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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 (*Populous 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 3 × 3 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 20-year results demonstrate that the effect of OM removal and soil compaction on soil properties is site-specific, which generally aligns with concepts of soil quality and its influence on vegetation growth. Although the LTSP study has proved invaluable in clarifying these linkages across North America, there are some limitations with measurement protocols that limit the overall utility of the soil assessment. These limitations inhibit the development of soil-based indices to identify high risk sites and practices at odds with sustainable forest management.

1. 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

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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., 2010) and soil compaction (Cambi et al., 2015, Greacen 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., 1997). 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., 1997). 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., 2010; 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 covertype 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.

2. Materials and methods

2.1. 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

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)[a]	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)

[a] Standard error in parenthesis.

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.

2.2. 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 cm^3 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 h, 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 2 mm 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 (<2 mm) mass estimate. All estimates are reported on an oven dry (105 °C) basis.

2.3. 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 pretreatment 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.

3. Results

3.1. 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 (Fig. 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.

3.2. 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 (Fig. 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

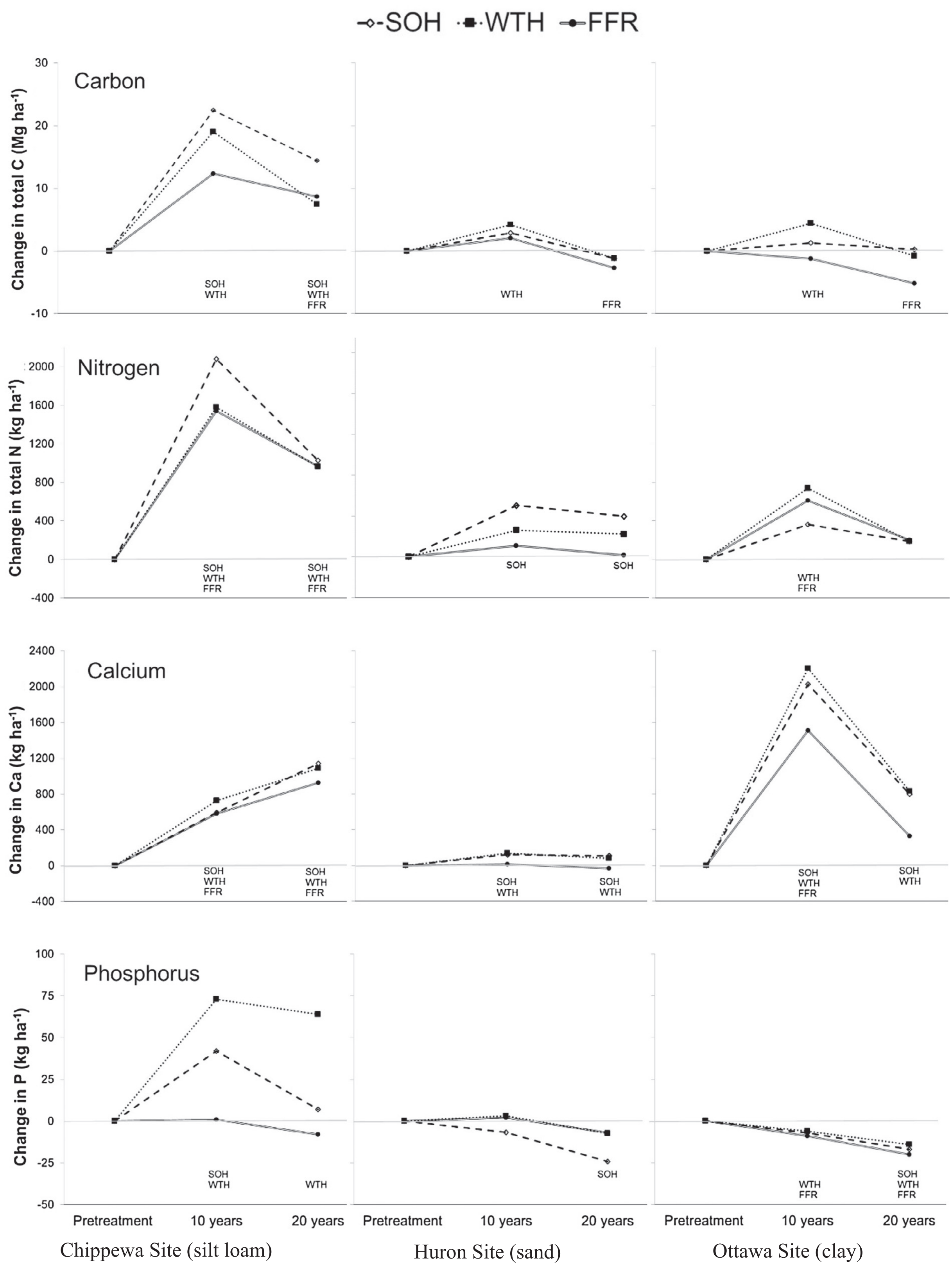

Fig. 1. Mean change in soil total C and N, and extractable Ca and P, by organic matter removal treatment at 10 and 20 years after harvest. Data is shown primarily to demonstrate patterns of response; numerical values and associated 90% confidence limits are shown in Tables 2 and 3. Treatment codes below 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.

and all treatments at the Ottawa site after 20 years (Fig. 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

Table 2
Mean change in soil total carbon, total nitrogen, and extractable phosphorus pools by site, treatment, and time. 90% 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[a]	**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)**

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

Table 3
Mean change in soil extractable calcium, magnesium, and potassium pools by site, treatment, and time. 90% confidence limits are in 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[a]	**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)

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

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 (Fig. 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 (Fig. 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 ($p = 0.110$).

3.3. 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).

3.4. 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 (Fig. 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 (Fig. 2). Similar non-significant trends were observed at the Chippewa site, where bulk density remained elevated in all treatments after 20 years.

4. 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.

4.1. 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 (Fig. 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 Thomas, 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 at that site soil P was significantly lower with FFR. 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

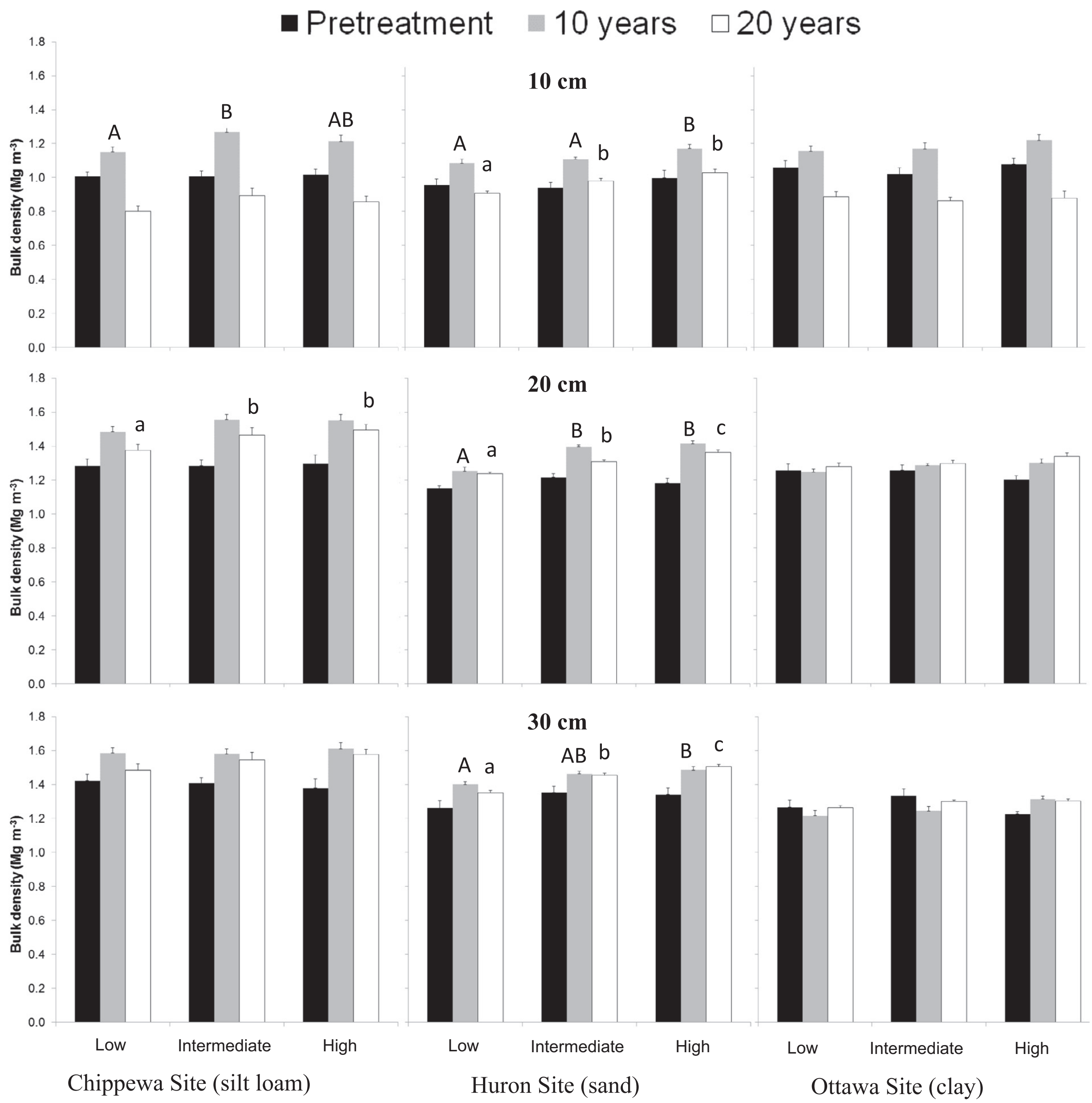

Fig. 2. Bulk density estimates by sample period, site, depth, and compaction treatment. Treatments within a time period-site-depth combination containing different letters are significantly different. Uppercase letters are for 10 year time period; lowercase letters are for 20 year time period. Treatments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

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 (Fig. 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.

4.2. 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 (Fig. 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 (Fig. 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 (Fig. 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.

4.3. 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, Fig. 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 et al. (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.

5. 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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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.03.005.

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