The effect of organic matter manipulations on site productivity, soil nutrients, and soil carbon on a southern loblolly pine plantation

Citation	Mack, J., Hatten, J., Sucre, E., Roberts, S., Leggett, Z., & Dewey, J. (2014). The effect of organic matter manipulations on site productivity, soil nutrients, and soil carbon on a southern loblolly pine plantation. Forest Ecology and Management, 326, 25-35. doi:10.1016/j.foreco.2014.04.008
DOI	10.1016/j.foreco.2014.04.008
Publisher	Elsevier
Version	Accepted Manuscript
Terms of Use	http://cdss.library.oregonstate.edu/sa-termsofuse

Title: The effect of organic matter manipulations on site productivity, soil nutrients, and soil carbon on a southern loblolly pine plantation

Authors: Jason Mack[1], Jeff Hatten[2*], Eric Sucre[3], Scott Roberts[1], Zakiya Leggett[3], Janet Dewey[4]

1 Mississippi State University, Department of Forestry
2 Oregon State University, Department of Forest Engineering, Resources & Management
3 Southern Timberlands Technology, Weyerhaeuser Company
4 University of Wyoming, Department of Geology and Geophysics
* Corresponding Author: jeff.hatten@oregonstate.edu

Highlights

1) Examined impacts of manipulating organic matter on soil C, N and P and productivity
2) Treatments were addition and removal of forest floor and harvest residues 15 years ago
3) Added treatments had greater stand volume at age 15
4) Volume was correlated (+) with surface N and P and greater C at 40-60cm
5) Productivity did not appear to change as a result of removal treatments

Abstract:

Forest harvesting intrinsically removes organic matter and associated nutrients; these exports may impact soil productivity and soil carbon stores of managed forests. This study examined the effect of manipulating forest floor and harvest residue inputs on nutrient availability and carbon content in the context of intensive forest management. Treatments were applied 15 years prior to this study and included removal and addition of forest floor and harvest residues, and a reference. We examined stand volume, litterfall, root biomass and foliar N and P at year 14 or 15. Soil moisture and temperature (0-10cm) and available N and P in the O and 0-20cm depths were measured once per month during year 15. Soil carbon and nitrogen were measured on whole soils as well as two density fractions in the O-horizon, 0-20, 20-40, and 40-60cm soil depths at year 15. In general, many of the initial responses found by an earlier study (age 10) have dissipated. Standing volume in the added treatment was 31% higher than the removed, but no significant difference was found between the removed and reference treatments. The added treatment resulted in higher concentrations of N in the light and heavy density fractions of the 0-20cm depth, which led to higher mass of N in both of these fractions. The added treatment had the greatest whole soil heavy fraction N mass. There were no differences in available N in the O-horizon or 0-20cm depth as tested using ion exchange membranes; however available P was significantly lower in the O-horizon of the removed treatment (37% lower than the reference). Bole volume was correlated with some measures of total and available N and P in the O and 0-20cm soil horizons, suggesting that increases in growth found in the added treatment were a result of additional nutrients. There were no significant differences between C concentration or mass of the 0-20cm or 20-40cm soil depths between the treatments; however the added treatment had significantly more (51% more than the reference) carbon at the 40-60cm soil depth. The added treatment had a significantly higher C:N relative to the reference in the 20-40cm (21.0 and 14.5, respectively) and 40-60cm (18.0 and 11.4, respectively) depths, suggesting that relatively fresh, undegraded organic matter had enriched this depth. This additional carbon sequestered at depth could contribute to a long-term soil carbon pool. The results of this study suggest that higher intensity use, such as forest floor removal and whole tree harvest, of these forests may not impact long term productivity at this site with typical soil nutrient status; however, more research is necessary to determine the mechanism(s) of this resilience.

1. Introduction

In the United States, standard harvesting operations of intensively managed plantations utilize bole-only harvesting techniques with best management practices (BMPs) that redistribute the tops, branches and needles across the site. However, if these BMPs are not followed then higher levels of nutrient and carbon removals could impact long-term soil productivity and soil carbon stores, especially on sites with coarse-textured soils and low soil organic matter (Powers et al., 2005). Furthermore, there are national level movements underway that may influence managers to intensively utilize residues from forest harvesting operations. For example, the Energy Independence and Security Act (EISA) of 2007 has set a goal of 36 billion gallons/year of biofuels by 2022 and, in general, set goals and regulations to reduce the United States' dependence on foreign sources of oil (EISA, 2007). There are also developing markets for biomass for electricity generation. While no single source of biomass will provide the feedstock for this effort (Kenney, et al., 2013), harvest residues represent an abundant, and currently low demand, biomass feedstock that could be used to generate renewable electricity and biofuels. Forest harvesting, bole-only or for biomass, intrinsically removes organic matter and associated nutrients; these exports may impact long-term soil productivity and soil carbon stores of managed forests.

Litter and slash are sources of soil organic matter (SOM) which is potentially a long-term sink for atmospheric carbon dioxide (CO_2). Soil organic matter plays a significant role in soil function; in particular, cation exchange capacity, soil structure, aeration, water holding capacity, and soil strength. Decomposing SOM provides the majority of the mineralized forms of nitrogen (N). Collectively, these characteristics of SOM play an integral role in sustaining site productivity (Fisher and Binkley, 2000).

Forest productivity is typically defined as the growth and maintenance of a forest (e.g. gross or net primary production). When dealing with forests grown for wood production, many forest managers are primarily interested in bole volume. Bole volume along with litter fall and root mass is how we have measured forest productivity in this paper. Detecting a decline in forest productivity is challenging due to the effects of tree genotype, management practices, plasticity of trees to adapt to a site, and changes in state factors (e.g. climate) at potentially masking any trends in productivity (Richardson et al., 1999; Morris and Miller, 1994). Furthermore, productivity declines may only occur after some threshold has been exceeded

(Richardson et al., 1999). One suggestion for detecting changes in the ability of a site or soil to grow trees is to use soil indicators (Burger and Kelting, 1999; Richardson et al., 1999).

Most forest floor removal studies that include a whole tree harvesting treatment have shown no significant effect on stand productivity (Powers et al., 2005; Ponder, 2008; Zerpa et al., 2010; Ponder et al., 2012). The North American long-term soil productivity (LTSP) network found no significant differences in tree productivity at age 10 after whole tree harvesting and floor removal on 18 sites across North America (Powers et al., 2005). However, at the regional level some conflicting treatment effects have been observed. For example, an intensively managed loblolly pine (*Pinus taeda* L.) plantation on the Lower Coastal Plain of North Carolina showed no significant differences in the aboveground biomass at either 5 or 10 years after treatment establishment (Li et al, 2003). On the other hand, Gulf Coastal Plain sites with noted phosphorus deficiencies exhibited bole volumes 15-66% less than the bole only removal treatment 5 years following complete removal of O-horizon and harvest residues (Scott et al., 2004). It appeared that site quality played an important role in stand response since the largest reductions in growth occurred on sites with the lowest site quality.

Changes in site productivity occurring after whole tree harvest are not always detected early in stand development (Sanchez et al., 2006); decline in productivity may not appear until subsequent rotations. Furthermore, changes in productivity may decline into perpetuity or reach a new steady state that is consistent with the management regime (Worrell and Hampson, 1997). In Scandinavia, several long-term studies examined the effects associated with whole tree harvesting for biomass have shown immediate impacts to stand productivity and after subsequent whole-tree thinning of stands regenerated after whole tree clear-cut harvesting (Helmisaari et al., 2011). The impact of intensive organic matter removal on long-term site productivity is more likely to be observed on nutrient poor sites, which often contain coarser textured soils. Furthermore, Ponder et al. (2008) suggested that the effect of O-horizon and harvest residue removal may not be apparent until crown closure when nutrient demands of the soil are highest, a hypothesis consistent with results from the Scandanavian study by Helmisaari et al. (2011). To determine the effects of intensive organic matter removal on stand productivity whole tree harvested stands from a range of sites need to be followed through an entire rotation, and preferably for multiple rotations (O’Hehir and Nambiar, 2010).

Relative to standard harvesting operations, intensive organic matter removal may alter soil carbon cycling by removing a source of soil carbon, causing a larger disturbance to the soil surface, and changing temperature and moisture regimes which influence heterotrophic respiration rates. Changes caused by these operations may lead to a loss of soil carbon capital, with the magnitude of change dependent on forest and soil type (Johnson et al. 2001; Jandl et al. 2007; Nave et al. 2010). Nave et al. (2010) reported an 8% average reduction in soil carbon stocks after bole-only clear-cut harvesting over all forest and soil types studied. These losses were primarily caused by reduced litter layer mass as a result of lower organic matter inputs from growing trees; in contrast, harvesting had little significant effect on mineral soil carbon or lead to increases as a result of incorporation of harvesting residues into the mineral soil. Due to the importance of slash incorporation in the studies examined by Nave et al., (2010) this would suggest that whole tree harvesting may be at higher risk of detrimentally impacting soil carbon stores. However, whole tree harvesting in addition to O-horizon removal has been shown to have little impact on soil carbon stores after 5 and 10 years in soils with moderate levels of soil carbon (Powers et al. 2005; Sanchez et al., 2006).

In many harvesting operations soil and slash are displaced, so that some areas may have exposed mineral soil (slash and O-horizon removed), while other areas may have additional O-horizon and slash. Adding organic matter to the forest floor following a harvest can increase soil nutrient capital and improve growth of aboveground biomass (Sanchez and Eaton, 2001; Zerpa et al., 2010). However, this process is costly and may not always achieve positive results (Sanchez and Eaton, 2001). Zerpa et al. (2010) observed an increase in available N, tree growth, and litterfall 10 years after harvest with the addition of organic matter (i.e., doubling the forest floor compared to reference). The difference in total N resulted in a significantly lower C:N ratio of the O-horizon in the doubled OM treatment. This was attributed to improved N quality in the Oi and Oe layers from the addition of organic matter. Consequently, adding organic matter following harvest increased soil nutrient capital, nutrient availability, and therefore tree productivity.

In this study, we utilize an organic matter addition treatment in addition to a removal treatment to explore the role that site quality has in affecting loblolly pine productivity 15 years after planting. This study is a follow-up on Zerpa et al. (2010) who examined these sites after 10 years of tree growth. We hypothesize that stand productivity is driven by soil resource availability, especially N and P, and if these pools decline then overall stand productivity may decline. Therefore, adding or removing nutrients from sites with nutrient limitations on growth should result in equal but opposite responses to soils and site productivity. Thus, the objective of this research was to assess changes in site productivity by examining the effect of manipulating forest floor and harvest residue inputs; specifically, we evaluated how these manipulations affect nutrient availability and soil C content in the context of intensive forest management 14 years after study installation.

2. Materials and methods

2.1 Site description

The Millport Organic Matter Study (Zerpa et al., 2010) is located in Lamar County, Alabama, USA (33°32’22.87”N, 88°77.53”W). The site is located on the Upper Coastal Plain physiographic province. Soils are classified as deep, well-drained Ruston series fine-loam, siliceous, semiactive, thermic Typic Paleudults (Soil Survey Staff, 2011). Average annual temperature from 1987–2010 was 16.9°C and ranged from 6.3°C in January to 27.1°C in July (NOAA, 2010). Mean annual precipitation was 1320mm with the wettest month occurring in February (137mm) and driest month in September (80mm) (NOAA, 2010). The weather station at Columbus Air Force Base was the closest to the site (17.7 kilometers NW) and will be used to characterize the precipitation and temperature during the period of study. The site index was 21m at 25 years, typical for the region.

A 34 year-old loblolly pine stand was clearcut in 1994 preceding the establishment of the current stand. The experimental design was a randomized complete block design, based on differences in slope, containing three treatments and four replicates (Figure 1). Loblolly pine was planted on 4.3x3m spacing (≈ 775 stems per hectare) on 0.16ha plots. Three treatments were established at the site: added, removed, and reference. Whole-trees were harvested and all slash and the entire forest floor was removed from the removed treatment. The residue treatments added or removed 118 Mg ha^{-1} of forest floor, harvest residue, and trampled understory. This amounted to 606 kg N ha^{-1} and 42 kg P ha^{-1} (unpublished data). The removed treatment is similar to the Long-Term Soil Productivity (LTSP) Network’s treatment OM2 with no compaction (i.e., OM2 C0) (Powers et al., 2005). The added treatment had bole-only harvest with the slash and forest floor from a removed treatment plot transferred evenly from an adjacent removed plot. There is no analogue of the added treatment in the LTSP study. The reference treatment had a bole-only harvest and standard harvest residue management.

2.2 Site and soil sample and data collection

Volume was determined at stand age 14 by measuring diameter at breast height (DBH) of all trees; ten randomly selected trees per plot (12% of all trees) were subsampled to determine average plot height (Burkhart, 1977). Periodic increment of volume was assessed by calculating the difference (i.e. growth) in volume between age 10 and 14. Each plot contained five sampling locations consisting of four plot corners and one center point (Figure 1). Soil moisture, soil temperature, soil, root cores, organic horizon (O-horizon), and litterfall data were collected at each of these five sampling locations.

Beneath the O-horizon, a 20cm deep and 15cm diameter root core was removed and roots were washed and sieved for root biomass. Cores were collected during the winter of 2011 at each of the five locations by plot for a total of 60 samples. Root cores were composited by plot and washed with a solution of sodium hexametaphosphate and rinsed through a 0.840mm sieve. The root washing process allowed for the separation of roots (dead & live) and collection of live roots >1mm in thickness. Clean root samples were oven dried at 55-60°C weighed and expressed as kg m^{-2}.

Five litterfall traps ($0.75m^2$) were placed throughout each plot to measure tree foliar productivity. Litterfall samples were collected and composited by plot each month for one year (December, 2010 to December, 2011). Samples were oven dried overnight at 55-60°C, weighed, and expressed as kg $m^{-2}yr^{-1}$. Every month three litterfall samples representing each treatment were sub-sampled and analyzed for C and N. Foliar samples were collected at age 15. Five trees were sampled and composited by plot and analyzed for N. Retranslocation was calculated as the difference between the foliar and litterfall N concentration multiplied by the mass of litterfall.

The O-horizon was collected one time at five points per plot but cutting around a field note book (12.5 x 19cm) and composited. Samples were oven dried at 55-60°C for 24 hours. O-horizon bulk density was determined by dividing the sample mass by the product of the surface area collected ($237.5cm^2$) and average thickness of the horizon measured at each sample point. O-horizon composites were mixed thoroughly, sub-sampled, ground, and analyzed for C and N.

Mineral soils were sampled one time at five locations per plot at 0-20cm, 20-40cm, and 40-60cm depth with a hammer corer. The five samples were composited by plot for a total of 12 soil samples for each depth. Soil samples were oven dried at 55-60°C. Additional soil samples were collected for bulk density. Soil samples collected specifically for bulk density were oven dried at 105°C for 48hrs. Collected soils of 0-20cm, 20-40cm, and 40-60cm were sub-sampled, ground (Dyna-Crush Soil Grinder, Customer Laboratory Inc.), and analyzed for C, N and pH.

Density fractionation of mineral soil is a common procedure to determine the dynamics of soil organic matter (Six et al., 1999). We utilized it to examine the relative lability or recalcitrance of organic forms of N. A low density fraction in the mineral soil represents a more labile form of N, while a higher density fraction indicates more recalcitrant forms of N. Mineral soil samples were separated into light and heavy fractions with a 1.64g cm^{-3} density sodium polytungstate (SPT) solution (Bock, 2000). Three grams of oven dried soil (55-60°C) were mixed with five grams of SPT solution and put in a centrifuge at 3000rpm for 10 minutes. After each centrifuge run, light fraction (LF) material floated to the top of the vial and was aspirated and collected in a separate vial. This process was done six times to assure all <1.64g cm^{-3} particles were collected. The SPT solution containing LF was filtered through 0.47 μm combusted (3h 350 °C) glass fiber filters, oven dried overnight (55-60°C), and processed by randomly punching holes in the filters and analyzing the adhered residue for total C and N. Heavy fraction (HF) samples were lyophilized, and analyzed for total C and N.

To purify SPT in between flights of samples, the spent solution was passed through a column containing a quartz wool, activated carbon (Darco® S-51, 4-12 mesh), and cation exchange resin (benzene diethenyl polymer; Six et al., 1999). After the solution was cleaned it was oven dried at 55-60°C until a density of higher than 1.64g cm^{-3}was achieved and adjusted to the appropriate density prior to reuse.

2.3 Monthly soil moisture, temperature, and available nutrients

Soil moisture and temperature were measured monthly for one year at each soil sampling location. A portable FieldScout TDR 300 Soil Moisture Meter measured volumetric moisture content and a bi-metal dial thermometer measured soil temperature in the top 10cm at five locations and averaged by plot.

Available N and phosphate was measured monthly at each soil sampling location to examine nutrient dynamics through time using two-sided, 5cm x 15cm cationic (Ionics CR67-HMR) and anionic (Ionics AR204-SZRA) exchange membranes. The active membrane surfaces mimic passive root uptake potential (Hangs et al., 2004). Membranes are easy to clean, can be reused, reduce soil disturbance, have a flat surface area, and give a dependable relative index of nutrient availability over time (Hangs et al., 2004). At each plot, five cation and five anion membranes were deployed in pairs at five random locations within each plot under the O-horizon and in the A-horizon for a total of 240 ion exchange membranes analyzed per month. Membranes were installed for approximately one month intervals and extracted/replaced 11 times (about1 year total from January, 2011 to December, 2011). Sets of anion and cation membranes were installed vertically to 7.5cm (A-horizon) and another set placed horizontally below the O-horizon. The membranes were charged with 1 M NaCl prior to deployment. When the membranes were collected on site, ten O-horizon and ten A-horizon membranes were composited from each plot for a total of 12 membrane sets per depth per month. Upon returning to the lab, membranes were rinsed with deionized water to remove adhered soil particles, set in quart size zip lock bags with 1 M NaCl solution for nutrient extraction, and put on a shaker at high speed for 1-2 hours to extract nutrients from the surface. The solution was filtered with Whatman 41 filter paper and stored frozen in plastic vials. From January 2011 to May 2011 the membranes were extracted in 1000mL of NaCl. This volume of extractant appeared to dilute some constituents below detectable limits (particularly PO_4^{-3}) so from June 2011 through December 2011 we used 100mL of NaCl solution to extract ions from the membranes. The volume of extracting solution was used as a covariate during the statistical analysis of available nutrients.

2.4 Laboratory analyses

Subsamples of oven dried O-horizon, litterfall, needles, and root samples were ground with a Thomas Wiley® Laboratory Mill Model 4 using a 60 mesh sieve prior to elemental analysis. Dried mineral soils were sub-sampled and ground with a mortar and pestle. Organic and mineral samples were analyzed for C and N using dry combustion (Costech ECS 4010). Reproducibility of standards and duplicates was determined by taking an average of all run standards/duplicates for % weight C and N. NIST traceable soil standards were interspersed throughout analytical runs to validate complete combustion and recovery of C and N. Reproducibility of standards for %C was determined to be 100.8%±0.99% and %N was 98.7%±8.0. Reproducibility of duplicates for %C was determined to be 100±8.35 and %N was 100±4.83. Foliar samples were digested using a microwave digester (EPA, 1996) and solutions analyzed for total PO_4 using the Molybdenum Blue Method (APHA et al., 2005).

Soil pH of all 12 plots at 0-20cm, 20-40cm, 40-60cm soil depths was measured at room temperature using a 1:1 soil:water ratio. Available NO_3^--N and NH_4^+-N extracted from the IEM were analyzed on an Auto-analyzer (BRAN+LUEBBE AutoAnalyzer3, Germany) using the Cd-reduction (NO_3^--N) and the indophenol blue (NH_4^+-N) methods (Keeney and Nelson, 1982; Mulvaney et al., 1996). The reproducibility of standards tested for $PO_4^{-3}$was 101.3%±6.12%, NH_4^+ 100.2%±6.14%, and NO_3^- 96.9%±6.32%. To examine the activity of H^+ in relation to available N and P we measured the pH of each extracted solution and calculated the molar concentration of hydrogen [H+] ions in solution which then converted to a mass concentration relative to the surface area of the membranes.

2.5 Statistical analysis

Analysis of variance (ANOVA) using a general linear model on a completely randomized block design (CRBD) was used to assess treatment effects of all parameters collected once during the duration of the study. A critical value of $\alpha = 0.10$ was used to test for significant differences. Post-hoc comparisons between the treatments were made using Tukeys HSD. The CRBD ANOVA and post-hoc comparisons tests were conducted using SPSS (IBM SPSS Statistics, Version 21).

Treatment effects on monthly soil moisture, soil temperature, available nutrients (PO_4-P, NO_3-N, NH_4-N), and H were analyzed using a repeated measures ANOVA from January 2011 to December 2011 (PROC MIXED package) with time as a repeated measure using the autoregressive (ar(1)) covariate structure. Several covariate structures were tested to determine the optimal structure for these data. This was determined by proper conversion of the model matrix and Akaike’s Information Criterion (AIC). Repeated measures ANOVA were performed using SAS version 9.2 (SAS Institute Inc., Cary, NC).

3. Results

3.1 Stand volume and periodic annual increment

Standing stand volume at age 14 in the added treatment was 31% higher than the reference. No significant difference was found between the removed and reference treatments (Table 1). There were no significant differences between treatments in periodic volume increment (age 10-14).

3.2 Environmental factors

Soil moisture and temperature followed air temperature and precipitation trends as shown by the data gathered from a nearby weather station at Columbus Air Force Base (Figure 2). Through most of 2011, differences in soil temperature among treatments were minimal. Repeated measures ANOVA found no significant time by treatment interactions in soil temperature or moisture. Soil temperature or moisture during 2011 likely did not influence differences among treatments.

3.3 Litterfall, roots, and foliar chemistry

Over half of the litterfall collected in 2011 fell during fall months. Total annual litterfall mass did not differ significantly among treatments (Table 1) despite consistently higher litterfall inputs in the added treatment every month of the year (data not shown). However, plot 1 (removed treatment) produced 31% more litterfall than the next closest plot which resulted in a high amount of variance for the removed treatment. When plot 1 was removed from the analysis the added treatment had significantly more litterfall than the other treatments p=0.0417. Litterfall total N content was not significantly different among the treatments; however the added treatment had a slightly greater %N than the reference and removed treatment (Table 1). Foliar N or P concentration was not significantly different among the treatments. While there was a trend of lower rates of retranslocation on the reference plot, it was not significant.

Root mass was not significantly different among treatments (Table 1); however there was a trend of higher root %N in the added treatment but it was not statistically significant. This lead to no significant difference found between the treatments with regard to total root N mass (Table 1).

3.4 Whole soils

O-horizon %N was significantly higher in the reference treatment compared to the added and removed treatments (Table 2). However, higher O-horizon mass (p=0.018) in the added treatment resulted in a trend of higher total N relative to the removed treatment (88% more), although it was not significantly different than the reference (Figure 3 and 4). We found that Significant differences between the treatments are becoming less apparent since the last time these plots were measured during year 10 by Zerpa et al. (2010) and year 0 (unpublished data).

Carbon and N concentrations in the mineral soil decreased with depth. Nitrogen concentration and mass did not differ among treatments across mineral soil depths (Table 2 and Figure 3). Interestingly, there were no significant differences in C concentration and mass in the 0-20cm or 20-40cm soil depths, but there was a significant difference at the 40-60cm soil depth where the added treatment contained 51% more carbon than the reference. Despite some differences in C and N contents of individual depths (Table 2 and Figure 3) there were no significant differences in whole profile soil C or N mass among treatments (p=0.107 and p=0.395, respectively).

Soil C:N ratios decreased with depth from the O-horizon to the 40-60cm depth (Table 2). The C:N ratio of the added plot was significantly lower than the other treatments in the O-horizon and significantly higher in the 20-40 and 40-60cm depths. Since C:N of organic matter decreases with degradation, this trend suggests that the forest floor of the added treatment had a higher relative state of decomposition, while the deeper horizons of the added treatments appear to be less degraded relative to the other treatments.

3.5 Density fractions

Mineral soils were fractionated into light and heavy fractions in order to determine the distribution of organic and mineral bound carbon and nitrogen. The fraction of whole soil N captured in the LF and HF fractions was 12 and 57%, respectively, with the remaining 31% made up of N that was not assessed in our method (e.g. soluble inorganic and organic forms). The N concentration of the LF and HF fractions of the 0-20 cm depth were significantly higher in the added treatment (Table 3). These differences in N concentration led to significant differences in both the LF and HF N mass in the 0-20cm depth. While the total LF N content of the 0-20cm depth of the added and removed treatments were significantly different from one another, neither was different from the reference. The mass of HF N in the 40-60cm soil depth was significantly different among the treatments (p=0.087); however no significant differences could be detected among the treatments during the post-hoc test. These trends led to significant differences among the treatments' HF N mass (p=0.093, data not shown) where the added and removed treatments were significantly different from one another but neither was different from the reference.

The LF had higher carbon concentrations than the HF, but there were no significant differences in carbon concentrations of the fractions across treatments or depths (Table 3). There were significant differences in the 0-20cm HF C content. Additionally, there were significant differences among the treatments' total soil HF C mass (p=0.024, data not shown) where the added and removed treatments were significantly different from one another they were not different from the reference.

The LF consistently had higher C:N ratios relative to HF which is consistent with the hypothesis that the LF is derived from fresh sources while the HF is derived from more degraded sources of organic matter (Table 4). There were no significant differences in the C:N between the treatments among the fractions derived from any depth. However, for any given depth the LF from the removed treatments consistently had a trend of higher C:N ratios and the added treatment had the a trend of lower C:N ratios although not significant. There were no significant differences or consistent trends in the C:N of the HF from any depth.

3.6 Available nutrients

Among treatments, pH did not differ significantly in the 0-20cm, 20-40cm, and 40-60cm depths (4.38, 4.65, and 4.81, respectively). The lack of significant differences in pH suggests that any differences in available nutrients and organic matter were not a result of changes to pH.

Ion exchange membranes from the A-horizon and O-horizon were analyzed for NO_3-N, NH_4-N, PO_4-P, and H monthly. No significant time by treatment interactions were found during the 11 months of sampling. For these reasons, we have confined our analysis of these data to the average annual nutrient concentration on the resin membrane (Table 5). Ammonium-N was more prevalent in both the O- and 0-20cm horizons compared to NO_3-N. Neither form of N was found to be significantly different among the treatments. Phosphate from the exchange resins installed in the O-horizon was significantly lower in the removed treatments relative to the reference and added treatments. Since orthophosphate activity in soils can be strongly affected by pH we also assessed the concentration of H ions on the exchange resins. We found no differences in exchangeable H among the treatments suggesting the trends in PO_4-P were not driven by the activity of protons in soil solution.

4. Discussion

The objective of this research was to assess the effect of manipulating forest floor and harvest residue inputs on indicators of productivity; specifically, to evaluate how these manipulations affect nutrient availability and C content in the context of intensive forest management 15 years after treatment. Major findings include higher stand volume following the addition of O-horizon and harvest residues to the loblolly pine plantation compared to the total forest floor removal treatment. Conversely, complete removal of the forest floor did not result in large differences in below or aboveground productivity 15 years after harvest. The addition of organic matter resulted in more N in the O- and A-horizons and increased C in lower soil horizons. We will explore possible mechanisms for these responses in the next section.

The reader should note that while this study's objective is to be a long-term research installation it is 15 years old. The discussion that follows will compare these results to longer and shorter studies of forest productivity in order to understand the mechanisms behind the response of a forest to organic matter manipulation.

4.1 Carbon and Organic Matter

We found that there was little effect of either organic matter removal or addition on soil carbon pools in the upper 40 cm of the soil profile. While there were trends (higher in the added and lower in the removed treatments) these did not translate into significant differences 15 years after treatment. We summarized the trends in O horizon mass found by this study, Zerpa et al. (2010), and the initial slash + forest floor biomass (unpublished data) in Figure 4. While different sampling methodologies were used between the three sets of measurements, it is clear that forest floor biomass decreased relatively rapidly after treatment on the reference and added treatments, while the removed treatments have recovered to reference levels. The forest floor biomass of the treatments has converged further since Zerpa et al. (2010) measured the site at age 10. Repeated sampling of these sites is needed in order to determine if O-horizon mass will continue to increase, as appears to be the trend between age 10 and 15.

The major significant difference with regard to soil organic matter was higher carbon content in the added treatment at depth (40-60cm). The addition of carbon at depth could come from a variety of sources including leachates from the O-horizon, desorbed organic matter from elsewhere in the profile, or increased production of roots at depth. We used Pearson correlations to explore differences in environmental conditions, productivity, and soil characteristics that may be driving soil carbon trends on these sites. Care must be taken when interpreting correlation coefficients because the correlated factors may not be mechanistically associated. However, this analysis does allow for some insight with regard to the effect of organic matter manipulations on tree production. There were significant correlations between stand volume and carbon concentration and mass of most soil horizons (Table 6). These results may have been driven by the treatments (adding or removing organic matter) or they could be a result of the treatments' effect on site productivity (e.g. higher productivity resulting in more soil carbon).

Elevated carbon content in this deep soil horizon was accompanied by significant increases in the added treatments C:N ratios at 20-40 and 40-60cm. Additionally, there was a positive correlation between mineral soil C:N and tree growth, suggesting that more C than N has been added to those horizons and that increased productivity has elevated inputs of fresh (high C:N) organic material and driven the increase in soil carbon. The source of this organic matter is either derived from elevated dissolved organic matter leaching from the O-horizon, or root production (unmeasured in this study) that coincided with the increase in aboveground production. Additionally, given that there was a slight increase in the carbon content of the depths above the 40-60cm depth, there may have been some displacement of higher C:N material that illuviated into the 40-60cm depth. More research is necessary to determine the ultimate source of this additional organic matter. An increase in carbon at depth could be important for carbon sequestration and long term carbon storage into subsequent rotations.

As with many other studies of intensive organic matter removal, we were unable to detect a change in the total soil carbon pool (e.g. Powers et al., 2005). This trend has been attributed to the incorporation of decaying roots into the soil carbon pool (Powers et al., 2005) as well as the difficulty in detecting change in soils (Homann et al., 2001). It is possible that there was a reduction in soil carbon pools within the first several years after harvesting and organic matter removal (e.g. Nave et al., 2010). However, at 10 years of age on these sites Zerpa et al. (2010) also found no effect of organic matter removal on soil carbon, suggesting that any reduction and recovery of the sites soil carbon pool would have taken place within the first decade following harvest. The lack of soil carbon trends at years 10 or 15 as a result of organic matter removal, it can be suggested that these soil carbon pools were resilient to the removal of above ground organic matter. The mechanism for this resilience is still uncertain and is another area that deserves further research.

4.2 Productivity and organic matter manipulations

Stand productivity was assessed through bole volume, litterfall, and root mass. The added treatments had significantly greater stand bole volume while the removed and reference treatments did not differ. Standing volume at age 15 exhibited comparable trends to the findings of Zerpa et al. (2010) at year 10 of the same study site. However, any differences in growth rate (i.e. periodic annual increment) that caused the treatment differences in standing volume have ceased (or the difference was below our detection limit). As noted by others (Richardson et al., 1999; Morris and Miller, 1994) stand productivity is a poor measure of the sustainability of a management system to produce wood and biomass. We have assessed several indicators of the soil's ability to provide nutrients and resources for a growing stand.

There were no significant correlations between stand volume and average annual soil temperature or moisture, suggesting that at this stage in stand development soil physical conditions were not responsible for the differences among the treatments (Table 6). Overall, the added treatments had more soil N, while the removed was not significantly different from the reference, and there were many significant correlations between stand volume and N concentration (+), N mass (+), and C:N (-) of soil horizons, particularly in the O and 0-20 cm horizons. There were also significant correlations between stand volume and LF N concentration (+), LF N mass (+),HF N concentration (+), and HF N mass (+) within the 0-20cm depth and LF C:N (-), HF C concentration (+), and HF C mass (+) in the 0-20cm and 20-40cm depths. The increase in total N appears to have led to more labile forms of N (i.e. LF) that may be more available to mineralization and uptake by the trees. This trend was similar to that reported by Zerpa et al. (2010), who found elevated levels of potentially mineralizable N (PMN) in the added treatment, and depressed PMN in the removed treatment. We suggest that the O-horizon and LF and HF N concentration and content of the 0-20 depth may be sensitive indicators of the soil's ability to provide resources, in particular N. Each of these parameters had a significant correlation with tree growth and showed a significant response to the treatments suggests that these parameters play a role in providing the tree with available N.

At age 15 there was no apparent effect of the treatments on available N as tested by the ion-exchange membranes, although NH_4-N concentration on the exchange resins from the 0-20 cm depth was near our critical value of $\alpha = 0.10$ and positively correlated with tree growth ($R=0.507$, $p=0.092$). Both ammonium and nitrate were positively correlated with root N ($R=0.705$, $p=0.010$ and $R=0.860$, $p<0.001$, respectively), suggesting that higher uptake rates are occurring in response to more available N. At age 10 Zerpa et al. (2010) found significantly higher nitrate availability in the A horizon of the added treatment while the removed treatments were not statistically different from the reference, suggesting that the effect of the added treatment was an early boost to available N that no longer exists or is below our detection limit at year 15.

Interestingly we found that exchangeable phosphate was significantly and positively correlated with stand productivity and it was found to be significantly lower in the removed treatments. Haywood and Burton (1989) found that loblolly pine plantations grown on the Ruston soil series had a positive response to P fertilization. This suggests that P may be co-limiting stand production with N. In general it appears that increased production in the added treatments was driven by higher nutrient availability in the soil. While there was no reduction in growth by the severe removal of organic matter there were some indications that it impacted soil resources negatively.

Differences in growth rates and productivity appear to have ceased at this stage in the stands' development. Zerpa et al. (2010) found significantly higher litterfall in the added treatment relative to the reference and removed treatments at age 10; however, at age 15 differences in litterfall between the treatments were less evident. All of the stands had reached crown closure and may have relatively equal amounts of leaf area which could be leading to similar litterfall production on all three treatments. Additionally, with identical planting densities, the canopies of all treatments should be similar. At age 10 Zerpa et al. (2010) found that litterfall had strong correlation ($R^2=0.940$) with stand volume; while, at year 15 no correlation was found. The convergence of growth rates could be a function of the current stand structure, convergence of limiting soil factors (e.g. nutrients or water), or both.

Phosphorus is commonly limited in southern pine plantations grown on old agriculture fields (Sanchez et al., 2006) particularly in much of the southern part of the Gulf Coastal Plain (Fox et al., 2011). Zerpa et al. (2010) found significantly higher levels of mineral soil extractable PO_4-P in the added treatment, but no significant differences between reference and removed treatments. Our findings were similar except that the exchangeable phosphate in the O-horizon of the added treatment was no longer different from the reference (but still different from the removed treatment), suggesting that PO_4-P availability was returning to some reference level for the added treatment. While not, measured in this study total P in the O-horizon may be increasing. Piatek and Allen (2001) concluded that the forest floor in mid-rotation loblolly pine stands is not a source of P but a possible sink. Zerpa et al. (2010) found that the O-horizon P content in the added treatment was more than double the reference (7.1 versus 18.2 kg ha^{-1} in the reference and added, respectively), while the removed treatment contained a similar amount of P in the O-horizon (6.8 kg ha^{-1}) as the reference. This is in contrast to N which was only 15% higher in the added and 37% lower in the removed treatments' O-horizon relative to the reference. These results support Piatek and Allen's (2001) conclusion that the O-horizon is a sink for P over the rotation of a stand. The convergence of growth rates could be affected by the sequestration of P in the O-horizon. This is supported by the lack of trends in foliar P concentrations.

Nitrogen immobilization by the heavy fraction may have also played a role in the convergence of the growth rates. The heavy fraction is thought to be a slower cycling pool of organic matter and a long-term pool of nutrients. The treatments manipulated of N in the O-horizon and harvest residues were approximately ±300 kg ha^{-1} (unpublished data). The HF N mass of the added treatment was 286 kg ha^{-1} greater than the reference, suggesting that 95% of the added N has been sequestered in the HF. Additionally, the HF N mass of the removed treatments was 321 kg ha^{-1} less than the reference, suggesting that this fraction may have contributed to the available nutrients during the early part of the stand's history. The HF does not appear to be as recalcitrant as thought, and appears to be playing a key role in moderating the effects of both organic matter manipulation treatments.

Even though many results are starting to converge onto reference levels, our results corroborate Zerpa et al. (2010) who suggested that higher bole volumes in the added treatment are a result of a fertilizer effect from the added nutrients. The added treatments' increased growth rate for a few years after treatment (<10 years) have since slowed to that of the reference at age 15. Most of this "fertilizer effect" appears to have come from an addition of N via the added organic matter, but there appears to also to have been some influence by P.

We have focused on the significant differences, which have mostly centered on the "fertilizer effect" of adding organic matter to a loblolly pine stand. More germane to the question of long-term soil productivity is the lack of a negative growth response to whole tree harvesting and O-horizon removal. There has been surprisingly little research on mechanisms behind the resiliency of stand productivity to a relatively extreme treatment such as slash and O-horizon removal. Initially, we hypothesized that if stand production is limited by nutrients then the addition or removal of those nutrients should result in equal but opposite responses to soils and site productivity. In this study we added and removed nutrients in the form of forest floor and harvest residues and our results pose a paradox of sorts in that adding organic matter resulted in a fertilization-like effect; however an equal *removal* of nutrients did not result in a corresponding decrease in stand productivity. The latter result has been shown across many sites (Powers et al., 2005; Ponder, 2008; Zerpa et al., 2010)

The process by which stand productivity resists change as a result of organic matter removal has been poorly explored. A release of nutrients by roots decaying at a faster rate has been hypothesized (Powers et al., 2005, and Sanchez et al., 2006). We suggest that an increases soil moisture and temperature immediately after the removal treatment (as seen by Li et al., 2003, Roberts et al., 2005) resulted in higher mineralization rates of labile pools of nutrients (including residual root systems) in the mineral soil of the removed plots as well as higher rates of nutrient retranslocation from senescing tissues.

Labile forms of organic matter have been observed to decrease after similar organic matter manipulations in other systems. Huang et al. (2011) found that the concentration of LF carbon in the surface mineral soil horizon can be reduced shortly after whole tree harvesting of radiata pine plantations. While not reported, there was probably a parallel response to the concentration of LF N in the surface mineral soil, suggesting that a stand may resist changes in growth if there is enough labile N in the mineral soil to compensate for the loss. Trees in nutrient limited soils tend to retranslocate nutrients from senescing tissue at a higher rate, so the removed treatment may have retranslocated N at a higher rate to compensate for the loss of N in the O-horizon and slash. And we did observe higher rates of N retranslocation on the removed plot relative to the reference and this trend was near our critical threshold of $\alpha=0.1$. However, Zerpa et al. (2010) did not observe any significant differences between the reference and removed stand foliar or litterfall N concentration at age 10, suggesting that higher rates of retranslocation may be a recent phenomenon. It is possible that the removed treatment stands are beginning to experience N limitation at mid-rotation as hypothesized by Ponder et al. (2008). There is much uncertainty around the factors that control the resiliency of stand productivity to organic matter removal and this is in need or further research to determine the long-term response of these stands to more intensive harvesting practices.

Most studies of organic matter removal have not examined a full post-treatment rotation. Helmisaari et al. (2011) studied whole tree harvesting of Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.) across Finland, Norway, and Sweden, and found an immediate reduction in growth after the initial treatment of many spruce stands; however reductions in growth in many Scots pine stands was not evident until the first thinning. The Nordic studies are some of the first of their kind, and it is unknown how widely these results may be applicable. Currently, many sites in the North American Long-Term Soil Productivity Experiment are approaching an age at which they may be thinned which typically occurs after crown closure. Since this stage in stand development is characterized by higher nutrient demands on the soil, the effect of O-horizon and harvest residue removal may reduce the growth rate of many stands as suggested by Ponder et al. (2008) and supported by Helmisaari et al. (2011). Crown closure and thinning may be an important turning point for the Long-Term Soil Productivity Experiments that have seen relatively little impact as a result of organic matter removal treatments.

5. Conclusions and Implications

The objective of this research was to assess changes in site productivity 14 years after organic matter manipulation by examining nutrient availability and soil C content. We found that organic matter additions acted as a fertilizer that increased stand bole volume, carbon at depth, and increased the amount of N in the system. Conversely, there did not appear to be significant reductions in below or above ground productivity as a result of severely removing the forest floor and harvest residues. Generally, whole tree harvest plus forest floor removal did not negatively impact site productivity or soil carbon compared to bole-only harvesting at least through year 15. The sites and soils appear to be resilient; however the persistence of these trends is unknown for the long-term as these sites undergo thinning or other forest management activities.

REFERENCES

APHA, AWWA, and WEF. 2005. Standard methods for the examination of water and wastewater. A. D. Eaton, L. S. Clesceri, E. W. Rice, and A. E. Greenberg (Eds.). (21st ed.). Washington, DC. pp. 1-22.

Bock, M. M. 2000. Mesodensity organo-clay association in near-shore sediment. Marine Geology 163: 65-75.

Burger, J. A., & Kelting, D. L. 1999. Using soil quality indicators to assess forest stand management. Forest Ecology and Management, 122(1-2), 155–166.

Burkhart, H. 1977. Cubic-foot volume of loblolly pine to any merchantable top limit Southern Journal of Applied Forestry. Southern Journal of Applied Forestry 1(2): 7-9.

EISA, Energy Independence and Security Act. H.R. 6. 110th Congress, 1st Session. 2007.

EPA. 1996. “Method 3052. Microwave assisted digestion of siliceous and organically based matrices. Revision 0. December 1996.U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C. In Test Methods for Evaluating Solid Wastes: Physical/Chemical Methods, EPA SW-846, Third Ed., Vol. I, Section A, Chapter 3 (Inorganic Analytes): 3052-1–3052-20.

Fisher, R. F., and D. Binkley. 2000. Ecology and Management of Forest Soils (3rd ed.). New York: John Wiley and Sons Inc.

Fox, T. R., B. W. Miller, R. Rubilar, J.L. Stape, T.J. Albaugh, E. Bünemann, A. Oberson, and E. Frossard. 2011. Phosphorus nutrition of forest plantations: The role of inorganic and organic phosphorus. Phosphorus in Action. Springer Berlin Heidelberg. 100: 317-338.

Hangs, R. D., K. J. Greer, and C. A. Sulewski. 2004. The effect of interspecific competition on conifer seeding growth and nitrogen availability measured using ion-exchange membranes. Canadian Journal of Forest Resources 34:754-761.

Haywood, J. and J. Burton. 1989. Phosphorus fertilizer, soils, and site preparation influence loblolly pine productivity. New Forests 3: 275-287. doi:10.1007/BF00030037.

Helmisaari, H.-S., Hanssen, K.H., Jacobson, S., Kukkola, M., Luiro, J., Saarsalmi, A., Tamminen, P., Tveite, B., 2011. Logging residue removal after thinning in Nordic boreal forests: Long-term impact on tree growth. Forest Ecology and Management 261, 1919-1927.

Homann, P.S., B.T. Bormann and J.R. Boyle. 2001. Detecting treatment differences in soil carbon and nitrogen resulting from forest manipulations. Soil Science Society of America Journal 65: 463-469.

Huang, Z., P.W. Clinton, M.R. Davis, and Y. Yang. 2011. Impacts of plantation forest management on soil organic matter quality. Journal of Soils and Sediments. 11: 1309-1316.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D.W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137, 253-268.

Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta analysis. Forest Ecology and Management 140, 227-238.

Keeney, D., Nelson, D., 1982. Nitrogen-inorganic forms. Methods Soil Anal. Part 2, 643–698.

Kenney, K.L., Smith, W.A., Gresham, G.L., Westover, T.L. 2013. Understanding biomass feedstock variability. Biofuels 4, 111-127.

Li, Q., H.L. Allen and C.A. Wilson. 2003. Nitrogen mineralization dynamics following the establishment of a loblolly pine plantation. Canadian Journal of Forest Research 33: 364-374.

Morris, L.A. and R.E. Miller. 1994. Evidence for long-term productivity change as provided by field trials. In: Dyck, W. J., Cole, D. W., & Comerford, N. B. (Eds.). Impacts of Forest Harvesting on Long-Term Site Productivity. Chapmand and Hall, London,. Pp 41-80.

Mulvaney, R., Sparks, D., Page, A., Helmke, P., Loeppert, R., Soltanpour, P., et al., 1996. Nitrogen-inorganic forms. Methods of soil analysis. Part 3-Chemical Methods, 1123–1184.

Nave, L.E., Vance, E.D., Swanston, C.W., Curtis, P.S., 2010. Harvest impacts on soil carbon storage in temperate forests. Forest Ecology and Management 259, 857-866.

NOAA. National Weather Service Forecast Office Birmingham, Alabama. NOWData, NOAA Online Weather Data. 2010. http://www.nws.noaa.gov/climate/xmacis.php?wfo=bmx date accessed 08/28/2011

O’Hehir, J.E. and Nambiar, E.K.S. 2010. Productivity of three successive rotations of P. radiata plantations in South Australia over a century. Forest Ecology and Management 259, 1857-1869

Piatek, K. B. and H. L. Allen. 2001. Are forest floors in mid-rotation stands of loblolly pine (*Pinus taeda*) a sink for nitrogen and phosphorus? Canadian Journal of Forest Research 31: 1164-1174.

Ponder, F. J. 2008. Nine-year response of hardwood understory to organic matter removal and soil compaction. Northern Journal of Applied Forestry 25: 25-31.

Ponder Jr, F., R.L. Fleming, S. Berch, M.D. Busse, J.D. Elioff, P.W. Hazlett, et al. 2012. Effects of organic matter removal, soil compaction and vegetation control on 10th year biomass and foliar nutrition: LTSP continent-wide comparisons. Forest Ecology and Management 278: 35-54. doi:http://dx.doi.org/10.1016/j.foreco.2012.04.014.

Powers, R. F., D. A. Scott, F. G. Sanchez, R. A. Voldseth, D. Page-Dumroese, and J.D. Elioff. 2005. The North American Long-Term Soil Productivity experiment: Findings from the first decade of research. Forest Ecology and Management 220: 31-50.

Richardson, B., Skinner, M. F., & West, G. 1999. The role of forest productivity in defining the sustainability of plantation forests in New Zealand. Forest Ecology and Management, 122(1), 125–137.

Roberts, S.D., C.A. Harrington and T.A. Terry. 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir seedling growth. Forest Ecology and Management 205: 333-350. doi:10.1016/j.foreco.2004.10.036.

Sanchez, F. G., and R. J. Eaton. 2001. Sequestering carbon & improving soils - benefits of mulching and incorporating forest slash. Journal of Forestry 99: 32-36.

Sanchez, F. G., A. E. Tiarks, J. M. Kranabetter, D. S. Page-Dumroese, R. F. Powers, and P. T. Sanborn. 2006. Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada. Canada Journal of Forest Resources 36: 565-576.

Scott, D.A., A. E. Tiarks, F. G. Sanchez, M. Elliott-Smith, and R. Stagg. 2004. Forest soil productivity on the Southern Long-Term Soil Productivity Sites at Age 5. In: Connor, K.F. (Ed.), Proceedings of the 12th Biennial Southern Silvicultural Research Conference. General Technical Report SRS-71. USDA Forest Service, Southern Research Station, Asheville, NC. 372–377.

Six, J., P. Schultz, J. Jastrow, and R. Merckx.1999. Recycling of sodium polytungstate used in soil organic matter studies. Soil Biology and Biochemistry 1193-1196.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/. Accessed August/21/2011.

Worrell, R., & Hampson, A. 1997. The influence of some forest operations on the sustainable management of forest soils — a review, Forestry 70(1).

Zerpa, J., H. Allen, R. Campbell, J. Phelan, and H. Duzan. 2010. Influence of Variable Organic Matter Retention on Nutrient Availability in a 10-year-old Loblolly Pine Plantation. Forest Ecology and Management 259: 1480-1489.

Table 1. Biomass pools and nutrient concentrations and contents of foliage, litterfall and roots in the upper 20cm of soil. P values are from an analysis of variance (ANOVA) using a general linear model on a completely randomized block design (CRBD); significant p values are in bold (α=0.10). Letters indicate similar subsets as determined by Tukey's HSD (a, b, c). Mean ± standard deviation.

	Added	Reference	Removed	*p*
Volume at age 10 (m^{3} ha^{-1})*	109±14^{a}	87±12^{b}	80±26^{b}	*0.013*
Volume at age 14 (m^{3} ha^{-1})	138.0±12.0^{a}	121.7±8.4^{ab}	110.8±24.9^{b}	*0.029*
Periodic Increment 2005-9 (m^{3} ha^{-1})	54.6±2.5	50.9±1.6	48.7±6.5	*0.147*
Litterfall mass (kg ha^{-1} yr^{-1})	4028.0±232.4	3501.6±378.1	3720.9±1181.5	*0.593*
Root mass 0-20cm (kg ha^{-1})	565.6±39.4	557.6±77.4	572.0±55.0	*0.930*
Foliar %N	1.40±0.34	1.38±0.26	1.20±0.20	*0.111*
Foliar %P	1.19±0.19	1.19±0.22	1.10±0.11	*0.671*
Litterfall %N	0.52±0.004^{a}	0.48±0.003^{b}	0.45±0.005^{c}	*<0.001*
Roots 0-20cm %N	0.52±0.06	0.43±0.04	0.45±0.07	*0.114*
Litterfall C:N	110.6±0.9^{a}	122.2±0.7^{b}	129.0±1.7^{c}	*<0.001*
Roots 0-20cm C:N	98.2±18.0^{b}	116.8±7.9^{ab}	109.6±12.9^{a}	*0.074*
Litterfall N mass (kg ha^{-1})	20.7±4.2	17.2±4.5	21.0±2.4	*0.181*
N Retranslocation (kg ha^{-1} yr^{-1})	35.0±11.0	26.7±6.0	31.7±11.2	*0.123*
Roots 0-20cm N mass (kg ha^{-1})	2.9±0.2	2.4±0.4	2.5±0.3	*0.260*

*from Zerpa et al. (2010)

Table 2. Soil carbon, nitrogen, and C:N ratio. P values are from an analysis of variance (ANOVA) using a general linear model on a completely randomized block design (CRBD); significant p values are in bold (α=0.10). Letters indicate similar subsets as determined by Tukey's HSD (a, b, c). Mean ± standard deviation

Horizon	Added	Reference	Removed	*p*
		Nitrogen (%)		
O-horizon	0.520±0.123^{b}	0.769±0.088^{a}	0.492±0.225^{b}	***0.044***
0-20cm	0.099±0.016	0.083±0.026	0.074±0.015	*0.261*
20-40cm	0.039±0.007	0.036±0.008	0.036±0.005	*0.748*
40-60cm	0.029±0.002	0.03±0.003	0.029±0.002	*0.952*
		Carbon (%)		
O-horizon	17.60±5.53^{b}	33.89±5.82^{a}	22.26±11.7^{ab}	***0.072***
0-20cm	2.12±0.65	1.61±0.74	1.30±0.42	*0.137*
20-40cm	0.72±0.23	0.45±0.17	0.46±0.13	*0.106*
40-60cm	0.45±0.08^{a}	0.29±0.09^{b}	0.30±0.04^{b}	***0.027***
		C:Nmolar		
O-Horizon	39.06±3.22^{b}	51.23±4.38^{a}	52.21±5.51^{a}	***0.018***
0-20cm	24.64±5.04	21.79±3.82	20.27±3.05	*0.132*
20-40cm	20.99±2.70^{a}	14.54±4.78^{b}	14.86±3.28^{b}	***0.051***
40-60cm	17.97±4.02^{a}	11.39±2.77^{b}	12.17±1.66^{b}	***0.013***

Table 3. Light (LF) and Heavy (HF) fraction total %N, %C, C mass, and N mass in soil horizons. P values are from an analysis of variance (ANOVA) using a general linear model on a completely randomized block design (CRBD); significant p values are in bold (α=0.10). Letters indicate similar subsets as determined by Tukey's HSD (a, b, c). Mean ± standard deviation

	Horizon	Added	Reference	Removed	*p*	Added	Reference	Removed	*p*
		Nitrogen (%)				Carbon (%)			
LF	0-20cm	0.94±0.07^{a}	0.72±0.07^{b}	0.60±0.16^{b}	***0.012***	38.98±2.17	37.18±3.93	34.75±5.44	*0.397*
	20-40cm	0.43±0.19	0.21±0.18	0.34±0.11	*0.162*	21.22±8.51	11.66±10.69	22.48±13.3	*0.408*
	40-60cm	0.14±0.13	0.24±0.28	0.07±0.04	*0.393*	6.59±5.23	11.98±16.17	4.78±4.18	*0.590*
HF	0-20cm	0.048±0.008^{a}	0.035±0.005^{b}	0.029±0.003^{b}	***0.016***	0.897±0.186	0.599±0.104	0.519±0.043	*0.130*
	20-40cm	0.03±0.009	0.022±0.006	0.021±0.005	*0.183*	0.391±0.167	0.264±0.07	0.257±0.044	*0.174*
	40-60cm	0.018±0.004	0.022±0.004	0.018±0.002	*0.153*	0.221±0.087	0.257±0.071	0.193±0.044	*0.562*
		Nitrogen content (kg ha^{-1})				Carbon content (Mg ha^{-1})			
LF	0-20cm	335.9±116.9^{a}	226.1±52.6^{ab}	163.1±66.4^{b}	***0.074***	13.93±4.82	11.62±2.89	9.62±4.41	*0.464*
	20-40cm	132.6±54.4	62.5±33	156.9±115	*0.327*	6.44±1.93	3.21±1.97	12±13.59	*0.395*
	40-60cm	80.3±42.4	94.8±94.4	54.3±45.3	*0.736*	4.22±3.19	4.36±4.09	3.7±4.13	*0.977*
HF	0-20cm	911.6±218.2^{a}	690.1±107.6^{ab}	539.1±50.3^{b}	***0.047***	17.15±4.64^{a}	11.75±2.14^{b}	9.8±0.76^{b}	***0.033***
	20-40cm	692.0±255.2	508.7±161.0	463.3±129.3	*0.268*	9.06±4.53	6.20±1.70	5.73±1.14	*0.245*
	40-60cm	507.5±119.0	625.9±96.2	500.7±60.7	*0.087*	6.36±2.43	7.47±1.93	5.44±1.15	*0.474*

Table 4. Molar C:N of light and heavy density soil fractions. Mean ± standard deviation

		Added	Reference	Removed	*p*
			C:N		
LF	0-20cm	51.4±9.7	60.7±9.2	70.4±19.6	*0.276*
	20-40cm	59.4±3.6	61.5±18.2	74.8±31.9	*0.438*
	40-60cm	57.1±18.8	69.0±30.4	74.6±26.6	*0.604*
HF	0-20cm	21.8±1.8	19.8±1.3	21.4±2.6	*0.195*
	20-40cm	14.8±2.4	14.4±2.4	15.1±3.9	*0.825*
	40-60cm	14.4±3.0	14.0±2.9	12.9±3.3	*0.820*

Table 5. Average extracted nutrients and hydrogen (mg m^{-2} resin strip). P values are from an Analysis of variance (ANOVA) using a general linear model on a completely randomized block design (CRBD); significant values are in bold (α=0.10). Letters indicate similar subsets as determined by Tukey's HSD (a, b, c). Mean ± standard deviation

	Horizon	Added	Reference	Removed	*p-value*
NH_4-N(mg m^{-2})	O	7.21±2.13	7.94±1.30	8.90±0.88	*0.435*
	0-20cm	11.74±4.00	6.89±0.74	9.24±1.64	*0.118*
NO_3-N (mg m^{-2})	O	2.10±1.50	1.49±0.37	1.79±0.25	*0.622*
	0-20cm	1.44±0.60	0.93±0.37	1.18±0.32	*0.397*
PO_4-P (mg m^{-2})	O	1.94±0.38^{a}	1.89±0.33^{a}	1.20±0.32^{b}	***0.038***
	0-20cm	1.31±0.52	1.44±0.63	0.72±0.31	*0.179*
H (mg m^{-2})	O	0.22±0.07	0.18±0.06	0.19±0.06	*0.665*
	0-20cm	0.19±0.10	0.11±0.01	0.15±0.02	*0.351*

Table 6. Pearson correlations of soil measurements and tree volume at age 15. * indicates significance at α=0.05 and ** indicates significance at α=0.001. n.m. = not measured. Abbreviations: WS = whole soil; LF = light fraction (< 1.64 g cm^{-3}); HF = heavy fraction (>1.64 g cm^{-3}).

Average Soil Temperature (year 15)	-.540
Average Soil Moisture Content (year 15)	-.211
Litter %N	**.750****
Litter Nitrogen Mass	.469
Foliar N	.238

Soil Horizon	**O**	**0-20**	**20-40**	**40-60**	**Total**
WS N (%)	.213	**.672***	.573	-.111	n.m.
WS C (%)	-.068	**.678***	**.789****	**.757****	n.m.
C:N	**-.708****	**.621***	**.751****	**.784****	n.m.
WS N Mass	**.809****	**.695***	.521	-.050	**.809****
WS C Mass	**.580***	**.703***	**.762****	**.759****	**.580***
LF N (%)	n.m.	**.769****	.524	.457	n.m.
LF C (%)	n.m.	.095	.051	.331	n.m.
LF C:N	n.m.	**-.671***	**-.588***	-.546	n.m.
LF N Mass	n.m.	**.686***	.065	.325	n.m.
LF C Mass	n.m.	.372	-.256	.125	n.m.
HF N (%)	n.m.	**.712****	.464	-.296	n.m.
HF C (%)	n.m.	**.767****	**.672***	-.092	n.m.
HF C:N	n.m.	.507	.503	.140	n.m.
HF N Mass	n.m.	**.718****	.472	-.274	n.m.
HF C Mass	n.m.	**.778****	**.656***	-.073	n.m.
Average NH_4^+-N	-.063	.507	n.m.	n.m.	n.m.
Average NO_3^--N	.256	.196	n.m.	n.m.	n.m.
Average PO_4^{-3}-P	**.577***	.260	n.m.	n.m.	n.m.

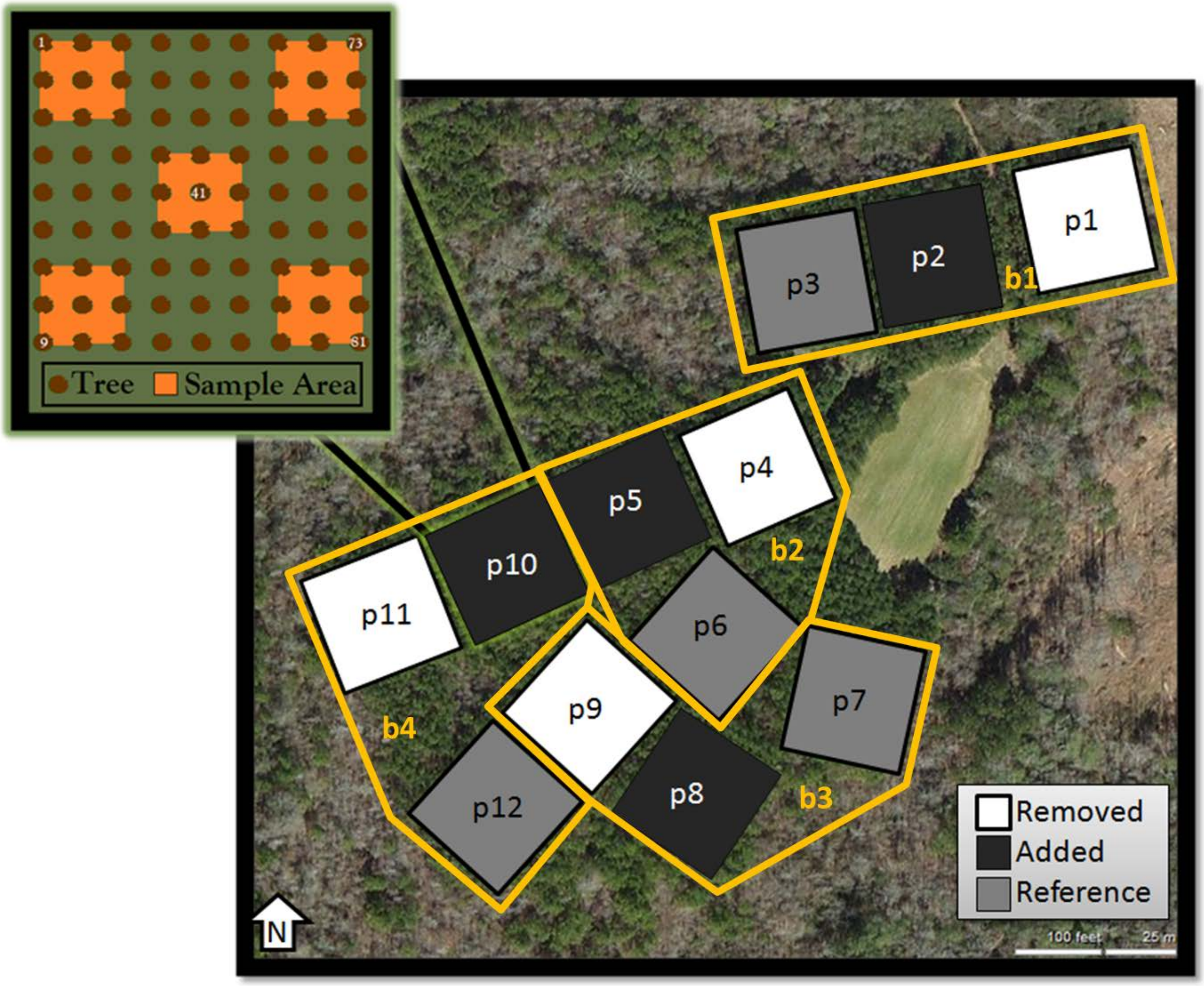

Figure 1. Treatment design of Millport Organic Matter Study.

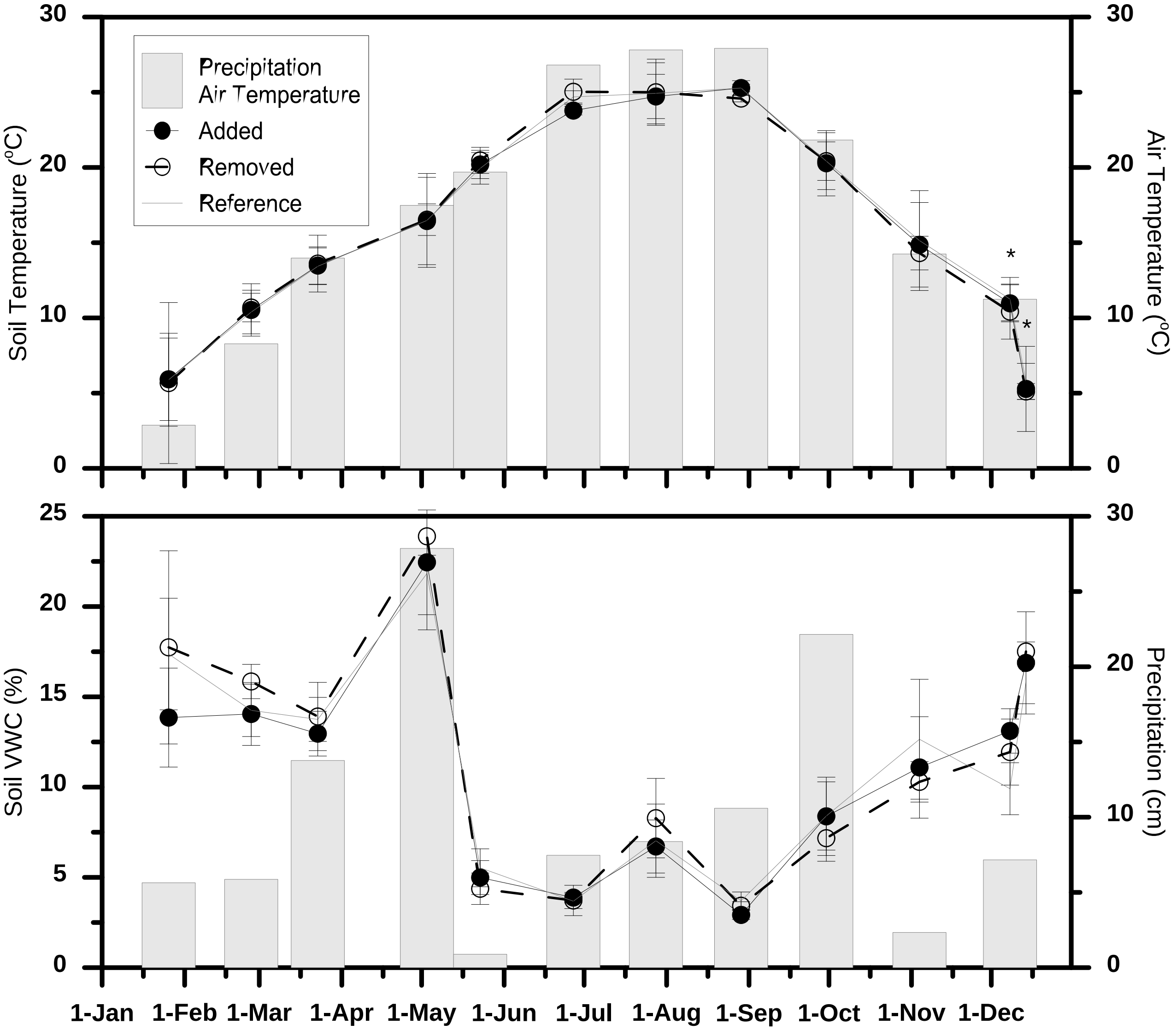

Figure 2. (top) Soil temperature (10cm depth) and monthly average air temperature taken from Columbus AFB (nearest weather station). (bottom) Soil moisture (Volumetric Water Content % to 10cm depth) and total precipitation between soil measurement periods from Columbus AFB (nearest weather station) from January 2011 to December 2011. *indicates periods when significant differences were detected among the treatments; however post-hoc testing found no significant difference among the treatments.

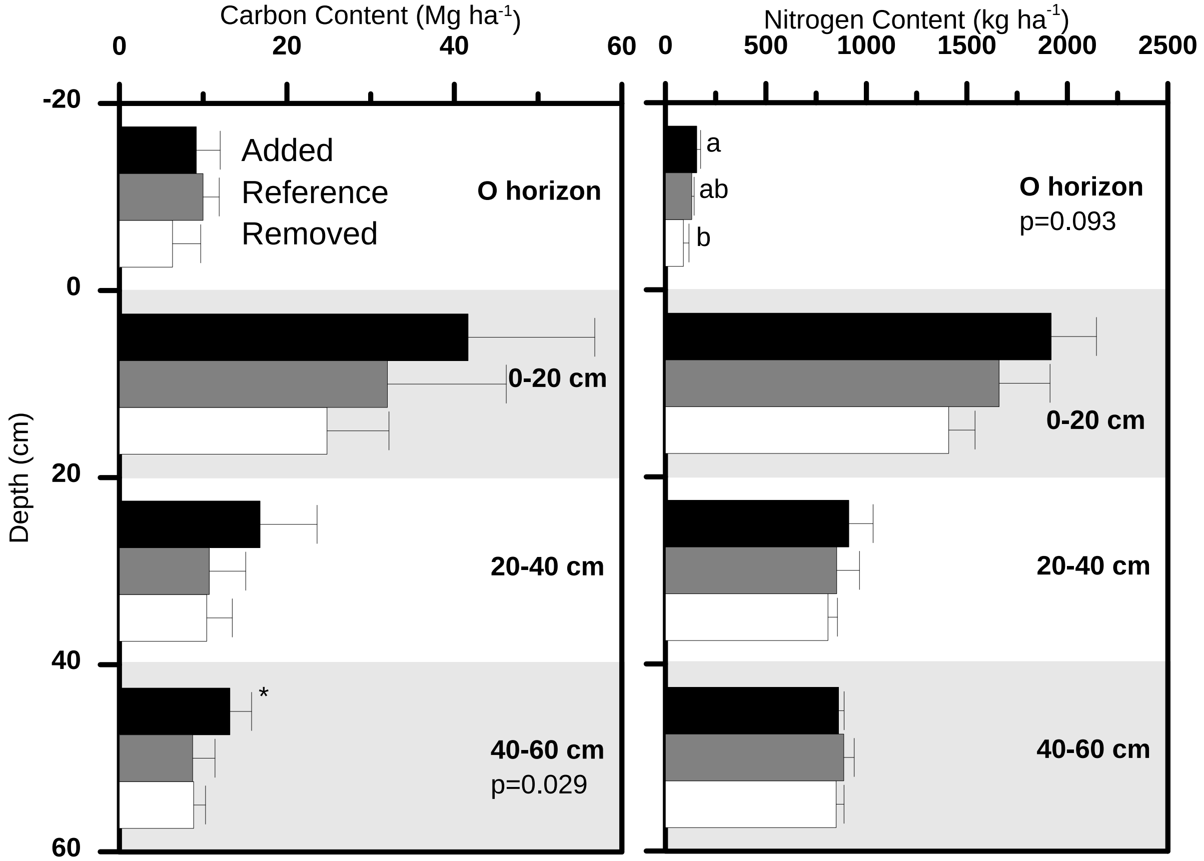

Figure 3. Carbon (left) and nitrogen (right) content of whole soils by depth. P values are from an analysis of variance (ANOVA) on a completely randomized block design (CRBD). Letters indicate similar subsets as determined by Tukey's HSD (a, b, c).

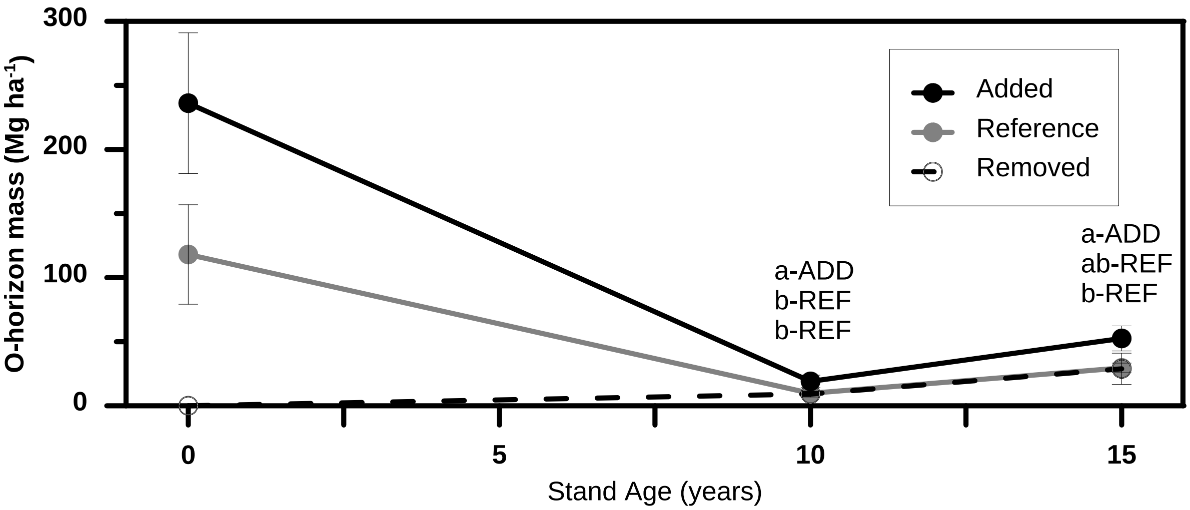

Figure 4. O-horizon mass over time. Error bars are standard deviations. Measurements from year 0 are from unpublished data from the 4 reference plots. The standard deviation of the added treatment from year 0 was calculated by propagating the error from the reference sites. No statistical test was possible on this data set. Year 10 data and the results of the statistical test are from Zerpa et al., (2010). Year 15 data and results of the statistical test are from this study.