**Changes in soil physical and chemical properties following organic matter removal and
compaction: 20-year response of the aspen Lake-States Long Term Soil Productivity
installations**

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Abstract

Soil functions that control plant resource availability can be altered by management activities such as increased organic matter (OM) removal and soil compaction during forest harvesting. The Long Term Soil Productivity study was established to evaluate how these practices influence soil and site productivity using experimental treatments that span a range of forest types and soil conditions at sites across North America. Here we report on the effects of these treatments on soil properties after 20 years at three of the oldest sites in the study. The sites all are located in aspen (*Populus tremuloides*) forests of the Lake States region USA, and span a soil texture (silt loam, sand, and clay) and productivity gradient. Treatments were applied in a 3x3 factorial design that included three levels of OM removal (stem only harvest, SOH; whole tree harvest, WTH; and WTH plus forest floor removal, FFR) and three levels of soil compaction (no additional, intermediate, and high). After 20 years, effects of OM removal were primarily associated with the extreme FFR treatment, and generally limited to the lower productivity sand and clay texture sites. At the sand texture site with low initial pools of C and nutrients, FFR resulted in soil C and Ca reductions over the 20-year period, which may have caused large reductions in aspen growth that were previously observed at that site. Although treatment effects of SOH and WTH were limited, soil P tended to decrease at all sites during the study period, which may affect future productivity at these sites. Effects of soil compaction treatments were generally linear and only apparent at the silt loam and sand texture sites. At all sites, bulk density in the upper 10 cm had fully recovered from harvest- and treatment-induced increases after 20 years, but remained elevated and increased with increasing compaction at depths below 10 cm. Previous work indicates that soil compaction had neutral to positive effects on growth at the sand texture site, but strongly negative effects on growth at the silt loam texture site. These

44 20-year results demonstrate that the effect of OM removal and soil compaction on soil properties
45 is site-specific, which generally aligns with concepts of soil quality and its influence on
46 vegetation growth. Although the LTSP study has proved invaluable in clarifying these linkages
47 across North America, there are some limitations with measurement protocols that limit the
48 overall utility of the soil assessment. These limitations inhibit the development of soil-based
49 indices to identify high risk sites and practices at odds with sustainable forest management.

Introduction

Maintaining functions important to soil quality is essential to sustainable forest management given their fundamental role in affecting ecosystem processes and structure (Schoenholtz et al. 2000, Burger 2009, Nambiar 1996). Soil functions related to plant resource supply (i.e., water and nutrient availability) are centrally important because of their overarching influence on site productivity (Powers et al. 1990). Because of this, a large body of research has focused on quantifying the influence of soil properties on forest productivity and explored the potential for management actions to alter it (increase, decrease, or maintain; Burger 2009). Although the linkages between soil properties and potential site productivity are widely recognized (Nambiar 1990), quantification of the relationship across a broad range of site conditions and how it may change with management remains challenging. In the management context, much attention has focused on potential impacts to soil that occur at the time of forest harvest, including changes associated with increasing organic matter (OM) removal (Thiffault et al. 2011, Nave et al. 2011) and soil compaction (Cambi et al. 2015, Greacan and Sands 1980).

One notable attempt to comprehensively assess the effects of OM removal and soil compaction on site productivity is the Long Term Soil Productivity (LTSP) study established in the early 1990s (Powers et al. 1990, Tiarks et al. 1989). The LTSP study is a network of sites that span a range of forest types, climate, and soils, with a similar experimental design to test the effects of increasing levels of aboveground OM removal and soil compaction on soil properties and aboveground productivity. These treatments reflect operational forest management considerations and are hypothesized to directly influence plant resource supply through their

effects on soil OM (or soil C as a surrogate) and soil porosity (Powers et al. 1990). Although soil OM and porosity are widely recognized as keystone soil properties influencing nutrient and water availability, available information to date has been insufficient for the development of broad soil sustainability criteria (Tiarks et al. 1989). This information gap is particularly vexing given the strong arguments in support of a soil-based indices for sustainable forest management (Burger and Kelting 1999, Fox 2000).

Summary results incorporating findings from LTSP installations across the network have been reported by Powers et al. (2005), Fleming et al. (2006), Page-Dumroese et al. (2006), Sanchez et al. (2006), and Ponder et al. (2012). These reports generally concluded that there are limited effects of OM removal on soil C content and aboveground biomass for up to 10 years after treatment. Ten-year effects of soil compaction on aboveground tree growth were found to be dependent on soil texture and generally were either neutral or positive, with the exception of aspen in the Lake States (Ponder et al. 2012). Effects of soil compaction on soil chemical parameters (including soil C) has not been widely reported on, nor have effects of OM removal on soil nutrients with the exception of soil N (Powers et al. 2005). Regardless, the findings reported to date generally indicate limited effects of extreme OM removal and compaction on stand productivity, with some exceptions at sites with lower quality soils. Many of the above reports have noted that longer-term effects may become more apparent, especially after canopy closure when peak nutrient demand occurs or following multiple rotations (Powers et al. 2005, Ponder et al. 2012).

One of the perceived strengths of the LTSP study is the controlled, experimental nature of the approach compared to other approaches such as input-output budgets (Ranger and Turpault 1999 Vadeboncoeur et al. 2014) and meta-analyses of previous (usually short-term) studies (Nave et al. 2011, Johnson and Curtis 2001). Long-term studies, such as the LTSP experiment, are powerful because they provide direct observations of soil change over time, and can provide evidence of the causal mechanism(s) contributing to it (Richter et al. 2007). Indeed, one of the primary objectives of the LTSP experiment was to remove equivocal assessments and address the information need “directly and unambiguously” (Powers et al. 2005). However, the degree to which this is achieved is heavily dependent on the base design as it relates to inference, sample error and its control on detectable change, and underlying assumptions regarding the chosen measurement variables and their relationship to functional ecosystem response (Lawrence et al. 2013).

Some of the earliest LTSP installations were established in the aspen coevertype of the Lake States region (Stone 2001). These sites occur on three contrasting soils, allowing for evaluation of soil type influence on potential response to OM removal and soil compaction. Reporting on the first decade of findings from these three sites, Voldseth et al. (2011) found that bulk density following soil compaction had begun to recover, that there was no effect of any treatment on soil C and N, and that treatment effects on nutrient cations were limited and varied by site. In contrast, Kurth et al. (2014) found significantly lower C following forest floor removal treatments at two of the three sites at 15 years post-harvest, perhaps indicating that effects of OM removal on soil chemical properties may become more apparent over time. Here we report on findings from these same sites 20 years after treatment. Our objectives were to 1) assess effects

of OM removal and soil compaction on the change in soil C, nutrients, and soil bulk density, and 2) use these 20-year results to evaluate the LTSP program with regards to its objectives, inference, and utility.

Materials and Methods

Site characteristics

The three LTSP study sites are located on USDA Forest Service national forests in the Great Lakes Region USA. within the Laurentian Mixed Forest Province. Soil at the Chippewa National Forest Site (Chippewa) is a silt loam derived from loess and till with intermediate levels of soil N and other macronutrients despite having the highest potential productivity based on aspen site index (Table 1). Soil at the Huron-Manistee National Forest site (Huron) is a sand formed from outwash that was relatively low in soil N and other macronutrients. Soil at the Ottawa National Forest Site (Ottawa) is a clay developed in calcareous lacustrine sediments with high levels of N and other nutrients but the lowest potential productivity (Table 1). Dominant cover was aspen at each site, but other common co-occurring species included red maple (*Acer rubrum* L.), northern red oak (*Quercus rubra* L.), eastern white pine (*Pinus strobus* L.), bigtooth aspen (*Populus grandidentata* Michx.), and balsam fir (*Abies balsamea* (L.) Mill.).

Sites were harvested during the winter in consecutive years starting in 1992. The experimental design was a completely randomized factorial with 2 factors that each had 3 levels. Factor 1 was organic matter (OM) removal and included: 1) stem-only harvest where all non-merchantable

tops and limbs were retained on site (SOH), 2) whole-tree harvest where all aboveground material was removed (WTH), and 3) whole-tree plus forest floor removal (FFR). Factor 2 was soil compaction and included: 1) soil compaction associated with harvesting, 2) intermediate compaction, and 3) high compaction. The compaction treatments, which were conducted after harvesting and OM treatment, were intended to increase bulk density by 15% and 30% in the intermediate and high compaction treatments, respectively (Stone 2001). Treatments were randomly assigned to plots 0.25 ha in size and each combination was replicated 3 times at each site with the exception of the Ottawa site where a mistake in treatment assignment resulted in 5 replicates of the WTH-no compaction treatment, 2 replicates of the SOH-intermediate compaction treatment, and only 1 replicate in the SOH-high compaction treatment. All sites were naturally regenerated to aspen primarily by root suckering. See Stone (2001) for more detailed descriptions of the sites and treatment application.

Soil sampling and analyses

Soils were sampled during the summer in the year preceding harvest (i.e., pretreatment) and at 5 year intervals thereafter; however, we only present findings from years 10 and 20 to focus on the long-term results and implications. In each treatment stand, samples were collected at 5 locations prior to harvest, and at 9 locations in years 10 and 20. All samples were collected by the same individual with a stainless steel corer (6.35 cm diameter; 190.5 cm³ volume) using an internal plastic sleeve to a depth of 30 cm. For pretreatment and year 10, the forest floor was collected as part of the sample core, but in year 20 the forest floor was collected using a 25.4 cm diameter PVC ring. Cores were transported to the laboratory and separated into forest floor and

10 cm mineral soil depth increments. Forest floor was dried at 70°C for 24 hours, weighed to determine mass per unit area, and then composited for analytical measures. Mineral soil was dried to 105°C until constant mass was attained, weighed to determine total mass per unit volume (i.e., bulk density), sieved to pass a 2mm mesh, weighed again to determine fine fraction mass per unit volume, and then composited for analytical measures. Mineral soil samples were ground with a mortar and pestle and pulverized on a roller mill. All samples were stored in airtight, plastic containers and archived after processing.

We conducted all analytical measures on archived samples (reanalyzing earlier sample years) to account for measurement error that may vary by method, analytical machines, and laboratory protocols (Ross et al. 2015). Total soil C and N were measured on a 1-g pulverized subsample with dry combustion using a LECO Dumas combustion technique on a Fisons NA1500 NCS Elemental Analyzer (ThermoQuest Italia, Milan, Italy). The Mehlich method (Mehlich 1984) was used to extract soil P, Ca, Mg, and K, and extract concentrations were measured with inductively coupled plasma spectroscopy (Varian Vista MPX, Varian, Palo Alto, CA, USA). Concentrations were converted to a mass basis using the fine fraction (<2mm) mass estimate. All estimates are reported on an oven dry (105°C) basis.

Data analysis

For all analyses, each site was analyzed independently in SAS (SAS Institute, Inc. 2013) with a significance level of 0.1 because of low statistical power associated with the level of replication and high inherent variability in some of the variables (Kurth et al. 2014). Forest floor and

mineral soil mass estimates of C and N were summed for analysis, and mass estimates of extractable macronutrients were summed for mineral soil only. We assessed treatment effects using the absolute change in soil C and nutrient pools over time to account for differences that may have existed in those pools prior to treatment (Homann et al. 2008). Change in soil C and nutrient content were calculated as the difference between pretreatment and the 10- and 20-post-treatment measurement periods, with negative values indicating absolute losses and positive values indicating gains. Effect of treatment on the change in soil C and nutrient content estimates was analyzed using mixed model analysis of variance (Proc Mixed in SAS; SAS Institute, Inc. 2013) for each time period, with pre-treatment values used as covariates when significant. In some instances, significant differences between treatments are associated with increases in one treatment and decreases in another. Confidence intervals were developed for the mean 10- and 20-year change in soil C and nutrients within a treatment to independently assess if any change over time was significantly different from zero. Examination of the residuals indicated assumptions of normality and homogeneity were valid. When F tests indicated significant treatment interactions, multiple comparisons with Tukey's adjustment were conducted to detect differences between treatment means.

Results

General patterns of response

Regardless of treatment and in most instances at all of the sites, soil C and nutrient pools tended to increase in the first decade, followed by decreased or stable pools in the second decade after treatment (Figure 1, Tables 2 and 3). In general, changes relative to pre-treatment pools were

greatest at the Chippewa site, intermediate at the Huron site, and lowest at the Ottawa site, which also had the largest initial pools of soil C and nutrients of the three sites (Table 1). At the Chippewa site, C and all nutrient elements except P were significantly higher compared to pretreatment values after 20 years (Tables 2 and 3). Change in soil P was not significantly different from 0 after 20 years at Chippewa, but there was a significant decrease in soil P after 20 years at the Huron and Ottawa sites in most treatments (Table 3). The 20-year change in soil Ca was significantly greater than 0 at all sites (except with FFR at Huron – see below), with magnitude of change decreasing in the order Chippewa, Ottawa, and Huron installations.

OM removal effects on soil chemistry

There was no significant difference among the OM removal treatments on the change in soil C and N mass for either time period at any of the sites ($p > 0.321$; Table S1). Despite the lack of difference among treatments, there was a significant reduction in soil C with FFR after 20 years at both the Huron and Ottawa sites (Figure 1, Table 2). At the Chippewa site, FFR treatments had a significantly lower change in soil P compared to the WTH treatments at both 10 ($p = 0.045$; 71 kg ha^{-1} 90% CI: 11-132) and 20 years ($p = 0.073$; 70 kg ha^{-1} 90% CI: 5-140). Change in soil P did not differ among treatments at either the Huron or Ottawa sites, but there was a significant reduction in the SOH harvest at the Huron site and all treatments at the Ottawa site after 20 years (Figure 1, Table 2). Note that there was significant interaction ($p = 0.099$; S1) between the treatment factors on the change in soil P after 20 years at the Ottawa installation, but multiple comparisons failed to detect significant differences among treatment combinations and there were no consistent trends in response (data not shown). Overall, there were only two instances

of treatment interactions between OM removal and compaction, both of which were only marginally significant (Table S2).

OM removal effects on soil nutrient cations were limited (Table S1). Interaction between the treatment factors on the change in extractable Ca was significant at the Chippewa site ($p=0.085$) 10 years after treatment, which was associated with lower change with FFR compared to WTH and SOH in the intermediate compaction treatment only, but all treatments had significant increases in soil Ca over time (Figure 1, Table 3). At the Huron and Ottawa sites, extractable soil Ca also increased in the SOH and WTH treatments after 20 years, but not the FFR treatments (Figure 1, Table 3). In the case of Huron after 20 years, the FFR treatment had significantly lower change in soil Ca compared to both the WTH treatment ($p=0.003$; 111 kg ha^{-1} 90% CI: 23-200) and the SOH treatment ($p=0.007$; 139 kg ha^{-1} 90% CI: 52-226). For extractable Mg at the Chippewa site, there was a significant main effect of OM removal after 20 years ($p=0.097$; S1), but no significant difference was found among treatment means using the Tukey adjustment ($p=0.110$).

Compaction effects on soil chemistry

There was a significant effect of soil compaction on the change in soil N at the Ottawa site 10 years after treatment, where intermediate compaction had a significantly greater positive change in soil N compared to the no compaction ($p=0.068$; 820 kg ha^{-1} 90% CI: 70-1569) and high compaction ($p=0.099$; 849 kg ha^{-1} 90% CI: 2-1696) treatments. No other compaction treatment effects on the change in soil C and N mass were significant at any site or time period (Table S1),

but there was a significant reduction in soil C after 20 years in the no and intermediate compaction treatments at the Huron site (Table 2). Main effects of soil compaction treatments on extractable cations was limited to soil K at the Huron ($p=0.096$) and Ottawa ($p=0.046$) sites 10 years after treatment only (Table S1). At Huron, change in soil K was significantly lower with no compaction compared to intermediate compaction ($p=0.084$; 52 kg ha^{-1} 90% CI: 2-102), which was a result of a decrease in the no compaction treatment and increase in the intermediate treatment. Similarly, at Ottawa, the change in soil K was also lower with no compaction compared to the high compaction treatment ($p=0.039$; 108 kg ha^{-1} 90% CI: 20-196), but in that instance the change after 10 years was positive in all treatments (Table 3).

Treatment effects on soil bulk density

Increases in soil bulk density were largely associated with effects of the compaction treatments, but there were some effects of OM removal on the change in soil bulk density at the Chippewa and Ottawa sites (Table S2). At the Chippewa site after 10 years, the increase in mineral soil bulk density at 0-10 cm depth was greater in the SOH treatment compared to the WTH treatment ($p=0.07$; 0.09 Mg m^{-3} 90% CI: 0.02-0.14), but there was no difference with FFR treatments. At the Ottawa site after 20 years, FFR had a greater increase in bulk density at 10-20 cm depth increment than either the SOH ($p=0.034$, 0.07 Mg m^{-3}) or WTH treatments ($p=0.073$; 0.05 Mg m^{-3}). No other effects of OM removal on bulk density were significant at any site or time period.

Soil compaction treatment effects were most pronounced in duration and across depth increments at the Huron site, intermediate at the Chippewa site, and not apparent at the Ottawa site. At all

sites, harvest- and treatment-induced increases in bulk density at 0-10 cm were greatest 10 years after treatment followed by full recovery by 20 years after treatment (Figure 2). At the Chippewa and Huron sites, bulk density remained elevated at 10-20 cm depth after 20 years, and the amount of recovery to pretreatment values decreased with increasing level of soil compaction. Similarly, there was a significant difference at 20-30 cm at the Huron site where the change in bulk density over 20 years increased with increasing level of soil compaction (Figure 2). Similar non-significant trends were observed at the Chippewa site, where bulk density remained elevated in all treatments after 20 years.

Discussion

Increased OM removal (e.g., for bioenergy feedstocks) and soil compaction at time of forest harvest have potential to reduce subsequent stand productivity via a reduction in soil C, nutrient pools, and total pore space (increased bulk density). We found some differences among OM removal and soil compaction treatments on soil C and nutrients 20 years after treatment, with the effects primarily limited to the lower productivity Huron and Ottawa sites. OM removal effects on the change in nutrient pools were generally associated with the extreme FFR treatment, but effects of soil compaction on nutrient pools were inconsistent with no apparent trends associated with increasing level of soil compaction. Soil compaction effects on bulk density were more straightforward and indicated that effects of increasing soil compaction on the change in bulk density were roughly linear, still apparent after 20 years at depths greater than 10 cm, and limited to the Chippewa and Huron sites. We explore these findings and related implications in more detail below.

Treatment effects on soil C and nutrient pools

Almost all of the effects of OM removal on soil chemical properties occurred with the most extreme FFR treatment, demonstrating the importance of the forest floor in maintaining total soil nutrient pools following harvesting (Powers et al. 2005, Ponder et al. 2012). In a similar assessment at these sites 15 years after treatment, Kurth et al. (2014) found that total pools of C were lower with FFR compared to other OM treatments at the Chippewa and Ottawa sites. Using a different approach that accounted for pretreatment variation in total pools and a longer period of assessment, we found that soil C was significantly reduced with FFR only at the Huron and Ottawa sites, and soil Ca was significantly lower with FFR at the Huron site (Figure 1). These results support the contention that certain soils are more susceptible to OM removal than others, particularly those with low initial pools of C and nutrients (Scott and Dean 2006, Egnell and Leijon 1999, O’Hehir and Nambiar 2010). These changes may result in reduced productivity over time; in fact Curzon et al. (2014) found that tree biomass was approximately 35% lower in the FFR compared to the bole only treatment at the Huron site 15 years after treatment. The limited treatment effects and general increases in soil C and nutrients at the Chippewa site highlights the resilience of relatively productive sites to extreme OM removal following harvest, but even soil P was significantly lower with FFR at this site. Indeed, it is not surprising that there are significant effects of complete FFR on C and soil nutrient pools, but rather, more surprising that effects of this treatment are not more pronounced across the range of soils that were assessed.

The lack of treatment effects, and in some instances absolute increases in soil pools over time, with lower levels of OM removal has been found in other studies, including earlier assessments at these sites (Voldseth et al. 2011, Kurth et al. 2014), in the larger LTSP network (Powers et al. 2005, Sanchez et al. 2006), and in other similar experimental manipulations in Lake States aspen forests (Alban et al. 1994, Silkworth and Grigal 1982). Specific to aspen ecosystems, the lack of treatment effects may be associated with rapid colonization of the site by aspen suckering which strongly mitigate changes in the soil environment that favor nutrient transformation and loss (Slesak 2013). Kurth et al. (2014) also noted the potential for parent root survival following aspen harvesting, which would moderate treatment effects on mineral soil pools because root decomposition is thought to be the primary source of post-harvest changes in soil C and nutrients (Powers et al. 2005). Based on this 20-year response, we generally conclude that there is little evidence for degradation of soil C and nutrient pools with commonly used harvesting techniques (whole-tree and bole-only harvesting) in aspen ecosystems. However, a caveat to this conclusion is soil P, as both the Huron and Ottawa sites showed consistent declines in soil pools over time regardless of treatment. Others have noted the potential for P limitation with increased OM removal, but have generally concluded that it would take multiple rotations for effects on productivity to become apparent (Vadeboncoeur et al. 2014, Wilhelm et al. 2013). Still, since aboveground P is a large component of aspen ecosystem P (Alban et al. 1978) and initial soil P pools at these sites were relatively low (Table 1), future soil P limitation is a concern, given the potential for P fertilizer shortages in the near future (Childers et al. 2011).

The significant, but inconsistent, effects of soil compaction on the change in nutrient content observed at the Huron and Ottawa installations could be due to changes in soil physical

properties (e.g., total pore space and size distribution) and their influence on decomposition and nutrient transformation (e.g., Shestak and Busse 2005), or be associated with compaction treatment effects on vegetation communities and related differences in nutrient retention and uptake following harvest. These possibilities and others are difficult to evaluate with the information available, but the lack of any treatment effects on bulk density at the Ottawa site (Figure 2) coupled with significant effects of treatments on community composition (Curzon et al. 2016) lends more support that the changes are driven by differences in vegetation and its influence on litter quality, nutrient uptake, and loss. It appears that compaction can alter some soil chemical properties at lower productivity sites over the time period assessed, with effects being either negative, positive, or neutral.

Compaction effects on soil bulk density

The increased bulk density in surface soil at all of the sites after 10 years was partially because of the harvesting which occurred prior to compaction treatment manipulation, with additional increases associated with compaction treatments at the Chippewa and Huron sites (Figure 2). A key management question associated with compaction is the time required for recovery to pre-disturbance conditions. Summarizing the first decade of findings at 26 LTSP installations, Powers (2005) found little evidence for recovery from severe compaction across a wide range of soil types. Here, we also found clear evidence that recovery was limited in the first decade after treatment, but surface soils across all sites had largely returned to pretreatment bulk density values within 20 years (Figure 2). Processes that influence recovery from compaction, such as root growth, are generally concentrated at the soil surface and decrease with depth, which is

highlighted by the continued elevation of bulk density at the Chippewa and Huron sites after 20 years in deeper portions of the soil. At those sites, some recovery at greater depth was apparent, but the magnitude was lower with increasing level of compaction. Based on these results, sites with soils susceptible to compaction are likely to have elevated bulk densities for a large portion of stand development.

Ultimately, the primary issue with regards to soil compaction is determining how it influences stand and ecosystem productivity. Curzon et al. (2014) assessed aboveground biomass (total, tree, and shrub) at the three sites 15 years after treatment application. Although interactions between treatments were significant in many instances, general trends indicated large reductions in total aboveground and tree biomass with increasing compaction at the Chippewa site, but higher aboveground biomass with increasing compaction at Huron (~25% increase with high compaction compared to no compaction; M. Curzon pers. comm.). In the case of the Chippewa site, the effect was due to decreasing aspen density which occurred within 5 years of treatment (Stone 2001); a finding consistent with other work examining compaction impacts on aspen regeneration (Puettmann et al. 2008). In contrast, the positive effect of soil compaction in the sand soil at Huron is likely associated with improved water-holding capacity as suggested by Powers et al. (2005) and Ponder et al. (2012).

An interesting finding was the differences in response to soil compaction treatments among sites, where effects (depth, magnitude, and duration) were most pronounced at the Huron site, intermediate at Chippewa, and not apparent at Ottawa. These effects are generally opposite of common perceptions related to soil texture and susceptibility to compaction (Steber et al. 2007.

Stone (2001) reported that operating conditions during pre-treatment harvesting at the Chippewa and Ottawa sites were less than ideal, with unfrozen soil or discontinuous frost present at these locations. These conditions likely contributed to increased bulk density in all treatments regardless of specified compaction level (Figure 1), and they may also explain the pattern of response among sites because compaction treatments would not have been as effective if significant compaction had already occurred during harvesting.

Assessment of the LTSP study: Inference and limitations

A key objective of the LTSP program was to provide direct answers regarding the influence of OM removal and compaction effects on forest productivity, how it varies by site, and the potential for recovery with time (Powers et al. 2005). Here, we found that effects of soil compaction and extreme OM removal on soil properties (and vegetation response as reported by Curzon et al. 2014) were site-specific with effects generally in agreement with concepts relating to buffering capacity with regards to OM removal (lower quality soils more susceptible) and available water holding capacity with regards to soil compaction. In this regard, our findings have directly identified some soil and site-conditions where impacts are evident within 20 years, and have also linked the soil-vegetation response as intended with the base design (Powers et al. 1990). However, we also found that there was limited effects of less intensive OM removal treatments (SOH and WTH) on soil properties in most instances at most sites. Even though this finding is supported by the evidence to date, there is considerable uncertainty in the long-term response, and the applicability of these findings to other settings.

Much of our uncertainty arises from the sampling and measurement design used at these and other installations involved in the LTSP study. In almost all instances, focus is placed on assessing the change in mineral soil fine fraction (<2 mm) pools, with little regard for larger mineral soil fractions (i.e., the “coarse” fraction) or other material (primarily large organic matter such as roots). In addition, most of the LTSP installations only collected shallow soil samples, usually to a depth of 30 cm as done at our sites. A number of recent studies have highlighted the limitations of these measurement aspects in accounting for changes in C and nutrients over time because considerable amounts of C and nutrients are found in other fractions and at depths deeper than 30 cm (Harrison et al. 2011, Homann et al. 2004, Vadeboncoeur et al. 2012). Not accounting for these additional pools, and other pools contributing to change in the mineral soil fine fraction, hinders our ability to evaluate long-term response. For example, it is likely that changes we found in the first two decades in the mineral soil fine fraction have been strongly influenced by belowground decomposition of roots (Powers et al. 2005), because changes in soil pools were roughly proportional to pre-harvest aboveground productivity (Table 1, Figure 1). Since this ecosystem pool and treatment effects on it have not been measured, it is very challenging to determine what the observed changes in the mineral soil fine fraction mean for future productivity.

We want to be clear that we are not criticizing the original LTSP investigators for adopting these protocols as they are almost universally used in soil studies, but we do feel strongly that the measurement protocols will constrain the overall utility in assessing the soil response to experimental manipulations of OM removal and soil compaction. Post hoc measures and assessments that are more comprehensive are still possible, but our ability to detect change

without pretreatment measurements that included additional pools (e.g., coarse mineral soils and deep soils) is greatly hampered (Homann et al. 2008) and may lead to false conclusions of no treatment effects (i.e., a Type 2 error) (Kravchenko and Robertson 2011). This is especially true for these installations and others which typically have only 3 replications of each treatment combination. For example, Kurth (2014) calculated low statistical power (<30%) for detection of significant treatment effects on C and N in the mineral soil 15 years after treatment at these sites, presumably because of the high spatial variability inherent to soil coupled with low replication.

The response of soil properties is only one aspect of the LTSP study, and much work has been done determining treatment effects on the aboveground vegetation response (Ponder et al. 2012, Curzon et al. 2014). In this regard, the experiment has been more straightforward and informative in assessing effects of OM removal and compaction, in addition to clarifying the direct and interactive effects of competing vegetation on the response (Fleming et al. 2006). Because vegetation and stand response integrate effect of treatment on all soil functions, including those not previously measured or currently known, we expect that the aboveground response at these and other sites associated with the LTSP network will ultimately be the most useful in evaluating the effects of OM removal and soil compaction on ecosystem productivity. Unfortunately, though, development of soil-based indices of sustainability (Burger 2009) will continue to be challenging, and the use of soil properties to identify high risk sites and practices will be constrained because of the limitations in the pretreatment data.

Conclusions

We conclude that effects of OM removal and soil compaction on soil and stand productivity are soil-specific, with coarse-textured, poorly buffered sands more susceptible to the effects of extreme OM removal, and finer-textured, well-structured loams being more susceptible to soil compaction. These results are consistent with commonly held perceptions of soil productivity with regard to concepts of soil quality and its relationship to vegetation growth. Although the extreme FFR treatment is not a common operational practice, Stone (2001) noted that it may emulate the effects of multiple whole tree harvests or localized impacts of intensive site preparation treatments, and may also be more reflective of intensive biomass removal treatments for securing energy feedstocks (Berger et al. 2013). Given our results, it is probably best to utilize harvesting and silvicultural practices that retain some OM on similar soil types to ensure maintained productivity into the future. Similarly, utilizing practices and strategies to minimize soil compaction on well-structured loams is advisable, as compaction has a disproportionate effect on water holding capacity and its influence on productivity on these soils relative to other types. Clearly, the LTSP experiment has helped to elucidate the influence of OM removal and soil compaction on soil properties and related effects on vegetation. However, the overall utility of the experiment to evaluate the soil response is constrained because of the measurement protocols employed, which inhibits the development of soil-based indices for sustainable forest management.

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678

679 Tables

680

681 Table 1. Site characteristics and pretreatment soil properties to a depth of 30 cm

Characteristic or property	Chippewa, MN	Huron, MI	Ottawa, MI
Latitude, longitude	47.32, -94.55	44.57, -83.98	46.63, -89.25
Year of initiation	1993	1994	1992
Mean annual precipitation (cm)	64	75	77
Mean annual temperature (C°)	3.8	6.2	4.5
Site index aspen (m, 50 year)	23	19	17
Soil texture (% sand, silt, clay)	Silt loam (45/51/4)	Sand (93/6/1)	Clay (23/27/50)
Bulk density (Mg m ⁻³)	1.24	1.12	1.19
Total C (Mg ha ⁻¹)	50.3 (10.2)*	36.7 (5.2)	62.3 (8.5)
Total N (Mg ha ⁻¹)	2.7 (0.6)	1.5 (0.7)	3.8 (0.8)
Calcium (kg ha ⁻¹)	1750 (550)	400 (140)	7010 (1650)
Magnesium (kg ha ⁻¹)	260 (60)	50 (10)	1870 (420)
Potassium (kg ha ⁻¹)	220 (40)	100 (20)	740 (140)
Phosphorus (kg ha ⁻¹)	300 (80)	110 (40)	70 (20)

682 * standard error in parenthesis

683 Table 2. Mean change in soil total carbon, total nitrogen, and extractable phosphorus pools by site, treatment, and time. 90%
684 confidence limits are in parentheses. Values in bold are significantly different from zero.

Treatment	Chippewa Site		Huron Site		Ottawa Site	
	10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment
	Carbon (Mg ha ⁻¹)					
SOH	22.4 (9.6, 35.3)	14.4 (8.6, 20.2)	2.9 (-0.3, 6.1)	-1.1 (-3.3, 1.0)	1.3 (-4.2, 6.9)	0.3 (-5.9, 6.4)
WTH	19.0 (6.2, 31.8)	7.5 (1.7, 13.2)	4.2 (0.9, 7.5)	-1.2 (-3.4, 1.0)	4.4 (0.7, 8.1)	-0.8 (-4.9, 3.3)
FFR	12.4 (-0.3, 25.0)	8.7 (3.0, 14.4)	2.0 (-1.3, 5.4)	-2.7 (-4.9, -0.5)	-1.2 (-5.2, 2.7)	-5.2 (-9.5, -0.8)
Low compaction	19.7 (6.6, 32.7)	15.7 (9.8, 21.5)	1.6 (-1.7, 4.8)	-3.0 (-5.2, -0.9)	3.5 (-0.1, 7.1)	-2.2 (-6.2, 1.8)
Inter. compaction	11.8 (-1.1, 24.6)	7.7 (1.9, 13.4)	2.3 (-0.9, 5.5)	-2.1 (-4.3, -0.3)	1.5 (-2.7, 5.7)	1.0 (-3.7, 5.6)
High compaction	22.4 (9.7, 35.1)	7.2 (1.6, 12.9)	5.3 (2.1, 8.5)	0.1 (-2.0, 2.3)	-0.6 (-5.9, 4.7)	-4.5 (-10.4, 1.4)
	Nitrogen (kg ha ⁻¹)					
SOH	2079 (1522, 2636)	1027 (764, 1290)	503 (90, 916)	395 (87,704)	364 (-192, 920)	288 (-14, 590)
WTH	1580 (1061, 2099)	964 (719, 1209)	260 (-165, 684)	222 (-95, 539)	738 (356, 1121)	187 (-21, 395)
FFR	1541 (1025, 2057)	968 (724, 1211)	107 (-299, 5130)	13 (-290, 316)	610 (200, 1021)	204 (-19, 427)
Low compaction	1804 (1294, 2314)	951 (710, 1191)	88 (-356, 531)	17 (-214, 448)	308 (-70, 685)	145 (-60, 351)
Inter. compaction	1756 (1246, 2267)	1013 (772, 1254)	551 (136, 966)	427 (117, 737)	1127 (688, 1567)	403 (164, 643)
High compaction	1640 (1111, 2169)	996 (746, 1245)	231 (-182, 643)	87 (-221, 395)	278 (-251, 807)	130 (-158, 417)
	Phosphorus (kg ha ⁻¹)					
SOH	42 (7, 78)	7 (-33, 47)	-7 (-24, 11)	-24 (-36, -13)	-7 (-14, 1)	-17 (-23, -10)
WTH	73 (38, 107)	64 (26, 103)	3 (-14, 20)	-7 (-19, 4)	-6 (-12, -1)	-14 (-19, -10)
FFR	1 (-33, 35)	-8 (-46, 30)	2 (-15, 19)	-7 (-18, 5)	-9 (-14, -3)	-20 (-25, -16)
Low compaction	39 (6, 73)	22 (-16, 60)	9 (-9, 26)	-9 (-20, 3)	-4 (-10, 1)	-18 (-22, -13)
Inter. compaction	47 (13, 82)	17 (-21, 56)	-2 (-20, 15)	-13 (-24, -1)	-10 (-16, -4)	-21 (-26, -16)
High compaction	29 (-5, 63)	24 (-14, 62)	-8 (-25, 10)	-17 (-29, -6)	-8 (-15, -1)	-13 (-19, -6)

685 * Abbreviations as follows: SOH = stem only harvesting; WTH = whole tree harvesting; FFR = forest floor removal; inter. = intermediate

686

687 Table 3. Mean change in soil extractable calcium, magnesium, and potassium pools by site, treatment, and time. 90% confidence limits are in
688 parentheses.

Treatment	Chippewa Site		Huron Site		Ottawa Site	
	10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment
	Calcium (kg ha ⁻¹)					
SOH	595 (329, 861)	1143 (882, 1403)	121 (51, 190)	108 (60, 157)	2027 (1158, 2896)	797 (276, 1318)
WTH	728 (475, 981)	1086 (838, 1335)	137 (67, 207)	81 (32, 130)	2201 (1604, 2798)	832 (474, 1189)
FFR	583 (326, 840)	928 (675, 1180)	17 (-53, 87)	-31 (-79, 18)	1511 (873, 2149)	331 (-52, 713)
Low compaction	626 (375, 877)	1145 (899, 1392)	81 (12, 150)	60 (11, 108)	1607 (1011, 2202)	470 (113, 827)
Inter. compaction	654 (403, 905)	1030 (783, 1276)	114 (42, 185)	67 (17, 117)	1899 (1209, 2589)	662 (248, 1075)
High compaction	627 (375, 878)	982 (735, 1229)	79 (8, 151)	32 (-18, 82)	2234 (1407, 3061)	828 (332, 1324)
	Magnesium (kg ha ⁻¹)					
SOH	112 (82, 142)	99 (75, 123)	17 (12, 23)	18 (13, 23)	498 (264, 731)	-66 (-199, 66)
WTH	68 (38, 98)	56 (32, 80)	11 (6, 17)	15 (10, 20)	545 (383, 706)	-38 (-130, 53)
FFR	81 (52, 110)	93 (69, 116)	9 (4, 15)	11 (6, 16)	429 (254, 604)	-2 (-101, 98)
Low compaction	81 (51, 110)	89 (66, 113)	12 (6, 17)	14 (9, 18)	346 (184, 508)	-145 (-237, -52)
Inter. compaction	103 (74, 132)	83 (60, 107)	13 (7, 18)	14 (9, 19)	530 (344, 717)	25 (-81, 131)
High compaction	78 (49, 107)	75 (52, 99)	13 (8, 19)	16 (11, 21)	595 (370, 819)	13 (-114, 141)
	Potassium (kg ha ⁻¹)					
SOH	90 (63, 117)	97 (70, 124)	34 (1, 68)	-16 (-28, -5)	122 (67, 177)	33 (-61, 126)
WTH	46 (20, 73)	71 (44, 98)	2 (-25, 29)	-5 (-13, 7)	176 (139, 214)	98 (34, 162)
FFR	50 (22, 78)	83 (55, 111)	-7 (-39, 24)	-3 (-13, 8)	167 (127, 208)	35 (-34, 104)
Low compaction	55 (28, 82)	78 (51, 105)	-16 (-44, 13)	-18 (-28, -9)	104 (65, 142)	19 (-47, 84)
Inter. compaction	63 (36, 89)	68 (41, 95)	37 (10, 64)	-4 (-13, 5)	150 (106, 194)	102 (27, 176)
High compaction	69 (43, 95)	105 (78, 132)	8 (-20, 35)	-2 (-11, 7)	212 (156, 267)	46 (-49, 140)

689 * Abbreviations as follows: SOH = stem only harvesting; WTH = whole tree harvesting; FFR = forest floor removal; inter. = intermediate

Figure captions

Figure 1. Mean change in soil total C and N, and extractable Ca and P, by organic matter removal treatment at 10 and 20 years after harvest. Data is shown primarily to demonstrate patterns of response; numerical values and associated 90% confidence limits are shown in Tables 2 and 3. Treatment codes below a given time period indicate that the associated treatment is significantly different from 0 at that time. SOH = stem only harvest, WTH = whole tree harvest, FFR = WTH plus forest floor removal.

Figure 2. Bulk density estimates by sample period, site, depth, and compaction treatment. Treatments within a time period-site-depth combination containing different letters are significantly different. Uppercase letters are for 10 year time period; lowercase letters are for 20 year time period. Treatments with no letters shown are not significantly different.

704 **Supplemental material**

705 Table S1. F statistic probabilities for treatment effects on the change in soil C and nutrients pools by site and time since treatment. Significant
706 values are shown in bold.

Soil Property	Effect	Chippewa Site		Huron Site		Ottawa Site	
		10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment
Carbon	OM	0.622	0.321	0.744	0.629	0.552	0.331
	Compaction	0.580	0.173	0.348	0.208	0.237	0.421
	OM x compaction	0.774	0.345	0.684	0.664	0.288	0.785
Nitrogen	OM	0.462	0.951	0.495	0.320	0.649	0.889
	Compaction	0.928	0.947	0.423	0.348	0.047	0.307
	OM x compaction	0.354	0.301	0.665	0.898	0.656	0.359
Calcium	OM	0.741	0.583	0.104	0.007	0.395	0.237
	Compaction	0.988	0.709	0.808	0.677	0.569	0.590
	OM x compaction	0.085	0.193	0.912	0.291	0.596	0.523
Magnesium	OM	0.215	0.097	0.218	0.273	0.709	0.782
	Compaction	0.525	0.762	0.956	0.809	0.262	0.102
	OM x compaction	0.237	0.522	0.515	0.126	0.466	0.475
Potassium	OM	0.113	0.506	0.373	0.361	0.369	0.445
	Compaction	0.812	0.249	0.096	0.109	0.046	0.358
	OM x compaction	0.444	0.712	0.233	0.393	0.258	0.325
Phosphorus	OM	0.055	0.075	0.755	0.143	0.846	0.313
	Compaction	0.810	0.976	0.529	0.673	0.505	0.194
	OM x compaction	0.930	0.987	0.984	0.881	0.104	0.099

707

708

709 Table S2. F statistic probabilities for treatment effects on the change in total bulk density by site, depth increment, and time since treatment.

710 Significant values are shown in bold.

711

Depth	Effect	Chippewa Site		Huron Site		Ottawa Site	
		10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment	10 years after treatment	20 years after treatment
0-10cm	OM	0.079	0.164	0.143	0.462	0.797	0.022
	Compaction	0.019	0.226	0.013	<0.001	0.424	0.408
	OM x compaction	0.966	0.617	0.618	0.974	0.690	0.554
10-20 cm	OM	0.215	0.133	0.520	0.987	0.025	0.830
	Compaction	0.126	<0.001	<0.001	<0.001	0.135	0.344
	OM x compaction	0.826	0.828	0.729	0.532	0.139	0.395
20-30 cm	OM	0.890	0.021	0.183	0.840	0.679	0.772
	Compaction	0.578	0.002	0.026	<0.001	0.102	0.175
	OM x compaction	0.906	0.611	0.719	0.689	0.312	0.399

Table S3. Absolute mean values and standard deviation for soil carbon and nutrient pools to 30 cm depth by site and time period.

Chippewa Site

	Pretreatment		10 years		20 years	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Carbon (Mg ha ⁻¹)						
SOH*	53.1	11.9	72.3	13.3	63.8	7.6
WTH	48.0	8.7	69.6	29.9	58.5	10.5
FFR	49.7	10.4	62.7	11.2	59.1	12.3
No compaction	53.8	12.0	69.3	13.0	64.8	11.7
Inter. compaction	47.5	4.9	62.5	8.8	58.8	9.1
High compaction	49.4	12.2	72.8	30.8	57.8	9.2
Nitrogen (kg ha ⁻¹)						
SOH	3040	810	4540	610	3740	410
WTH	2490	230	4370	1230	3620	380
FFR	2510	370	4320	540	3630	400
No compaction	2800	600	4410	650	3640	420
Inter. compaction	2800	610	4360	920	3700	330
High compaction	2430	480	4470	960	3650	430
Phosphorus (kg ha ⁻¹)						
SOH	260	70	320	50	290	50
WTH	330	70	390	70	370	60
FFR	320	100	310	70	300	80
No compaction	310	80	350	70	330	70
Inter. compaction	280	90	340	80	310	90
High compaction	310	90	340	60	330	60
Calcium (kg ha ⁻¹)						
SOH	2040	720	2630	710	3060	460
WTH	1640	330	2370	490	2770	430
FFR	1560	470	2150	710	2570	620
No compaction	1710	410	2340	580	2870	530
Inter. compaction	1730	580	2380	700	2770	560
High compaction	1800	700	2420	740	2760	570
Magnesium (kg ha ⁻¹)						
SOH	280	60	390	110	370	60
WTH	240	30	300	40	300	30
FFR	260	80	340	90	350	90
No compaction	270	60	350	100	350	60
Inter. compaction	250	50	350	90	340	50
High compaction	260	70	330	90	330	90
Potassium (kg ha ⁻¹)						
SOH	210	30	310	40	310	50
WTH	220	30	260	30	290	30
FFR	240	40	290	70	320	70
No compaction	220	30	280	50	300	50
Inter. compaction	230	40	290	50	300	50
High compaction	220	40	290	50	330	60

Table S3 (continued)

Huron Site

	Pretreatment		10 years		20 years	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
	Carbon (Mg ha ⁻¹)					
SOH	36.6	5.7	39.5	5.9	35.5	2.4
WTH	38.8	5.0	41.3	6.5	35.3	3.5
FFR	34.7	4.4	38.3	3.4	34.1	4.6
No compaction	37.6	6.1	38.4	3.8	33.6	2.8
Inter. compaction	36.2	5.9	38.9	4.2	34.6	4.5
High compaction	36.2	3.7	41.9	7.3	36.8	2.6
	Nitrogen (kg ha ⁻¹)					
SOH	1250	330	1930	950	1770	490
WTH	1760	990	1750	560	1780	600
FFR	1340	600	1540	240	1420	450
No compaction	1880	1080	1590	200	1720	680
Inter. compaction	1230	290	1970	1070	1800	550
High compaction	1240	230	1660	270	1460	270
	Phosphorus (kg ha ⁻¹)					
SOH	110	40	100	10	90	30
WTH	100	50	110	40	90	30
FFR	100	30	100	30	90	30
No compaction	90	30	100	40	90	30
Inter. compaction	110	40	100	40	90	30
High compaction	110	50	100	30	90	30
	Calcium (kg ha ⁻¹)					
SOH	400	130	520	110	510	90
WTH	430	200	540	150	490	120
FFR	370	90	410	50	360	40
No compaction	410	150	480	110	460	90
Inter. compaction	450	150	520	140	480	160
High compaction	350	120	470	120	420	60
	Magnesium (kg ha ⁻¹)					
SOH	50	10	70	10	70	10
WTH	50	10	30	10	70	10
FFR	50	10	60	10	60	10
No compaction	50	10	60	10	60	10
Inter. compaction	60	10	70	10	70	10
High compaction	50	10	60	10	70	4
	Potassium (kg ha ⁻¹)					
SOH	120	20	130	70	100	20
WTH	100	10	110	40	100	20
FFR	90	10	100	30	90	20
No compaction	100	20	90	30	80	10
Inter. compaction	100	10	140	80	100	20
High compaction	110	20	110	30	100	10

Table S3 (continued)

Ottawa Site

	Pretreatment		10 years		20 years	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Carbon (Mg ha ⁻¹)						
SOH	61.8	14.0	64.8	9.1	63.1	4.6
WTH	60.9	5.3	66.6	5.6	61.5	6.8
FFR	64.5	7.9	61.4	5.9	57.7	8.8
No compaction	61.8	9.0	66.0	7.2	60.6	5.5
Inter. compaction	63.1	7.3	64.0	7.4	63.2	8.7
High compaction	62.2	10.2	62.3	5.4	57.5	7.6
Nitrogen (kg ha ⁻¹)						
SOH	3740	950	4090	400	4020	300
WTH	3610	590	4470	750	4020	410
FFR	4030	840	4430	1020	3980	380
No compaction	3650	610	4120	330	3980	300
Inter. compaction	4030	920	5030	1080	4170	390
High compaction	3730	840	3990	400	3860	420
Phosphorus (kg ha ⁻¹)						
SOH	70	10	60	10	50	10
WTH	70	20	60	10	50	10
FFR	60	10	60	10	50	10
No compaction	60	20	60	10	50	10
Inter. compaction	70	20	60	20	50	10
High compaction	70	20	60	10	50	10
Calcium (kg ha ⁻¹)						
SOH	7210	1620	8730	1020	7640	890
WTH	6760	2130	9170	700	7780	550
FFR	7180	1030	8540	1340	7360	640
No compaction	6810	2160	8690	790	7490	770
Inter. compaction	7180	1050	8970	1000	7720	380
High compaction	7130	1460	8960	1460	7650	820
Magnesium (kg ha ⁻¹)						
SOH	1830	440	2240	350	1730	260
WTH	1780	440	2400	230	1810	130
FFR	1990	390	2320	350	1880	190
No compaction	1760	440	2230	270	1720	210
Inter. compaction	1950	340	2400	230	1900	140
High compaction	1940	480	2410	400	1860	140
Potassium (kg ha ⁻¹)						
SOH	740	140	840	80	760	80
WTH	740	180	920	70	830	170
FFR	750	120	910	90	780	80
No compaction	700	160	850	70	760	90
Inter. compaction	740	100	900	60	850	180
High compaction	820	160	960	100	790	60

* Abbreviations as follows: SOH = stem only harvesting; WTH = whole tree harvesting; FFR = forest floor removal; inter. = intermediate