Fifteen-Year Patterns of Soil Carbon and Nitrogen Following Biomass Harvesting

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The substitution of forest-derived woody biofuels for fossil fuel energy has garnered increasing attention in recent years, but information regarding the mid- and long-term effects on soil productivity is limited. We investigated 15-yr temporal trends in forest floor and mineral soil (0–30 cm) C and N pools in response to organic matter removal treatments (OMR; stem-only harvest, SOH; whole-tree harvest, WTH; and whole-tree plus forest floor removal, FFR) at three edaphically distinct aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) forests in the Great Lakes region. The OMR and temporal effects were generally site specific, and both were most evident in the forest floor and combined profile (mineral soil and forest floor) compared with the mineral soil alone. Forest floor and combined profile C and N pools were generally similar in the SOH and WTH treatments, suggesting that slash retention has little impact on soil C and N in this time frame. Temporal changes in C and N at one of the three sites were consistent with patterns documented following exotic earthworm invasion, but mineral soil pools at the other two sites were stable over time. Power analyses demonstrated that significant effects were more likely to be detected for temporal differences than the effects of OMR and in the combined profile than in the mineral soil. Our findings are consistent with previous work demonstrating that OMR effects on soil C and N pools are site specific and more apparent in the forest floor than the mineral soil.

Abbreviations: FFR, forest floor removal; OMR, organic matter removal; SOH, stem-only harvest; WTH, whole-tree harvest.

A growing interest in utilizing forest-derived biofuels as a substitution for fossil fuels has led to related questions about the long-term impacts of increasing organic matter removal on forest structure and function (Jurgensen et al., 1997; Janowiak and Webster, 2010; Berger et al., 2013). In particular, the removal of entire trees, including boles, tops, and branches (whole-tree removal, WTH), is likely to cause a greater depletion of soil organic matter and nutrients over time compared with conventional stem-only harvest (SOH), and this may ultimately limit site productivity (Proe and Dutch, 1994; Burger, 2002; Walmsley et al., 2009). Nonetheless, literature reviews and meta-analyses have often concluded that harvest-related impacts on mineral soil C pools are negligible (Johnson, 1992; Johnson and Curtis, 2001; Nave et al., 2010), and many broad-scale studies have been confounded by site-to-site complexity among climate, vegetation, and soil factors, which limits the ability to generalize the impacts of organic matter removal (Paré et al., 2002; Sanchez et al., 2006; Thiffault et al., 2006; Strömgren et al., 2013). Additional field experiments that assess medium- and long-term effects of WTH and SOH across a gradient of mineral soil textures and organic C contents would both improve cross-site comparisons and contribute to more robust meta-analyses (Johnson, 1992; Thiffault et al., 2011).

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Forest management practices that remove organic matter may be detrimental to long-term site productivity because organic matter is critical to many soil physical and chemical properties, including nutrient availability and aggregate stability (Powers et al., 1990; Henderson, 1995; Binkley and Fisher, 2013). In addition to the direct removal of organic material, harvesting may indirectly affect the soil environment, including altering the soil temperature and/or moisture content (Devine and Harrington, 2007; Slesak, 2013) and increasing extremes in soil temperature (Van Miegroet et al., 1992), both of which may influence rates of nutrient transformation and organic matter decomposition (Edwards and Ross-Todd, 1983; Slesak et al., 2010). Disruption of the forest floor during harvesting operations may intensify these effects and, depending on the moisture regime, increase nutrient loss via leaching (Henderson, 1995). However, despite the well-known importance of the forest floor to the mineral soil as a source of organic matter and physical protection (Currie, 1999), rarely have studies both manipulated the forest floor and documented its response over time.

Few studies have compared the medium-term responses (15–20 yr) of soil C and N pools to varying harvest intensities (e.g., SOH and WTH), and those with incremental measurements may have been confounded by natural temporal variability. For example, while specific management-related effects may not be observed, pool changes over time may still be detected (Johnson et al., 2002), and, indeed, interannual variability can be high (Knoepp and Swank, 1997). Medium- and long-term monitoring of various temperate forest types has suggested that temporal patterns of soil C and N pools can vary independently of harvesting (Knoepp and Swank, 1997; Johnson and Todd, 1998; Trettin et al., 1999; Johnson et al., 2007). Assessments of medium-term harvest impacts on soil C and N pools have suggested that differences between SOH and WTH are small and usually site specific, but they have not often included incremental measurements that could characterize temporal changes (Olsson et al., 1996; Johnson and Todd, 1998; Thiffault et al., 2006).

Our objective was to understand the medium-term (~15 yr) effects of biomass harvesting on soil C and N pools at three different aspen-dominated sites in the Great Lakes region. The sites were fully replicated with three levels of manipulated organic matter removal, including SOH, WTH, and whole-tree harvest plus forest floor removal (FFR), and they represented a range of soil textures (silt loam, sand, and clay). We focused on the soil C and N pools (mineral soil and forest floor) because they are valuable indices of long-term site productivity given the relative importance of organic matter and the high potential for N limitation in intensively managed sites (Johnson 1994). We expected that responses would vary somewhat due to differences in soil texture but that, generally, forest floor C and N pools would be more susceptible to harvest-related impacts than those in the mineral soil, and the overall effects on the combined profile (forest floor plus mineral soil) would follow a disturbance gradient of organic matter removal (SOH > WTH > FFR). The second objective of our study was to assess the capacity of this long-term data set to detect the effects of organic matter removal and changes over time in soil C and N pools. We compared the calculated probabilities (power) of detecting significant main effects in our results with the goal of better informing future long-term study designs.

MATERIALS AND METHODS

Study Sites and Experimental Design

This study was conducted at three aspen forests in the Great Lakes region that are part of the Long-Term Soil Productivity Network (Powers et al., 2005; Powers, 2006). The sites vary climatically and edaphically (Table 1; Stone, 2001), but all

Table 1. Site characteristics and soil pretreatment properties (mineral soil: 0–30 cm) of the three aspen forest sites in the northern Great Lakes region.

Characteristic or property	Chippewa (Minnesota) silt loam	Huron (Michigan) sand	Ottawa (Michigan) clay
Latitude, longitude	47.32, −94.55	44.57, −83.98	46.63, −89.25
Year of treatment initiation	1993	1994	1992
Soil classification	Frigid Haplic Glossudalfs	Frigid Typic Udipsamments and Frigid Entic Haplorthods	Frigid Vertic Glossudalfs
Mean annual precipitation, cm	64	75	77
Mean annual temperature, °C	3.8	6.2	4.5
50-yr site index, aspen, m	23	19	17
Soil texture, %†			
Sand	45	93	23
Silt	51	6	27
Clay	4	1	50
Coarse fragments by mass, %	1.6	1.0	0
Bulk density, Mg m^{-3}	1.24	1.12	1.19
Total C, Mg ha^{-1}‡			
Forest floor	27.5	9.7	20.4
Mineral soil	25.8	30.6	41.9
Total N, Mg ha^{-1}‡			
Forest floor	1.3	0.4	0.9
Mineral soil	1.4	1.2	3.2

† Using hydrometer method.

‡ Total C and N determined by dry combustion. Mass was estimated using <2-mm bulk density.

were fully stocked, mature aspen stands before treatment. The Chippewa site (Chippewa National Forest, Minnesota) has till-derived silt loam soils, and co-occurring tree species include red maple (*Acer rubrum* L.), basswood (*Tilia americana* L.), sugar maple (*Acer saccharum* Marsh.), northern red oak (*Quercus rubra* L.), and eastern white pine (*Pinus strobus* L.). The Huron site (Huron National Forest, northeastern Lower Peninsula of Michigan) has sandy-textured soils that formed on an acidic outwash plain. Associated tree species include bigtooth aspen (*Populus. grandidentata* Michx.), red maple, northern red oak, eastern white pine, and black cherry (*Prunus serotina* Ehrh.). The Ottawa site (Ottawa National Forest, western Upper Peninsula of Michigan) has clay-textured soils that formed from calcareous, lacustrine clay parent material. Co-occurring species at Ottawa include white spruce [*Picea glauca* (Moench) Voss], balsam fir [*Abies balsamea* (L.) Mill.] and red maple.

Harvest treatments were initiated in consecutive years, beginning with Ottawa in 1992 and followed by Chippewa in 1993 and Huron in 1994. At each site, treatment plots (50 by 50 m) were randomly established in a 3 × 3 factorial randomized block design before harvest, with three levels of organic matter removal (OMR) and three levels of soil compaction. The OMR treatments were designed to represent a disturbance gradient: the SOH treatment removed boles, but slash (branches and tops) was left on site; the WTH treatment removed all woody biomass (trees and shrubs) from the site; and the FFR treatment removed all woody biomass as well as the forest floor material from the site. The FFR treatment represented an extreme disruption of the forest floor during harvest activities, which could potentially occur on landings or skid trails. We confined this study to the lowest level of soil compaction (no additional compaction beyond that accrued through harvest activities), given that we were primarily interested in the effects of biomass harvesting practices on soil productivity. Each treatment was replicated three times per site ($n = 3$ plots); however, an error during treatment application at the Ottawa site resulted in five plot replicates for the WTH treatment. Harvests occurred under frozen soil conditions in January or February of each treatment initiation year (Table 1), and the plots naturally regenerated to aspen following treatment. An unharvested control was added to each site 2 yr after treatment installation; however, inconsistencies in sampling intensity and timing preclude us from including this treatment in our analyses. Full descriptions of treatment applications were provided by Stone (2001).

Soils were sampled on five dates: in the summer before harvest (preharvest), in the fall following harvest (Year 0), and in the spring every 5 yr subsequently (Years 5, 10, and 15). Before harvest (pretreatment), two subsamples were randomly collected from each plot and composited for analysis. Subsequently, permanent subsample locations were established uniformly throughout each plot. Initially, eight subsample locations were established (Year 0), but one additional location was added for Years 5, 10, and 15 (nine subsamples). At each location, soils were sampled at a random azimuth and distance (1–3 m) from the permanent marker (>1 m from any previous sampling collections). Forest floor (organic horizon) and mineral soil (0–30 cm) samples were extracted using a stainless steel corer (6.35-cm diameter; 190.5-cm^3 volume) fitted with a plastic tube. Forest floor and mineral soil boundaries were delineated using changes in color and texture. Tubes were removed and taken to the laboratory for processing. To maintain consistency in sampling, one technician oversaw all of the soil collection at all of the sites throughout the 15-yr study period.

Soil Analyses

For each subsample, the forest floor thickness was recorded and then separated from the mineral soil. Forest floor material was dried at 70°C for 24 h. Plot subsamples were composited and then ground to 1 mm using a Thomas-Wiley laboratory mill. Mineral soil subsamples were divided into three depths (0–10, 10–20, and 20–30 cm), sieved to 2 mm, and oven dried at 105°C to a constant mass. Mineral soil plot subsamples were then composited, finely ground using a mortar and pestle, and pulverized on a roller mill for 2 d. Total C and total N were determined for forest floor and mineral soil samples by dry combustion. The initial results obtained incrementally using two different analyzers, a Carlo Erba Model NA 1500 series (CE Elantech, Inc.) for pretreatment to Year 10 and a Leco TruSpec CHN analyzer (Leco Corp.) for Year 15, were inconsistent over time, so all archived samples were reanalyzed in 2013 using the Leco analyzer. Nitrogen values that were below the instrument's detection limit (0.04%) were replaced with half the detection limit (0.02%). Total bulk density was calculated for each subsample at each depth using the oven-dried mass (including coarse fragments), sample volume, and moisture content; the fine fraction (<2-mm) bulk density plot mean at each sampling date was used to convert C and N values to a mass basis.

Statistical Analyses

The three study sites were analyzed separately because of variations in soil texture, climate, and treatment initiation year. Our goal was to be consistent with previous Long-Term Soil Productivity Network studies that examined mineral soil properties by 10-cm increments; however, we acknowledge the potential difficulties in delineating the boundary between the forest floor and the surface mineral soil in the field that could impede the accuracy of both measurements (Yanai et al., 2003; Don et al., 2012). To balance these issues, we chose to analyze pools of C and N and the C/N ratios for the forest floor and mineral soil (0–30 cm) separately and then combined (combined profile, forest floor + mineral soil; Homann et al., 2001). Combining the three mineral soil depths did not alter the overall conclusions. For each variable (C, N, C/N ratio, and total bulk density), we used a repeated measures analysis of covariance (ANCOVA) model that included OMR and time as fixed effects and plot as a random effect. Sample year (Years 0, 5 10, and 15) was the repeated factor within a first-order autoregressive covariance structure. The pretreatment data were included as a covariate to account

Table 2. Probabilities (*F* statistics) from repeated measures ANCOVA testing of main effects of organic matter removal (OMR) and time (T) on forest floor, mineral soil (0–30 cm), and combined profile (mineral soil + forest floor) C, N, C/N ratio, and bulk density (BD) for three aspen forest sites in the northern Great Lakes region. Time was the repeated factor, and pretreatment data were used as a covariate in the model. Italicized *p* values are significant ($p < 0.1$).

Source	Forest floor			Mineral soil				Combined profile		
	Total C	Total N	C/N ratio	Total C	Total N	C/N ratio	BD	Total C	Total N	C/N ratio
					Chippewa (silt loam)					
OMR	*0.072*	*0.021*	0.586	0.955	0.460	0.134	0.399	*0.060*	*0.056*	0.405
Time	*<0.001*	*0.001*	*0.036*	0.163	0.307	0.420	*0.003*	*<0.001*	*<0.001*	0.472
OMR × T	0.1328	0.326	*0.013*	0.656	*0.028*	*0.074*	*0.016*	0.225	*0.093*	0.140
					Huron (sand)					
OMR	*0.073*	0.135	0.659	0.793	0.425	0.315	0.487	0.114	0.142	0.264
Time	0.107	*0.020*	*0.070*	0.389	*0.001*	*0.003*	*0.059*	0.649	*0.034*	*0.002*
OMR × T	0.658	0.740	0.972	0.973	0.184	0.324	*0.065*	0.712	0.192	0.273
					Ottawa (clay)					
OMR	*0.025*	*0.041*	0.459	0.473	0.439	0.124	0.483	*0.001*	*0.049*	0.918
Time	*<0.001*	*<0.001*	*0.034*	*<0.001*	*0.025*	*0.0003*	*0.008*	*0.003*	0.160	*0.005*
OMR × T	0.141	0.224	*0.057*	0.290	*0.039*	*0.002*	0.252	0.499	*0.077*	*0.014*

for inherent soil variability (VandenBygaart, 2009), and degrees of freedom were assigned using the Satterthwaite approximation. Tukey–Kramer tests were used to separate means of significant main effects. When significant treatment effects or OMR × time interactions were encountered, the SLICE command was used to separate means within the two effects.

Residuals were visually inspected for each model, and data were transformed (inverse, square root, or natural logarithm) as necessary to meet the assumptions of ANOVA. An a priori significance level of $\alpha = 0.1$ was set because of low replication ($n = 3$) and the inherent variability in repeatedly sampled soils. All analyses were conducted using the MIXED procedure in SAS (Version 9.3, SAS Institute), which is effective when applied to unbalanced designs. The probability (power) of detecting a statistically significant ($\alpha < 0.1$) time or OMR treatment effect was assessed for each site and variable (C, N, and C/N ratio) using PROC MIXED in SAS based on the steps outlined by Littell et al. (2006).

RESULTS

Carbon

Forest floor C was generally more variable among OMR treatments and over time than mineral soil C (Tables 2, 3, and 4). At Chippewa, forest floor C was lower in the FFR than the SOH treatment ($p = 0.072$) and it peaked in Year 10 (Year 10 > Years 0, 5, and 15; $p < 0.001$). At Huron, forest floor C was also lower in the FFR than the SOH treatment ($p = 0.073$), but it did not change over time. At Ottawa, forest floor C was lower in the FFR than SOH and WTH treatments ($p = 0.025$), and it had a declining trend over time (Year 15 < Years 0, 5, and 10; Year 5 > Years 0 and 10; $p < 0.001$). Mineral soil C pools were not affected by the OMR treatments at any of the sites. Mineral soil C was stable over time at Chippewa and Huron but increased at Ottawa (Year 0 < Years 10 and 15; Years 5 and 10 < Year 15; $p < 0.001$).

The combined profile C responses were similar to those for the forest floor. At Chippewa, the combined profile C in the FFR was lower than the SOH treatment ($p = 0.060$), and it peaked in Year 10 (Years 0, 5, and 15 < 10; Year 5 > Year 15; $p < 0.001$; Fig. 1). At Huron, the combined profile C was not affected by the OMR treatments nor did it change over time (Fig. 1). At Ottawa, the combined profile C was lower in the FFR than the WTH and SOH treatments ($p = 0.001$), and it increased over time (Year 0 < Years 5 and 15; $p = 0.003$; Fig. 1).

Table 3. Forest floor total C and N for three aspen forest sites in the northern Great Lakes region in response to organic matter removal treatments (SOH, stem-only harvest; WTH, whole-tree harvest; and FFR, whole-tree harvest plus forest floor removal). Samples were taken before treatment (Pre), in the fall following treatment (Year 0), and 5, 10, and 15 yr following treatment.

Sampling time	Total C			Total N		
	SOH	WTH	FFR	SOH	WTH	FFR
			Mg ha^{-1}			
			Chippewa (silt loam)			
Pre	30.8 (6.9)†	29.7 (5.5)	22.1 (1.1)	1.4 (0.2)	1.2 (0.1)	1.2 (0.1)
Year 0	33.1 (3.8)	31.5 (4.8)	18.9 (0.8)	1.4 (0.1)	1.3 (0.1)	0.8 (0.1)
Year 5	39.0 (5.0)	23.7 (3.4)	18.5 (1.2)	1.6 (0.1)	1.1 (0.1)	0.9 (0.1)
Year 10	54.9 (3.7)	36.2 (9.9)	37.5 (9.5)	2.5 (0.2)	1.6 (0.3)	1.5 (0.4)
Year 15	30.5 (0.6)	21.1 (3.9)	16.6 (1.1)	1.3 (0.1)	1.1 (0.1)	0.7 (0.1)
			Huron (sand)			
Pre	6.4 (1.0)	14.6 (4.3)	8.0 (2.1)	0.2 (0.1)	0.5 (0.1)	0.3 (0.1)
Year 0	16.8 (3.5)	10.9 (2.1)	6.0 (2.7)	0.6 (0.1)	0.4 (0.1)	0.3 (0.1)
Year 5	9.4 (3.1)	9.4 (3.6)	2.2 (0.1)	0.3 (0.1)	0.3 (0.1)	0.1 (0.1)
Year 10	8.7 (1.2)	10.7 (4.7)	4.8 (0.1)	0.3 (0.1)	0.4 (0.2)	0.2 (0.1)
Year 15	10.8 (2.3)	11.9 (4.9)	4.8 (1.8)	0.4 (0.1)	0.5 (0.2)	0.2 (0.1)
			Ottawa (clay)			
Pre	17.0 (2.7)	22.7 (1.6)	20.0 (2.1)	0.7 (0.1)	1.0 (0.1)	0.8 (0.2)
Year 0	23.2 (1.9)	27.2 (2.8)	8.3 (2.5)	0.9 (0.1)	1.2 (0.1)	0.3 (0.1)
Year 5	26.3 (0.6)	30.8 (3.0)	15.8 (6.8)	1.1 (0.1)	1.2 (0.1)	0.8 (0.3)
Year 10	20.5 (1.2)	19.9 (3.1)	11.9 (1.7)	0.9 (0.1)	0.9 (0.1)	0.5 (0.1)
Year 15	14.3 (3.8)	10.2 (2.3)	5.3 (1.3)	0.6 (0.1)	0.4 (0.1)	0.2 (0.1)

† Values are means of three plots, with SE in parentheses.

Table 4. Mineral soil C, N, and bulk density (0–30 cm) for three aspen forest sites in the northern Great Lakes region in response to organic matter removal treatments (SOH, stem-only harvest; WTH, whole-tree harvest; FFR, whole tree harvest plus forest floor removal). Samples were taken before treatment (Pre), in the fall following treatment (Year 0), and 5, 10, and 15 yr following treatment.

Sampling time	Total C			Total N			Bulk density†		
	SOH	WTH	FFR	SOH	WTH	FFR	SOH	WTH	FFR
	Mg ha^{-1}						Mg m^{-3}		
				Chippewa (silt loam)					
Pre	27.6 (2.2)‡	25.7 (1.1)	24.0 (1.2)	1.4 (0.1)	1.5 (0.1)	1.3 (0.1)	1.28 (0.05)	1.23 (0.06)	1.20 (0.02)
Year 0	29.0 (1.1)	29.3 (1.7)	26.2 (2.2)	1.8 (0.3)	1.8 (0.1)	1.4 (0.1)	1.48 (0.07)	1.38 (0.05)	1.35 (0.06)
Year 5	29.1 (2.7)	28.7 (1.2)	29.9 (2.9)	1.7 (0.2)	1.7 (0.2)	1.5 (0.4)	1.39 (0.08)	1.29 (0.05)	1.38 (0.07)
Year10	31.4 (3.4)	28.9 (1.2)	30.1 (1.1)	1.6 (0.1)	2.0 (0.4)	2.0 (0.4)	1.45 (0.04)	1.35 (0.03)	1.42 (0.07)
Year15	26.9 (2.1)	28.5 (3.4)	24.9 (4.0)	1.9 (0.2)	2.1 (0.3)	1.1 (0.1)	1.46 (0.06)	1.38 (0.06)	1.43 (0.07)
				Huron (sand)					
Pre	29.1 (1.7)	31.1 (1.7)	31.4 (4.5)	1.0 (0.1)	1.2 (0.1)	1.3 (0.2)	1.19 (0.05)	1.12 (0.02)	1.06 (0.03)
Year 0	30.0 (1.3)	29.0 (4.2)	26.9 (2.6)	1.0 (0.1)	1.1 (0.2)	0.9 (0.1)	1.27 (0.01)	1.30 (0.02)	1.29 (0.02)
Year 5	31.4 (2.2)	33.0 (1.9)	31.2 (4.6)	1.5 (0.1)	1.5 (0.1)	1.2 (0.1)	1.28 (0.03)	1.23 (0.02)	1.25 (0.02)
Year10	29.7 (2.1)	31.3 (0.7)	31.4 (2.1)	1.8 (0.3)	1.6 (0.2)	1.8 (0.2)	1.25 (0.02)	1.22 (0.02)	1.27 (0.01)
Year15	31.2 (1.5)	33.5 (5.8)	31.7 (2.8)	1.5 (0.4)	2.0 (0.1)	1.0 (0.1)	1.22 (0.02)	1.27 (0.04)	1.27 (0.01)
				Ottawa (clay)					
Pre	37.4 (2.7)	41.9 (1.9)	46.5 (7.4)	3.0 (0.1)	3.0 (0.3)	3.6 (0.2)	1.12 (0.03)	1.25 (0.06)	1.17 (0.04)
Year 0	37.6 (1.7)	41.8 (2.9)	40.5 (1.2)	3.0 (0.2)	3.0 (0.1)	2.8 (0.1)	1.26 (0.01)	1.23 (0.02)	1.24 (0.01)
Year 5	43.4 (2.2)	43.5 (2.0)	42.8 (3.6)	3.5 (0.8)	3.5 (0.3)	2.1 (0.4)	1.30 (0.01)	1.28 (0.02)	1.26 (0.03)
Year10	46.1 (6.8)	50.2 (4.2)	51.9 (3.7)	3.1 (0.3)	3.5 (0.2)	3.5 (0.4)	1.14 (0.06)	1.23 (0.02)	1.22 (0.05)
Year15	62.1 (4.9)	70.0 (4.9)	56.4 (2.5)	3.4 (0.1)	3.5 (0.2)	3.4 (0.1)	1.27 (0.02)	1.30 (0.02)	1.28 (0.04)

† Bulk density average of 0–10-, 10–20-, and 20–30-cm depths.

‡ Values are means of three plots, with SE in parentheses.

Nitrogen

The overall forest floor and mineral soil N response patterns were similar to those for C (Tables 2, 3, and 4). At Chippewa, forest floor N was lower in the FFR than the SOH treatment ($p = 0.021$), and it peaked in Year 10 (Year 10 > Years 0, 5, and 15; $p < 0.001$). At Huron, forest floor N was not affected by OMR, but it varied slightly over time (Year 0 > Year 5; $p = 0.020$). At Ottawa, forest floor N was lower in the FFR than the SOH and WTH treatments ($p = 0.041$), and it declined over time (Year 0 < Year 5; Year 5 < 10; Years 0, 5, and 10 < Year 15; $p < 0.001$). The interaction between OMR and time was significantly related to mineral soil N at Chippewa ($p = 0.028$); temporal differences were primarily within the FFR treatment (Year 10 > Year 15), but no OMR differences were observed. At Huron, mineral soil N was not affected by the OMR treatments, but it increased slightly over time (Year 0 < Years 5, 10, and 15; Year 5 < Year 10; $p = 0.001$). At Ottawa, a significant OMR × time interaction existed for mineral soil N ($p = 0.039$), with OMR differences in Year 5 (FFR < WTH) and time differences in the FFR treatment (Year 5 < Years 10 and 15).

The responses of combined profile N reflected those for forest floor N. There was a significant OMR × time interaction ($p = 0.009$) for combined profile N at Chippewa (Fig. 1); subsequent pairwise comparisons revealed changes over time in the FFR treatment (Year 0 < Year 10; Year 10 > Year 15) and the SOH treatment (Year 0 < Year 10), as well as OMR treatment differences in Year 15 (FFR < SOH and WTH). Combined profile N at Huron was not affected by OMR but changed over time (Years 0 and 5 < Year 10; $p = 0.034$; Fig. 1). At Ottawa, the effects of the OMR treatments on the combined profile N varied among the sample years (OMR × time interaction $p = 0.077$; FFR < SOH and WTH in Year 5; Fig. 1).

Carbon/Nitrogen Ratio

The responses of the C/N ratios were less consistent than those of the total C and N pools (Table 2). At Chippewa, the forest floor C/N ratio varied over time by treatment (OMR × time interaction $p = 0.013$; Year 5 < Year 10 in the FFR treatment). The OMR treatments did not affect the forest floor C/N ratio at Huron, but it showed a slight declining trend over time (Year 5 > Year 15; $p = 0.070$). Despite a significant OMR × time interaction ($p = 0.057$) for the forest floor C/N ratio at Ottawa, no specific temporal or OMR treatment differences were detected by Tukey–Kramer analysis. Similarly, a significant OMR × time interaction in the mineral soil C/N ratio at Chippewa ($p = 0.074$) did not result in differences among treatments or years. At Huron, the mineral soil C/N ratio decreased slightly over time (Year 0 < Year 10; $p = 0.001$). A significant OMR × time interaction ($p = 0.002$) occurred for the mineral soil C/N ratio at Ottawa, with the C/N ratio varying among the OMR treatments in Year 5 (FFR < SOH and WTH) and over time in the FFR treatment (Year 0 < Year 5; Year 5 > 10) and the WTH treatment (Years 0, 5, and 10 < Year 15). The combined profile C/N ratio at Chippewa was not affected by the OMR treatments nor did it change over time. At Huron, the combined profile C/N ratio was not affected by the OMR treatments, but it declined slightly over time (Year 0 > Year 10; $p = 0.002$). A significant OMR × time interaction ($p = 0.014$) existed at Ottawa for the combined profile C/N ratio; subsequent Tukey–Kramer analyses revealed treatment-specific temporal changes (FFR: Year 0 <

Year 5; WTH: Years 5 and 10 < Year 15) and OMR treatment effects at Year 5 (FFR > WTH).

Bulk Density

The mineral soil bulk density responses to the OMR treatments and time varied inconsistently among the three sites. At Chippewa, temporal changes in bulk density varied among the OMR treatments (OMR × time interaction $p = 0.016$; FFR: Year 0 < Year 10 and Year 15; WTH: Year 5 < 15). Similarly, a significant OMR × time interaction ($p = 0.065$) occurred at Huron, but Tukey–Kramer analyses did not detect significant differences over time or among treatments. At Ottawa, bulk density varied over time across the OMR treatments (Year 10 < Years 5 and 15; $p = 0.008$).

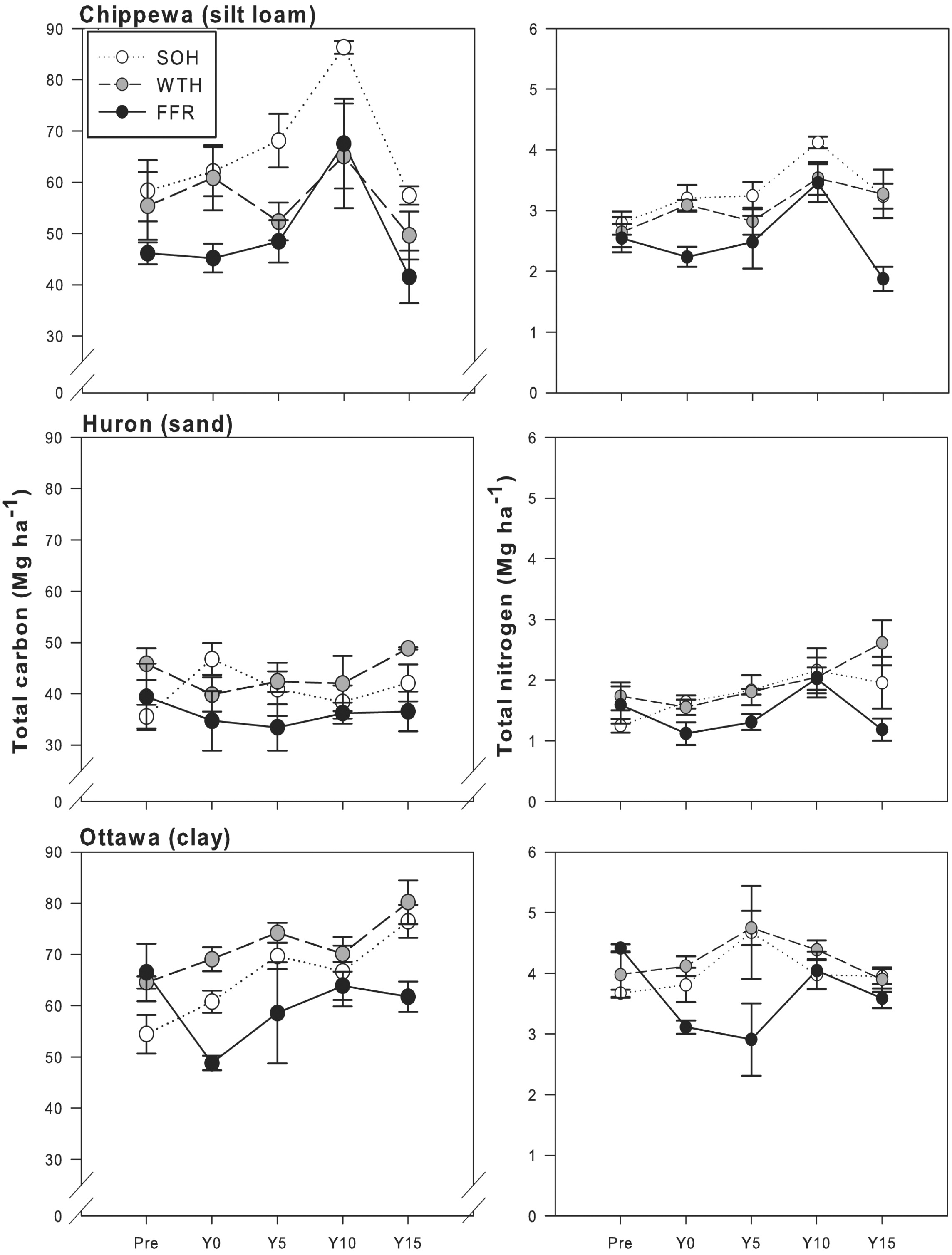

Fig. 1. Combined profile (forest floor + mineral soil, 0–30 cm) total C (left) and N (right) pools over time since organic matter removal treatments of stem-only harvest (SOH), whole-tree harvest (WTH), and forest floor removal (FFR) at three aspen forest sites in the northern Great Lakes region.

Power Analysis

The probabilities (power) of observing a statistically significant OMR treatment effect was generally higher in the forest floor (55–86%) and combined profile (51–99%) than the mineral soil (11–25%; Fig. 2). Temporal changes in C and N (73–100% for forest floor; 31–100% for the mineral soil; 25–100% for the combined profile) were generally more likely to be detected than OMR treatment effects. In general, when probabilities for either OMR or temporal effects were >80%, significant ANCOVA effects were observed, with the exception of the combined profile C at Huron. Additionally, for six site and variable combinations, significant OMR treatment effects were observed despite relatively low detection probabilities (50–80%; Chippewa forest floor and combined profile C, Huron forest floor C, Chippewa combined profile N, and Ottawa forest floor and combined profile N).

DISCUSSION

Our results show that the long-term impacts of harvest and forest floor removal on soil C and N pools in aspen forests of the Great Lakes region are site specific, and they illustrate the complex interactions that regulate soil organic matter dynamics, including edaphic conditions, climate, and vegetation (Thiffault et al., 2011). In particular, soil parent material (Paré et al., 2002), texture (Borchers and Perry, 1992; Sanchez et al., 2006), and soil order (Nave et al., 2010) have been associated with influencing forest management effects on site biogeochemistry. For example, coarse-textured soils are expected to be more sensitive to alterations in organic matter inputs from forest management (Carlyle, 1993; Henderson, 1995; Thiffault et al., 2011), while finer textured soils have more physically protected N, which can buffer losses due to treatment (Borchers and Perry, 1992). Our findings from these three edaphically different sites were counter to these predictions. The sandy soil site (Huron) was the least impacted by harvest treatment (combined profile). High variability at this site, as demonstrated by consistently higher coefficients of variation (data not shown), may have made it difficult to detect harvest treatment effects and suggests that more intensive sampling is required in coarse-textured soils.

Harvest effects on C and N pools were most evident in the forest floor and the combined profile rather than the mineral soil, as we predicted based on previous research (Johnson, 1992; Nave et al., 2010; Thiffault et al., 2011). Forest floor and combined profile C pools were lower in the most extreme FFR treatment than the two more moderate SOH and WTH treatments at Ottawa (clay) and lower for FFR than SOH at Chippewa (silt loam). These results partially support our prediction that soil C in the combined profile would decrease as the severity in the disturbance gradient increased (SOH > WTH > FFR), and they suggest that SOH and WTH have similar impacts on soil C pools in these forests. Powers et al. (2005) suggested that removal of the forest floor has the greatest consequences for soil productivity compared with SOH or WTH harvest, and both medium-term empirical and long-term modeling results suggest

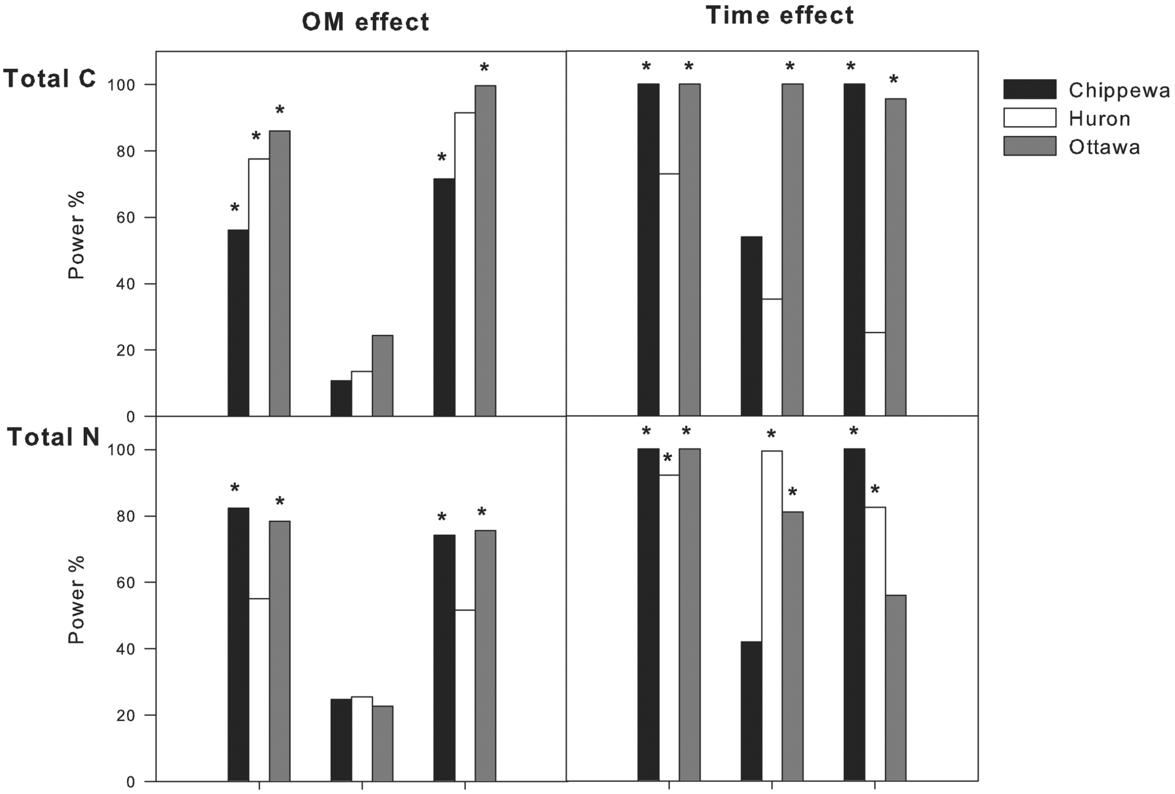

Fig. 2. Probability (power) of detecting a statistically significant ($p < 0.1$) organic matter (OM) removal treatment (left) or time effect (right) in total C and N in the forest floor, mineral soil (0–30 cm), or the combined profile (combined forest floor + 0–30-cm mineral soil) at three aspen forest sites in the northern Great Lakes region. *Statistically significant main effect was observed.

that the differences between SOH and WTH on soil C pools are small (Bengtsson and Wikstrom, 1993; Olsson et al., 1996). This is potentially because the majority of C in logging debris is released to the atmosphere over time as CO_2 (Mattson et al., 1987; Johnson and Todd, 1998; Palviainen et al., 2004).

Harvest residue removal may indirectly influence both mineral soil C and N pools, either through modification of the soil microclimate (Van Miegroet et al., 1992; Slesak, 2013), which could influence belowground decomposition, or by reducing the amount of substrate for microbes, which would result in lower microbial biomass (Hassett and Zak, 2005; Tan et al., 2005) and exacerbated N losses via leaching (Vitousek and Matson, 1985). Both of these may affect site productivity; indeed, differences in aboveground productivity between the SOH and WTH treatments have been observed at these sites (Voldseth et al., 2011). Thus, although our results suggest that residue removal (SOH vs. WTH) does not affect soil C and N pools in the medium term in these forests, these results are not necessarily indicative of other ecosystem-level responses, and treatment effects may be more visible after multiple rotations.

A key strength of this study is the documentation of soil C and N pools over time since treatment. Mineral soil C pools often increase initially following harvest (Alban et al., 1994; Butnor et al., 2006; Sanchez et al., 2006), potentially as a result of fine root mortality and decomposition, but they are predicted to decline over time (Powers et al., 2005). Similar to previous work at these sites, we did not observe this pattern (Voldseth et al., 2011); instead, the mineral soil pools of C and N were relatively stable at two of the sites we studied (Chippewa and Huron) and increased over time at the third (Ottawa). Changes in bulk density over time were spurious and do not explain the trends observed at Ottawa. However, forest floor C and N pools declined over time at Ottawa (Table 3), and mineral soil C in the 0- to 10-cm depth showed an increasing trend over time (data not shown). Therefore, we might attribute these changes to sampling inconsistencies; for example, variability in how the forest floor was separated from the mineral soil could lead to inconsistent amounts of organic matter in both pools (Homann et al., 2001; Yanai et al., 2003). Still, this seems unlikely because: (i) the changes were steady over time; (ii) they occurred at only one of the three study sites; and (iii) the combined profile C and N pools also increased over time. Instead, the temporal pattern at Ottawa appears more consistent with C trends observed in the region on earthworm-invaded sites (Alban and Berry, 1994; Hale et al., 2005). Verification of this explanation was precluded by the lack of unharvested reference plot data and early records of earthworm abundance at this site; however, earthworm presence was confirmed anecdotally at Ottawa in 2012 (J. Elioff, personal communication).

Soil C pools and fluxes in aspen-dominated systems may differ markedly from other temperate forests. Harvested aspen forests regenerate quickly via suckering and require little to no site preparation or planting (Frey et al., 2003). The decomposition of fine roots is thought to be a major source of soil C following harvest in temperate forests (Powers et al., 2005); however, because of suckering, the proportion of aspen roots that die and decompose to those that carry over to the next generation following harvest may be lower than in other forest types. Although extensive fine root mortality has been noted in the first 2 yr following harvest in aspen forests (Visser et al., 1998), the specific amount of mortality and the rate of decomposition are uncertain. The effects of fine root decay may be more transient for aspen than associated species because aspen tissues have higher nutrient concentrations (Alban et al., 1978) and thus may decompose faster. Taken together, the rapid growth, nutrient uptake, and potential carryover of root biomass may moderate short- and medium-term harvest treatment effects on belowground C and N pools in aspen forests and explain why we did not observe marked differences between SOH and WTH. However, over the long-term, conducting WTH for multiple rotations in aspen forests may eventually lead to site nutrient limitations given the relatively high nutrient concentration of aspen tissues (Alban et al., 1978).

Treatment effects were more evident when we analyzed the forest floor as well as the combined profile (forest floor and mineral soil) compared with the mineral soil alone (0–30 cm). However, by limiting our study to surface sampling of the mineral soil, we potentially missed subsurface changes in C (Strahm et al., 2009). Surface sampling is not always informative compared with sampling at depth (~60 cm; Harrison et al., 2011), especially when assessing management effects, because harvesting may destabilize soil C (Diochon and Kellman, 2009). Further, aspen forests tend to hold greater amounts of organic C at depth than coniferous species in boreal (Laganière et al., 2013) and western seasonally dry (Woldeselassie et al., 2012) forests. Collectively, this suggests that future work in the Great Lakes region should examine subsurface C pools, especially in coarse-textured Spodosols (e.g., Huron) where downward redistribution of C may be high (Ussiri and Johnson, 2007).

Spatial variability in mineral soils and forest floors is high in most forests (Conant et al., 2003; Yanai et al., 2003; Oliver et al., 2004), which increases the likelihood of committing a Type II error (i.e., failing to reject a false null hypothesis). However, a lack of statistical difference in soil C pools does not necessarily mean that no differences exist, and, in such situations, post-hoc power analysis is recommended (Kravchenko and Robertson, 2011). In our study, where replication was relatively low ($n = 3$), treatment and temporal effects were inconsistent among sites, especially in the mineral soil, and the probability of detecting an OMR effect on the mineral soil C or N was <30%. Statistical power increased when the combined profile was analyzed, probably because OMR treatment and temporal differences were more detectable in the forest floor. Power was also higher for detecting temporal changes than OMR effects, which suggests that long-term study designs need to be sufficiently intensive to capture treatment effects within potential temporal variability. Our study illustrates that an experiment designed to achieve 80% power may be adequate for detecting treatment effects on a combined profile; however, soil texture has a large influence. Coarser textured soils (e.g., Huron) with low levels of organic material have more spatially heterogeneous C and N pools and therefore may require greater sampling intensity (Conant et al., 2003).

We emphatically endorse the recommendations outlined by Lawrence et al. (2013) for the implementation and maintenance of long-term soil studies. In our study, one technician managed all of the sample collection throughout the entire study period, and thus we are reasonably confident that sampling inconsistencies that may occur among technicians (for example, inconsistently defining the forest floor and mineral soil boundary; Yanai et al., 2003) were minimized. Soil processing methodologies were standardized and all samples were carefully archived. However, our initial statistical analysis revealed that the total C and N analyses done incrementally were inconsistent (data not shown), and, had we not reanalyzed all of the archived samples (data presented), these analyses may have led us to falsely conclude that levels of C and N declined in the mineral soil at Year 15. The inconsistencies in C and N analysis that we encountered highlight the importance of not only archiving samples from long-term studies but also of conducting repeated analyses. Different analytical methods for quantifying soil C and N can alter results and conclusions, especially at low concentrations (Brye and Slaton, 2003), and interannual variability may be high (Knoepp and Swank, 1997; Brye et al., 2002; Johnson et al., 2002). This highlights the need to reanalyze archived samples from long-term studies when instruments are replaced and to continuously and meticulously monitor data for instrument-based error.

SUMMARY AND CONCLUSIONS

The global significance of the forest soil C pool, as well as the influence of soil C on site productivity (Dixon et al., 1994; Jurgensen et al., 1997; Grigal and Vance 2000), underscores the need to quantify the responses of forest soil C stocks to management. This need is particularly acute because of an increased focus on the removal of woody residues and other traditionally non-merchantable material (e.g., stumps) for biofuel feedstocks (Berger et al., 2013). In our regionally replicated experiment, OMR effects varied among the three sites but soil C and N did not differ between the SOH and WTH treatments, suggesting that logging debris from a single harvest does not substantially contribute to these pools within the 15-yr time frame; however, differences may be more apparent after multiple rotations. The OMR effects on soil C and N were greatest with WTH plus FFR, which emphasizes the importance of minimizing forest floor disruption during harvest activities. Sites on coarse-textured soils are more variable than those on finer textured soils, and they may require greater sampling intensity to detect management effects. Finally, our study highlights the need to carefully design and maintain medium- and long-term studies to capture both management and temporal changes.

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