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Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years

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Abstract

The long-term soil productivity (LTSP) study was initiated to examine the effect of soil porosity and organic matter (OM) levels on net primary productivity (NPP). The study design calls for three levels of OM removal (bole, whole tree and whole tree plus forest floor) and three levels of compaction (none, moderate and severe) being imposed on harvested sites prior to planting. Additionally, the effect of understory control on NPP was examined as a split-plot treatment. The study has been installed on 62 sites covering a range of climates, soil types and tree species across the United States and Canada. The inclusion of 46 closely related affiliated sites has created the world's largest coordinated research network devoted to investigating the relationship between land management and sustainable forest productivity. In the forefront of the LTSP network are the installations in North Carolina (NC) and Louisiana (LA) which focus on loblolly pine (*Pinus taeda* L.) growth. The rapid growth at these sites has resulted in the trees reaching crown closure much earlier than any other LTSP installation. Consequently, these sites may provide the earliest glimpse as to the treatment effects on NPP. Tenth year data from these sites show that large OM removals and severe soil compaction (main treatments) had no significant ($\alpha \leq 0.1$) effect on stand volume but control of the understory (split-plot treatment) resulted in greater stand volume compared to plots with no understory control. Plots ameliorated by a one-time fertilizer addition (NC and LA) and bedding (NC only) resulted in small (+8 and −8% for NC and LA, respectively) to large (+69 and +15% for NC and LA, respectively) changes in mean stand volume compared to the experimental plots. Although there were no main treatment effects on stand volume, extractable soil phosphorus in NC and LA were reduced with increasing OM removal. The reduction of extractable soil phosphorus with increasing OM removal on these already phosphorus deficient sites may affect tree growth in the future but have not yet translated to stand volume differences over 10 years.
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Keywords: Compaction; Understory control; Net primary productivity; Loblolly pine; Residual biomass; Soil nutrients; Foliar nutrients

1. Introduction

In the late 1980s, a long-term soil productivity (LTSP) experiment was developed in response to the National Forest Management Act of 1976 and related legislation that mandated that the productivity potential of National Forest lands be maintained. A cooperative of National Forest land managers and Forest Service research scientists designed a study that would examine fundamental soil characteristics typically altered during forest management operations that could potentially impact net primary productivity (NPP). An extensive literature review suggested two site properties most likely to impact long-term productivity were soil organic matter and soil porosity (Powers et al., 1990). The team concluded, however, that the existing information was too sparse and anecdotal to be of broad value. They, therefore, proposed a nationally coordinated field study, the LTSP experiment (Powers et al., 1989).

The first LTSP installation was a loblolly pine (*Pinus taeda* L.) stand established in 1990 on the Louisiana (LA) Coastal Plain. Since then, the LTSP program has expanded to 62 research sites in the United States and Canada, covering a broad range of climates, tree species and soil types. Additional affiliated sites across the United States bring the number of sites investigating soil disturbances to well over 100. The criteria for inclusion of the affiliated sites in the LTSP network were: (1) the studies must include some basic elements of the core LTSP design, (2) the treatment plots must be large enough to have minimal edge effect at time of crown closure and (3) researchers must agree to share their findings (Powers et al., 1996). Consequently, the LTSP program has become the world's largest organized research network addressing basic and applied science issues of forest management and sustained productivity.

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Prominent within the LTSP network are the loblolly pine installations in North Carolina (NC) and LA. These sites cover the extremes of the natural range for loblolly pine (Jokela et al., 2004) and the range in precipitation and potential evapotransporation found on the southern Coastal Plain (Tiarks et al., 1999). Loblolly pine is an ecologically and economically important tree species encompassing over 13 million ha in the southern United States (Schultz, 1997). The warm climate and extended growing season in this region contributes to rapid tree growth. Consequently, these sites have achieved crown closure much faster than other LTSP installations, and may provide an early glimpse into treatment effects on NPP. In this manuscript, we discuss 10th year treatment effects on tree growth, and soil and foliar nutrients.

2. Materials and methods

2.1. Site descriptions

Three NC installations (NC1–NC3) were established in 1992 on the Croatan National Forest in Craven County. The sites receive an average of 1360 mm of rainfall annually and the average air temperature is 16 °C. An approximately 60-year-old mixed pine hardwood stand occupied each site prior to harvest. Soils in NC1 were fine-loamy, siliceous, thermic Aquic Paleudults in the Goldsboro soil series. Soils in NC2 and NC3 were fine-loamy, siliceous, thermic aeric Paleaqults in the Lynchburg soil series.

The LA sites (LA1–LA4) were established in 1990–1993 on the Kisatchie National Forest in central LA. The sites receive an annual rainfall of 1050 mm and average daily temperature is 19 °C. The soils are in the Malbis (fine-loamy, siliceous, subactive, thermic Plinthic Paleudults) (LA1 established in 1990), Glenmora (fine-silty, siliceous, thermic Glossaquic Paleudalfs) (LA2 established in 1992), Metcalf (fine-silty, siliceous, semiactive, thermic Aquic Glossudalfs) (LA3 established in 1993) and Mayhew (fine-smectitic, thermic Chromic Dystraquerts) (LA4 established in 1993) series. The LA2–LA4 sites were previously occupied by an approximately 55-year-old mixed pine hardwood stand. The previous stand at each site had received controlled burns on either a 5–7 years (LA2) or a 3–5 years (LA3 and LA4) cycle. LA1 differed in that it was previously occupied by a 37-year-old direct-seeded loblolly pine stand that was periodically grazed and burned for forest range management research. Although the sites were established in different years, only 10th year data will be presented.

2.2. Treatments

Nine 0.4 ha plots within each installation were randomly assigned to a 3 × 3 factorial combination of organic matter removal and soil compaction treatments with a split-plot design for competition control treatments. The organic matter removal treatments included removing all merchantable boles (OM_0), the whole tree (OM_1) and the whole tree plus forest floor (OM_2). The compaction treatments were no compaction (C_0), moderate compaction (C_1) and severe compaction (C_2). The C_2 treatment was intended to achieve bulk densities within 20% of root limiting levels (Daddow and Warrington, 1983) while the C_1 bulk density levels were intermediate between C_0 and C_2 values. In practice, compaction did not result in a change from pre-harvest bulk density values in the LA installations (1.36, 1.33 and 1.35 Mg m^{-3} for the pre-harvest and post-harvest C_1 and C_2 treatments, respectively) but better results were achieved at the NC installations (1.33, 1.46 and 1.45 Mg m^{-3} 3 for the pre-harvest and post-harvest C_1 and C_2 treatments, respectively). The post-harvest measurements were taken 1 year after treatment installation. Following organic matter removal and compaction treatments, each plot was halved with understory control treatments (no control (U_0) or complete control (U_1)) randomly assigned. The U_1 treatments were achieved by mechanical (brush saw) and chemical (Accord, Arsenal and Oust[1]) means. In LA, volunteer pines were mechanically removed in all plots including the U_0 treatments. Following treatment, all plots were planted with a mix of half-sib loblolly pine bare root seedlings on a 2.5 m × 2.5 m (LA) or 3 m × 3 m (NC) spacing.

Studies examining the effects of compaction on forest plant growth are often confounded by associated factors including soil displacement, mixing, rutting and reduced understory competition (Miller et al., 1989). Consequently, great care was taken during plot establishment to maintain the integrity of the treatments. On C_0 plots, tree boles were removed by cranes working from outside the plot. When necessary, residual organic matter including branches and associated foliage (OM_1) and forest floor (OM_2) were removed manually. In NC, the soil was compacted with one pass of a smooth drum vibrator roller without vibration for the C_1 treatment. The C_2 treatment received two passes with full vibration. In LA, compaction was achieved by six passes of a weighted multi-tire road compactor with 3.6 and 6.4 Mg ballast for the C_1 and C_2 treatments, respectively. At each site, depending on the organic matter treatment, branches and foliage and/or forest floor were redistributed manually after compaction.

The LTSP treatments were not intended to mimic operational management practices; rather, they are designed to bracket the extremes in organic matter removal and compaction that could occur during a harvest operation. However, study designers felt it would be desirable to examine whether effects of the LTSP experimental treatments could be ameliorated by conventional management practices for each region. Consequently, an additional treatment plot, herein referred to as the ameliorated plot, was installed to approximate the conventional operational management practice for each location. Ameliorated plots were installed in each site in NC and in two of the four sites in LA (LA1 and LA3). In NC, this treatment was installed as an intermediate level of organic matter removal and compaction (OM_1C_1) treatment followed by bedding and fertilization with a one-time

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application of 224 kg ha^{-1} of triple superphosphate, which supplied 45 kg P. The split-plot subtreatment of understory control was applied as in the core LTSP experimental design. In LA, the ameliorated treatment included whole tree harvest using wheeled skidders. There was no experimental compaction or understory control; however, since there is some compaction from the wheeled skidders, this plot approximated the $OM_1C_1U_0$ experimental plot. The ameliorated plots were split, with half the plot being fertilized with 250 kg ha^{-1} of diammonium phosphate, supplying 50 kg P, just prior to the fourth growing season.

2.3. Analytical methods

Within the measurement plots, tree heights were measured with a hipsometer and diameter at breast height (DBH) was measured with calipers. Pine volume was calculated using the method of Baldwin and Feduccia (1987). Soil samples at both sites were collected with a hammer driven 6.3 cm × 30 cm soil sampler. Soil cores were divided into three sections corresponding to 0–10, 10–20 and 20–30 cm depths. In NC, samples were collected from three sample points within each split-plot. In LA, 10 samples were collected per split-plot. On the ameliorated plots in NC, two sets of samples were taken: within and between beds. The proportion of area covered by beds was estimated to be two-thirds, and average soil nutrient pools across the plots were calculated accordingly.

All soil samples were dried, passed through a 2-mm sieve and weighed. Subsamples were analyzed for total C and N by dry combustion (NA 1500 Carlo-Erba CNS analyzer in NC, and Leco 2000 CNS analyzer in LA). Soil nutrients (phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K)) were determined by extraction with Mehlich III solution and analysis on a Thermo Jarrell Ash 61E Inductively Coupled Plasma (ICP) spectrometer (Council on Soil Testing and Plant Analysis, 1992) for the NC samples. In LA, soil P was extracted with Mehlich III solution and analyzed on a Hewlett Packard 8453 colorimetric spectrometer. Cations were extracted with $BaCl_2$ (Hendershot and Duquette, 1986) and analyzed on a Perkin-Elmer 2100 Atomic Absorption (AA) spectrometer.

At each plot in NC, one tree was felled at senescence (September and October) and second year foliage was collected from the upper third of the crown. In LA, the second year foliage was shot out of the upper third of the crown of five randomly selected trees on each split-plot. The five subsamples where mixed together to make up a composite sample for the split-plot. Foliage samples were oven dried, ground and analyzed for C and N concentrations by dry combustion. In NC, foliar nutrients were determined by placing 0.5 g soil subsamples into porcelain crucibles and then dry ashing the samples at 450 °C for 4 h. The samples were cooled in a closed furnace and then removed. Twenty milliliters of 20% HCl was added to the ash. After an hour the sample was filtered through Whatman #2 filter paper and the filtrate was analyzed for total nutrients by ICP spectrometry. In LA, foliage was digested by perchloric acid without dry ashing prior to colorimetric and AA spectrometry analysis.

2.4. Statistical analysis

Analysis of variance (ANOVA) using the GLM procedure for split-plot design (SAS, 2000) was used to test for treatment effects on stand volume and soil and foliar nutrients. Differences between treatments were determined significant at $\alpha \leq 0.10$ level using the Tukey's Paired Comparison Procedure. The NC and LA installations were analyzed as separate studies. Significant interactions at each location were rare and inconsistent. Additionally, these interactions usually involved a treatment that was highly significant as a "stand alone" effect, so the interactions will not be presented. The ameliorated plots were not included in the analysis since they were not randomized in the core LTSP experimental design. A one-way ANOVA was used to compare treatment means for the ameliorated plots and the corresponding experimental ($OM_1C_1U_0$ and $OM_1C_1U_1$) plots.

3. Results

3.1. Stand volume

The OM removal and compaction treatments did not significantly ($\alpha \leq 0.1$) affect stand volume on either site (Table 1). There was no discernable difference in the mean stand volumes on the bole only removal (OM_0) plots and the whole tree removal plots (OM_1) (data not shown) or the whole tree plus forest floor removal (OM_2) plots (Fig. 1A). Comparisons of mean stand volumes for non-compacted plots (C_0) to severely compacted plots (C_2) showed slight increases in LA and slight decreases in NC (Fig. 1B) on the severely compacted plots. The mean stand volumes for the moderate compaction plots (C_1), when compared to the C_0 plots, showed the same trend as the C_2 plots (data not shown). The overriding treatment effect on stand volume was understory control (Table 1; Fig. 1C). The effect of understory control on tree growth is well documented (Larcque and Marshall, 1993; Morris et al., 1993; Nambiar and Sands, 1993; Henderson, 1995; Ludovici and Morris, 1997). The increased competition for site resources (i.e., water and nutrients) when an understory

Table 1
Mean stand volume (m^3 ha^{-1}), at year 10, for the different treatments at North Carolina and Louisiana

	North Carolina			Louisiana		
	Mean	S.E.	$P > F$	Mean	S.E.	$P > F$
OM_0	75.06	10.86	0.88	140.27	5.93	0.73
OM_1	78.77	12.57		133.03	6.89	
OM_2	70.31	12.15		135.91	6.42	
C_0	91.15	14.44	0.16	126.30	6.90	0.12
C_1	73.33	9.04		144.40	6.02	
C_2	59.65	10.31		138.51	5.82	
U_0	62.31	6.78	0.07	118.44	3.33	<0.0001
U_1	87.12	11.31		154.37	5.02	

Treatment codes are OM_0 (bole removal), OM_1 (whole tree removal), OM_2 (whole tree plus forest floor removal), C_0 (no compaction), C_1 (moderate compaction), C_2 (severe compaction), U_0 (no understory control) and U_1 (complete understory control).

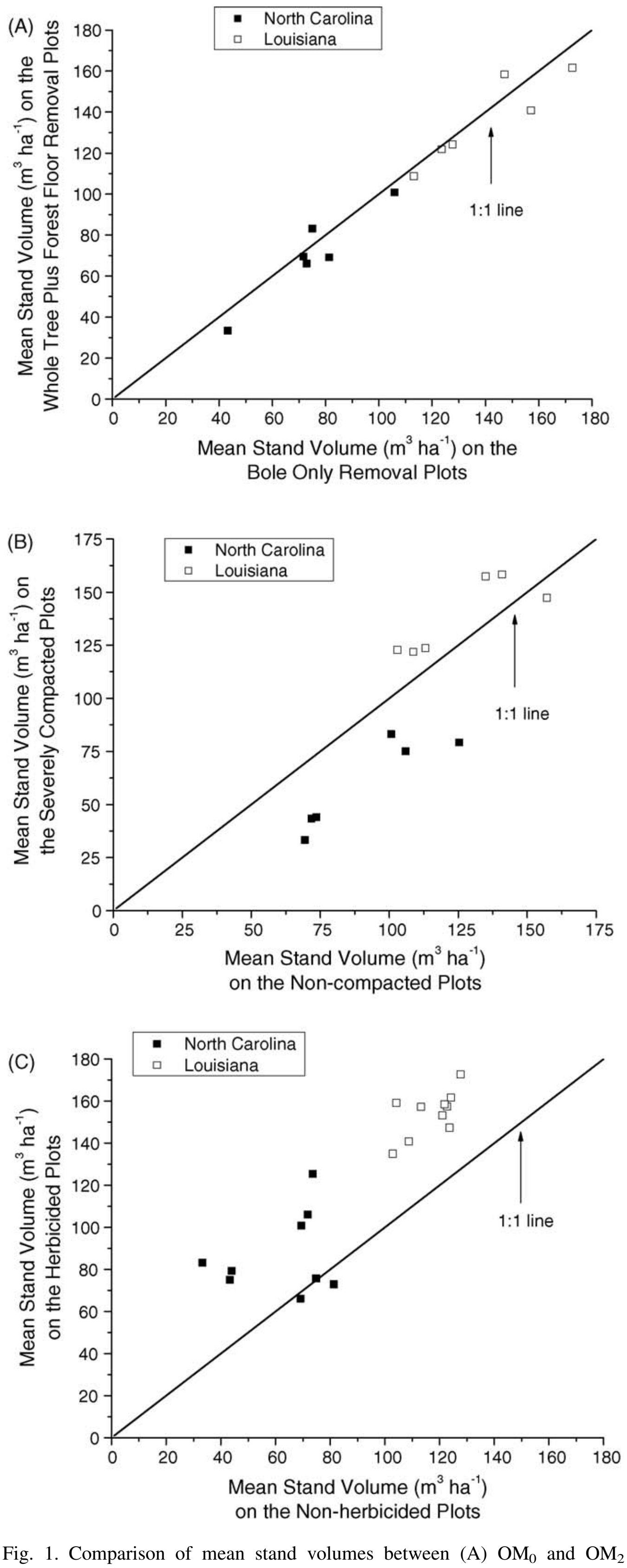

Fig. 1. Comparison of mean stand volumes between (A) OM_0 and OM_2 treatment plots, (B) C_0 and C_2 treatment plots and (C) U_0 and U_1 treatment plots.

is present can decrease tree growth. Both the NC and LA sites showed greater mean stand volumes on the U_1 plots compared with the U_0 plots with this effect being greater on the NC plots due to the greater amount of understory biomass as compared to LA plots (Fig. 1C).

3.2. Soil nutrients

Statistical analyses of the 10th year soil nutrient indicated that the treatments had significant effects on soil total N and/or extractable P but not other nutrients. Extractable P is an index of plant available P and total soil N is primarily organic N which provides plant available N through mineralization (Rowell, 1994). Organic matter removal did not significantly ($\alpha \leq 0.1$) affect soil N content at any site or depth except for the 0–10 cm depth in LA where soil N content was lower on the OM_1

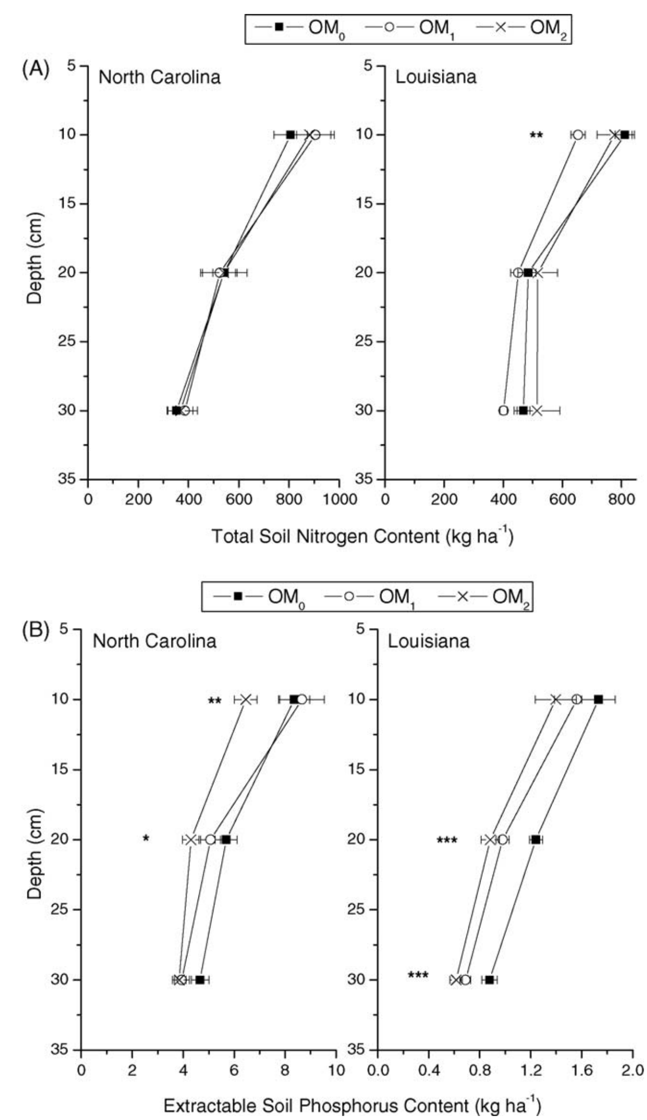

Fig. 2. Organic matter removal treatment effects on (A) total soil nitrogen and (B) extractable soil phosphorus contents at the 0–10, 10–20 and 20–30 cm depths on the North Carolina and Louisiana plots. Asterisks (*, ** and ***) indicate that for a depth/site combination the means are significantly different at $\alpha \leq 0.1$, 0.05 and 0.01 levels.

treatment plots compared with the OM_0 and OM_2 plots (Fig. 2A). Organic matter removal was the dominant effect on extractable soil P for both NC and LA. Removing organic matter reduced extractable soil P at each depth (Fig. 2B) with the amount of the reduction generally greater with the amount of organic matter removed. One exception is noted in the 0–10 cm depth in NC where the OM_1 treatment had no effect on extractable soil P. Soil compaction did not significantly ($\alpha \leq 0.1$) affect total soil N in LA (Fig. 3A) or extractable P in either site (Fig. 3B). However, moderate compaction (C_1) increased soil N content in the NC plots (Fig. 3A). Understory control increased soil total N (Fig. 4A) and extractable P (Fig. 4B) at each depth in NC. Conversely, control of the understory decreased soil total N content in LA, but only in the upper 10 cm of the mineral soil, and had no effect on extractable P.

3.3. Foliar nutrients

Only the extreme treatments (OM_0, OM_2, C_0 and C_2) with understory control (U_1) plots were done in NC, providing only limited information on treatment effects for these sites. However, all the treatment plots were examined in LA, allowing for a thorough investigation of treatment effects on total foliar nutrient concentrations. The foliar nutrient concentrations were not significantly affected by the organic matter removal or compaction treatments in LA but control of the understory did significantly affect foliar nutrient concentrations (except for N and Ca) (Table 2). Of particular interest is the highly significant ($p = 0.0001$) effect of understory control in decreasing total foliar P concentrations. Since the foliage and soil are generally P deficient for both the LA and NC sites (Tables 3 and 4), maintenance of this nutrient is critical for tree growth.

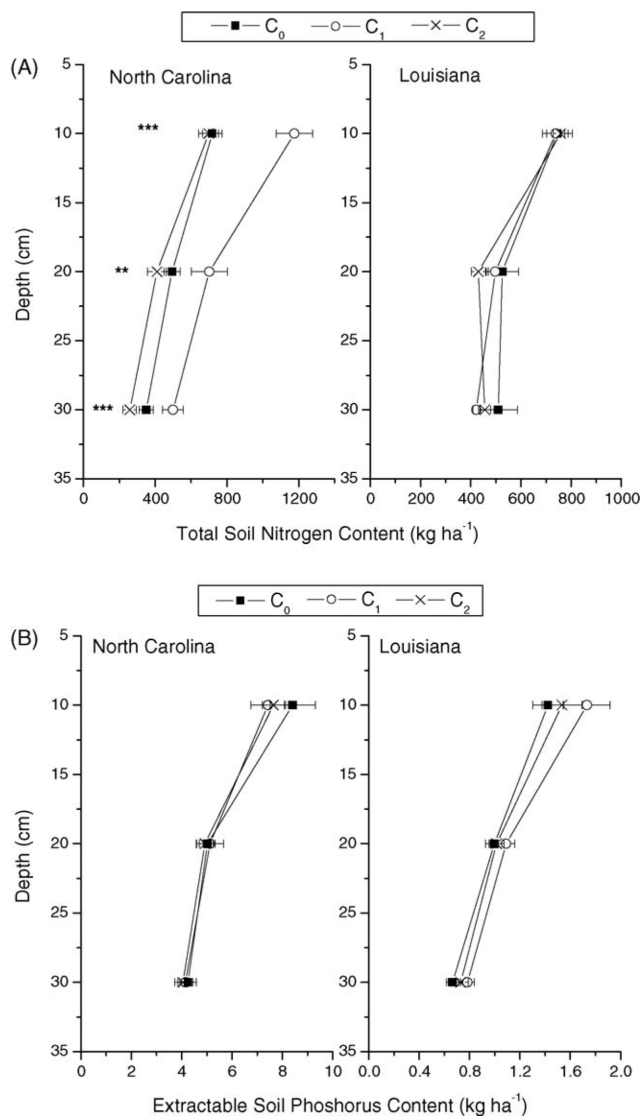

Fig. 3. Compaction effects on (A) total soil nitrogen and (B) extractable soil phosphorus contents at the 0–10, 10–20 and 20–30 cm depths on the North Carolina and Louisiana plots. Asterisks (*, ** and ***) indicate that for a depth/site combination the means are significantly different at $\alpha \leq 0.1$, 0.05 and 0.01 levels.

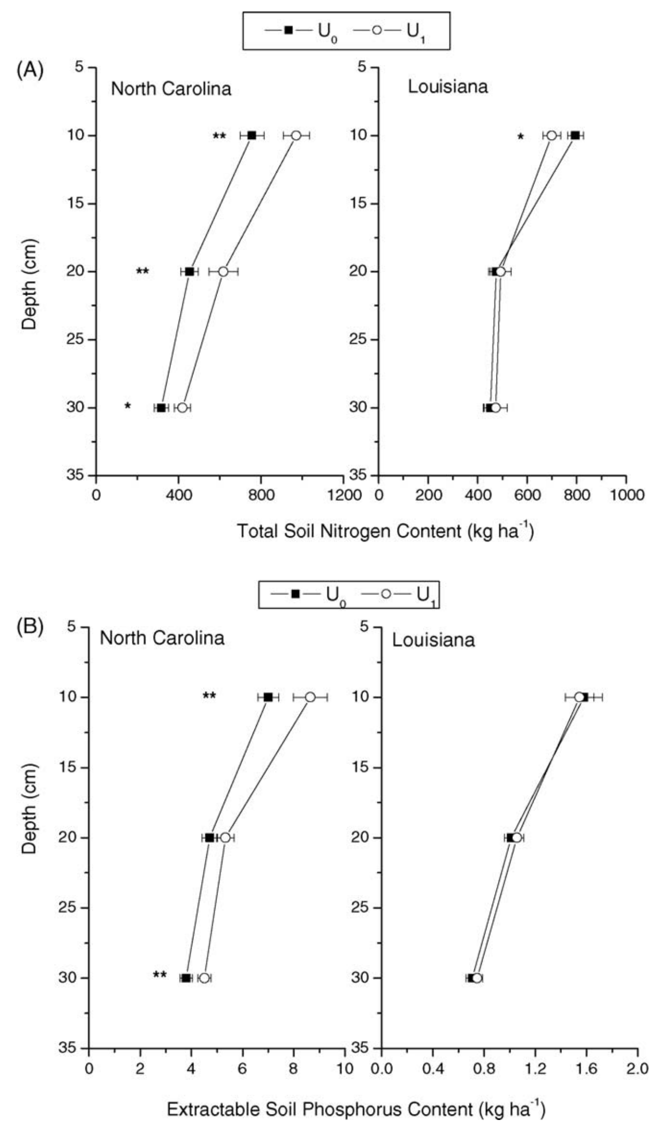

Fig. 4. Understory control effects on (A) total soil nitrogen and (B) extractable soil phosphorus contents at the 0–10, 10–20 and 20–30 cm depths on the North Carolina and Louisiana plots. Asterisks (*, ** and ***) indicate that for a depth/site combination the means are significantly different at $\alpha \leq 0.1$, 0.05 and 0.01 levels.

Table 2
Mean foliar nutrient concentration (g kg^{-1}), at year 10, for the different treatments at Louisiana

Treatment	N			P			K			Ca			Mg		
	Mean	S.E.	$P > F$	Mean	S.E.	$P > F$	Mean	S.E.	$P > F$	Mean	S.E.	$P > F$	Mean	S.E.	$P > F$
OM_0	10.87	0.22	0.88	0.72	0.02	0.93	3.91	0.14	0.12	1.57	0.09	0.54	0.98	0.02	0.82
OM_1	10.96	0.16		0.72	0.02		3.72	0.12		1.54	0.11		0.98	0.02	
OM_2	10.88	0.21		0.73	0.02		4.09	0.13		1.70	0.18		1.00	0.02	
C_0	10.91	0.18	0.84	0.73	0.02	0.98	3.88	0.12	0.94	1.70	0.18	0.43	0.96	0.02	0.38
C_1	10.96	0.16		0.72	0.02		3.89	0.13		1.59	0.12		1.00	0.02	
C_2	10.84	0.25		0.72	0.02		3.94	0.15		1.51	0.09		1.00	0.02	
U_0	10.90	0.16	0.99	0.76	0.01	0.0001	4.06	0.12	0.004	1.55	0.08	0.34	0.96	0.02	0.04
U_1	10.91	0.16		0.69	0.01		3.75	0.09		1.65	0.13		1.01	0.02	

Treatment codes are OM_0 (bole removal), OM_1 (whole tree removal), OM_2 (whole tree plus forest floor removal), C_0 (no compaction), C_1 (moderate compaction), C_2 (severe compaction), U_0 (no understory control) and U_1 (complete understory control).

3.4. Ameliorated plots

The ameliorated plots in LA and NC examined the potential ameliorative effect of fertilization and/or bedding on the mid-level experimental treatment (OM_1C_1). In NC, the ameliorated plots (whole tree harvest with moderate compaction) including fertilization and bedding with and without understory control and were compared to the $OM_1C_1U_1$ and $OM_1C_1U_0$ plots, respectively. Only the potential ameliorative effect of fertilization on plots with no understory control was examined in the LA sites. The fertilized ameliorated plots (whole tree harvest with trees removed using a wheeled skidder) were compared to the unfertilized ameliorated plots and the $OM_1C_1U_0$ plots.

In the NC sites, the small difference in mean stand density between the ameliorated plots with total understory control and the corresponding $OM_1C_1U_1$ plots (Fig. 5A) indicated that fertilization and bedding did not provide an ameliorative effect on plots where the understory was controlled. In contrast, when the understory was present, fertilization and bedding increased mean stand volume compared to the $OM_1C_1U_0$ treatment (Fig. 5A). This effect may be an artifact of drier soil conditions on the plots without understory control (see Section 4).

A different situation was seen in the LA ameliorated plots, where fertilized and non-fertilized treatments were compared in addition to the experimental $OM_1C_1U_0$ plots. Since the ameliorated treatments were only applied on two sites (LA1 and LA3), the results were compared to the $OM_1C_1U_0$ means for those same sites. No significant difference in mean stand volume was detected between the treatments (Fig. 5B). These results are contrary to the observations for the in NC where the ameliorated plots without understory control had 69% greater mean stand volume than the corresponding $OM_1C_1U_0$ plots (Fig. 5A).

4. Discussion

4.1. Stand volume

Dissolved organic matter leaching from the forest floor increases N mineralization (Li et al., 2003) and tree growth. Consequently, organic matter removals would be expected to lower N mineralization and hinder tree growth. In the LTSP experiment, the organic matter removal treatments resulted in a considerable amount of surface biomass and N being removed. The OM_2 treatments removed 77 and 40 Mg ha^{-1} more biomass and 425 and 218 kg ha^{-1} more N, for NC and LA, respectively, than the OM_0 treatments (Powers et al., 2005). Despite the large removal of biomass and N, no significant ($\alpha \leq 0.1$) differences in mean stand volume were detected between the organic matter removal treatments (Table 1; Fig. 1A). This observation suggests that the nutritional needs of loblolly pine were being adequately, although maybe not optimally, provided by the mineral soil at these sites.

In both LA and NC, the effect of soil compaction on mean stand volume was slight and not significant at $\alpha \leq 0.1$ level

Table 3
Mean foliar nutrient concentrations (g kg^{-1}), at year 10, for the control and ameliorated (with understory control) plots in North Carolina and Louisiana

State	N	P	K	Ca	Mg
Control plots ($OM_0C_0U_1$)					
NC	10.3	0.84	3.52	3.23	1.18
LA	10.9	0.72	3.91	1.60	0.99
Ameliorated plots					
NC	10.1	0.92	3.33	4.36	1.32
LA	10.1	0.88	3.70	1.58	0.96

Treatment codes are OM_0 (bole removal), C_0 (no compaction) and U_1 (complete understory control).

Table 4
Mean soil nutrient contents (kg ha^{-1}), at year 10, for the control ($OM_0C_0U_1$) plots at North Carolina and Louisiana

Depth (cm)	N	P	K	Ca	Mg
North Carolina					
0–10	853	8.04	44	291	41
10–20	553	5.07	34	134	21
20–30	370	4.12	38	106	23
Louisiana					
0–10	754	1.59	22	371	91
10–20	489	1.05	17	456	129
20–30	466	0.72	26	572	249

Treatment codes are OM_0 (bole removal), C_0 (no compaction) and U_1 (complete understory control).

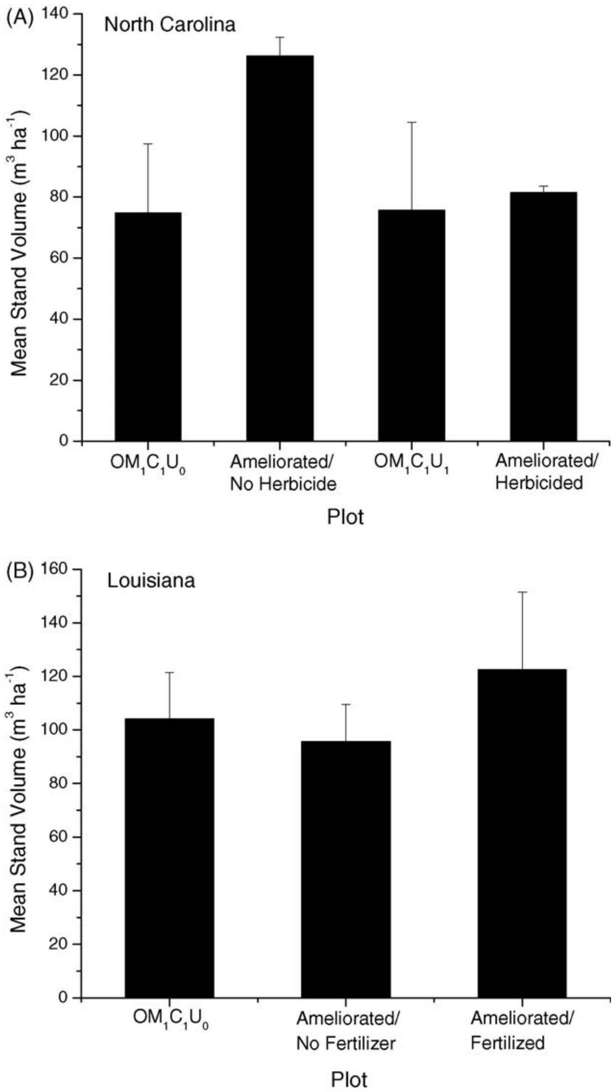

Fig. 5. Mean stand volume for the experimental ($OM_1C_1U_0$ and/or $OM_1C_1U_1$) and ameliorated plots in (A) North Carolina and (B) Louisiana. In NC, the ameliorated plots had a whole tree harvest, moderate compaction followed by bedding and fertilization. In LA, the ameliorated plots had a whole tree harvest with the trees removed with wheeled skidders resulting in moderate soil compaction.

(Table 1). However, the compaction treatment yielded differing results in NC and LA (Table 1; Fig. 1B). In NC, increasing levels of soil compaction resulted in a trend towards decreasing mean stand volumes. This observation is consistent with research indicating that compaction reduces root growth and ultimately stand productivity (Morris and Miller, 1994; Fleming et al., 1998; Williamson and Neilsen, 2000). In contrast, mean stand volume generally increased with increasing soil compaction in LA (Table 1; Fig. 1B). The observed increases in LA may have been due to compaction decreasing understory biomass (Stagg and Scott, in press), which may have improved nutrient and water availability to the planted pine.

Control of the understory was the most dominant effect on stand volume, increasing the mean stand volume by 40 and 30% for the NC and LA sites, respectively (Table 1; Fig. 1C). The understory is an effective competitor for site resources including water and nutrients (Nambiar and Sands, 1993; Henderson, 1995; Ludovici and Morris, 1997). The understory biomass was substantially (approximately a factor of 2) greater in NC than in LA, resulting in greater differences between the U_0 and U_1 treatments.

4.2. Soil nutrients

The soils at both the LA and NC sites are nutrient deficient for loblolly pine growth (Wells et al., 1986; Jokela and Long, 2004), especially in LA (Table 4). In the southern United States, soils low in C and nutrients depend upon continuous organic matter decomposition for part of their nutrient supply (Ellert and Gregorich, 1995). The availability of essential nutrients, especially N and P, commonly limits growth of pine forests in the southern United States (Allen, 1987; Gurlevik et al., 2003). Additionally, Jokela et al. (2004) emphasize that maintaining adequate levels of soil nutrients is the dominant factor for maintaining high productivity within the natural range of loblolly pine.

Soil organic matter is the major source of plant available N and provides as much as 65% of the total soil P (Bauer and Black, 1994). Consequently, removal of organic material during harvest may diminish plant available soil N and P for a site. Generally, total soil N contents were not affected by the organic removal treatments in our study, except for the OM_1 treatment in LA (Fig. 2A). The OM_1 treatment had lower total soil N content as compared to the OM_0 and OM_2 treatments, although this difference was only significant ($p = 0.02$) in the upper 10 cm of the mineral soil. The reason for this deviation is unclear; however, the trend was consistent for all depths at the LA site. Ten years after the study was installed, reductions in extractable soil P with increasing organic matter removal were still detected at the NC and LA sites (Fig. 2B), indicating that removing organic matter may have long-term consequences on the extractable soil P levels on these already deficient sites.

Compaction did not affect total soil N contents in LA (Fig. 3A) and extractable soil P in NC and LA (Fig. 3B). However, soil N on the compacted NC sites yielded an unexpected observation. At each depth, moderate compaction plots (C_1) resulted in higher levels of soil N (Fig. 3A). Close examination of the data and the plot layout elucidated that, although statistically significant, the observed differences in total soil N between the plots were probably not due to compaction. In NC, site selection was done based on small differences in drainage (somewhat poorly drained (NC2 and NC3) and moderately well drained (NC1)). This small difference in drainage has resulted in there being a significant site effect for every measure in the NC study. In addition to the drainage differences between sites, in NC3 there were some plots that were particularly wet due to a depression within the site. When the treatment plots were randomized, chance resulted in all the C_0 and C_2 plots assigned to NC3 being placed in this particularly wet depression area. Soil N levels for plots in that area were considerably lower than any other plots and lowered the mean soil N values for the C_0 and C_2 plots. If the NC3 plots were excluded from the soil N calculations, the trends for the soil N values for NC closely resembled those for LA (Fig. 3A). This bias did not alter other determinations of significance for any other measure. In other words, eliminating the data from NC3 did not make soil Mg levels, for example, statistically significant when they were previously insignificant. This situation illustrates the potential consequences of stand heterogeneity on experimental measurements.

Control of the understory increased total soil N and extractable soil P in NC but had no effect on either nutrient in LA (Fig. 4A and B). An exception is noted in LA where understory control significantly reduced ($p = 0.05$) total soil N in the upper 10 cm of the mineral soil (Fig. 4A). The greater understory biomass in NC takes up more soil nutrients per hectare and thus results in a larger difference between the U_0 and U_1 treatments compared to the LA sites. Although both NC and LA are deficient in soil P, the LA plots are particularly deficient (Table 4). It is possible that in LA any available soil P is rapidly taken up by plants resulting in no difference between the U_0 and U_1 plots.

4.3. Foliar nutrients

In LA, organic matter removal and compaction treatments did not significantly affect any foliar nutrient concentration (Table 2). Additionally, there was no discernable trend in foliar nutrient concentrations with increasing organic matter removal or compaction levels. There was an exception for foliar Ca concentrations which were lowered with increasing compaction, although not significantly ($p = 0.43$) (Table 2). Understory control reduced foliar P and K concentrations, increased foliar Ca and Mg concentrations and had no significant ($p = 0.99$) effect on foliar N concentrations. The increase in foliar Ca and Mg is probably due to more being available for tree uptake instead of being taken up by the understory; however, the decrease in foliar P and K is unclear.

Although extractable soil P was reduced with increasing levels of organic matter removal (Fig. 2B), this effect did not translate into the trees as there was no difference in foliar P between the organic matter removal treatments (Table 2). This suggests that the available soil P levels are sufficient to maintain tree growth although not optimally. Loblolly pine with foliar P concentrations between 0.80 and 1.0 g kg^{-1} are considered deficient for P. Concentrations lower than 0.80 g kg^{-1} indicates a severe P deficiency (Wells et al., 1986). Additionally, trees with foliar N concentrations lower than 12 g kg^{-1} are deficient for N (Wells and Allen, 1985). The trees at both the NC and LA plots are P and N deficient, and the LA plots are severely deficient in P (Table 3). One-time fertilizer applications (N and P in LA and only P in NC) on the ameliorated plots slightly alleviated some of the P deficiency but foliar P (and N) levels are still below sufficiency levels (Table 3). The treatments may respond to a mid-rotation fertilization scheme as suggested by Albaugh et al. (2003) and the Forest Nutrition Cooperative (2004).

Table 5
Mean stand volume, at year 5, for the experimental and ameliorated plots in North Carolina

Treatment	Mean stand volume (m^3 ha^{-1})	S.E.	$P > F$
OM1C1U0	14.73	2.50	0.013
Ameliorated (no herbicide)	47.75	7.33	
$OM_1C_1U_1$	37.02	1.05	0.0007
Ameliorated (herbicided)	61.26	2.40	

Treatment codes are OM_1 (whole tree removal), C_1 (moderate compaction), U_0 (no understory control) and U_1 (complete understory control).

4.4. Ameliorated plots

In both NC and LA, the small difference in mean stand volume between the ameliorated plots and the corresponding experimental plots (Fig. 5A and B) suggested that neither fertilization nor fertilization plus bedding had an ameliorative effect on 10th year stand volume. An exception is noted for the ameliorated plots without understory control. Fifth year data from the NC plots showed a significant difference in mean stand volume for the experimental plots and the corresponding ameliorated plots (Table 5). However, by the 10th year this difference was no longer significant with the exception of the ameliorated with no understory control plots (Fig. 5A). This begs the question: What is different about the ameliorated with no understory control plots? The combination of bedding and maintaining an intact understory should result in drier soil conditions. Although loblolly pine grows well even under waterlogged conditions (Siegel-Issem et al., 2005), lowering the soil water content at the NC sites may result in a more favorable environment for microbial activity and nutrient availability (Li et al., 2003; Drury et al., 2003; Paul et al., 2003). If excess soil water is a factor on these installations, then the effect of reducing soil moisture by bedding and maintaining an intact understory should be most evident on the wetter

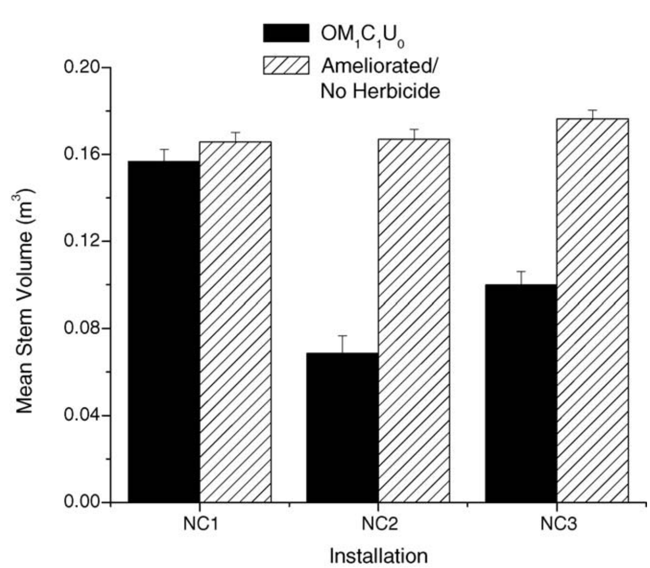

Fig. 6. Mean stem volume for the experimental ($OM_1C_1U_0$) and ameliorated plots without understory control in North Carolina.

installations. In NC, the NC1 installation had 11.5% lower soil water content than the NC2 and NC3 installations (Li et al., 2003). Mean stem volume of trees on the ameliorated plots (no understory control) was considerably greater than trees on the $OM_1C_1U_0$ plots in the NC2 and NC3 installations; whereas, there was no significant different between these plots in the drier NC1 installation (Fig. 6). Creating a drier environment improved tree growth on inherently wet sites but did not impact already dry sites. This observation supports the assertion that excess soil water is negatively impacting tree growth.

5. Conclusions

This study demonstrates that, through 10 years, soil compaction and losses of surface organic material did not have appreciable effects on tree growth on these sites. The dominant effect on tree growth was seen through the control of the understory and hence competition for site resources such as water and soil nutrients. This effect was more evident at the NC sites where the understory was considerably greater than that in LA. Although there was no evidence that tree growth was affected by the main treatments in the LTSP experiment, it is possible that P deficiencies resulting from increasing organic matter removal treatments may become evident later in the rotation or into the next rotation and may then negatively impact productivity. These potential nutrient deficiencies may be alleviated by fertilization; however, as the ameliorated plots on both sites demonstrated, a one-time fertilization may not be sufficient to bring soil or foliar nutrients into optimal levels. Consequently, multiple fertilization treatments may be required to achieve optimal growth.

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