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Soil Ecosystem Services in Loblolly Pine Plantations 15 Years after Harvest, Compaction, and Vegetation Control

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Site productivity has long been identified as the primary ecosystem service to be sustained in timberlands. However, soil C sequestration and ecosystem biodiversity have emerged as critical services provided by managed forest soils that must also be sustained. These ecosystem services were assessed in response to gradients of organic matter removal, soil compaction, and noncrop vegetation control on the thirteen 15-yr-old sites of the international Long-Term Soil Productivity (LTSP) study located in North Carolina, Mississippi, Louisiana, and Texas in the Atlantic and Gulf coastal plains of the southern United States. Whole-tree harvesting without removing the forest floor reduced tree volume at one site while removing the forest floor to achieve maximum nutrient removals reduced stand volume by 7% overall. Conversely, soil compaction increased pine volume production by 10% overall. Vegetation control increased pine stand volume production by 46% overall. Mineral soil C storage in the surface 0.3 m was similar overall regardless of treatment. Soil compaction and organic matter removal did not alter overall woody species richness or Shannon's Index of diversity. Overall, these results suggest that biomass harvesting and intensive organic matter removal from southern pine stands has limited and site-specific effects on three soil ecosystem services: timber volume production, mineral soil C storage, and woody plant diversity.

Abbreviations: C0, no soil compaction; C1, moderate soil compaction; C2, severe soil compaction; DBH, diameters at breast height; H0, no herbicide; H1, multiple herbicide applications; LTSP, Long-Term Soil Productivity; OM0, bole-only organic matter removal; OM1, whole-tree harvest organic matter removal; OM2, whole-tree harvest plus forest floor organic matter removal.

Forest site productivity has for many years been defined as the maximum volume or biomass of wood produced on a piece of land in a given period of time, and soil productivity is the ability of a soil to produce wood volume for a given species or set of species within a specific climate region. Foresters, ecologists, and soil scientists recognize that forests and other ecosystems provide more than timber or plant biomass (Wilde, 1958). Timber productivity has been a useful standard measure of soil productivity, but it must be expanded as society recognizes the importance of other ecosystem services.

Ecosystem services can be broadly categorized into four groups: (i) supporting (e.g., nutrient cycling and productivity), (ii) provisioning (e.g., timber and nontimber products), (iii) regulating (e.g., of climate, water quality), and (iv) cultural (Reid et al., 2005). Forest soils specifically produce tree biomass, high-quality water for consumption and aquatic habitat, C sequestration, and recreation. Forest plantation management may affect soil productivity through a variety of treatments, including species selection and vegetation management, harvesting, site

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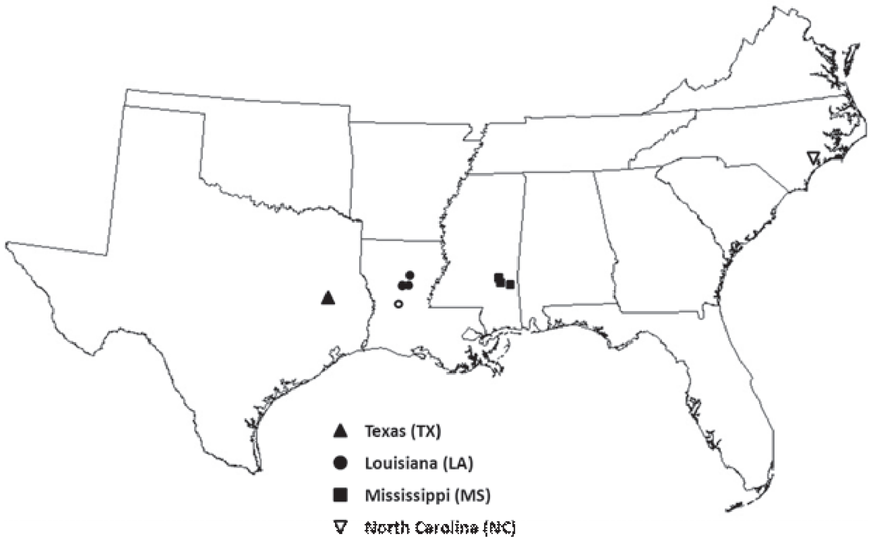

Fig. 1. Location of the 13 blocks of the Long-Term Soil Productivity Study in the Southeastern United States. Large symbols represent three replicated blocks on the same site, while small symbols represent individual blocks. Closed symbols indicate Alfisols, while open symbols indicate Ultisols.

preparation, and fertilization. Treatments shown to reduce soil productivity alter site organic matter or soil porosity (Powers et al., 1990). Harvesting of biomass energy feedstock has the potential to alter both. Harvest intensity is increasing in many areas of the southern United States due to the increase in biomass processing facilities, yet management guidelines to sustain multiple ecosystem services for these operations do not currently exist.

The North American LTSP study was designed to address changes in site organic matter and soil porosity. The study's experimental organic matter removal and compaction treatments have documented soil productivity losses in loblolly pine (*Pinus taeda* L.) sites in the southern United States that vary with site conditions and stand age (Scott et al., 2004; Sanchez et al., 2006a; Scott and Dean, 2006). This region is of substantial importance, as southern pine forests accounted for 65% of the timber harvested in the South in 2002, which translated to 37% of the total U.S. forest harvest (Adams et al., 2006). Therefore, the objective of the current study is to determine how organic matter removal and soil compaction affect soil ecosystem values of extensively managed loblolly pine plantations. The services or indicators of services chosen were stand volume, soil C storage, and woody plant biodiversity as an indicator of wildlife habitat. We hypothesized that intensive organic matter removal and soil compaction would reduce stand volume production and soil C sequestration similarly due to their clearly established links to plant productivity, but woody plant biodiversity would be affected by restructuring the community due to changes in the relative suitability of species on soils with different fertility or physical conditions.

METHODS AND MATERIALS

The LTSP Study in the Gulf and Atlantic coastal plains of the southeastern United States was established from 1989 through 1998 as 13 replicate sites (blocks) within four separate study areas. Four replicates were installed in Louisiana, while three replicate blocks each were installed in Mississippi, North Carolina, and Texas (Fig. 1). The Mississippi and Texas sites were each replicated on a single soil series, while the Louisiana sites were replicated across four soil series and the North Carolina sites were replicated on two similar soil series (Table 1).

Treatments and measurements were generally similar among all replicate blocks, although some details differed slightly among establishment and measurement protocols (Scott et al., 2004; Sanchez et al., 2006a; Scott and Dean, 2006). Briefly, each site (block) was a mature southern pine-dominated forest before implementation of the study. The site locations were chosen in part to create a gradient of potential water deficit (Thornthwaite and Mather, 1955, 1957) based on 30 yr of temperature and precipitation data obtained from each county's soil survey. This gradient ranged from essentially no deficit in North Carolina (1 mm) to a high deficit in Texas (150 mm) along a similar latitude. The experimental design is a 3 by 3 factorial split-plot design, with three organic matter removal intensities (bole-only [OM0], whole-tree

Table 1. Locations and site information for 13 replicate blocks of the Long-Term Soil Productivity Study in the southern United States.

Site†	Location (Lat., Long.)	Year est.	Soil series	Soil taxonomy	Geology and age‡	Surface texture§	Subsoil texture
LA1	31.0, −92.7	1990	Malbis	Plinthic Paleudults	Int. terraces, Pleistocene	fsl	l
LA2	31.7, −92.5	1992	Glenmora	Glossaquic Paleudalfs	Int. terraces, Pleistocene	fsl	cl
LA3	31.7, −92.6	1993	Metcalf	Glossaquic Paleudalfs	Vicksburg Group, Oligocene	sil	sc
LA4	31.7, −92.6	1993	Mayhew	Chromic Dystraquerts	Vicksburg Group, Oligocene	sil	sicl
MS123	31.5, −89.0	1994	Freest	Aquic Paleudalfs	Pascagoula and Hattiesburg formations, Miocene	sil	l
NC1	34.9, −76.8	1992	Goldsboro	Aquic Paleudults	Yorktown and Duplin formations, Miocene	lfs	scl
NC2&3	34.9, −76.8	1993	Lynchburg	Aeric Paleaquults	Yorktown and Duplin formations, Miocene	lfs	scl
TX123	31.1, −95.2	1998	Kurth	Oxyaquic Glossudalfs	Manning formation, Eocene	fsl	scl

† Sites were arranged into four study areas named for the state the sites were located in (Louisiana, LA; Mississippi, MS; North Carolina, NC; Texas, TX).

‡ Geologic formations determined from the Bureau of Economic Geology (1992), U.S. Geological Survey (1998), Moore (1969), and North Carolina Dep. of Environment, Health, and Natural Resources (1998).

§ Soil texture abbreviations are: lfs, loamy fine sand; fsl, fine sandy loam; l, loam; sil, silt loam; sc, sandy clay; cl, clay loam; scl, sandy clay loam; sicl, silty clay loam.

harvest [OM1], and whole-tree harvest plus forest floor removal [OM2]), three levels of soil compaction (none [C0], moderate [C1], severe [C2]), and two levels of noncrop vegetation control (no herbicide [H0] and multiple herbicide applications [H1]). The two levels of noncrop vegetation control were imposed to determine what influence the understory vegetation has on soil productivity and to attempt to reduce unwanted interference in using planted trees as a bioassay of soil productivity (Powers, 1999). Data on biomass quantities removed and compaction effectiveness have been previously published (Powers et al., 2005; Page-Dumroese et al., 2006).

After organic matter removal and soil compaction, containerized loblolly pine seedlings from 10 known half-sib families were planted at a 2.5- by 2.5-m spacing in the Gulf coastal plain sites and at a 3- by 3-m spacing in North Carolina. Each 0.4-ha treatment plot was then split into two 0.2-ha plots. One of the split-plots was kept clear from competing vegetation when needed by manual removal and directed-spray herbicide applications (primarily glyphosate, imazypyr, and sulfometuron methyl) depending on site and vegetation. Competing vegetation was allowed to grow freely on the other split-plot. Volunteer pines were controlled manually on the Gulf coastal plain sites (Texas, Louisiana, Mississippi) but not on the no-competition control split plots on the North Carolina sites. Measurement plots were the interior 0.1 ha of each split-plot.

Measurements

Diameters at breast height (DBH) were measured on every tree in the 0.1-ha measurement plots, while heights were measured on 10% of the trees except in North Carolina, where all tree heights were measured. Heights of unmeasured trees were estimated from measured trees according to a height-diameter model based on Schnute (1981) ($p < 0.0001$, $R^2 = 0.99$). Tree volume was calculated from DBH and height (actual or estimated) according to Baldwin and Feduccia (1987) and summed for each measurement plot to calculate stand volume.

Mineral soil bulk density and soil organic C were sampled from five 6-cm-diam. soil core samples (three in North Carolina) per measurement plot from each of the 0- to 10-, 10- to 20-, and 20- to 30-cm depths. Soil was passed through a 2-mm screen to remove large organic fragments, dried at 60°C, and pulverized. Soil organic C concentration was determined by combustion (Leco 2000 CNS analyzer for the Mississippi and Louisiana sites, a NA1500 Carlo-Erba CNS analyzer for the North Carolina sites, and a Carlo Erba EA-1108 elemental analyzer for the Texas sites). Soil organic C content (Mg C ha^{-1}) was computed from the soil organic C concentrations and bulk densities in each depth increment and then summed for the 0- to 30-cm soil depth.

Understory woody vegetation was sampled in each nonherbicide-treated subplot in the Gulf coastal plain sites at age 15 and on four of the nine treatment plots per site in North Carolina at age 14. In the Gulf coastal plain plots, all nonplanted vegetation less than 1.37 m in height was measured within three 1.37-m radius quadrats, while vegetation taller than 1.37 m was measured in three 4.4-m radius quadrats. Plant height (length if plant was not upright) was determined for the tallest individual in a rootstock (for sprouting species), diameter at 1.37 m height (DBH) was measured on all stems with DBH > 5cm, and the total number of stems in each rootstock were counted. Because data were originally intended only to provide biomass estimates, some species were combined (i.e., oaks [*Quercus* spp.] were grouped into the red oaks [Erythrobalanus] or white oaks [Leucobalanus]). Biomass was determined for all individuals with DBH < 5 cm from equations developed from 75 destructively sampled individuals of all species (Scott et al., 2006) and for individuals with DBH $\geq$ 5 cm from established volume equations for oaks, hard maples, and hickories (Jenkins et al., 2003). Relative abundance was determined based on biomass for each species, and the Shannon Index (Shannon, 1948) was calculated using relative abundance of each species to assess diversity. In North Carolina, a more comprehensive understory study was undertaken on the OM0 and OM2 harvest levels on the C0 and C2 compaction plots (Vierra, 2007). Understory was not measured on the OM1 or C1 plots in North Carolina. In North Carolina, only the stem counts taken for each species in one of seven diameter at breast height classes (0–1, 1–2.5, 2.5–5, 5–10, 10–15, 15–20, and 20–25 cm, respectively) in a single 200-m^2 quadrat were used, as they best matched data available from the Gulf coastal plain sites. Dominance was then estimated as the sum of diameters (using the mean diameter for each class for each individual) for each species in a plot, and the Shannon Index was calculated.

The effects of compaction, organic matter removal, vegetation control, and their interactions on stand volume, soil C, species richness, and Shannon Index were analyzed in a split plot, mixed model analysis of variance. Sites were considered random blocks. Compaction and harvest intensity were arranged in a factorial design with herbicide treatment applied in a split plot. Data were analyzed with all study areas combined and study area was considered a fixed effect (Federer and King, 2007). Least squares means for each treatment overall and within study areas were estimated and compared with Tukey's adjustment at $p < 0.05$; data reported in text and tables were arithmetic means. Linear contrasts were used to determine individual treatment effects within a study site. Linear regression was used to investigate the relationships among inherent site productivity as estimated by stand volume on the OM0 C0 plots and treatment responses. We calculated the ratio of stand volume to mineral soil C content for each plot and compared treatment effects using a mixed-model ANOVA.

RESULTS

Stand Volume

Across the study areas, mean stand volume did not follow the gradient of potential water deficit (North Carolina < Mississippi < Louisiana < Texas). Study area means ranged from 147 m^3 ha^{-1} in Mississippi with the second-lowest potential water deficit to 216 m^3 ha^{-1} in Louisiana with the second-highest potential deficit. Stand volume was significantly affected by all

Table 2. Stand volume of loblolly pine plantations 15 yr following three levels of soil compaction, three levels of harvest intensity, and two levels of vegetation control across the Gulf and Atlantic coastal plains of the southeast United States.

	Compaction levels			Harvest Intensity			Vegetation Control	
State	C0†	C1	C2	OM0	OM1	OM2	H0	H1
				m^3 ha^{-1}				
NC	177.2a‡ (24.0)	182.5a (22.5)	187.3a (25.1)	186.7a (23.3)	195.6a (26.4)	164.7b (21.1)	88.8b (5.3)	275.9a (6.8)
MS	128.1b (9.0)	158.4a (8.7)	153.5a (7.9)	163.4a (8.8)	137.0b (8.4)	139.6b (8.7)	131.4b (5.3)	161.9a (8.0)
LA	204.4b (11.6)	227.8a (10.0)	215.7ab (9.8)	219.5a (10.5)	211.0a (10.6)	217.3a (10.8)	191.9b (5.8)	240.0a (9.1)
TX§	146.8a (11.4)	161.2a (9.0)	157.7a (11.6)	163.8a (10.2)	156.3a (11.6)	143.7a (8.6)	153.3a (8.0)	157.6a (9.2)
Overall	167.7b (8.1)	186.0a (7.4)	182.0a (7.8)	186.1a (7.4)	177.8ab (8.3)	171.7b (7.7)	145.1b (4.7)	212.2a (6.2)

† C0, C1, and C2 refer to uncompacted, moderate compaction, and severe compaction based on predetermined Proctor tests. OM0, OM1, and OM2 refer to bole-only, whole-tree, and whole-tree plus forest floor and coarse woody debris removal. H0 and H1 refer to no herbicide or repeated applications of herbicide to control nonplanted species.

‡ Individual contrasts were used to test least-squares means within each site. Arithmetic means within a row and treatment type followed by the same letter are not significantly different at $p < 0.05$, and standard errors are in parentheses.

§ The Texas sites had 2 of 27 plots omitted from the results due to plantation failure before age 3. No data were available for these plots. Additionally, a wildfire burned in an additional three plots 2 mo before tree measurement, killing ~90% of the trees in those plots. Standing dead trees were measured and counted as live for this measurement.

treatments, but the effects varied by treatment, site, and in some cases, treatment combinations.

Vegetation control had the greatest impact on stand volume on all study areas except Texas (Table 2). The average stand volume increase in response to vegetation control across all treatments and sites was 46%. North Carolina stand volume had the greatest response, with a threefold increase in the vegetation control split-plots vs. the split-plots without vegetation control. Vegetation control had a comparatively moderate effect on stand volume in Louisiana (25%) and Mississippi (23%). In contrast, vegetation control had no effect on stand volume in Texas, where the herbicides used were ineffective at controlling the understory (data not shown).

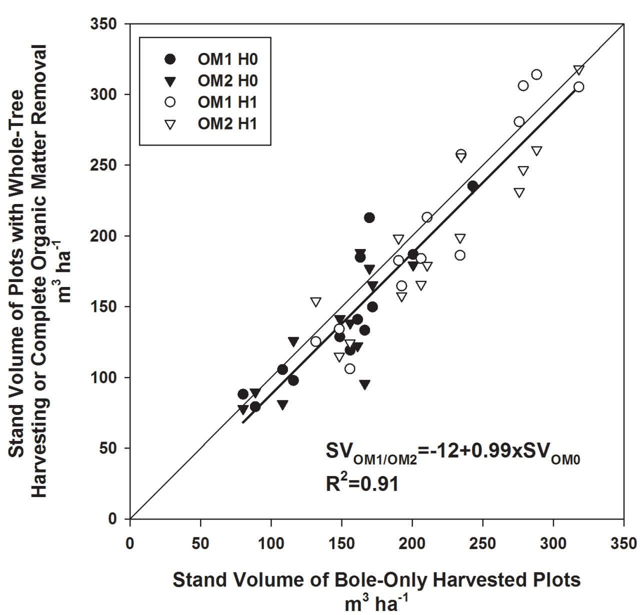

Fig. 2. Loblolly pine stand volume at age 15 yr on intensively harvested plots compared to stand volume of bole-only harvested plots on the same site across 13 replicate blocks of the Long-Term Soil Productivity Study in the Gulf and Atlantic coastal plains of the southeastern United States. H0, no herbicide; H1, multiple herbicide applications; OM0, bole-only organic matter removal; OM1, whole-tree harvest organic matter removal; OM2, whole-tree harvest plus forest floor organic matter removal.

Soil compaction before planting had a consistent positive effect on stand volume at age 15; stand volume on the compacted plots was 10% greater ($p < 0.003$) than on the uncompacted plots across all sites (Table 2). The site by compaction interaction term was not significant, but individual site contrasts revealed that North Carolina and Texas volumes were similar across compaction treatments while moderate compaction (but not severe) increased volume in Louisiana. In MS, both compaction treatments increased volume by about 22%.

Intensive organic matter removal generally had little effect on stand volume, although some sites showed negative volume responses. The OM2 treatment reduced stand volume by about 8% across all study areas ($p < 0.04$, Table 2) while stand volume on OM1 plots was similar to that of OM0 plots. In Mississippi, both OM1 and OM2 had similar effects, reducing stand volume by about 15% compared to OM0 plots. In North Carolina, the OM2 treatment reduced stand volume by about 12% compared to the OM0. Neither OM1 nor OM2 reduced stand volume in Louisiana or in Texas.

Previous work at age 10 on a subset of these 13 sites (Scott and Dean, 2006; Scott et al., 2007) indicated that initial soil fertility gradients (available P and exchangeable cations) at least partially controlled stand volume and also the site response to organic matter removal intensity, with the sites with lowest initial extractable soil P having the most negative response to OM1 and OM2 treatments. We examined this relationship for all the southern LTSP sites at age 15, but separated the split-plots between no vegetation control and with vegetation control. We found that stand volume response to organic matter removal was linearly related to site productivity (slope = 0.99, $p < 0.0001$, R^2 = 0.91) (as assessed by the OM0 plot stand volume) at age 15 across all sites (Fig. 2).

Understory Woody Plant Composition

Mean species richness of woody plants on the Gulf coastal plain study areas was 10 per 0.1-ha plot, but across the 10 blocks, at least 32 species were found (Table 3). Actual richness was slightly higher, as not every individual was keyed to species level, for example, *Vaccinium* spp. were not identified to species level. Diversity of the nonplanted vegetation as assessed by the Shannon Index averaged 1.4 across all study areas. Diversity was highest in Louisiana (1.6) and lowest in Texas (1.0). In North Carolina, 35 individual species from tree or shrub forms were found on the 12 plots sampled (all species were keyed to species and not grouped for richness). Neither compaction nor harvest intensity had any significant impact either on richness or Shannon Index.

Table 3. Mean plot-level, non-crop, woody species richness and diversity (Shannon Index) of loblolly pine plantations 15 yr following three levels of soil compaction and three levels of harvest intensity across the Gulf and Atlantic coastal plains of the southeast United States.

State	Mean	C0†	C1	C2	OM0	OM1	OM2
				Species Richness (S)			
NC	15 (0.9)	16 (0.9)	n/a	14 (1.5)	16.3 (1.1)	n/a	13.7 (1.3)
MS‡	9.1 (0.5)§	10.0a (0.4)	8.4a (1.1)	9.0a (1.0)	10.8a (0.9)	8.4b (0.8)	8.2b (0.8)
LA‡	11.7 (0.3)	11.8a (0.7)	11.4a (0.6)	11.8a (0.5)	12.3a (0.5)	11.6a (0.8)	11.3a (0.5)
TX‡	6.3 (0.3)	6.9a (0.6)	6.4a (0.6)	5.5a (0.2)	6.3a (0.6)	6.0a (0.5)	6.9a (0.7)
Mean¶	9.5 (0.3)	9.9a (0.5)	9.0a (0.6)	9.5a (0.6)	10.1a (0.6)	9.1a (0.6)	9.2a (0.5)
				Shannon Index H′			
NC	2.0 (0.05)	2.0 (0.07)	n/a	2.0 (0.07)	2.1 (0.05)	n/a	1.9 (0.05)
MS‡	1.46 (0.1)	1.5a (0.1)	1.4a (0.1)	1.5a (0.2)	1.7a (0.1)	1.4a (0.1)	1.4a (0.1)
LA‡	1.63 (0.1)	1.7a (0.1)	1.6a (0.1)	1.6a (0.1)	1.6a (0.1)	1.7a (0.1)	1.6a (0.1)
TX‡	1.01 (0.04)	1.0a (0.1)	1.0a (0.1)	1.1a (0.1)	1.0a (0.1)	1.0a (0.04)	1.1a (0.1)
Mean¶	1.4 (0.04)	1.4a (0.1)	1.4a (0.1)	1.4a (0.1)	1.4a (0.1)	1.4a (0.1)	1.4a (0.1)

† C0, C1, and C2 refer to uncompacted, moderate compaction, and severe compaction based on predetermined Proctor tests. OM0, OM1, and OM2 refer to bole-only, whole-tree, and whole-tree plus forest floor and coarse woody debris removal.

‡ Richness and diversity is underestimated on the Gulf coastal plain sites, as certain groups of species were not identified to species.

§ Individual contrasts were used to test least-squares means within each site. Arithmetic means within a row and treatment type followed by the same letter are not significantly different at $p < 0.05$, and standard errors are in parentheses.

¶ Mean of Gulf coastal plain sites; NC was not included due to differences in methodology

Soil Carbon Storage

Soil C storage in the upper 30 cm of mineral soil averaged about 47 Mg C ha^{-1} across all study areas, but substantial differences were evident among the NC sites on the Atlantic coastal plain and the Gulf coastal plain sites (Table 4). Soils at the NC site stored about 92 Mg C ha^{-1}, whereas the Gulf coastal plain sites stored about 33 Mg C ha^{-1} and were all similar (31.7–36.3 Mg C ha^{-1}). Unlike stand volume, soil C was relatively unaffected by soil compaction or vegetation control and had inconsistent response to organic matter removal treatments. Soil C was similar among compaction treatments overall and within each study area. Vegetation control had no effect on soil C overall or within study area. Soil C was not significantly different among organic matter removal treatments across all sites, but the site by organic matter removal interaction effect was significant due to the exceptionally high treatment effect in NC. Individual contrasts in NC indicated that soil C content was about 25% less in OM2 compared to the other treatments. Furthermore, the reduction in soil C in NC was highly variable; the relative difference in soil C storage between OM1 and OM2 ranged from +2 to −40%, respectively, across the three blocks (data not shown). Whole-tree harvested plots (OM1) had similar soil C contents to bole-only harvested plots (OM0) across the study areas.

DISCUSSION

Vegetation Control

Vegetation control, while not strictly related to biomass harvesting, is nonetheless a common treatment in southern pine stands of all ownership classes, and due to its potential impact on the forest soil ecosystem services of wildlife habitat and stand volume, deserves attention. In addition, understory elimination has been shown to significantly reduce mineral soil C in other southern pine stands (Shan et al., 2001; Sartori et al., 2007). In our study, vegetation control had significant positive effects on stand volume everywhere except in Texas. This was expected, as interspecific competition has been shown to be one of the most important variables affecting pine plantation volume (Miller et al., 2002). In Texas, stand volume did not respond well to competition control because the competing vegetation was not well controlled (Scott and Stagg, 2013) due to a restriction on herbicide type and the presence of yaupon (*Ilex vomitoria* Sol. ex Aiton), a very aggressive understory component.

Soil C stocks were unaffected by herbicide application overall or at any study area, as was found for a similar study in a Mediterranean climate (Powers et al., 2013), but in contrast to other studies of southern pine plantations. Shan et al. (2001) and Sartori et al. (2007) both reported reduced soil C after 16 to

Table 4. Soil C storage (Mg C ha^{-1} in surface 0.3 m) of loblolly pine plantations 15 yr following three levels of soil compaction, three levels of harvest intensity and two levels of vegetation control across the Gulf and Atlantic coastal plains of the southeast United States.

State	C0†	C1	C2	OM0	OM1	OM2	H0	H1
				Mg C ha^{-1}				
NC	90.0ab‡ (6.6)	88.8b (7.1)	96.1a (8.4)	98.9a (7.5)	101.5a (7.2)	74.7b (5.7)	91.0a (6.3)	92.3a (5.8)
MS	35.8a (2.2)	34.0a (2.1)	32.6a (1.3)	31.4a (1.3)	37.9a (2.4)	33.1a (1.6)	33.9a (1.1)	34.4a (1.9)
LA	31.3a (1.3)	32.0a (1.5)	29.9a (1.1)	33.2a (1.3)	28.9a (1.3)	31.1a (1.3)	32.3a (1.1)	29.8a (1.0)
TX	32.5a (1.4)	33.0a (1.6)	31.2a (1.4)	34.0a (1.1)	31.9a (1.8)	30.8a (1.3)	32.8a (1.4)	31.7a (1.0)
Overall	46.2a (3.2)	45.8a (3.2)	46.1a (3.7)	48.1a (3.6)	48.4a (3.8)	41.5a (2.5)	47.0a (2.7)	46.4a (2.8)

† C0, C1, and C2 refer to uncompacted, moderate compaction, and severe compaction based on pre-determined Proctor tests.

‡ Individual contrasts were used to test least-squares means within site. Arithmetic means within a row and treatment type followed by the same letter are not significantly different at $p < 0.05$, and standard errors are in parentheses.

17 yr with competition control and indicated the reduction was likely due to reduced fine root turnover from understory plants early in the rotation, as previously modeled (Ewel and Gholz, 1991). Although each study area received at least five herbicide applications, a few understory plants were present and provided above and belowground C inputs until canopy closure.

Soil Compaction

Stand volume was generally greater on C1 and C2 compared with C0. This was in contrast to commonly cited concerns of compaction reducing tree growth, which have permeated the forest soils literature since the 1950s since tractor logging increased in the Pacific Northwest (Steinbrenner, 1955; Steinbrenner and Gessell, 1955). While many studies have reported on negative or inconclusive tree response to compaction (and more broadly, soil disturbance), see Miwa et al. (2004), few have highlighted potentially positive responses to compaction. Recently, Ampoorter et al. (2011) performed a meta-analysis and found that effects were primarily inconclusive with a few studies finding negative responses on silty soils and other studies finding neutral to positive responses on sandy and loamy soils. Greacen and Sands (1980) show conceptually, and the nonlimiting water range (Letey, 1985) and least-limiting water range models (LLWR) (da Silva et al., 1994) describe how soil compaction affects root growth and water uptake in positive and negative ways. Multiple studies have shown that compacting coarse-textured forest soils can increase soil water holding capacity and, thus, improve tree growth (Gomez et al., 2002a, 2002b; Zou et al., 2000). While some of the sites in the current study have coarse-textured surface soils, specifically the Kurth soils (fine-loamy, siliceous, semiactive, thermic Oxyaquic Glossudalfs) in Texas and the Goldsboro (fine-loamy, siliceous, subactive, thermic Aquic Paleudults) and Lynchburg (fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults) soils in North Carolina (Table 1), compaction had relatively minor to no impact on volume on these plots. Conversely, compaction had the greatest positive effect on medium-textured soils in Mississippi and Louisiana.

The increases in productivity in our study have no clear explanation but may be related to the type of disturbance, the use of containerized seedlings, noncrop vegetation control, or some other mechanism. The soil compaction treatments were very uniform for a field trial but did not disrupt soil structure as is typically associated with rutting or churning. Second, we used containerized seedlings known to survive better than bare-root seedlings on poor soils (South and Barnett, 1986; Yeiser and Paschke, 1987); this planting stock may have been less affected by increased soil strength or reduced aeration from soil compaction. Lastly, soil compaction reduced interspecific competition on our study areas, which has been shown to affect productivity (Gellerstedt and Aust 2004). Ideally, the vegetation control plots should have given us the opportunity to test this hypothesis. We would have expected to see a vegetation control by compaction interaction whereby only the split-plots receiving no vegetation control would have had increased stand volume when compacted. However, the herbicide used was never 100% effective, and we found that the herbicide was more effective on compacted plots (Stagg and Scott, 2006). Therefore, even the split-plots with vegetation control still showed an improvement in stand volume with compaction.

Organic Matter Removal

Harvesting wood for energy encompasses a wide range of actual harvesting practices, including whole-tree harvesting, harvesting of coarse woody debris, harvesting otherwise nonmerchantable plants, and stump harvesting (Berger et al., 2013). Our treatments provide a range of harvest intensity from stem-only harvests to removal of all organic matter above the mineral soil, which is well beyond operational practice.

Intensive organic matter removal had inconsistent impacts on stand volume. Stand volume was reduced by both OM1 and OM2 in Mississippi and by OM2 in North Carolina but was unaffected in Louisiana or Texas. These same study areas, as well as other similarly treated study areas in the Gulf coastal plain, showed clear reductions in stand volume productivity at earlier ages (Scott et al., 2004, 2007; Scott and Dean, 2006) primarily on the P-deficient soils in Louisiana, Mississippi, and Texas (Scott et al., 2007; Dean et al., 2013). Soils with higher initial P availability, such as the Metcalf (fine-silty, siliceous, semiactive, thermic Glossaquic Paleudalfs) and Mayhew (fine, smectitic, thermic Chromic Dystraquerts) soils in Louisiana and the Lynchburg and Goldsboro soils in North Carolina, showed no reductions in stand volume at earlier ages (Sanchez et al., 2006a) nor did they show reductions at age 15 (Table 2). Operational applications of P fertilizer have been shown to ameliorate these stand volume reductions (Scott and Dean, 2006).

While many studies have examined short-term tree growth or soil nutrient removals with biomass harvesting, few North American studies have examined long-term tree growth responses to intensive harvesting. Previously, Johnson et al. (2002) found no differences in regenerating biomass 15 yr after whole-tree or bole-only harvest of a deciduous forest in Tennessee, but they did find a 17% reduction in biomass 18 yr after whole-tree harvest of a loblolly pine stand in the Piedmont of South Carolina compared to a bole-only harvest. Roxby and Howard (2013) recently examined 14 whole-tree harvested and 15 bole-only harvested sites in New Hampshire and Maine and found no differences in tree growth 10 to 14 yr post-harvest. More widely, Thiffault et al. (2011) reviewed forest biomass harvesting on soil and site productivity across temperate and boreal regions and found few generalities other than a tendency for intensively managed European forests to exhibit stand volume losses more commonly than North American forests, possibly due to the longer history of intensive harvests. In this study, reductions in tree growth at earlier ages in Texas and Mississippi (Scott and Dean 2006) were either no longer significant (Texas) or were less pronounced (Mississippi) at age 15. Thus, volume reductions due to biomass harvesting or even complete organic matter removal may be temporary, which was hypothesized by Powers et al. (2005).

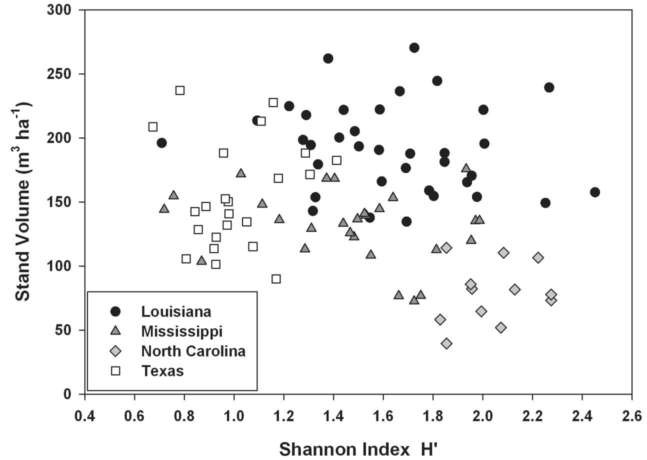

Fig. 3. Plot-level stand volume and Shannon Index for woody understory vegetation at age 15 yr across the Long-Term Soil Productivity Study plots in the Gulf and Atlantic coastal plains of the southeastern United States.

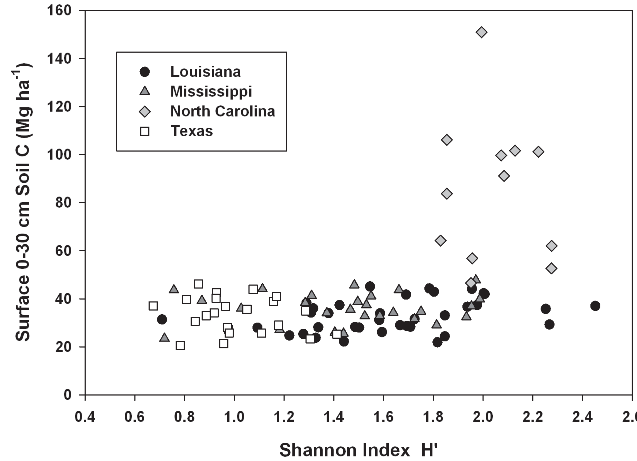

Fig. 4. Plot-level surface soil (0–30 cm) C content and Shannon Index of woody understory vegetation at age 15 yr across 13 blocks of the Long-Term Soil Productivity Study in the Gulf and Atlantic coastal plains of the southeastern United States.

Intensive harvesting had little clear impact on understory plant composition. Richness was reduced by about one species in the OM1 but was not significantly different in the OM2 plots. Shannon's index values were similar across all treatments, and relative abundance of the species present changed little (data not shown). This was somewhat surprising, as we expected to find reductions in the more nutrient-demanding understory species and increases in others.

Harvesting effects on mineral soil C pools were inconsistent across the study areas. Soil C content was significantly reduced by the OM2 treatment in North Carolina. The Mississippi and Louisiana sites showed no reductions in soil C with either OM1 or OM2 treatments. These results are similar to those found at age 5 in NC and LA (Laiho et al., 2003), although Butnor et al. (2006) found no differences in soil C on a subset of plots in North Carolina at age 10. The lack of change in the Gulf coastal plain sites compared to the North Carolina sites may be due to their relatively lower C pools, which may be more recalcitrant to mineralization. Also, soil C estimates were less precise in North Carolina due to lower sampling intensity (Sanchez et al., 2006b). Regardless, except for the OM2 treatment, which is well beyond operational biomass removal, soil C contents in the surface 30 cm did not change with whole-tree removal biomass harvesting, as has been shown for the larger LTSP network (Powers et al., 2005) and is consistent with the majority of findings from managed forests (Nave et al., 2010).

Tradeoffs

A tradeoff in ecosystem services would occur if one service increases but another service decreases, that is, one is gained at the expense of another. We first examined whether the three services appeared to be related across all sites to determine if tradeoffs might be occurring, and if so, if they were related to treatments. Only two of the three ecosystem services appeared to be related to each other. Neither stand volume (Fig. 3) nor soil C storage (Fig. 4) showed any relation to Shannon's index of diversity regardless of treatment on the Gulf coastal plain sites. Soil C storage and stand volume were inversely related ($p < 0.0002$, $r = 0.39$) across the Gulf coastal plain study areas (Fig. 5). This inverse relationship was unexpected, as we did not impose treatments, such as fertilization, that would both increase tree growth and soil C mineralization in the short-term. Organic matter removal had no influence on the ratio of stand volume to mineral soil C but severely compacted plots had a higher ratio of stand volume to mineral soil C than uncompacted plots ($p < 0.02$), while moderately compacted plots were similar ($p < 0.18$) (Fig. 6). Since stand volume was increased by compaction (Table 2) but soil C was unaffected by compaction (Table 4), no negative tradeoff occurred between stand volume and soil C.

CONCLUSIONS

Forest soils provide a host of ecosystem services, but intensive harvesting for biomass and conventional wood products has the potential to reduce their capacity to provide those services. Across 13 mid-rotation loblolly pine stands in the Atlantic and Gulf Coastal Plains of the southern United States, we found that

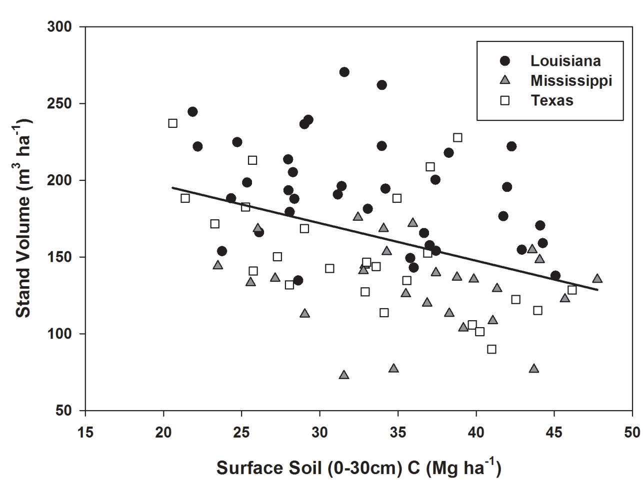

Fig. 5. Plot-level stand volume and surface soil (0–30 cm) C content at age 15 yr across 10 blocks of the Long-Term Soil Productivity Study in the Gulf coastal plain of the southeastern United States.

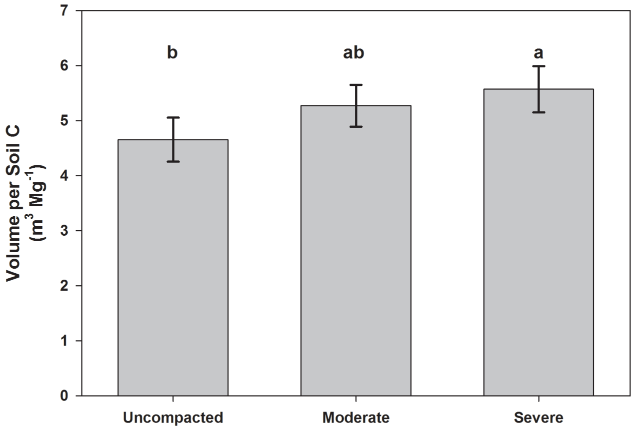

Fig. 6. Age 15 yr stand volume to surface (0–30 cm) soil C content across three levels of experimentally applied soil compaction on 10 replicate blocks of the Long-Term Soil Productivity Study in the Gulf coastal plain of the southeastern United States. Error bars represent standard errors, and letters indicate significant difference at $p < 0.05$.

intensive organic matter removal and soil compaction, which often accompanies intensive harvesting, had relatively minor impacts on three ecosystem services: stand volume production, mineral soil C storage, or understory diversity. Whole-tree harvesting reduced productivity on a single site, and complete organic matter removal reduced volume production on the most nutrient-deficient sites. Soil compaction had a positive effect on stand volume and caused no substantial reduction in soil C storage or understory diversity. Multiple herbicide applications increased stand volume by 46% on average, yet had no negative impact on soil C. Landowners of inherently nutrient-deficient (especially of P) coastal plain loblolly pine stands should be aware of possible reductions in stand volume following intensive harvesting, but otherwise biomass harvesting does not substantially diminish these forest soil ecosystem services on the site types examined in this study.

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