MASS LOSS AND NUTRIENT CONCENTRATIONS OF BURIED WOOD AS A FUNCTION OF ORGANIC MATTER REMOVAL, SOIL COMPACTION, AND VEGETATION CONTROL IN A REGENERATING OAK-PINE FOREST

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Abstract.—Mass loss and nutrient concentrations of northern red oak (*Quercus rubra*) and white oak (*Q. alba*) wood stakes were measured 30 months after their burial in the upper 10 cm of soil in a regenerating forest after harvesting and soil disturbance. Disturbance treatments were two levels of organic matter (OM) removal (only merchantable logs removed or removal of all woody material plus forest floor) with two levels of soil compaction (C), not compacted and severely compacted. Treatments were arranged in a factorial design with each treatment plot split with and without vegetation control (VC). The VC treatment increased the northern red oak stake decomposition by 32 percent and increased nitrogen and sulfur concentrations in northern red oak and white oak stakes. The VC treatment also increased phosphorus and calcium concentrations in white oak stakes, even though decomposition of these stakes was nominal and not statistically significant. Findings suggest that postharvesting efforts to reduce competition during forest regeneration will have a greater impact on belowground woody debris decomposition and nutrient availability than do OM removal and C in xeric, low fertility oak-hickory and oak-pine ecosystems in the Central Hardwood region.

INTRODUCTION

Nutrient availability in forest ecosystems can be influenced by organic matter (OM) decomposition that is in turn influenced by factors such as climate, initial site nutrient level, and litter quality (Melillo et al. 1982). Decomposition is a critical process in nutrient cycling within temperate forest ecosystems (Binkley and Fisher 2013). Decomposition of detritus can provide 69–87 percent of the nutrients needed annually for forest growth (Waring and Schlesinger 1985). This material provides habitat for numerous vertebrates and invertebrates and serves as substrate for a variety of fungi and other microorganisms. Nutrient deficiencies, especially nitrogen (N) and phosphorus (P), are often found in highly leached soils, such as Alfisols and Ultisols, which are common soils throughout the Central Hardwood Forest region. Therefore, on these soils, the removal of forest biomass could represent the loss of many potential site nutrients that would otherwise be available after decomposition. This would affect site productivity.

Forest harvesting affects the decomposition rates of OM and consequently nutrient availability through a number of mechanisms (Ponder et al. 2012, Yanai et al. 2003). Forest harvesting changes soil moisture and temperature and removes nutrients stored in the aboveground biomass (Page-Dumroese et al. 2010). Soil compaction caused by harvesting equipment can increase or

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decrease water-holding capacity, reduce aeration, and restrict root growth and nutrient uptake (Page-Dumroese et al. 2006). The subsequent regrowth of forest vegetation reduces nutrient availability through plant uptake where excessive biomass has been removed (Mendham et al. 2003). The forest floor is particularly important for moderating water storage, for protecting the soil surface from erosion, and for providing nutrients through mineralization. Harvesting has the most impact on the forest floor (Page-Dumroese et al. 2010, Tiedemann et al. 2000).

Considerable research has been conducted to identify factors that influence litter decomposition rates. Factors such as litter quality (Giardina et al. 2001, Melillo et al. 1982), macroclimate and microclimate variables (Zhang et al. 2008), soil fertility (Prescott 2010), and microbial and fungal biotic activity (Kamplichler and Bruckner 2009, Seastedt 1984) have been identified. During decomposition, nutrient changes generally follow three phases: (1) initial nutrient release through leaching, (2) net immobilization when the microorganisms retain or import nutrients during decomposition, and (3) nutrient release from the OM at a rate close to mass loss (Prescott et al. 1993). Variability in factors associated with OM decomposition such as soil fauna (Yan et al. 2004), in addition to differences in OM type and quality, species, and ecosystem can, however, alter this pattern (Sanchez 2001).

After conventional harvesting in mature oak-hickory (*Quercus-Caraya*) and oak-shortleaf pine (*Quercus-Pinus*) forest types, large amounts of forest biomass from the harvested trees remain on site as branch wood and roots. In these ecosystems less than half the standing biomass in a forest clearcut is removed (Ponder and Mikkelson 1995). The relative contribution of woody as opposed to leaf biomass, however, has received less attention as a component of decomposition and nutrient cycling. Depending on the size of the material, wood may take longer than leaf litter to decompose. Several studies have shown how land management alters forest floor decomposition (Berg 2000, Berg et al. 1996, Breymeyer 2003) or woody material on the soil surface (Brown et al. 1996, Palviainen et al. 2004), but few studies describe wood decomposition within the mineral soil (Jurgensen et al. 2006).

The importance of woody debris decomposition for retaining carbon, replenishing nutrients, and maintaining soil quality in managed forests remains controversial (Holub et al. 2001, Laiho and Prescott 2004, Smith et al. 2007). Although some studies suggest that woody debris comprises only a small proportion of carbon and nutrient pools in forest ecosystems (Laiho and Prescott 2004), others indicate that woody debris serves as an important sink for nutrients during decomposition (Johnson et al. 2014, Shortle et al. 2012, Smith et al. 2007) and that the slow release of stored nutrients during woody debris decomposition may be a significant source of nutrients, particularly in infertile soils.

The primary aim of this study was to measure mass loss and nutrient (N, P, potassium [K], calcium [Ca], magnesium [Mg], and sulfur [S]) dynamics of decomposing wood in mineral soil. Wood stakes from two tree species that commonly inhabit forests in the Central Hardwood region—northern red oak (*Q. rubra* L.) and white oak (*Q. alba* L.)—were used as surrogates for woody debris of these two species. The specific objective was to compare the effects of OM removal and soil compaction, with and without vegetation control, on mass loss and nutrient concentrations in the decomposing wood stakes after burial in a regenerating forest for 30 months.

MATERIALS AND METHODS

Site Description

The study is in the U.S. Department of Agriculture, U.S. Forest Service's Long-Term Soil Productivity (LTSP) site located in the Current River Conservation Area in Shannon County, MO. The soil is primarily derived from Ordovician and Cambrian dolomite with some areas of pre-Cambrian igneous rock (Missouri Geological Survey 1979). Weathered material forms a deep mantle of cherty hillslope sediments, which overlie cherty residuum (Gott 1975). Soils derived from this residuum are primarily of the Clarksville series (loamy-skeletal, mixed, mesic Typic Paleudults). The soils are excessively drained and have an available water-holding capacity of <10 cm. Initial soil chemical properties of the 0- to 20-cm depth were pH, 5.7; total carbon, 33 g kg^{-1}; total N, 1.1 g kg^{-1}; P, 16.9 mg kg^{-1}; Ca, 789 mg kg^{-1}; and Mg, 61 mg kg^{-1} (Ponder et al. 2000). Before harvest, the site was occupied by a fully-stocked, mature, second-growth oak-hickory forest. The site index indicated that the height of 50-year-old black oak (*Q. velutina*) ranges from 23 to 24 m on this site (Hahn 1991). Data from a weather station on site indicated that the mean annual precipitation is 1120 mm and the mean annual temperature is 13.3 °C.

EXPERIMENTAL DESIGN

The experiment was a three-factor randomized split-plot design with three replications of two forest floor removal treatments (whole plot), two compaction treatments (whole plot), and two vegetation control (VC) treatments (split plot). The two levels of OM removal were (1) merchantable boles only (OM_0), in which only merchantable saw logs were removed, and (2) removal of all woody material during harvesting plus forest floor (OM_2), in which all aboveground biomass (merchantable and unmerchantable trees plus forest floor) was removed. Litter that accumulated during the study was not removed. The two levels of soil compaction (C) were none (C_0) and severe compaction (C_2). During harvesting, heavy equipment was kept off the C_0 plots. Soil compaction was accomplished by using heavy road-construction equipment to make multiple passages over the plot. Mean bulk density in the C_2 plots increased to 1.8 g cm^{-3} after site preparation compared to 1.3 g cm^{-3} for the C_0 treatment. The two levels of VC were no vegetation control (VC_0) and vegetation control (VC_1). VC included the annual application of glyphosate to all vegetation that competed with northern red oak, white oak, and shortleaf pine seedlings that were planted at this location as part of the LTSP study. The only plants remaining in the VC_1 treatment were the planted northern red oak and white oak and shortleaf pine seedlings at a spacing of 3.66 m. There was a ratio of three oaks of each of the two species to each shortleaf pine seedling planted. This treatment was applied to half of each 0.4-ha square plot. Ponder and Mikkelson (1995) give a complete description of the site and the LTSP installation.

Treatment units were established in 1994 and wood stakes were installed 5 years later. Three control (unharvested) plots were located adjacent to the harvested stand, with stocking and site index that were similar to harvested treatment plots.

Preparation of Wood Stakes

Two mature trees—a northern red oak and a white oak from the site—were processed into stakes that were 15.24 cm long × 2.54 cm wide × 0.31 cm thick. The fresh logs were first cut into 2.54 cm thick boards (96.52 cm × 15.24 cm wide × 2.54 cm thick). After drying for 3 months, boards were ripped lengthwise to 0.31 cm thick and cut into 15.24 cm lengths. Holes that were 0.31 cm were drilled into stakes for bundling replicates. Machining burs, sawdust, and other wood fragments were removed from the stakes. The stakes were numbered and weighed before oven-

drying at 70 °C for 72 hours. Once oven-dried, 10 stakes of the same species were weighed, strung together (grouped) in a circle with aluminum wire, labeled according to plot, and stored in plastic bags in a cool dry storage room until they were placed in plots. Each group contained a numbered aluminum identity tag.

Field Installation of Wood Stakes

Approximately 5 years after the OM was removed and C treatments were applied, two groups of 10 stakes of each species were buried within the buffer area on each of 12 treated plots and 3 uncut control plots. The buffer area, which received the same treatment as the core or measurement plot, was the outer 6- to 9-m-wide area of the plot that was designated for auxiliary studies that would not interfere with the integrity of core plot area. An area measuring 182.9 cm × 121.9 cm was excavated to a depth of 10.2 cm. Within the excavated area of each plot, the two groups of each species of stakes were placed flat (wide side down) in the soil, side by side with wire still attached. Numbered pins were inserted through the aluminum wire strung through each group of stakes and in the soil to mark the location. Stakes were covered with soil to the original approximate soil depth and bulk density. Reference stakes (those not buried) of each species were kept in plastic bags in a frost-free refrigerator for the duration of the study and analyzed for macronutrient element concentrations when buried stakes were analyzed.

Stake Removal, Mass Loss Calculation, and Chemical Analysis

Approximately 29-30 months after burial, a masonry tool (Fig. 1A) and broom (Fig. 1B) were used to carefully excavate the stakes. The groups of stakes (Fig. 1C and Fig. 1D) were placed in individual plastic bags; labeled according to plot, treatment, date, and species; and transported to the laboratory. At the laboratory, they were removed from the bags and inspected for decay. All attached soil was also gently removed before the stakes were oven-dried at 70 °C for 72 h and

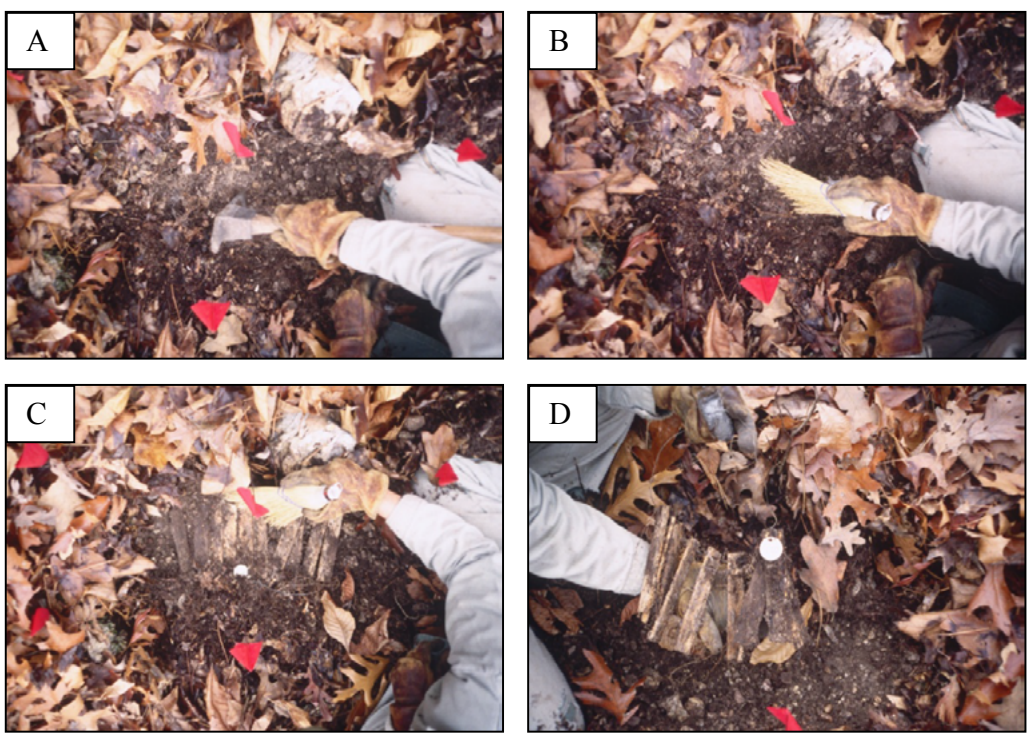

Figure 1.—Procedure for lifting stakes after 30 months for mass loss and nutrient determinations. Photo sequence includes excavating with a masonry tool (A) and broom (B and C). Final photo shows a group of 10 stakes fastened together with a wire loop (D).

weighed. Percent mass loss was calculated as the difference between the initial oven-dry-mass minus the 30-month (final) oven-dry mass expressed as a percentage of the initial oven-dry mass. We followed the approach used by Risch et al. (2013) to calculate the decay constant k and the half-life of the stakes using equations (1) and (2):

$$k = \ln (M_0/M_t)/t \quad (1)$$

$$\text{half-life} = 0.693/k \quad (2)$$

Where

M_0 = the initial mass of the wood stake before burial, and

M_t = the mass t months after removal (which was 29 or 30 months depending on the exact removal date).

Depending on the amount of decay, stakes were either broken by hand or sawed with a band saw into pieces small enough to be ground in a Wiley mill to pass through a 2 mm mesh sieve. Samples of unburied (reference) stakes were also prepared and analyzed for nutrients. Chemical analyses were conducted at the University of Arkansas Agricultural Diagnostic Laboratory at Fayetteville. Total N was determined by dry combustion (Pella 1990). Other nutrients (P, K, Ca, Mg, and S) were determined by inductively coupled plasma emission spectroscopy (PerkinElmer Corporation 1983) from samples extracted with a HNO_3-H_2O_2 digestion procedure (Plank 1992).

Statistical Analysis

Analysis of variance was used to test for treatment effects on mass loss and N, P, K, Ca, Mg, and S concentrations for wood stakes removed after 30 months. The data were analyzed with the GLIMMIX procedure (Version 9.3, SAS Institute, Inc., Cary, NC) where fixed effects included the OM, C, and VC treatments, their first-order interactions, and the three-way interaction among OM removal, C, and VC treatments. Because of the split-plot design, a random statement was included in the model to specify that the VC × plot interaction was the error term. Control plots were not included in the analysis because they did not include the OM removal, C, or VC treatments, but data are presented for comparative purposes.

Table 1.—Percent mass loss ± standard error for northern red oak and white oak wood samples 30 months after burial in the soil surface in regenerating forest plots with organic matter removal, compaction, and vegetation control treatments

Treatment[a]	Northern red oak	White oak
	---------- Percent loss ----------	
OM_0	65.3 ± 5.4	52.3 ± 4.2
OM_2	81.0 ± 6.6	65.8 ± 5.5
C_0	74.4 ± 6.1	61.9 ± 4.9
C_2	71.4 ± 5.8	55.6 ± 4.7
VC_0	**62.8 ± 4.7**	56.5 ± 4.5
VC_1	**83.2 ± 6.2**	60.9 ± 5.2
Control	81.6 ± 6.1	60.1 ± 12.8

[a] Treatment codes are OM_0 (bole removal), OM_2 (whole tree plus forest floor removal), C_0 (no compaction), C_2 (severe compaction), VC_1 (with vegetation control), VC_0 (without vegetation control), and control. For each OM, C, or VC treatment, values that are significantly ($P < 0.05$) different from each other are shown in bold. Control was not included in the analysis.

RESULTS

Mass Loss

Thirty months after burial, the mass loss (percent weight basis) of northern red oak stakes was 1.3 times greater ($P = 0.02$) in the VC_1 treatment than in the VC_0 treatment (Table 1). There were no other significant treatment effects on northern red oak stake decomposition, although there was a nominal increase in decomposition in the OM_2 relative to the OM_1 treatment. There were no significant treatment effects for the mass loss of buried white oak stakes, even though there were nominal differences that paralleled those of the northern red oak stakes. In addition, the mass loss for northern red oak stakes was about 1.5 times greater than for the white oak stakes, independent of treatment.

Because VC was the only significant treatment associated with mass loss, we calculated the mean (± standard error) half-life for northern red oak and white oak stakes for this treatment. For northern red oak stakes, the half-lives for stakes were estimated to be 11.2 ± 1.2 and 17.2 ± 1.2 months for the VC_1 and VC_0 treatments, respectively. For the white oak stakes, the half-lives were 20.1 ± 1.2 and 23.2 ± 1.2 months for the VC_1 and VC_0 treatments, respectively.

Nutrient Concentrations

The VC treatment, with one exception, was the only treatment that exhibited significant effects on nutrient concentrations in the buried stakes (Table 2). In stakes of both species, the N ($P < 0.01$) and S ($P < 0.03$) concentrations increased by at least 1.5 times in the VC_1 treatment compared to the VC_0 treatment after burial for 30 months. In the white oak stakes, the VC_1 treatment also increased the P concentrations by 2 times ($P = 0.01$) and the Ca concentrations by 1.5 times ($P = 0.04$). The only other significant treatment effect occurred with the OM treatment; the Mg concentration of the buried white oak stakes that received OM_2 was 1.5 times greater ($P = 0.04$) than that observed after the OM_0 treatment. For most nutrients, concentrations in the buried stakes were similar to those buried in the control treatment and generally 2-10 times greater than in the unburied reference stakes (Table 2).

Table 2.—Mean nutrient concentrations ± standard error for northern red oak and white oak stakes buried in the surface soil of a regenerating forest plots with organic matter removal, compaction, and vegetation control treatments

Treatment[a]	N	P	K	Ca	Mg	S
	----------	----------	----------	g kg^{-1}	----------	----------
Northern red oak						
OM_0	5.63 ± 0.65	0.18 ± 0.04	0.76 ± 0.08	5.46 ± 1.17	0.33 ± 0.07	0.41 ± 0.06
OM_2	6.26 ± 0.67	0.25 ± 0.05	0.73 ± 0.07	4.27 ± 1.16	0.54 ± 0.11	0.39 ± 0.05
C_0	6.16 ± 0.70	0.22 ± 0.05	0.78 ± 0.08	5.32 ± 1.17	0.40 ± 0.08	0.41 ± 0.06
C_2	5.72 ± 0.63	0.20 ± 0.04	0.71 ± 0.07	4.45 ± 1.16	0.44 ± 0.09	0.39 ± 0.05
VC_0	**4.43 ± 0.42**	0.18 ± 0.04	0.73 ± 0.34	4.11 ± 1.15	0.42 ± 0.09	**0.32 ± 0.04**
VC_1	**7.95 ± 0.77**	0.25 ± 0.05	0.75 ± 0.07	5.67 ± 1.15	0.42 ± 0.09	**0.49 ± 0.06**
Control	3.86 ± 0.74	0.18 ± 0.06	0.74 ± 0.25	3.97 ±1.04	0.31 ± 0.11	0.31 ± 0.05
Not buried (reference)	1.42 ± 0.46	0.02 ± 0.01	0.55 ± 0.05	1.08 ± 0.81	0.10 ± 0.05	0.10 ± 0.03
White oak						
OM_0	4.61 ± 0.41	0.16 ± 0.02	0.72 ± 0.12	5.85 ± 1.15	**0.29 ± 0.04**	0.38 ± 0.04
OM_2	4.84 ± 0.42	0.18 ± 0.02	0.58 ± 0.09	5.22 ± 1.15	**0.43 ± 0.05**	0.35 ± 0.04
C_0	5.35 ± 0.48	0.19 ± 0.02	0.78 ± 0.13	5.85 ± 1.15	0.41 ± 0.05	0.41 ± 0.05
C_2	4.18 ± 0.37	0.15 ± 0.02	0.54 ± 0.09	5.22 ± 1.15	0.30 ± 0.04	0.33 ± 0.04
VC_0	**3.89 ± 0.31**	**0.12 ± 0.01**	0.59 ± 0.09	**4.56 ± 1.14**	0.35 ± 0.04	**0.30 ± 0.03**
VC_1	**5.74 ± 0.43**	**0.25 ± 0.03**	0.71 ± 0.10	**6.70 ± 1.13**	0.35 ± 0.04	**0.45 ± 0.04**
Control	3.95 ± 0.82	0.19 ± 0.07	0.61 ± 0.22	3.76 ± 0.96	0.40 ± 0.09	0.32 ± 0.08
Not buried (reference)	1.49 ± 0.05	0.02 ± 0.01	0.58 ± 0.03	0.69 ± 0.51	0.06 ± 0.04	0.08 ± 0.02

[a] Treatment codes are OM_0 (bole removal), OM_2 (whole tree plus forest floor removal), C_0 (no compaction), C_2 (severe compaction), VC_1 (with vegetation control), VC_0 (without vegetation control), and control. For each OM, C, or VC treatment, values that are significantly ($P < 0.05$) different from each other are shown in bold.

DISCUSSION

We observed that the OM and C treatments had little effect on the mass loss or nutrient concentrations in oak stakes that were buried for approximately 30 months. The OM_2 treatment may have marginally enhanced decomposition compared to the OM_0 treatment, but not sufficiently to cause statistically significant increases in decomposition or in nutrient accumulation in buried stakes. The only exception was an increased Mg concentration observed in buried white oak stakes. The reason why only the Mg concentration increased in this treatment is unclear.

The lack of a compaction effect may partly be a result of the wood stake installation process, which may have alleviated some of the compaction as experienced by the wood stakes. The method used caused some soil disturbance, but probably no more than that caused by a coring tool used to create standardized holes for wood stakes described by Jurgensen et al. (2006). In addition, Shestak and Busse (2005) reported that despite increases in forest soil bulk density, variables such as pore-size distribution, water-holding capacity, gas diffusion, and microbial biomass indicators—all factors that could affect the mass loss of buried wood—were either unaffected by compaction or showed inconsistent responses. In a study of soil compaction in an agricultural field, Entry et al. (2006) reported a similar lack of response. The researchers found that significant increases in bulk density had no consistent effect on active bacterial or active fungal biomass either in the top 7.5 cm of soil or in the 15- to 20-cm depth of soil.

Table 3.—Soil water and temperature by treatment measured in 2000 (adapted from Page-Dumroese et al. 2006)

	OM_0	OM_2	C_0	C_2	VC_0	VC_1
Soil water (%)						
June	13.4	20.4	20.6	18.4	10.5	30.1
July	19.4	26.3	23.9	29.7	13.9	36.2
August	24.9	36.2	29.5	34.9	20.6	40.6
September	19.9	24.6	22.2	26.0	15.6	34.1
Mean	**19.4**	**26.9**	**24.1**	**27.3**	**15.2**	**35.3**
Soil temperature (°C)						
June	13.3	16.4	15.2	15.1	10.6	18.7
July	18.0	18.8	18.6	19.8	15.1	21.7
August	15.7	20.3	17.8	21.3	15.8	22.3
September	12.4	15.9	12.7	18.3	14.1	17.9
Mean	**14.9**	**17.9**	**16.1**	**18.6**	**13.9**	**20.2**

Although environmental factors were not measured during this wood stake decomposition study, another report from this study site (Page-Dumroese et al. 2006) showed that when this study began, the surface soil temperature in the VC_1 treatment was 6 °C warmer and the soil water content was 2.3 times greater (15 vs. 35 percent) than in the VC_0 treatment from June through September (Table 3). The greater temperature and soil water content of the VC_1 treatment was due to the lack of vegetation other than the planted seedlings to shade the ground and transpire soil water. Soil moisture and temperature are positively correlated to woody debris decomposition rates across a number of ecosystems (Risch et al. 2013). In our study region, soil moisture becomes limiting to tree growth during dry periods in midsummer because of high evaporative demand and the low water-holding capacity of the soils (Jenkins and Pallardy 1995). It is also reasonable to assume that a lack of soil moisture is limiting to microbial activity and consequently to wood decay during those dry periods regardless of soil temperature. We could not determine, however, whether temperature or moisture was the most important factor causing the decomposition differences between VC_0 and VC_1 treatments.

We expected the faster decomposition and the shorter half-life of northern red oak stakes compared to white oak stakes. The heartwood of white oak group species has long been known to resist decay much more effectively than that of red oak group species (Carteret al. 1976, Scheffer et al. 1949). As decomposition progressed, nutrient concentrations in the wood increased for both species compared to reference stakes. Decaying wood in soil has been shown to induce nutrient deficiencies in plants by stimulating microbial growth, which depletes the surrounding soil of some available nutrients. In the current study, however, correlations between soil nutrient concentrations and mass loss of wood were not statistically significant (data not presented). There was also no strong correlation between nutrient concentrations of buried wood stakes and nutrient concentrations of soil in the plots. Perhaps this is partially due to the relatively low nutrient status of the soil and the small differences in nutrient concentrations commonly reported for the Clarksville soils in the study area (King 1997).

Others have reported significant increases in nutrient concentrations within decomposing woody debris including N, P, and Ca (Johnson et al. 2014) and Ca and Mg (Smith et al. 2007), which suggests that woody debris plays an important role as a nutrient sink during early stages of decomposition. The duration and magnitude of nutrient immobilization are reportedly

dependent on substrate quality (Bosatta and Berendse 1984) before a period of release or mineralization (Lousier and Parkinson 1978). Periods of nutrient accumulation longer than 24 months have been reported for forest litter (Weber 1987). Results from Blair (1988) and Kaczmarek et al. (1998) show that total P content of deciduous leaf litter tended to increase for at least 2 years, despite significant losses in litter mass. Idol et al. (2001) suggested that a delay can occur in N mineralization for dead and down wood for several decades depending on the age and decomposition class of the wood. Idol et al. (2003) also reported that for a chronosequence of upland hardwood stands in Indiana, N mineralization was greatest in the oldest stand (80-100 years old) and lowest in the next-oldest stand compared to stands ranging from 1 to 14 years since harvesting. They speculated that large inputs of logging debris, the mixing of fresh forest floor litter, and the death of coarse root systems in recently harvested stands led to increases in N immobilization because of the generally high C:N ratio of woody debris (Idol et al. 2003). During the accumulation period, the decomposing material is N poor and limiting to microbial activity, causing microorganisms to import nutrients from the immediate surroundings into the material (Blair 1988).

Despite apparent increased decomposition and enhanced nutrient immobilization, Ponder et al. (2012) demonstrated that the growth of planted tree seedlings in the VC_1 treatment was greater than that of planted seedlings in the VC_0 treatment at our study site and elsewhere where similar experiments were conducted. Foliar nutrient concentrations in planted seedlings were also higher in the VC_1 treatment (Ponder et al. 2012). Collectively, this suggests that if enhanced nutrient immobilization by decaying wood was occurring in this treatment that it was not sufficient to reduce tree growth during the first decade after planting, even in the nutrient-deficient sites such as those examined in this study.

CONCLUSION

The findings indicate that in the regenerating mixed-oak forests on these xeric and nutrient-poor sites, OM removal and compaction resulted in negligible changes in the mass loss and nutrient concentrations of buried wood stakes. VC, however, appears to enhance stake decomposition and increase nutrient concentrations within the stakes, at least initially. This suggests that extensive biomass removals during harvesting operations or incidental compaction associated with skidder activity would have little impact on woody debris decomposition dynamics in mineral soil on this and similar sites. Immobilization of N and possibly P and Ca may occur where VC is practiced as part of a regeneration strategy. The immobilization of nutrients in buried woody debris on these nutrient-poor Missouri Ozark sites may also serve to reduce nutrient loss to leaching. The slow release of immobilized nutrients in wood through decomposition and mineralization appears to be one mechanism for retaining nutrients on xeric, nutrient-deficient sites.

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LITERATURE CITED

Berg, B. 2000. **Litter decomposition and organic matter turnover in northern forest soils.** Forest Ecology and Management. 113: 13-22.

Berg, B.; Ekbohm, G.; Johansson, M.B.; McClaugherty, C; Ritigliano, F. [et al.]. 1996. **Maximum decomposition limits of forest litter types: a synthesis.** Canadian Journal of Botany. 74(5): 659-672.

Binkley, D.; Fisher, R.F. 2013. **Ecology and management of forest soils. 4th ed.** Hoboken, NJ: Wiley-Blackwell. 362 p.

Blair, J.M. 1988. **Nitrogen, sulfur and phosphorus dynamics in decomposing deciduous leaf litter in the southern Appalachians.** Soil Biology and Biochemistry. 20: 693-701.

Bosatta, E.; Berendse, F. 1984. **Energy or nutrient regulation of decomposition: implications for the mineralization-immobilization response to perturbations.** Soil Biology and Biochemistry. 16: 63-67.

Breymeyer, A.I. 2003. **Rate of change of pine litter fall and decay in response to changing climate along N-S transect.** Polish Journal of Ecology. 51(4): 553-556.

Brown, S.; Mo, J.; McPherson, J.K.; Bell, D.T. 1996. **Decomposition of woody debris in western Australian forests.** Canadian Journal of Forest Research. 26: 954-966.

Carter, F.L.; Amburgey, T.L.; Manwiller, F.G. 1976. **Resistance of 22 southern hardwoods to wood-decay fungi and subterranean termites.** Wood Science. 8: 223-226.

Entry, J.A.; Reeves, D.W.; Backman, C.B.; Raper, R.L. 1996. **Influence of wheel traffic and tillage on microbial biomass, residue decomposition and extractable nutrients in a coastal plain soil.** Plant and Soil. 180: 129-137.

Giardina, C.P.; Ryan, C.P.; Hubbard, R.M.; Binkley, D. 2001. **Tree species and soil texture controls on carbon and nitrogen mineralization rates.** Soil Science Society of America Journal. 65: 1271-1279.

Gott, J. 1975. **Soil survey of the Mark Twain National Forest area Missouri (Parts of Carter, Oregon, Reply, and Shannon Counties).** Rolla, MO: U.S. Department of Agriculture, Forest Service. 56 p.

Hahn, J.T. 1991. **Timber resource of Missouri.** Res. Bull. NC-119. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 123 p.

Holub, S.M.; Spears, J.D.H.; Lajtha, K. 2001. **A reanalysis of nutrient dynamics in coniferous coarse woody debris.** Canadian Journal of Forest Research. 31: 1894-1902.

Idol, T.W.; Figler, R.A.; Pope, P.E.; Ponder F., Jr. 2001. **Characterization of coarse woody debris across a 100 year chronosequence of upland oak-hickory forests.** Forest Ecology and Management. 149(1-3): 153-161.

Idol, T.W.; Pope, P.E.; Ponder F., Jr. 2003. **N mineralization, nitrification, and N uptake across a 100-year chronosequence of upland hardwood forests.** Forest Ecology and Management. 176(1-3): 509-518.

Jenkins, M.A.; Pallardy, S.G. 1995. **The influence of drought on red oak group species growth and mortality in the Missouri Ozarks.** Canadian Journal of Forest Research. 25: 1119-1127.

Johnson, C.E.; Siccama, T.G.; Denny, E.G.; Koppers, M.M.; Vogt, D.J. 2014. **In situ decomposition of northern hardwood tree boles: decay rates and nutrient dynamics in wood and bark.** Canadian Journal of Forest Research. 44: 1515-1524.

Jurgensen, M.F.; Reed, D.; Page-Dumroese, D.; Laks, P.; Collins, A. [et al.]. 2006. **Wood strength loss as a measure of decomposition in northern forest mineral soil.** European Journal of Soil Biology. 42: 23-31.

Kaczmarek, D.J.; Pope, P.E.; Scott, D.A.; Idol, T.W. 1998. **Foliar and belowground nutrient dynamics in mixed hardwood forest ecosystems.** In: Waldrop, T.A., ed. Proceedings of the ninth biennial southern silvicultural research conference; 1998 February 25-27; Clemson, SC. Gen. Tech. Rep. SRS-20. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC: 136-142.

Kampichler, C., Bruckner, A. 2009. **The role of microarthropods in terrestrial decomposition: a meta-analysis of 40 years of litterbag studies.** Biological Review. 84(3): 375-389.

King, N.T. 1997. **Phosphorus distribution and availability in a Missouri Ozark watershed.** Columbia, MO: University of Missouri. 104 p. M.S. thesis.

Laiho, R.; Prescott, C.E. 2004. **Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis.** Canadian Journal of Forest Research. 34: 763-777.

Lousier, J.D.; Parkinson, D. 1978. **Chemical element dynamics in decomposing leaf litter.** Canadian Journal of Botany. 56: 2795-2812.

Melillo, J.M.; Aber, J.D.; Muratore, J.F. 1982. **Nitrogen and lignin control of hardwood leaf litter decomposition dynamics.** Ecology. 63(3): 621-626.

Mendham, D.S.; Grove, T.S.; O'Connell, A.M.; Rance, S.J. 2003. **Residue management effects on soil carbon and nutrient contents and growth of second rotation eucalypts.** Forest Ecology and Management. 181: 357-372.

Missouri Geological Survey. 1979. **Geologic map of Missouri.** Rolla, MO: Missouri Department of Natural Resources.

Page-Dumroese, D.S.; Jurgensen, M.F.; Terry T. 2010. **Maintaining soil productivity during forest or biomass-to-energy thinning harvests in the western United States.** Western Journal of Applied Forestry. 25(1): 5-11.

Page-Dumroese, D.S.; Jurgensen, M.F.; Tiarks, A.E.; Ponder, F., Jr.; Sanchez, F.G. [et al.]. 2006. **Soil physical property changes at the North American long-term soil productivity study sites: 1 and 5 years after compaction.** Canadian Journal of Forest Research. 36: 551-564.

Palviainen, M.; Finér, L.; Kurka, A.-M.; Mannerkoski, H.; Piirainen, S. [et al.]. 2004. **Decomposition and nutrient release from logging residues after clear-cutting of mixed boreal forest.** Plant and Soil. 263: 53-67.

Pella, E. 1990. **Combustion gas analyzer method for total carbon and total nitrogen.** In: Pella, E., ed. Elemental organic analysis 1. historical developments. American Laboratory. 22: 116.

PerkinElmer Corporation. 1983. **Inductively coupled plasma manual.** Norwalk, CT: Perkin-Elmer Corporation.

Plank, C.O. 1992. **Plant analysis reference procedures for the southern region of the United States.** Southern Cooperative Series Bulletin #368. Southern Extension Research Activity-Information Exchange Group-6. Athens, GA: University of Georgia. 68 p.

Ponder, F., Jr. 2005. **Effect of soil compaction and biomass removal on soil CO_2 efflux in a Missouri forest.** Communications in Soil Science and Plant Analysis. 36: 130-1311.

Ponder, F., Jr.; Fleming, R.L.; Berch, S.; Busse, M.D.; Elioff, J.D., et al. 2012. **Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons.** Forest Ecology and Management. 278: 35-54.

Ponder, F., Jr.; Fumin, L.; Jordan, D.; Berry, E.C. 2000. **Assessing the impact of *Diplocardia ornate* on physical and chemical properties of compacted forest soil in microcosms.** Biology and Fertility of Soils. 32: 166-172.

Ponder, F., Jr.; Mikkelson, N.K. 1995. **Characteristics of a long-term forest soil productivity research site in Missouri.** In: Gottschalt, K.W.; Fosbroke, S.L.C., eds. Proceedings, 10th central hardwood forest conference; 1995 March 5-8; Morgantown, WV. Gen. Tech. Rep. NE-197. Radnor, PA: U.S. Department of Agriculture, Forest Service: 272-281.

Prescott, C.E. 2010. **Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils?** Biogeochemistry. 101: 133-149.

Prescott, C.E.; Taylor, B.R.; Parsons, W.F.J.; Durall, D.M.; Parkinson, D. 1993. **Nutrient release from decomposing litter in Rocky Mountain coniferous forests: influence of nutrient availability.** Canadian Journal of Forest Research. 23: 1576-1586.

Risch, A.C.; Jurgensen, M.F.; Page-Dumroese, D.S.; Schütz, M. 2013. **Initial turnover rates of two standard wood substrates following land-use change in subalpine ecosystems in the Swiss Alps.** Canadian Journal of Forest Research. 43(10): 901-910.

Sanchez, F.G. 2001. **Loblolly pine needle decomposition and nutrient dynamics as affected by irrigation, fertilization, and substrate quality.** Forest Ecology and Management. 152: 85-96.

Scheffer, T.C.; Englerth, G.H.; Duncan, C.G. 1949. **Decay resistance of seven native oaks.** Journal of Agricultural Research. 78: 129-152.

Seastedt, T.R. 1984. **The role of microarthropods in decomposition and mineralization processes.** Annual Review of Entomology. 29: 25-46.

Shestak, C.J.; Busse, M.D. 2005. **Compaction alters physical but not biological indices of soil health.** Soil Science Society of America Journal. 69: 236-246.

Shortle, W.C.; Smith, K.T.; Jellison, J.; Schilling, J.S. 2012. **Potential of decaying wood to restore root-available base cations in depleted forest soils.** Canadian Journal of Forest Research. 42: 1015-1024.

Smith, K.T.; Shortle, W.C.; Jellison, J.; Connolly, J; Schilling, J. 2007. **Concentrations of Ca and Mg in early stages of sapwood decay in red spruce, eastern hemlock, red maple, and paper birch.** Canadian Journal of Forest Research. 37: 957-965.

Tiedemann, A.R.; Klemmendson, J.O.; Bull, E.L. 2000. **Solutions of forest health problems with prescribed fire: Are forest productivity and wildlife at risk?** Forest Ecology and Management. 127: 1-8.

Waring, R.H.; Schlesinger, W.H. 1985. **Forest ecosystems: concepts and management.** New York and Toronto: Academic Press. 340 p.

Weber, M.G. 1987. **Decomposition, litter fall and forest floor nutrient dynamics in relation to fire in eastern Ontario jack pine ecosystems.** Canadian Journal of Forest Research. 17: 1496-1506.

Yan, S.; Wang, S.; Yu, X. 2004. **Effect of mixtures with alders on soil fauna in plantation forest of Chinese fir.** Chinese Journal Applied Environmental Biology. 10: 462-466.

Yanai, R.D.; Currie, W.S.; Goodale, C.L. 2003. **Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered.** Ecosystems. 6: 197-212.

Zhang, D.; Hui, D; Luo, Y.; Zhow, G. 2008. **Rate of litter decomposition in terrestrial ecosystems: global patterns and controlling factors.** Journal of Plant Ecology. 1: 1-9.

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