In 2013, we established a study on three LTSP study sites in Michigan and Minnesota to assess the effect of timber harvesting and surface OM removal on decomposition across a mineral soil productivity gradient approximately 20 years after timber harvesting. While both soil compaction and OM removal have been shown to affect soil microbial activities and OM decomposition (Xu et al., 2015), we focused on OM removal because it can have long term impacts on soil microbial activity (Wilhelm et al., 2017), and because the effects of the soil compaction treatments had already begun to diminish when our study began (Voldseth et al., 2011;Slesak et al., 2017).

We used wood stakes of two species, loblolly pine (*Pinus taeda*), and trembling aspen (*Populus tremuloides*) as our OM substrate, both of which have been used as an index of how soil properties, soil microclimate, and wood quality affect decomposition (e.g. Finér et al., 2016; Jurgensen et al., 2019; Wang et al., 2019), and in forest management models to predict stand productivity and C sequestration (Blanco et al., 2018). Aspen and pine wood have different chemical properties (e.g. lignin type, lignin %, N content), which provides information on how different soil microbial communities respond to changes in soil properties (Blanchette, 1984; Wang et al., 2018). We hypothesized that 1) surface OM removal after timber harvesting would have a long-term negative effect on wood stake decomposition in the mineral soil (2) OM decomposition in the mineral soil of the 20-year old stands would be less than in the older uncut reference stands, and 3) OM decomposition would reflect differences in stand productivity.

We also characterized the soil microbial community at each site to help elucidate possible pathways of decomposition. In May and June of 2013, we placed wood stakes of the two species into the mineral soil at each of three LTSP sites: Chippewa National Forest (Minnesota), Huron National Forest (Michigan), and Ottawa National Forest (Michigan), and on two of the OM removal treatments: bole-only harvest (BO), and whole tree harvest + forest floor removal (WT + FF). Wood stakes were also placed in the mineral soil of plots established in an adjacent unharvested aspen stand (REF; 35–70 years old when the LTSP treatments were installed).

2. Methods and materials

2.1. Study areas

Each LTSP site in the Lake States region represents a distinct soil texture and as reflected in aspen site index, they also present a range in forest productivity (Table 1). However, there are many similarities among the three sites, as all were fully stocked, even-aged stands of quaking aspen and big-toothed aspen (*Populus grandidentata* Michx.) prior to treatment and have similar climate (Stone, 2001; Slesak et al., 2017).

The Chippewa LTSP site was established in 1993 and is located on the Chippewa National Forest in northern Minnesota, USA. The soil is an Itasca silt loam soil and classified as Frigid Haplic Glossudalfs. It was formed in loess and till and has the highest site productivity (Site Index = 23 m). The Huron LTSP site was established in 1994 on the Huron-Manistee National Forest in eastern Michigan, USA, and represents moderate site quality (Site index = 19 m). The soil is a Graycalm-Grayling sand, and classified as Frigid Typic Udipsamments and Frigid Entic Haplorthods formed in outwash sands. Established in 1992, the Ottawa LTSP site is located on the Ottawa National Forest in the upper peninsula of Michigan, USA. The soil is a Froberg clay, formed in lacustrine clays and is classified as Frigid Vertic Glossudalfs. Despite having high levels of soil N, it had the lowest site quality (Site index = 17 m).

2.2. Wood stakes methods

Two field mineral soil "daughter" stakes (2.5 × 2.5 × 20 cm) were cut from kiln-dried, knot free aspen and loblolly pine sapwood "mother" stakes (2.5 × 2.5 × 50 cm), and the remaining center 10 cm control section was used to determine field stake mass loss ($\mathbf{t_0}$). The top of each field soil stake was treated with a wood sealer to reduce moisture loss after installation. In May or June of 2013, we placed stakes of both aspen and pine vertically into the mineral soil of three replicate plots on two OM treatments on each of the three LTSP sites: 1) bole only harvest, where all of the logging slash was left on the soil surface (BO) and 2) whole tree harvest + forest floor removal (WT + FF). Stakes were also placed in the mineral soil of three plots in an adjacent unharvested stand (REF). To minimize soil compaction at the wood stake-mineral soil interface and damage to the stake during installation, all mineral soil stakes were placed into 2.5 cm^2 holes ~30 cm apart made by a square 2.5 cm soil-coring tool so that the stake tops were flush with the mineral soil surface. A total of 1350 stakes were used in our study: 3 LTSP sites × 3 treatments × 3 replicate plots × 2 stake species × 5 sample periods × 5 stakes.

Five stakes of each tree species were removed annually (2014–2018) from each treatment plot, and weighed in the field on a portable electronic balance to determine moisture content. After air drying, samples were shipped to the College of Forest Resources and Environmental Science at Michigan Technological University for processing and testing, using established protocols and methods (see Jurgenson et al., 2006). In the laboratory, adhering soil was removed from the stakes, which were then dried at 105 °C for 48 h and weighed. Wood decomposition (mass loss) at each sampling date was determined by comparing the dry weight of each field stake with the weight of its 10 cm control (**t0**). Additional details on stake mass loss calculations are presented in Jurgensen et al. (2020).

2.3. Phospholipid fatty acid analysis (PLFA) methods

At the time of stake installation, bulk soil samples were collected for characterization of microbial community structure using PLFA analysis (Buyer and Sasser, 2012). At each treatment plot, the surface litter layer was brushed aside and three mineral soil samples were collected (0–15 cm), using a soil push probe. These samples were composited in a single

Table 1
Site characteristics, Lake States LTSP study sites.

Location	Latitude, Longitude	Year LTSP treatments applied	Mean annual temperature (°C)	Mean annual precipitation (cm)	Soil texture	Aspen site index (m, 50 yrs)
Chippewa	47.32, −94.55	1993	3.9	64	Silt loam	23
Huron	44.57, −83.98	1994	6.1	75	Sand	19
Ottawa	46.63, −89.25	1992	5.0	77	Clay	17

bag and stored on ice or in the refrigerator until shipped to Microbial ID Laboratory (Newark, DE) for the PLFA analysis. We present data as percent of community composition for major groups, based on the protocols of Microbial ID, as described in Veum et al. (2019). There was one composited sample per treatment replicate plot for a total of 9 samples per site.

2.4. Statistical analyses

The average weight loss of five stakes removed from each treatment plot at each sampling date and location was calculated and used for the statistical analyses. SAS PROC GLM was used to conduct an analysis of variance (ANOVA). The experimental design included 4 factors: site (3), wood species (2), extraction date (5), and treatment (3). The dependent variable was stake mass loss as a proportion of the original mass. All main effects and possible interactions were considered in the model. Assessments of significant effects and interactions were conducted *Post hoc* with SAS PROC MEANS using Tukey's range test. For the PLFA data, means were compared between sites and treatment using simple ANOVA, analysing main effects. All statistical tests were assessed with a level of significance of $\alpha = 0.05$, and conducted using SAS version 9.4 (SAS Institute, Cary, NC).

3. Results

3.1. Stake mass loss

As expected, the full ANOVA model shows the strong impact of stake time (years) in the soil (Table 2). However, the explanatory power of wood species (F value) in the model was very large, which could confound the separation of the LTSP treatments and three study sites from the other study variables. Therefore, we analyzed mass loss of the two wood stake species separately, which reduced the power of the test, but increased the clarity of the treatment terms.

There were significant differences in aspen stake mass loss among treatments at both the Huron and Ottawa LTSP sites for one or two sample years (Table 3), but over the five-year study, the clearcut harvest and surface OM removal had little impact on aspen stake decomposition in the mineral soil. When averaged across all treatments and study sites, aspen stake mass loss was almost 20% after the first year and over 70% by the end of the fifth year (Fig. 1). Aspen decomposition was significantly greater at the high productivity Chippewa site than at the lower productivity Huron and Ottawa sites (Fig. 2).

In contrast to aspen, there was no significant effect of clearcut harvest and OM removal on pine stake mass loss in mineral soil at any of the sites (Table 4). However, when averaged across the 5 years, pine decomposition was significantly greater in the WT + FF treatment than the REF and BO treatments in both the Chippewa and the Ottawa soil. Mass loss was also generally greater at the high productivity Chippewa site than the two lower productivity sites (Fig. 3). When averaged across all treatments and sites, pine stake mass loss was 4% after one year in the mineral soil, which was 4.5 times less than aspen (Fig. 1), and 40% (1.5 times lower than aspen) at the end of the five-year study.

Table 2
Results of GLM identifying factors, and interactions for wood stake decoposition. Stake mass loss is the dependent factor and site, wood species, year of extraction (year) and treatments and their higher interactions are independent factors. Statistically significant P values are shown in bold.

Source	DF	F Value	P value
Site	2	33.32	**<0.0001**
Species	1	760.00	**<0.0001**
Site * species	2	2.15	0.1172
Year	4	371.75	**<0.0001**
Site * year	8	1.02	0.4172
Species * year	4	10.44	**<0.0001**
Site * species*year	8	1.05	0.3938
Treatment	2	1.33	0.2653
Site * treatment	4	6.34	**<0.0001**
Species * treatment	2	0.51	0.6033
Site * species * treatment	4	3.37	**0.0094**
Year * treatment	8	0.48	0.8715
Site * Year * treatment	16	1.49	0.0953
Species * Year* treatment	8	0.70	0.6937
Site * species * Year * treatment	16	0.53	0.9315

3.2. Microbial community

Among the 3 sites, there was relatively little variation in community composition (Fig. 4). Consistently, the Gram-negative bacteria and Gram-positive bacteria made up the largest proportion of the microbial community at each site. Total fungi (AM Fungi + Fungi) ranged from 10 to 15% of the community across the sites, with the greatest percentage in the Ottawa soil, but treatment was not statistically significant. There were statistically significant differences among sites for the Gram-positive and Gram-negative bacteria, the Actinobacteria, and the AM Fungi. In general, the lower productivity Huron and Ottawa sites were similar to each other and distinct from the higher productivity Chippewa site.

4. Discussion

We compared our levels of wood stake decomposition after 5 years for loblolly pine and aspen to studies using these same wood stake species and protocols in other climatic/forest types. In general, decomposition levels in the mineral soil of our aspen stands were greater than those reported for several boreal forests (Finér et al., 2016; Jurgenson et al., 2006), approximately comparable to those in a temperate *Pinus tabuliformis* plantation in China (Wang et al., 2019), and less than warmer temperate forest sites in the U.S. (Jurgensen et al., 2019; Adams unpublished data). Thus, our results reflect decompositions conditions for the relatively cool northern Lake States region. As expected, the aspen wood stakes decomposed more quickly than the pine stakes, which was likely due to lower initial lignin and higher N concentrations in aspen wood relative to loblolly pine (Wang et al., 2018). A lower lignin concentration and C:N ratio in woody material has been correlated with higher decomposition rates (Laiho and Prescott, 2004; Risch et al., 2013; Wang et al., 2018; Jurgensen et al., 2019).

4.1. OM removal

In contrast to our first hypothesis, wood stake decomposition in the mineral soil was not reduced by the removal of surface OM (WT + FF) but showed a weak but significant enhancement in the mineral soil on two study sites. Loss of surface OM can increase mineral soil temperature

Table 3
Percent mass loss of aspen wood stakes in the mineral soil of three Lake States LTSP study sites, by sampling date and treatment. Average is the average by treatment across sampling dates. Different letters in bold within a site and date represent statistically significant differences among treatments.BO = Bole only harvest, WT + FF = Whole tree harvest plus forest floor removal, and REF = uncut reference.

Site	Treatment	Sampling date					
		2014	2015	2016	2017	2018	Average
		Mass loss – %					
Chippewa	**BO**	25.7	40.6	60.8	75.5	79.1	56.3
	WT+FF	18.8	34.4	53.9	70.6	82.8	52.1
	REF	21.3	46.3	56.6	74.4	79.6	55.6
Huron	**BO**	15.1	29.4	**34.6[a]**	**50.3[a]**	74.4	39.6
	WT+FF	19.8	28.4	**47.9[ab]**	**57.9[ab]**	75.0	41.1
	REF	16.7	31.2	**52.7[b]**	**71.5[b]**	77.8	41.9
Ottawa	**BO**	**16.2[ab]**	31.3	42.1	57.0	68.4	49.7
	WT+FF	**20.8[a]**	32.2	51.2	62.0	69.7	53.8
	REF	**13.8[b]**	28.9	42.6	54.5	73.2	49.8

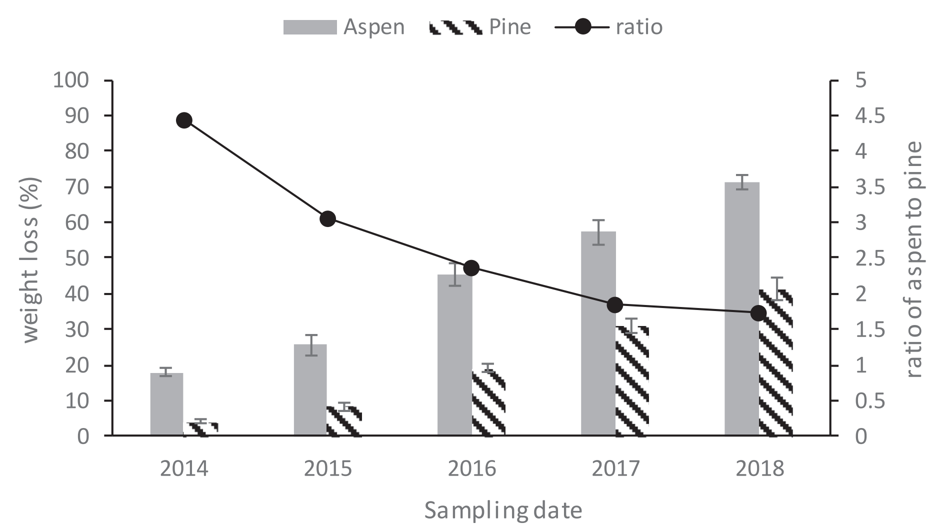

Fig. 1. Stake weight loss, expressed as percent of original weight, for aspen and pine stakes (across all sites and treatments), and the ratio of aspen to pine weight loss. Vertical lines represent standard errors of the mean.

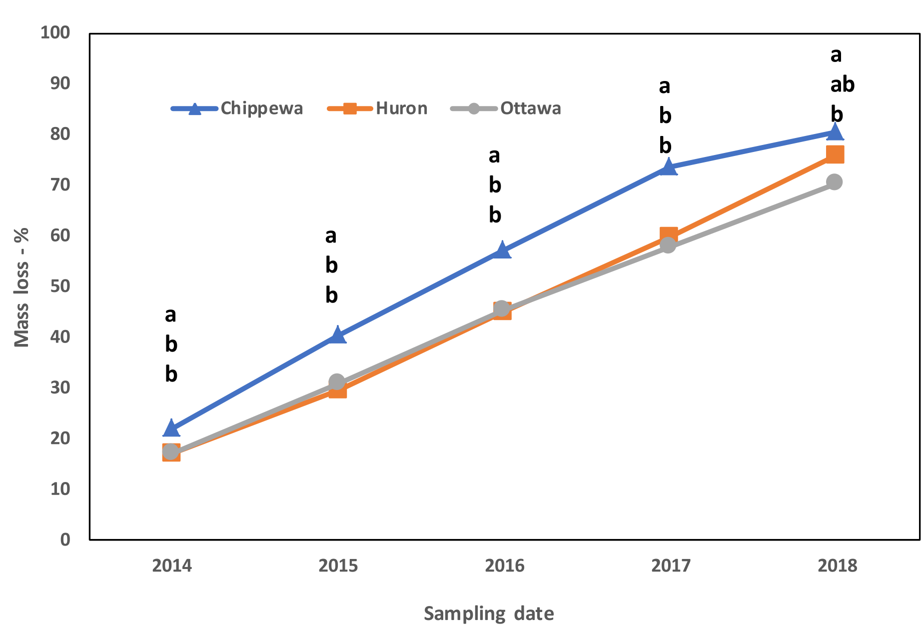

Fig. 2. Average mass loss from aspen wood stakes in the mineral soil at three LTSP study sites over 5 sampling dates. Letters indicate statistically significant differences among sites within a single year.

Table 4
Percent mass loss of pine wood stakes in the mineral soil of three Lake States LTSP study sites by sampling date and treatment. Average is the average by treatment across sampling dates. Different letters in bold within a site and date represent statistically significant differences among treatments. BO = Bole only harvest, WT + FF = Whole tree harvest plus forest floor removal, and REF = uncut reference.

Site	Treatment	Sampling date					
		2014	2015	2016	2017	2018	Average
		Mass loss – %					
Chippewa	**BO**	5.2	10.5	20.5	39.4	52.3	**25.6**^{ab}
	WT + FF	5.7	19.1	27.0	46.7	58.1	**31.3**^{a}
	REF	5.6	21.9	19.6	30.6	41.6	**23.9**^{b}
Huron	**BO**	4.8	5.6	20.4	28.2	34.6	18.7
	WT + FF	4.7	5.4	16.4	22.1	32.6	16.2
	REF	3.3	8.3	23.7	31.2	41.1	21.5
Ottawa	**BO**	3.1	5.6	17.2	29.2	34.3	**17.9**^{b}
	WT + FF	3.1	10.4	16.9	32.7	36.9	**20.0**^{a}
	REF	3.7	5.7	16.8	34.4	36.5	**19.4**^{ab}

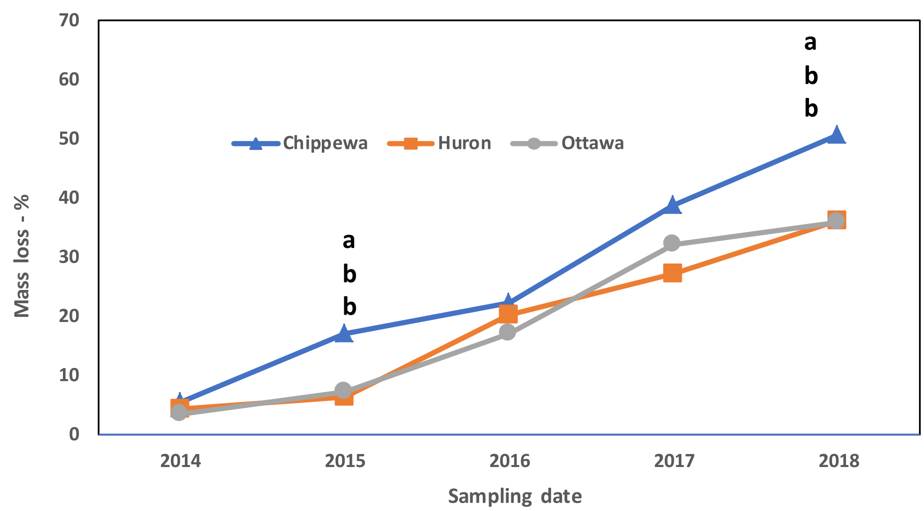

Fig. 3. Average mass lost from pine wood stakes in the mineral soil at three LTSP sites over 5 sampling dates. Letters indicate statistically significant differences among sites within a single year.

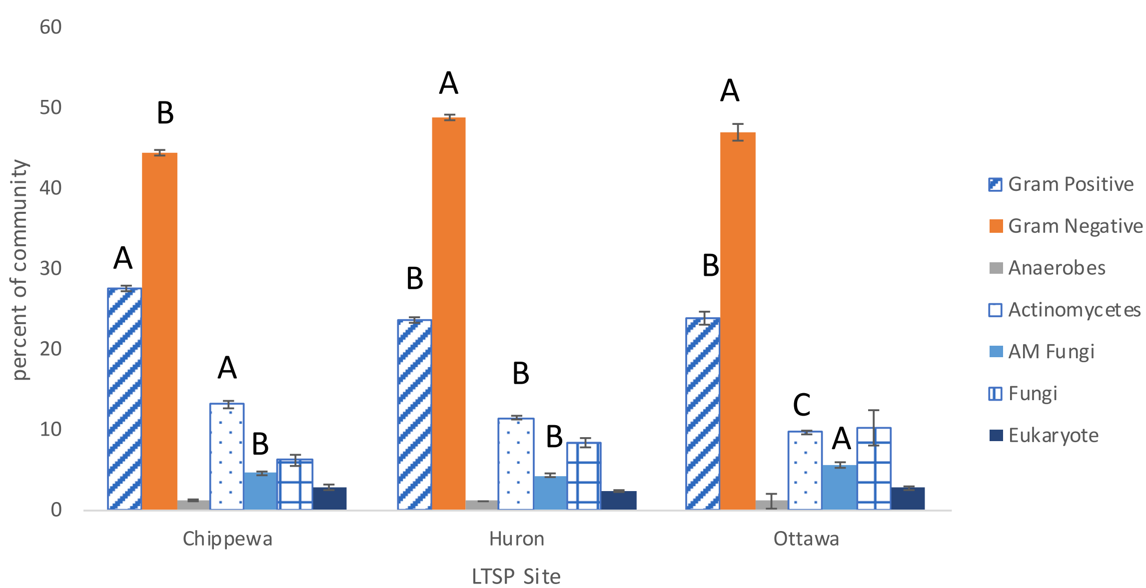

Fig. 4. Soil microbial composition by functional group, expressed as percent of community composition (biomass basis), as determined by PLFA analysis, for three Lake States LTSP sites. Vertical lines represent standard errors. Statistically significant differences among sites within a functional group are indicated by different letters.

(Eaton et al., 2004) and either increase or reduce soil water content, which could increase microbial activity (Marais et al., 2020) in the short-term. However, due to rapid regrowth from aspen suckering, crown closure has occurred on all 3 study sites (Kurth et al., 2014), which can ameliorate soil temperature and moisture conditions. We were unable to obtain satisfactory soil temperature and water contents over the study period, so are unable to confirm the effect of soil temperature and moisture on wood stake mass loss here. However, other factors such wood quality, soil nutrients, and microbial community diversity and functioning can also affect the decomposition process (Laiho and Prescott, 2004; Risch et al., 2013).

An important factor in our study results is the recovery of OM in the mineral soil as the new stand developed. Subsequent inputs of surface litter or fine roots would mitigate the effect of this OM removal treatment on soil properties, depending on the extent of OM additions. Curzon et al. (2016) reported a decrease in aboveground biomass production after 15 years in the WT + FF treatment, which suggested that OM inputs to the soil after this treatment would be decreased. Slesak et al. (2017) also found that total soil C stocks were significantly lower 20 years after the WT + FF treatment on all three sites, but mineral soil C and N contents were similar among treatments at each site. In a related LTSP study, Stone and Elioff (1998) estimated that the forest floor biomass would approach that of unharvested controls stands after 15 years. Therefore, the OM removal treatments may no longer be influencing soil physical and chemical properties that regulate decomposition, at least partly due to a recovered forest floor. However, Kersey and Myrold (2021) reported that the WT + FF treatment was detrimental to most soil nutrient pools and microbial activity measurements in six western LTSP sites 15–25 years after treatments were implemented, although these properties recovered in the less extreme OM removal treatments.

4.2. Timber harvesting

We hypothesized that wood stake decomposition would be less in the mineral soil of uncut reference stands than in the two clearcut harvest treatments, but our results showed no significant effect of harvesting on wood mass loss. In contrast, Finér et al. (2016) reported that clearcutting a boreal forest in Finland significantly increased wood stake mass loss over a 5-year period. Similar increases in wood stake decomposition have been reported after stand thinning (Wang et al., 2018), and wildfire (Page-Dumroese et al., 2019). All these studies were initiated within several years after harvesting or fire, and decomposition results were attributed to increased soil temperature and moisture, and these may be short-term phenomena, as described above. However, Ponder et al. (2017) reported that northern red oak and white oak wood stakes on the uncut control plots on the Missouri LTSP study site decayed at a rate greater than or equal to those in the OM removal plots. These results with aspen (Lake States) and mixed hardwood (Missouri) stands suggest that while abiotic factors such as soil moisture and temperature are important in affecting wood decomposition in soil, biotic factors may also play an important role. Maynard et al. (2018) concluded that biotic processes may provide more control on wood decay by fungal communities, overwhelming abiotic conditions as a controlling factor. Research by Hu et al. (2021) provides some support for this idea, although soil moisture, pH and C:N ratio were also significant in influencing wood decomposition in forests of differing ages. Treatment effects were not statistically significant, but there were site differences in some community groups and the trends reflect the trends we observed in the decomposition of wood stakes. For example, the proportion of Fungi (AM fungi + Other fungi) in the community increased as the site productivity decreased. Also, microbial community composition in the high productivity Chippewa silt loam site was generally distinct from the lower productivity Huron and Ottawa sites.

We consistently observed trends in decomposition that differed among the sites, pointing to the importance of inherent site quality in controlling decomposition. The higher productivity silt loam Chippewa site had greater decomposition than the lower productivity Huron (sand) and Ottawa (clay) sites. In their study of western LTSP sites Kersey and Myrold (2021) noted that the inherent site properties obscured treatment effects on soil nutrient pools and microbial activity, except for the WT + FF treatment. Littke et al. (2020) also reported that the long-term effects of OM removal on soil and site productivity were variable at each of their sites, partly due to pre-treatment differences in soil nutrients and competing vegetation. Thus, the interplay between inherent site quality and microbial control of decomposition processes needs additional study.

5. Management implications

Timber harvesting and surface OM removal on the Lake States LTSP aspen sites have been detrimental to total soil C stocks, but after 20 years they had little impact on decomposition in the underlying mineral soil. However, the recovery from these management impacts in these midwestern aspen stand would likely vary in other forest types with different soil and climatic conditions.

Inherent site quality was an important factor in the decomposition of OM in mineral soil, so forest managers need to be aware of soil properties and their limitations when evaluating the effect of management practices on site productivity and C cycling.

Declaration of Competing Interest

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

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