Impacts of pine species, stump removal, cultivation, and fertilization on soil properties half a century after planting

J.R. Butnor, K.H. Johnsen, F.G. Sanchez, and C.D. Nelson

Abstract: To better understand the long-term effects of species selection and forest management practices on soil quality and soil C retention, we analyzed soil samples from an experimental planting of loblolly (*Pinus taeda* L.), longleaf (*Pinus palustris* Mill.), and slash (*Pinus elliottii* Engelm.) pines under different management intensities in Mississippi. The treatments included stump removal and cultivation (CULT), a one-time application of fertilizer combined with stump removal and cultivation (CULT+F), and a control (CON). After 49 years, pine species had no significant effect on any soil physical or chemical parameter examined, despite species differences in basal area. CULT exhibited significantly higher soil bulk density and lower soil C and soil N than CON and CULT+F in the upper 10 cm of soil. Stump removal is not a common practice in southern pine silviculture today; however, as demand for bioenergy fuels or feedstocks increases, more complete biomass utilization will be considered. Residual stumps play an important role in soil nutrient and C retention in pine plantations. Our results show that stump removal can lead to reduced soil C (–21%) and soil N (–35%) compared with controls, although it is possible to mitigate nutrient losses on poor sites with fertilization.

Résumé : Dans le but de mieux comprendre les effets à long terme du choix des espèces et des pratiques d'aménagement forestier sur la qualité du sol et la rétention du C, nous avons analysé des échantillons de sol provenant de plantations expérimentales de pin à encens (*Pinus taeda* L.), de pin des marais (*Pinus palustris* Mill.) et de pin d'Elliott (*Pinus elliottii* Engelm.) soumises à différentes intensités d'aménagement au Mississippi. Les traitements incluaient l'enlèvement des souches et des pratiques culturales (CULT), une application unique de fertilisant combinée à l'enlèvement des souches et à des pratiques culturales (CULT+F) et un traitement témoin (CON). Après 49 ans, les espèces de pin n'avaient pas d'effet significatif sur aucun des paramètres physiques ou chimiques du sol qui ont été étudiés malgré les différences de surface terrière entre les espèces. Dans les premiers 10 cm de sol, la densité apparente du sol était plus grande et la teneur en C et N du sol était plus faible dans le traitement CULT que dans les traitements CON et CULT+F. L'enlèvement des souches n'est pas une pratique courante de la sylviculture actuelle des pins du sud. Cependant, à mesure que la demande pour la biodiversité et les matières premières augmente, une utilisation plus complète de la biomasse sera envisagée. Les souches résiduelles jouent un rôle important dans la rétention de C et des nutriments dans le sol des plantations de pin. Nos résultats montrent que l'enlèvement des souches peut entraîner une diminution de C (–21 %) et de N (–35 %) dans le sol comparativement au traitement témoin bien qu'il soit possible d'atténuer les pertes de nutriments dans les stations pauvres par la fertilisation.

[Traduit par la Rédaction]

Introduction

Intensive silviculture is employed to enhance seedling survival, improve tree quality, and increase stand productivity. This may be through practices that improve site conditions for tree growth or in the selection of tree species that are well suited to the native conditions. While the focus is primarily on aboveground production, the long-term effects of silvicultural prescriptions on soil quality and soil nutrients will affect the productivity and sustainability of future rotations (Page-Dumroese et al. 2010). In southern pine plantations, cycles of afforestation followed by harvest can increase soil C over time (Johnson and Curtis 2001), but the nuances of specific practices to optimize resources and retain C continue to be studied. In nutrient-limited soils common across the Southeast (especially N and P limited), intensive management often includes fertilizer additions (Fox et al. 2007).

Loblolly pine (*Pinus taeda* L.) is very responsive to nutrient additions and easy to propagate and establish across a broad range of sites, so over the last several decades, it was planted widely across the region displacing slower growing

Received 29 November 2011. Accepted 11 February 2012. Published at www.nrcresearchpress.com/cjfr on 14 March 2012.

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Can. J. For. Res. **42**: 675–685 (2012) doi:10.1139/X2012-024 Published by NRC Research Press

pine species. For longleaf pine (*Pinus palustris* Mill.), problems propagating quality stock and slow early growth caused it to be disfavored as a plantation species in much of its historical range. Whether the selection of different southern pine species could influence soil properties is unknown, but possible mechanisms by which pine species could impact soil properties include resistance to disturbance (i.e., survive floods, hurricanes), rooting patterns, belowground allocation of C, wood density, and resistance to decay (Jandl et al. 2007). Longleaf pine has been thought to have a more developed tap root and commit more resources to belowground production than other southern pines, but this has not be confirmed with quantitative data.

Nutrient-poor sites are often characterized by tight cycling where the nutrients accumulated in biomass represent a significant proportion of the total in the system. Removal of biomass or addition of fertilizer can cause a marked shift in productivity (positive or negative). Annual fertilization of pine plantations typically results in net increases in soil C and N relative to unfertilized plots (e.g., Rafai et al. 2010). Single applications of fertilizer at planting can result in long-term gains in production, but enhancement of soil C is not always observed (Shan et al. 2001; Leggett and Kelting 2006). The capacity of soil to accumulate C and protect it from oxidation or leaching is largely a function of mineralogy, texture, and drainage class (Hassink et al. 1997). In conifer plantations, successive rotations of harvesting stems and replanting increase soil C (Johnson and Curtis 2001), although removal of stumps and the associated disturbance can diminish this response (Walmsley and Godbold 2010).

The purpose of this study was to quantify the effects of pine species selection, stump removal, cultivation, and fertilization implemented a half century ago on soil nutrient and physical properties, with a focus on soil fertility and C storage. The research was conducted on the Harrison Experimental Forest in southeast Mississippi.

Methods

Site and experimental design

The site (30.65′N, 89.04′W; elevation 50 m) is located 32 km north of Gulfport, Mississippi. The soils are variable but best described by the Poarch and Saucier series (coarse-loamy, siliceous, semiactive, thermic Plinthic Paleudults) and the Saucier–Susquehanna complex with well-drained upland, fine sandy loams and slopes from 1% to 4%. There was no prior history of agriculture on the site; the original naturally regenerated old-growth longleaf stand was cut around 1900 and again naturally regenerated. The experiment was established in 1960 after the longleaf pine stand was clearcut (Schmidtling 1973). Using a split-plot design with four blocks, the whole plots were randomly assigned one of three species (loblolly, longleaf, and slash (*Pinus elliottii* Engelm.) pines) and the split plots were silvicultural treatments of varying intensity. Blocks were located in well-drained, upland soils (1%–4% slope) conducive to pine silviculture; poorly drained draws and gullies where clay soils predominate were avoided. The five split plots are (*i*) no cultivation, fertilization, or stump removal, (*ii*) cultivated with no fertilization, (*iii*) cultivated with a single application (1×) of N (112 kg·ha^{-1}), P (56 kg·ha^{-1}), and K (56 kg·ha^{-1}), (*iv*) cultivated with a single application (2×) of N (224 kg·ha^{-1}), P (112 kg·ha^{-1}), and K (112 kg·ha^{-1}), and (*v*) cultivated with a single application (4×) of N (448 kg·ha^{-1}), P (224 kg·ha^{-1}), and K (224 kg·ha^{-1}). Cultivated plots were cleared of all stumps and slash, plowed, and then disked prior to planting. They were then disked three times each season for 3 years to reduce woody competition and then mowed in years 4 and 5. Fertilizer was applied with an agriculture spreader and disked into the soil 1 year after planting.

Seed sources, tree growth, and basal area determination

In February and March 1961, one hundred 1-year-old bare root seedlings were bar-planted with 3.05 m spacing in each square measurement plot (30.5 m × 30.5 m) enclosed by an additional two rows of buffer trees. Seedlings for the experiment were grown in a nursery using open-pollinated seed from local source parents that were classified by their measured wood specific gravity: high specific gravity and low specific gravity. High specific gravity or low specific gravity parentage had no significant effect on the specific gravity of the progeny (Clark and Schmidtling 1988), so the low specific gravity progeny plots were randomly selected for soil sampling and analyses. This design resulted in 60 subplots (three species, five treatments, four blocks). Although prescribed burning did occur prior to 1994, complete fire records are unavailable: since January 1994 (age 33 years), the study site has been burned in the dormant season in 1994, 1998, 2001, 2002, and 2003. Growth through 25 years (fall 1984) has been reported by Smith and Schmidtling (1970), Schmidtling (1973), and Clark and Schmidtling (1988). Hurricane Katrina struck the experiment in 29 August 2005 with sustained winds greater than 145 km·h^{-1} with peak gusts up to 225 km·h^{-1} (Kupfer et al. 2007). In December 2006, all trees in the measurement plots were rated with respect to damage from the storm (Johnsen et al. 2009) and the diameter at breast height of all living trees was recorded. Diameter at breast height just prior to the storm for killed trees was estimated by adjusting individual tree diameter at breast height growth from the 1999 survey by the average growth rate in that plot. This information was used to measure plot-level basal area (BA) in 2005 before and after the hurricane and quantify the BA lost during the storm.

Treatment effects reported earlier in the rotation

At age 9, intensive management increased productivity of all species; however, loblolly pine had greater height and volume than longleaf or slash pine. Yield differences between species in the highest fertilizer treatment were considerable: loblolly, 41 Mg·ha^{-1}; slash, 29 Mg·ha^{-1}; longleaf, 12 Mg·ha^{-1} (Schmidtling 1973). Twenty-four years after planting, cultivation alone had deleterious impacts on soil productivity, evidenced by significant reductions in organic matter, K, and Cu, but these reductions were mitigated by the fertilizer treatments (Schmidtling 1985). Data on N, C, and bulk density were not collected, making it difficult to identify any physical artifacts of treatments or understand differences in soil C storage, other than what could be inferred from soil organic matter content. By age 25, longleaf had surpassed both slash and loblolly pines in height in the control plots, characterized by low nutrient availability. At the highest level of intensity, loblolly pine was on average 2 m taller than the other two species (Schmidtling 1987). By age 39, longleaf pine attained similar height as loblolly pine across all treatments, although it lagged behind slash pine in height and diameter growth (Dr. John Kush, unpublished height and diameter survey, 1999). At age 45, Hurricane Katrina struck the plantation directly and longleaf pine suffered the least mortality followed by slash and loblolly pines, respectively (7%, 15%, and 26%) (Johnsen et al. 2009). Species-specific mortality caused by Hurricane Katrina shifted the mean BA across all treatments so that longleaf pine was now the greatest (23.4 $m^2 \cdot ha^{-1}$) followed by slash (19.4 $m^2 \cdot ha^{-1}$) and loblolly (12.4 $m^2 \cdot ha^{-1}$) pines. While this implies a greater resilience of longleaf pine on a nutrient-poor, hurricane-prone site (the stand has been impacted by a total of six hurricanes), little is known about the combined effects of pine species selection and forest management on long-term soil quality.

Soil heterogeneity

While considerable soil heterogeneity exists on this experimental forest site, its complexity is characteristic of land devoted to pine production in the region and several steps were taken to adequately characterize mean plot soil parameters: (*i*) statistical blocking, (*ii*) extensive subsampling to create composite samples for soil nutrient analysis, and (*iii*) extensive subsampling of unique samples (not composite) for soil bulk density determination. The statistical blocks were spatially based and were not determined by soil mapping a priori. Intraplot variation was constrained with subsampling and any block effects are incorporated into the error term.

Soil sampling and analysis

Considerable point to point soil heterogeneity exists at this site with Poarch fine sandy loam and Saucier fine sandy loam predominating and a lesser component of the Saucier–Susquehanna complex. To contend with this variability and adequately capture plot-level mean soil nutrient characteristics, extensive subsampling was used to within each 930 m^2 measurement plot. Twenty soil samples for C, N, and macronutrient analysis were collected along a diagonal transect at three depths (0–10, 10–20, and 20–30 cm) in each plot using a push-tube in March 2009. Subsamples (20) from each plot (60) and depth (three) representing a total of 3600 subsamples were thoroughly mixed to create composite samples. Prior to analysis, samples were air dried and sieved through a 2 mm screen to remove roots and break up aggregates. Total soil C and N concentrations were determined by dry combustion with detection by thermal conductivity (Carlo Erba NA 1500 Series II C/N/S analyzer (Fisons Instruments, Danvers, Massachusetts)). Soil macronutrients were determined by extraction with Mehlich III solution and analysis on a Thermo Jarrell Ash 61E Inductively Coupled Plasma spectrometer (Council on Soil Testing and Plant Analysis 1992). Carbon, N, and macronutrient concentrations were converted to content values scaled to mass per hectare using plot-level bulk density means collected the following year.

To adequately assess plot-level mean soil bulk density, samples were collected from 10 random locations at three depths (0–10, 10–20, and 20–30 cm) within each plot with a lined AMS soil sampler (American Falls, Idaho) in April 2010. Cylindrical samples 5 cm in diameter by 5 cm deep (98.17 cm^3) were collected from the upper portion of each depth increment and weighed after drying overnight at 105 °C. The samples were then corrected for root mass and volume. Each plot had 30 unique samples that were individually analyzed for a total of 1800 bulk density samples.

Statistical analysis

The effects of pine species and silvicultural treatments on soil properties and live-tree BA were tested with mixed model statistics (PROC MIXED, SAS version 9.10; SAS Institute Inc., Cary, North Carolina) using a randomized complete block design. In this mixed model design, any block effects are incorporated into error terms. Correlation analyses among growth and soil parameters were performed with PROC CORR. It is important to note that there are no plot-level data available on soil chemical or physical properties prior to treatment. The data were collected 49 years after treatment establishment. Ideally, comparisons would be made between pre- and post-treatment nutrient status; however, no reference soils are available for this experiment, limiting analysis to comparisons between species and silvicultural treatments at age 49.

Results and discussion

Treatment consolidation

No statistical difference in soil physical or chemical properties was observed between the three fertilizer treatments; to simplify presentation, they were combined into one treatment for analysis. Three treatments, control (CON), cultivated (CULT), and cultivated plus fertilizer (CULT+F), were used to describe the silvicultural treatments applied at the beginning of the experiment. It is likely that excess nutrients in the high-fertilizer treatments (2× and 4×) that were not captured by the trees or herbaceous cover or stabilized in the soil in the years after application were lost to runoff and leaching, diminishing the difference between rates applied.

Bulk density

There was no effect of pine species on soil bulk density, although silvicultural treatment was highly significant in the 0–10 depth interval (Table 1) and bulk density increased with soil depth (Fig. 1). Soils in the CON and CULT+F treatments were significantly less dense (0–10 cm only) than in CULT treatments 49 years after site establishment (Fig. 1). Cultivation is usually employed in forest site preparation to increase aeration (creation of macropores) and lower bulk densities; however, soil aggregates and associated macropores produced by tillage may have lower stability than those formed in undisturbed soils (Kasper et al. 2009), making them more prone to slaking during wet periods. Compaction from stump removal operations and erosion related to repeated cultivation during the first 3 years for weed control in CULT and CULT+F likely contributed to increased bulk densities. In the Pacific Northwest, stump removal after harvest has been used to reduce the incidence of root disease and protect the health of the next rotation. Consequently, a body of literature has developed on the impacts of stump removal on soil and plant productivity. Depending on soil texture (fine soils being more susceptible to compaction) and moisture conditions during and after stump removal, stump removal has been reported to have either no effect (e.g., Hope

Table 1. Mixed model *p* values for soil C, N, and bulk density collected from three depths in the 49-year-old species × culture study at the Harrison Experimental Forest (Saucier, Mississippi).

	C ($Mg \cdot ha^{-1}$)	N ($Mg \cdot ha^{-1}$)	Bulk density ($g \cdot cm^{-3}$)
Depth 0–10 cm			
$p > F$			
Species	0.9648	0.1635	0.6995
Treatment	0.0028	0.0013	0.0002
Species × treatment	0.0505	0.1595	0.1911
Depth 10–20 cm			
$p > F$			
Species	0.9003	0.8761	0.2410
Treatment	0.0201	0.9463	0.6066
Species × teatment	0.0149	0.1414	0.6989
Depth 20–30 cm			
$p > F$			
Species	0.4747	0.5004	0.6081
Treatment	0.7005	0.1140	0.4846
Species × treatment	0.6653	0.3975	0.8715

Fig. 1. Effect of treatment on mean soil bulk density (±SE). Depths shown are the midpoint of the depth increments sampled.

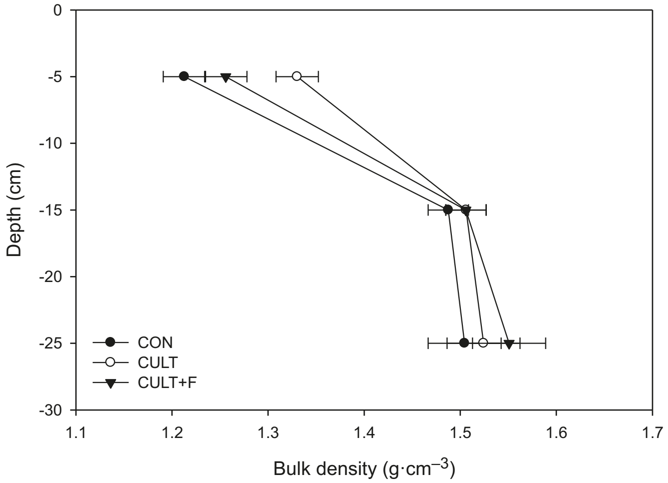
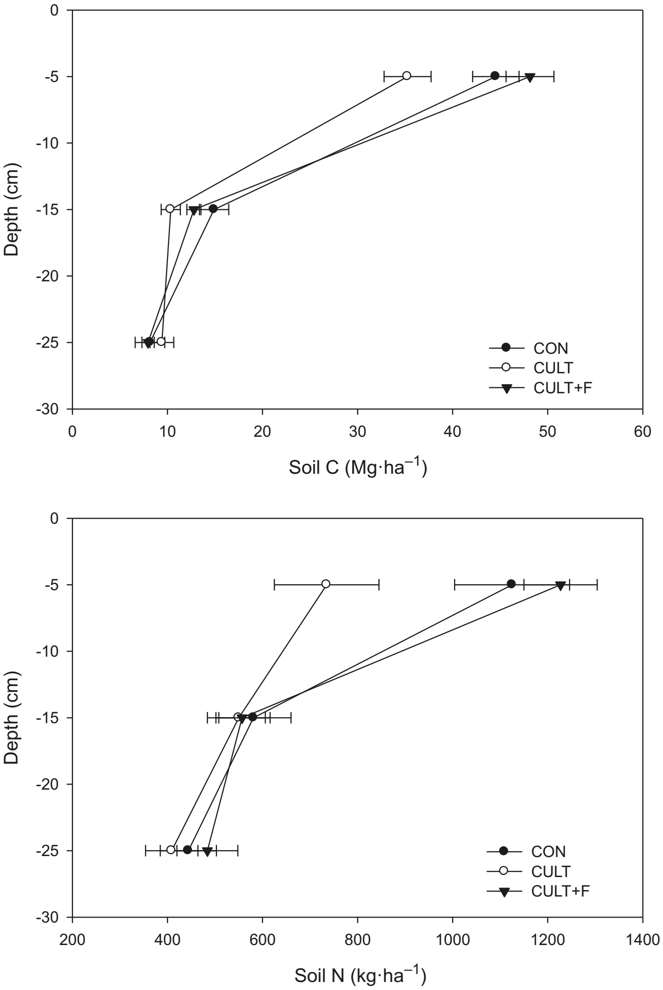


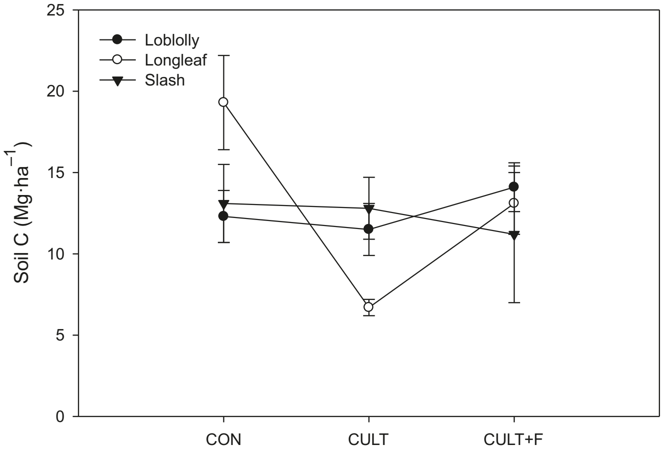
Fig. 2. Effect of treatment on mean soil C and soil N (±SE). Depths shown are the midpoint of the depth increments sampled.



2007) or minor increases in bulk density in the long term. On a site in northern Idaho on light volcanic soils, minor increases in bulk density were observed at 20–30 cm depth shortly after mechanical removal of stumps but did not impede root development (Page-Dumroese et al. 1998). In a region-wide assessment of long-term effects of stump removal in the Pacific Northwest, two out of five sites showed increased bulk density of approximately 6% 22–29 years after stump removal (Zabowski et al. 2008). Similar increases of 7% were reported 10 years after stump removal on a silty clay loam in mixed-species stand in Oregon (Thies et al. 1994). By comparison, our study showed the CULT bulk density was 10% higher than CON bulk density and CULT+F bulk density was 4% higher than CON bulk density in the upper 10 cm of soil 49 years after stump removal and cultivation. Significantly lower bulk density in CULT+F versus CULT could be related to amelioration by enhanced root proliferation and turnover in the more productive CULT+F treatment.

In addition to stump removal, the long-term effect of disking nine times in the first 3 years after planting likely contributed to the increased bulk density in the upper 10 cm of

Fig. 3. Species × treatment interaction plot for mean soil C (±SE) in the 10–20 cm depth interval.



soil. When soils are cultivated year after year, they become more dense than similar soils that remain as undisturbed prairie (Mudgal et al. 2010) or pasture land (Barral et al. 2007). It is notable that these effects could persist for 49 years in the present study. Cultivation likely decreased soil density initially, given fine-textured soils and high annual rainfall (1.65 m) at the Harrison Experimental Forest (Adams et al. 2003), but reduced soil aggregate stability eventually led to denser conditions via reconsolidation and (or) erosion compared with uncultivated soil (Kasper et al. 2009).

Soil C and N

As expected, soil C and N both decreased with soil depth (Fig. 2). There was no significant effect of species on soil C or N at any depth (Table 1). Soil C in CULT was significantly lower than in CON or CULT+F in the 0–10 and 10–20 cm depths. Removal of stumps at establishment and subsequent disking for 3 years after planting may have broken up coarse root systems in CULT and CULT+F, effectively removing or degrading a significant portion of the C from the previous stand. Soil C in CULT was 21% lower than in CON and 27% lower than in CULT+F in the upper 10 cm. Application of fertilizer 1 year after establishment in CULT+F mitigated any C lost to removal and mechanical disturbance, possibly through increased fine-root production and subsequent turnover, channeling more C into the near-surface soil (King et al. 2002).

There was a significant species × treatment interaction for soil C in the 10–20 cm depth interval (Table 1). The interaction plot (Fig. 3) showed that longleaf pine had higher soil C accumulation in CON and lower soil C in CULT, creating an interaction with treatment but not a significant species effect. Soil N was significantly lower in CULT than in the other treatments in the 0–10 cm depth (Table 1; Fig. 2). Similar to the pattern observed with soil C, soil N in CULT was 35% lower than in CON and 40% lower than in CULT+F. In the case of CON, this highlights the value of leaving debris and root systems and minimizing soil disturbance. The lasting impact of a single fertilizer application on cultivated plots is remarkable; 49 years after planting, there is 492 kg·ha^{-1} more N and 12.9 Mg·ha^{-1} more C on CULT+F than on CULT plots.

Harvesting operations may increase soil C and N accumulation over time in conifer stands; meta-analyses by Johnson and Curtis (2001) reported these gains to average approximately 20%–25% for conifers, while mean losses were reported for hardwood and mixed stands. Building on this concept, the completeness of tree removal, whether sawlog, whole-tree (aboveground only), or complete-tree removal (above- and belowground), is not thought to significantly affect soil C contents in southern pine systems; soil C contents recover quickly after disturbance. A comparison of sites in North Carolina, South Carolina, and Tennessee found no difference in soil C between sawlog and whole-tree removal 15–16 years after harvest and no difference in soil C between whole-tree and complete-tree removal at a site in Florida (Johnson et al. 2002). Site preparation for CULT and CULT+F treatments was essentially a complete-tree harvest and we observed declines in C and N. The meta-analysis by Johnson and Curtis (2001) did not include recent stump removal studies where declines in nutrients have been observed (Zabowski et al. 2008; Walmsley and Godbold 2010). There is growing concern that stump removal for enhanced fuel wood extraction will lead to increased CO_2 emissions and reduced soil C in northern Europe, limiting the ability of forests to produce renewable energy and wood products (Jarvis et al. 2009). While stump removal for bioenergy fuels or feedstocks is not common in the southern United States, the observations from the present study show that the practice can lead to reduced soil C compared with controls 49 years after implementation. These results are controversial and run counter to observations in other southern pine plantations (e.g., Johnson et al. 2002). It should not come as a surprise that overextraction of biomass via stump removal and its associated disturbance led to a lower soil C content as compared with controls on this low-fertility site. The lack of pre-treatment soil C data precludes a better understanding of quantitative change in soil C over the 49-year rotation.

Stump removal and cultivation as employed to establish CULT and CULT+F treatments had a strong impact on bulk density, soil C, and soil N. In hindsight, it would have been useful to create an uncultivated, fertilized treatment with stumps left in place to test whether the addition of fertilizer with the disturbance and biomass removal would have pushed soil and tree productivity beyond what is observed in CULT+F. The experimental design did not allow separation of fertilizer effects from stump removal and cultivation. Soil in the vicinity of decaying stumps is high in C, N, and extractable ammonium and nitrate (Sucre and Fox 2009) and trees growing near these stumps can benefit from increased productivity (Van Lear et al. 2000); it would be interesting to know if fertilizer amendments would have additive effects on pine production and soil nutrient contents. Despite these complications, the contrast of presence of old stumps (CON), removal of stumps (CULT), and mitigation of nutrient losses by fertilization (CULT+F) illustrates the contribution of residual root systems to nutrient cycling between rotations.

Soil macronutrients and pH

Pine species had no effect on soil pH or any soil macronutrient analyzed in this study (Table 2). Treatment had no effect on pH at any depth. In the upper 10 cm of soil, K was

Table 2. Effect of species and treatment on soil chemistry and associated mixed model p values.

	pH	P (kg·ha^{-1})	K (kg·ha^{-1})	Mg (kg·ha^{-1})	Ca (kg·ha^{-1})
Depth 0–10 cm					
Species					
Loblolly pine	4.31±0.04	7±1	112±6	93±8	323±26
Longleaf pine	3.98±0.37	5±1	90±11	72±8	245±25
Slash pine	4.32±0.03	6±1	104±6	77±3	294±15
Treatment					
CON	4.32±0.04	5±1	100±7ab	80±4	292±16
CULT	3.99±0.36	6±1	91±11a	76±11	259±31
CULT+F	4.31±0.03	7±1	115±4b	87±3	311±11
$p > F$					
Species	0.5189	0.4245	0.2501	0.1976	0.1774
Treatment	0.4692	0.4917	0.0452	0.4187	0.2630
Species × treatment	0.4473	0.6945	0.1438	0.3280	0.5728
Depth 10–20 cm					
Species					
Loblolly pine	4.55±0.04	6±1	111±11	90±11	268±18
Longleaf pine	4.54±0.04	5±1	106±7	88±12	267±17
Slash pine	4.59±0.06	6±1	99±9	78±5	264±14
Treatment					
CON	4.55±0.05	5±1	87±7	67±4a	230±12a
CULT	4.53±0.06	6±1	114±12	103±14b	290±19b
CULT+F	4.60±0.02	6±1	114±6	86±4b	278±10b
$p > F$					
Species	0.7798	0.7274	0.6816	0.6344	0.9831
Treatment	0.5681	0.7721	0.0638	0.0283	0.0121
Species × treatment	0.4491	0.0315	0.6973	0.5261	0.2932
Depth 20–30 cm					
Species					
Loblolly pine	4.43±0.15	5±1	121±11	132±21	393±38
Longleaf pine	4.66±0.06	6±1	114±7	142±26	367±30
Slash pine	4.54±0.04	6±1	116±11	117±13	364±57
Treatment					
CON	4.62±0.07	5±1	98±10	109±12	316±20
CULT	4.63±0.05	6±1	129±10	163±30	442±67
CULT+F	4.40±0.13	6±1	123±5	118±8	359±22
$p > F$					
Species	0.4011	0.9013	0.8765	0.7356	0.9446
Treatment	0.0837	0.7011	0.0637	0.1130	0.0890
Species × treatment	0.2531	0.2197	0.9067	0.7351	0.8552

Note: For each depth increment, means (±SE) within a column followed by the same letter are not significantly different at the $\alpha \leq 0.05$ level.

significantly higher in CULT+F than in CULT but not different than in CON (Table 2). In the 10–20 cm depth, Mg and Ca were lower in CON than in the cultivated plots. Whether these treatment differences are biologically important to the trees in the plantation is debatable. These differences may be a legacy of plantation establishment or early growth patterns of the pines. The rate of pine biomass accumulation was much higher in the cultivated treatments, which may have enabled them to retain mobilized nutrients that were lost to leaching in CON (Pritchett and Wells 1978).

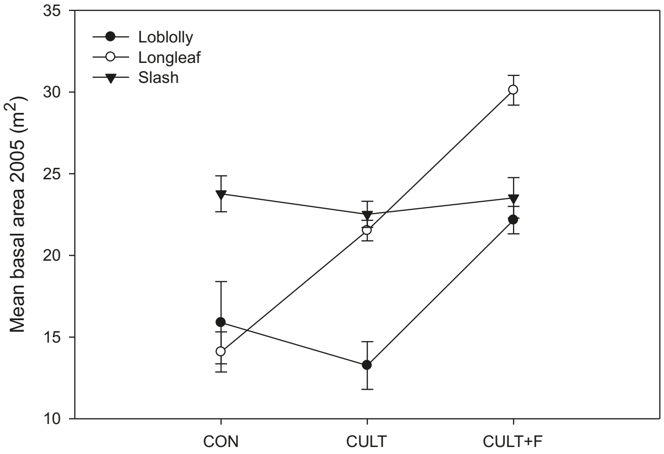
In 1983, soils were collected from 0 to 25 cm and analyzed for soil macronutrients (P, K, Mg, and Ca) and reported as treatment means for loblolly and longleaf pines only (Schmidtling 1985). These data were recalculated from parts per million to kilograms per hectare (using 2009 mean bulk density from 0 to 20 cm) to permit direct comparison with soil macronutrient data collected in 2009 (Table 3). Although we were unable to statistically analyze the significance of the change over time, minor losses in P were noted (–5%) as were large percentage increases in K (+103%), Mg (+69%), and Ca (+263%). At age 24, differences in soil chemistry between treatments were not considered large enough to explain differences in growth (Schmidtling 1985). Schmidtling (1985) concluded that the cultivated and fertilized plots contained larger total quantities of nutrients, both within the trees and recycling through litterfall, and this explained the continued response to fertilizer at age 24. Now at age 49, after years of storm damage, recent tree mortality, and repeated cycles of understory growth followed by prescribed fire, macronutrients (with the notable exception of P) are accumulating in the soil. It is difficult to determine whether the soil nutrient levels are limiting pine growth; most limitation mod-

Table 3. Comparison of soil pH and soil macronutrients collected in 1983 and 2009.

	pH	P (kg·ha^{-1})	K (kg·ha^{-1})	Mg (kg·ha^{-1})	Ca (kg·ha^{-1})
1983					
Treatment					
CON	4.78	10	100a	94	131
CULT	4.84	11	95a	111	170
CULT+F	4.74	14	115b	100	154
Mean	4.79	12	103	102	152
2009					
Treatment					
CON	4.42	12	190	151	528
CULT	4.17	9	211	188	539
CULT+F	4.45	13	227	176	587
Mean	4.34	11	209	172	551
% change from 1983 to 2009					
Mean	–9	–5	+103	+69	+263

Note: Values are means of loblolly and longleaf pines (slash pine was omitted from the 1983 set). The 1983 data are recalculated from Schmidtling (1985) using bulk density values from 2009; the samples were collected from 0–25 cm depths but were scaled to 0–20 cm for direct comparison of data collected in 2009 (0–20 cm). It was not possible to statistically analyze data between years. Within years, means within a column followed by the same letter are not significantly different at the $\alpha \leq 0.05$ level.

Fig. 4. Species × treatment interaction plot for mean basal area (±SE) prior to Hurricane Katrina in 2005.



els use foliar nutrient content instead of soil nutrient content (e.g., Valentine and Allen 1990). Comparing soil P with criteria developed by Wells et al. (1973), P is not severely limiting to loblolly pine growth at this site compared with other Coastal Plain soils but would likely get a growth response from P additions.

Relation of applied treatments to current silvicultural practices

Mechanical site preparation techniques and recommendations are varied but are usually intended to ameliorate soil drainage or compaction issues or reduce woody competition. On poorly drained sites, subsoiling or bedding can increase longleaf pine growth (Knapp et al. 2006). On well-drained sites, as in the current study, stump shearing and windrowing of debris combined with herbicide and prescribed fire are recommended for competition control. Areas with considerable hardwood competition may also be drum chopped and burned prior to planting (Boyer 1988). The site preparation used in CULT and CULT+F (stump removal, plowing, repeated cultivation for weed control) caused far more soil disturbance than practices used today. The value of these results is not so much in their direct applicability to current practices but in understanding the negative impact of stump removal and soil disturbance and the ameliorative effects of fertilization and tree productivity on highly disturbed sites. The contribution of belowground biomass from the prior rotation to soil quality and the hazards of disturbing this material become apparent when treatments such as these are monitored over time.

Current recommendations for fertilization of southern pine plantations are usually based on tests for soil or foliar deficiencies and the management goals (short rotation, sawlog production, or pine straw). On P-deficient southern pine plantations, P additions (45–55 kg·ha^{-1}) are applied prior to planting and have positive responses that last from 15 to 20 years (Moorhead 1998). After a harvest, N and P mineralization rates increase and soils usually have sufficient nutrient availability for young trees. Fertilization with N and P is performed when trees are 5–10 years old and repeated as needed every 5–7 years or after a thinning (Moorhead 1998). While soil and foliar nutrient testing is widely available allowing for highly customized prescriptions, Moorhead (1998) recommended midrotation N additions ranging from 170 to 225 kg·ha^{-1} combined with 28–56 kg·ha^{-1} of P and additions of up to 56 kg·ha^{-1} of K depending nutrient analysis. The fertilizer applied 1 year after planting in the 2× treatment (N (224 kg·ha^{-1}), P (112 kg·ha^{-1}), and K (112 kg·ha^{-1})) was similar to what would be recommended for a midrotation application today. Appling fertilizer 1 year after planting had lasting effects on tree growth and soil C and N but was likely inefficient, for it was applied when young trees were less able to capture it.

Pine BA

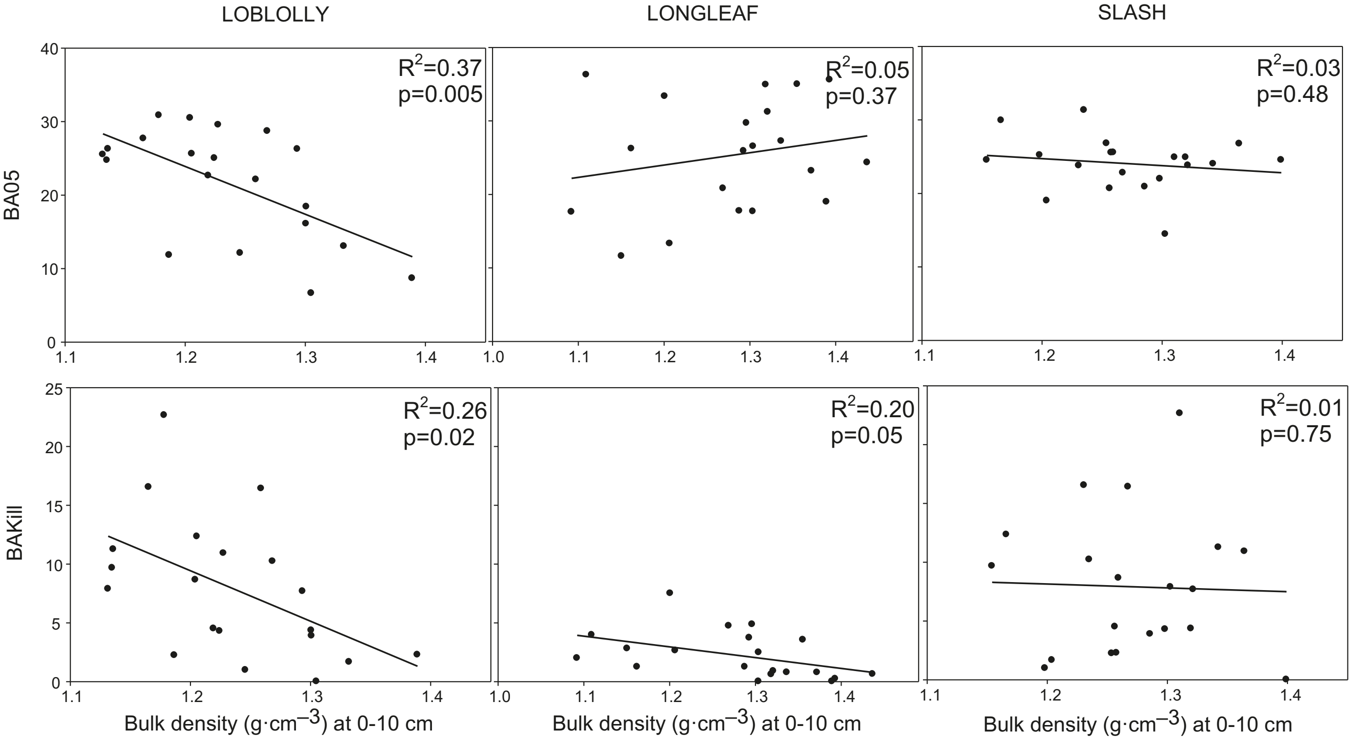
Soil quality and fertility drive productivity, especially in aggrading plantings that have developed under standardized site preparation. Using both high and low specific gravity plots from the entire experiment, there were statistically sig-

Table 4. Linear correlation (r) between pine basal area in 2005 (BA05) prior to Hurricane Katrina and pine basal area killed during Hurricane Katrina (BAKill) on 29 August 2005 with soil variables in the upper 10 cm.

	n		C	N	Bulk density	Mg
All species	60	BA05	0.28303	0.21331	–0.06932	0.13422
			0.0284	0.1017	0.5987	0.3108
		BAKill	0.14261	0.3643	–0.40432	0.00697
			0.277	**0.0042**	**0.0014**	0.9582
Loblolly pine	20	BA05	0.26932	0.44044	–0.60349	0.011
			0.2509	**0.050**	**0.0048**	0.9633
		BAKill	0.47421	0.48773	–0.50817	–0.0392
			0.0347	**0.0291**	**0.0222**	0.8697
Longleaf pine	20	BA05	0.4942	0.242	0.21225	0.48844
			0.0268	0.304	0.369	**0.0338**
		BAKill	0.30736	0.32851	–0.44445	–0.39916
			0.1874	0.1573	**0.0496**	0.0905
Slash pine	20	BA05	–0.19956	0.09367	–0.16647	0.1226
			0.3989	0.6945	0.483	0.6066
		BAKill	–0.23807	–0.06702	–0.07458	–0.24368
			0.3121	0.7789	0.7547	0.3005

Note: Pearson correlation coefficients and associated p values were calculated using all 60 plots. No significant correlations were found at the 10–20 or 20–30 cm depth intervals or for soil pH, P, K, or Mg. p values significant at the $\alpha \leq 0.05$ level are in bold type.

Fig. 5. Linear regression of plot-level mean basal area in 2005 (BA05) and basal area killed by Hurricane Katrina (BAKill) with soil bulk density by pine species.



nificant effects of treatment (F = 19.05, p < 0.0001) and species (F = 11.51, p = 0.0088) on mean plot BA in 2005 prior to Hurricane Katrina as well as a significant species × treatment interaction (F = 7.95, p = 0.0007). The interaction of species and management intensity is explained by very different species responses to the treatments. Before Hurricane Katrina struck in 2005, longleaf pine exhibited a stepwise increase in BA with silvicultural intensity, slash pine BA was the same across all treatments, and loblolly BA in CON and CULT was lower than in CULT+F (Fig. 4). Comparing the low mean BA in longleaf CON (Fig. 4) may seem incongruous with the high soil C contents observed for longleaf CON (Fig. 3), but the herbaceous and understory shrubs are also contributing to soil C inputs. At age 12, herbaceous biomass (kilograms per hectare) was 2–4 times higher in CON (CON, 1043; CULT, 463; CULT+F, 272) and browse crown area (square metres per hectare) was 4–14 times higher in CON (CON, 2488; CULT, 175; CULT+F, 559) than in the other treatments (Wolters and Schmidtling 1975). The soil C and nutrient pool data at age 49 reflect the long-term impact of site preparation and fertilization as well as the cumulative response of both the planted pine and naturally regenerated understory vegetation. The focus of this study was the effect of species and silvicultural intensity on soil quality and not the nuances of soil and pine productivity per se. Ongoing studies will address biomass accumulation, C allocation, and nutrient storage in live trees.

Correlations between soil variables, pine BA, and pine BA killed by Hurricane Katrina

As evidenced by change in BA, Hurricane Katrina's winds damaged longleaf pine (–2.1 $m^2 \cdot ha^{-1}$) less than slash pine (–4.3 $m^2 \cdot ha^{-1}$) or loblolly pine (–7.2 $m^2 \cdot ha^{-1}$); treatment and species × treatment interactions were not significant (Johnsen et al. 2009). Species differences in mortality from hurricane winds were not a function of mean plot tree height or density, indicating that longleaf pine is more resistant to wind damage than either slash or loblolly pine (Johnsen et al. 2009).

The samples for soil chemistry were collected 3.5 years after the damage caused by the hurricane. It is difficult to separate cumulative effects of biomass accumulation over the first 45 years of the study from the sudden input of downed material, the death and decomposition of root systems, and the loss of function from trees that perished in the hurricane (loblolly pine, 26% mortality; slash pine, 14% mortality; longleaf pine, 7% mortality (Johnsen et al. 2009)) from the tree production. Using all pine species, BA in 2005 (BA05) and the BA killed (BAKill) were regressed to soil parameters by depth ($n = 60$). Significant correlations were only found in the upper 10 cm of soil in the relationships of BA05 and soil C, BAKill and soil bulk density, and BAKill and soil N (Table 4). Given the treatment × species interactions in Fig. 4, the correlation analyses were also run by species and depth ($n = 20$). There were no significant correlations with slash pine but some interesting correlations with loblolly and longleaf pine BA05 and soil variables in the upper 10 cm increment. Loblolly BA05 was negatively correlated with soil bulk density and positively correlated with soil N. Keeping in mind that these are simple correlations that cannot reveal cause and effect, the negative relationship between loblolly BA05 and soil bulk density could relate to bulk density inhibiting pine growth or conversely the lower pine productivity and root development are not "loosening" the compacted soils (or some combination of these two scenarios). Longleaf BA05 was positively correlated with both soil C and soil Mg (Table 4). At age 24, annual litterfall in longleaf pine was more than double that of loblolly pine (Schmidtling 1985). If this was a consistent pattern over the subsequent years, it might have contributed to increased soil C from enhanced litter inputs. There is not a precedent in the literature comparing litterfall between these species while holding other stand variables constant (i.e., stem density, BA). Soil bulk density was inversely correlated with the amount of BA lost in loblolly and longleaf pines.

When BA05 and BAKill are plotted against bulk density by pine species (Fig. 5), it does not appear that higher bulk density is conveying any protection against hurricane mortality in loblolly pine. BA05 and BAKill both follow the same trajectory; at the highest bulk density, there is the least BA05 and the least BAKill. There is some weak evidence that longleaf mortality is lower on denser soils, since there is no significant correlation between bulk density and BA05, but there is a negative relationship between bulk density and BAKill, although the slope is less steep than that observed in loblolly pine. Considering the large loss of loblolly BA, the correlation with soil C and soil N in the upper 10 cm of soil 3.5 years after the hurricane seems logical; the most recent inputs (from aboveground and belowground necromass) were observed in the 0–10 cm depth.

Conclusions

Effects of intensive silviculture, including stump removal, cultivation, and one application of fertilizer, had lasting effects on soil physical and chemical properties as well as pine biomass 49 years after establishment. Stump removal and subsequent disking for weed control increased bulk density in the upper 10 cm of soil. Relative to controls, cultivation (and stump removal) reduced both soil C and soil N, while application of fertilizer mitigated these losses. There were no interactions between pine species and any soil physical or chemical parameter, although species did influence the relationship between BA and some soil parameters. Stump removal is not a typical practice in southern pine silviculture today; however, as demand for bioenergy fuels or feedstocks increases, more complete biomass utilization may be considered. Our results show that this practice can lead to reduced soil C compared with controls 49 years after implementation on a nutrient-deficient site. If it is necessary to conduct whole-tree harvests or use intensive mechanical site preparation to increase survival of planted pines, fertilization may be needed to maintain soil fertility on nutrient-poor sites. While the ameliorating effects of fertilizer can be very longlasting, minimizing soil disturbance during site preparation by using fire and (or) herbicide to reduce competition and leaving root systems undisturbed may prevent long-term negative impacts on bulk density, soil C, and soil N.

Acknowledgements

We would like to thank Peter Anderson, Joel Burley, Thomas Christensen, Robert Eaton, Larry Lott, and Karen Sarsony for their experienced assistance in the field and laboratory. We appreciate and value the efforts made by Dr. Ronald Schmidtling (US Forest Service, retired) to document the species response to intensive management over the years and providing us with a quality long-term forest experiment to study.

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