SOIL PHYSICAL EFFECTS ON LONGLEAF PINE PERFORMANCE IN THE WEST GULF COASTAL PLAIN

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Abstract--We summarize 8 years of soil physical property responses to herbicide manipulation of the understory in two young longleaf pine stands growing on either Ruston fine sandy loam or Beauregard silt loam soils. We also describe relationships between pine sapling vigor and the soil physical environment across a 3-year period on the Ruston soil and a 2-year period on the Beauregard soil. It is hypothesized that understory control affects soil porosity, bulk density, and the ability to store plant-available water by a change in the amount and distribution of non-pine roots. Furthermore, *Pinus* vigor may be reduced when the inherent physical nature of a soil limits pine root elongation. We observed temporal changes in soil porosity fractions and bulk densities, possibly representing natural soil recovery after disturbance. Near the surface of the soil, soil perturbation by grass roots may have aided pine vigor by increasing the water-holding capacity of soil micropores. In the subsoil, pine vigor was correlated with bulk density and microporosity. Relationships between pine vigor and subsoil physical properties were different between the two soil types. Clay illuviation and sand content in the two soil types may have played a role in these relationships. Our results provide insight regarding soil variables that impart some degree of control on pine root system expansion and tree vigor on the West Gulf Coastal Plain.

INTRODUCTION

Southern pine root systems normally supply adequate water to sustain pine vigor across the southeastern United States. Subsoil water may be accessed by roots growing along interped spaces and in pores created by roots and soil fauna (Van Lear and others 2000). This means of water acquisition is vital in the West Gulf Coastal Plain, where many forest soils are characterized by root-growth-limiting subsoil bulk densities (Patterson and others 2004, Scott and others 2007). The proliferation of pine ectomycorrhizae and rhizomorphs near the surface of the soil and the elongation of deep pine roots also enable water to be hydraulically redistributed near the soil surface by its nocturnal, deep-root absorption, ascension, and shallow-root release (Dawson 1993; Warren and others 2006, 2008).

In addition to root system expansion, soil porosity controls water uptake by roots. Soil micropores with surface tensions > 1.5 MPa reduce the volume of water available for plant uptake, while those with surface tensions > 0.3 MPa and < 1.5 MPa favor water accessibility to plant roots (Kramer and Boyer 1995). Furthermore, the movement and decomposition of plant roots and soil fauna create macropores that serve as conduits for root elongation, and over time these macropores accelerate the development of large micropores capable of supplying plant-available water.

Herbicide application and prescribed fire change the amount and composition of competing vegetation above the soil surface (Haywood 2009, 2011). It is likely that parallel changes in rooting occur belowground. We found, for example, that repeated prescribed fire in March and July increased non-pine rooting in the upper 5 cm of the A horizon compared to no prescribed burning or prescribed fire in May (Sword Sayer and Haywood 2012). This effect was attributed to greater grass and forb competition when prescribed fire was applied in March or July compared to no prescribed fire or its application in May.

We hypothesize that vegetation management treatments indirectly affect soil porosity and bulk density by changing the amount and distribution of non-pine rooting. Also, where the inherent physical nature of a soil type has the potential to limit pine root elongation, negative effects on soil porosity and bulk density caused by vegetation management treatment may be seen as a reduction in *Pinus* vigor. The first objective of this analysis was to summarize long-term soil physical property responses to herbicide application during establishment of young longleaf pine (*Pinus palustris* Mill.) plantations on two West Gulf Coastal Plain forest loam soils. Our second objective at these two sites was to assess relationships between two physiological variables representative of *Pinus* vigor and soil physical properties.

MATERIALS AND METHODS

Study Site

The study is located at two sites in the Kisatchie National Forest in central Louisiana. Site 1 supports two replications on a Ruston fine sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) containing some Malbis fine sandy loam (fine-loamy, siliceous, subactive, thermic Plinthic

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Paleudults) and Gore very fine sandy loam (fine, mixed, active, thermic Vertic Paleudualfs) (31° 6' N, 92° 36' W). Site 2 supports three replications on a Beauregard silt loam (fine-silty, siliceous, superactive, thermic Plinthaquic Plaeudults) and Malbis fine sandy loam complex (31° 1' N, 92° 37' W). A mixed pine-hardwood forest originally occupied both sites. In 1996, site 1 was clearcut harvested and roller-drum chopped, followed by burning in 1997. In 1991, site 2 was clearcut harvested, sheared, and windrowed, and burned in 1993 and 1996. Container-grown longleaf pine seedlings from genetically improved Louisiana (site 1) and Mississippi (site 2) sources were planted (1.8 by 1.8 m) in November 1997 and March 1997, respectively. Treatment plots, 22- by 22-m (0.048 ha), were established at each location, and blocks were delineated by soil drainage and topography. Treatment plots contained 12 rows of 12 seedlings, and measurement plots were the internal 8 rows of 8 seedlings in each treatment plot.

In each block, the competing vegetation of one plot was not treated (C, control), while that of a second plot was chemically treated (H, herbicide). Herbicides were applied after planting longleaf pine seedlings to control herbaceous and arborescent plants. On site 2, sethoxydim and hexazinone in aqueous solution were applied in bands centered over the rows of unshielded seedlings in May 1997 and April 1998. The rate of sethoxydim application was 0.37 kg active ingredient (ai)/ha, and the rate of hexazinone application was 1.12 kg ai/ha. At site 1, hexazinone was similarly banded in April 1998 and 1999. At both sites in April 1998 and May 1999, triclopyr at 0.0048 kg acid equivalent/liter was tank-mixed with surfactant and water and applied as a directed foliar spray to competing arborescent vegetation. Brush that recovered by February 2001 was cut by hand.

Diameters at breast height (d.b.h., cm) of the measurement trees were measured annually during the dormant season (December through February). Basal areas (BA_{tree}) of measurement trees were calculated. In early 2002, 2004, 2006, and 2009, three sample trees from among those of average height per measurement plot were randomly identified on site 1 for additional physiology and soil measurements. Similarly at site 2, three sample trees per plot were identified in early 2004, 2006, and 2009.

Soil Physical Property Measurements

A tractor-mounted hydraulic probe was used to extract one long (5.1 cm diameter by 61 cm long) and one short (5.1 cm diameter by 30.5 cm long) soil core about 1 m from the base of each sample tree in 2002, 2004, 2006, and 2009. Cores were placed in capped plastic liners and refrigerated until processing. Intact core increments 10 cm in length were excised from the A and upper and lower Bt1 horizons of long soil cores and the A horizon of short soil cores. First, the depth to the top of the argillic (i.e., Bt1) horizon (DAH) of the long cores was estimated by soil color and texture. From the long cores, two 1-cm sections were excised from the A horizon core increment (2 to 12 cm), the upper Bt1 core increment, and the lower Bt1 core increment (50 to 60 cm) using a band saw. The upper Bt1 horizon core increment was defined as the 2- to 12-cm soil core section below the top of the Bt1 horizon. From short soil cores, two 1-cm sections were excised from the 2- to 12-cm depth using a band saw. In each year, 60 soil cores were processed for A horizon information, and 30 soil cores were processed each for upper and lower Bt1 horizon information.

One of each pair of 1-cm sections was positioned on an equilibrated -0.1 MPa or -1.5 MPa ceramic pressure plate. The water retention method was used to estimate total porosity fraction (TOP), microporosity fraction (MIP), macroporosity fraction (MAP), and plant-available water holding capacity (PAWHC) (Klute 1986). The water content of 1-cm core sections at -0.03 MPa was defined as soil water content at field capacity (WATFC), and that at -1.5 MPa was defined as soil water content at permanent wilting point (WATWP). The core bulk density method was used to measure bulk density (BD) (Blake and Hartge 1986).

Predawn Needle Water Potential and Net Photosynthesis Measurements

The fascicle gas exchange of each sample tree was measured in 2003, 2004, and 2005. Measurements were conducted in May, July, and September 2003, April and July 2004, and May and October 2005. Within a consecutive 3-day period, two blocks were measured on each of the first two days and the fifth block was measured on the third day.

Between 0500 and 0600 hours on the day of gas exchange measurements, one current-year, mature, mid-crown fascicle was detached, placed in a plastic bag, and stored in darkness on ice. Predawn needle water potentials (PWP) were measured by a

pressure chamber (PMS Instrument Co., Corvallis, OR) within 1 hour of detaching.
On each gas exchange day, the light saturated net photosynthesis rate (A_{sat}) in the upper crown of each sample tree was measured in the afternoon (1300-1530 hours) with a portable photosynthesis system (Model 6400, Li-Cor, Inc. Lincoln, NE) and a standard leaf chamber equipped with a light emitting diode light source (Model 6400-02B, Li-Cor, Inc. Lincoln, NE). For each measurement, two fascicles with three needles each from the south side of a sample tree were detached and placed in the leaf chamber. Measurements were an average of 20 one-second readings, taken after the chamber environment had stabilized. Time between fascicle detachment and measurement was approximately 2 minutes. All measurements were conducted at a photosynthetically active radiation value of 1400 umol/m^2/s. After each measurement, fascicles were placed in plastic bags on ice, and needle surface areas in the leaf chamber were determined by the displaced needle volume method (Johnson 1984). Values of A_{sat} were expressed on a total leaf surface area basis as μmol CO_2/m^2/s.

Statistical Analysis

For each site, mean values of BD, MIP, MAP, and PAWHC for each horizon were transformed, as needed, to natural logarithm or square root values to establish normally distributed experimental errors and evaluated by analysis of variance using a split-plot in time, randomized complete block design. Sites 1 and 2 had two and three blocks, respectively. Year was the whole plot effect, and vegetation management treatment was the subplot effect. Means were compared by the Tukey test and considered significantly different at $\alpha = 0.05$.

For each site, the mean depth to DAH was calculated, and trees with DAH within one standard deviation of mean DAH were partitioned into two subsets by PWP. The first subset contained trees with PWP ≥ -0.6 MPa (moist), and the second subset contained trees with PWP < -0.6 MPa (dry). A PWP value of -0.6 MPa was chosen to distinguish two levels of water status based on the results of Sword Sayer and others (2005) who found that the new root growth of longleaf pine seedlings was significantly reduced when PWP was < -0.6 MPa.

Ordinary least squares regressions between 2 dependent variables (PWP, A_{sat}) and 14 independent variables (year, DAH, and BD, MIP, MAP, and PAWHC of the A, and upper and lower Bt1 horizons) were conducted by site, vegetation management treatment (control and herbicide), and water status (moist and dry) with SAS statistical software (SAS Institute, 9.2 ed., Cary, NC) using the generalized linear model procedure. Original regressions included tree basal area, but this independent variable was excluded from the final analysis because it was not significant. Correlation coefficients (r) were determined for significant regression relationships. The *F* statistics and coefficients of determination (R^2) were considered significant at $P \leq 0.05$.

RESULTS AND DISCUSSION

Soil Physical Properties

The physical properties of the two soil types changed over time and in response to vegetation management treatment. For example, all measured physical properties (BD, MIP MAP, PAWHC) of the Beauregard A horizon changed significantly by year (table 1). No significant effect of year, however, was observed in the A horizon of the Ruston soil (table 2). Subsoil bulk densities and porosities of both soil types were significantly affected by year in most comparisons, with a tendency for BD to decrease with time after planting (fig. 1). Specifically, the BD of the A and lower Bt1 horizons of the Beauregard soil decreased 7 and 6 percent respectively, and that of the upper and lower Bt1 horizon of the Ruston soil decreased 5 and 6 percent, respectively, between 2004 and 2009. A similar effect was observed in the Beauregard soil with 20, 16, and 9 percent lower MIP in the A, and upper and lower Bt1 horizons, respectively, between 2004 and 2009 (fig. 2). The only significant effect of year on Ruston MIP was observed in the lower Bt1 horizon with an 11 percent decrease between 2004 and 2009. As MIP decreased over time, significant increases in MAP were observed in the A and lower Bt1 horizons of the Beauregard soil and the upper and lower Bt1 horizons of the Ruston soil.

Table 1--Analyses of variance of mean soil physical properties at three depths of the Beauregard silt loam soil[a] in response to no vegetation management or vegetation management by herbicide application in central Louisiana

	A horizon			Upper Bt1 horizon			Lower Bt1 horizon		
Source of variation	df[b]	MS	Pr > *F*	df	MS	Pr > *F*	df	MS	Pr > *F*
Beauregard[a] bulk density (BD)									
Block (B)	2	0.00370	0.5277	2	0.01720	0.1687	2	0.00785	0.3727
Vegetation management (T)	1	0.00054	0.7518	1	0.00005	0.9195	1	0.00001	0.9618
error a[c]	2	0.00414		2	0.00349		2	0.00466	
Year (Y)	2	0.01682	0.0019	2	0.01529	0.1413	2	0.01682	0.0194
T x Y	2	0.01398	0.0040	2	0.00032	0.9484	2	0.00202	0.5137
error b[c]	8	0.00110		8	0.00606		8	0.00278	
Beauregard macroporosity (MAP)									
Block (B)	2	0.00247	0.5484	2	0.00388	0.1548	2	0.00240	0.2483
Vegetation Management	1	0.02200	0.1135	1	0.00012	0.7248	1	0.00023	0.6449
error a	2	0.00300		2	0.00071		2	0.00079	
Year	2	0.01485	<0.0001	2	0.00714	0.0609	2	0.00636	0.0107
T x Y	2	0.00014	0.6340	2	0.00013	0.9311	2	0.00023	0.7473
error b	8	0.00029		8	0.00176		8	0.00076	
Beauregard microporosity (MIP)									
Block	2	0.00446	0.1779	2	0.00050	0.4625	2	0.00042	0.0977
Vegetation Management	1	0.01962	0.0459	1	0.00005	0.7665	1	0.00034	0.1122
error a	2	0.00097		2	0.00043		2	0.00005	
Year (Y)	2	0.00563	0.0011	2	0.00360	0.0159	2	0.00118	0.0113
T x Y	2	0.00116	0.0716	2	0.000003	0.9946	2	0.00003	0.8139
error b	8	0.00031		8	0.00050		8	0.00014	
Beauregard plant-available water holding capacity (PAWHC)									
Block	2	29.5509	0.1453	2	37.6864	0.1957	2	6.60352	0.0297
Vegetation Management	1	135.772	0.0351	1	26.3824	0.2320	1	17.2386	0.0115
error a	2	5.02395		2	9.1713		2	0.2022	
Year	2	35.5328	0.0105	2	29.2363	0.0720	2	6.75891	0.5371
T x Y	2	8.58627	0.1907	2	1.85665	0.7948	2	0.69449	0.9338
error b	8	4.18200		8	7.85483		8	10.05080	

[a]Site 2 is mostly Beauregard silt with some Malbis fine sandy loam.
[b]df = degrees of freedom; MS = mean square; Pr > *F* = probability greater than *F*-value.
[c]error a df = (T-1) x (B-1); error b df = T x (B-1) x (Y-1).

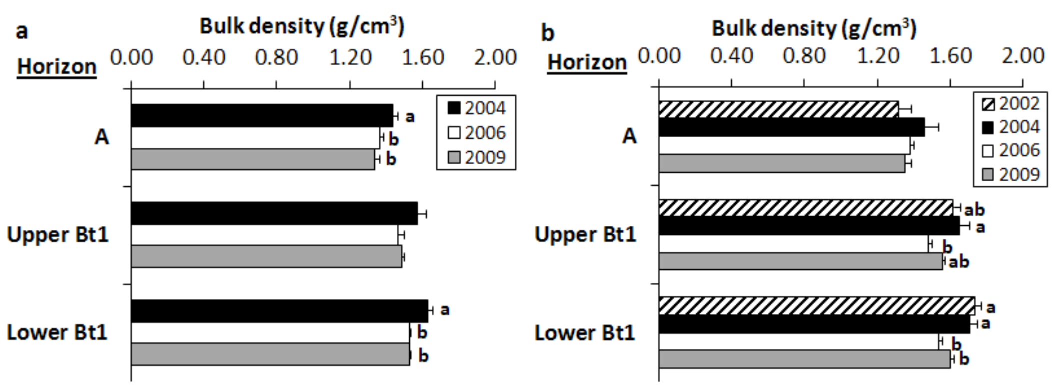

Figure 1--Mean bulk density of the A horizon, the upper Bt1 horizon, and the lower Bt1 horizon at (a) site 2 (Beauregard silt loam) and (b) site 1 (Ruston fine sandy loam) between 2002 and 2009. Bars represent one standard error of the mean. Means within a site and horizon associated with a different lower case letter are significantly different by the Tukey test at α = 0.05.

Table 2--Analyses of variance of mean soil physical properties at three depths of the Ruston fine sandy loam soil[a] in response to no vegetation management or vegetation management by herbicide application in central Louisiana

	----------A horizon----------			-----Upper Bt1 horizon-----			------Lower Bt1 horizon------		
Source of variation	df[b]	MS	Pr > *F*	df	MS	Pr > *F*	df	MS	Pr > *F*
	--Ruston[a] bulk density (BD)--								
Block (B)	1	0.04324	0.0491	1	0.00820	0.2690	1	0.01103	0.5783
Vegetation management (T)	1	0.03463	0.0548	1	0.00005	0.8897	1	0.00028	0.9209
error a[c]	1	0.00026		1	0.00166		1	0.01813	
Year (Y)	3	0.01351	0.3693	3	0.02364	0.0350	3	0.03492	0.0040
T x Y	3	0.01044	0.4611	3	0.02273	0.1047	3	0.00115	0.6442
error b[c]	5	0.01033		5	0.00362		5	0.00192	
	------------------------------------Ruston macroporosity (MAP)------------------------------------								
Block (B)	1	0.01152	0.3756	1	0.00009	0.5699	1	0.00004	0.8240
Vegetation Management	1	0.00249	0.6137	1	0.00039	0.3422	1	0.00191	0.3488
error a	1	0.00517		1	0.00014		1	0.00051	
Year	3	0.00279	0.5285	3	0.00330	0.0113	3	0.00546	0.0059
T x Y	3	0.00166	0.6993	3	0.00191	0.0344	3	0.00050	0.2521
error b	5	0.00333		5	0.00029		5	0.00025	
	------------------------------------Ruston microporosity (MIP)------------------------------------								
Block	1	0.00080	0.7691	1	0.00129	0.2616	1	0.00006	0.6419
Vegetation Management	1	0.00059	0.8001	1	0.000002	0.9400	1	0.00171	0.1826
error a	1	0.00557		1	0.00025		1	0.00015	
Year (Y)	3	0.00087	0.2298	3	0.00194	0.0664	3	0.00185	0.0419
T x Y	3	0.00012	0.8370	3	0.00089	0.2158	3	0.00019	0.6346
error b	5	0.00043		5	0.00042		5	0.00031	
	------------------Ruston plant-available water holding capacity (PAWHC)------------------								
Block	1	7.67860	0.7754	1	3.83116	0.6436	1	31.26675	0.5990
Vegetation Management	1	1.22113	0.9072	1	2.03810	0.6759	1	1.36180	0.9039
error a	1	56.6397		1	9.75411		1	58.83439	
Year	3	7.55600	0.1444	3	4.56002	0.6785	3	3.54153	0.0772
T x Y	3	1.24326	07169	3	4.44498	0.6862	3	0.86217	0.4541
error b	5	2.65142		5	8.53021		5	0.83685	

[a]Site 1 is mostly Ruston fine sandy loam with some Malbis fine sandy loam and Gore very fine sandy loam.
[b]df = degrees of freedom; MS = mean square; Pr > *F* = probability greater than *F*-value.
[c]error a df = (T-1) x (B-1); error b df = T x (B-1) x (Y-1).

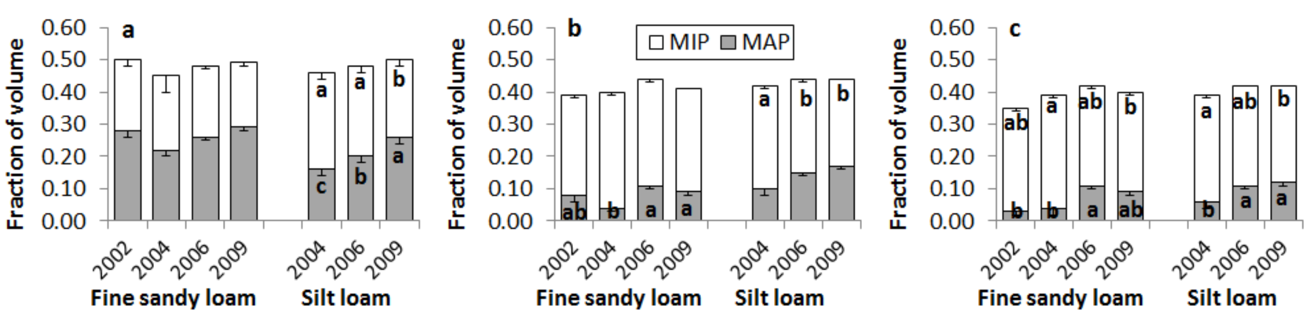

Figure 2--Mean macroporosity (MAP) and microporosity (MIP) of the A (a), upper Bt1 (b), and lower Bt1 (c) horizons at site 1 (Ruston fine sandy loam) and site 2 (Beauregard silt loam) between 2002 and 2009. Bars represent one standard error of the mean. Means within a site and horizon associated with a different lower case letter are significantly different by the Tukey test at α = 0.05.

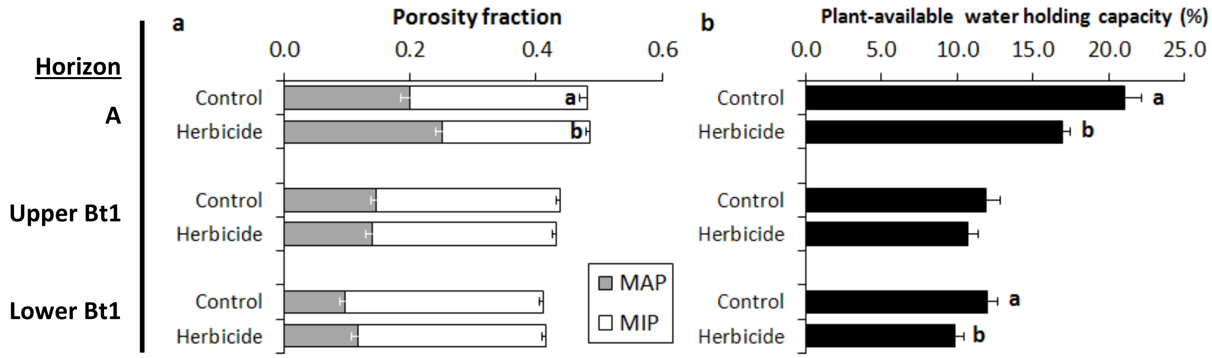

Figure 3--(a) Mean macroporosity (MAP) and microporosity (MIP) and (b) plant-available water holding capacity (PAWHC) at site 2 (Beauregard silt loam) in response to no vegetation management or vegetation management by herbicide application at the time of longleaf pine establishment. Bars represent one standard error of the mean. Means within a variable and horizon associated with a different lower case letter are significantly different by the Tukey test at α = 0.05.

Vegetation management treatment did not impact physical properties of the Ruston soil (table 2) but had a significant effect on the surface soil MIP and PAWHC of the Beauregard soil (table 1). Specifically, herbicide application resulted in 20 and 24 percent reductions in A horizon MIP and PAWHC, respectively, and a 16 percent drop in PAWHC in the lower Bt1 horizon (fig. 3). Two significant interactions between vegetation management treatment and year were also observed, with one indicating that the significant effect of year on the A horizon BD of the Beauregard soil was driven by a decrease in BD between 2004 and 2009 from 1.5 to 1.3 g/cm^3 for the H plots but no change in BD between 2004 (1.4 g/cm^3) and 2009 (1.4 g/cm^3) for the C plots. The second significant interaction was observed for upper Bt1 MAP in the Ruston soil with dramatically lower MAP on the C plots in 2004 compared to all other years regardless of vegetation management treatment. This effect is due to one measurement that was 83 percent lower than the average of all other comparable measurements. We attribute this unusual measurement and significant interaction to either an artifact of the soil sample or a measurement error.

Typical Beauregard and Ruston soils have average Bt1 bulk densities of 1.6 and 1.7 g/cm^3, respectively (National Cooperative Soil Survey 2013). The subsoils of these two soil types have the potential to restrict pine root system expansion because root growth limitations can be expected as BD exceeds 1.6 g/cm^3 (Kelting and others 1999, Pritchett 1979). In our study, average Bt1 bulk densities on the Beauregard and Ruston soils were 1.5 and 1.6, respectively, by 2009. Comparison between typical and actual BD values, and the temporal decreases in BD that we observed, suggest that the establishment of young longleaf pine plantations moderated the root-growth-limiting character of the subsoil at each site. A similar subsoil response was found 10 years after pines were harvested from six coastal plain soils across Texas, Louisiana, and Mississippi (Scott and others 2007, Sword and Tiarks 2002).

Soil porosities also suggest that the soil became more favorable for root growth between 2004 and 2009. On the Beauregard soil, losses in A and Bt1 horizon MIP that occurred between 2004 and 2009 were correlated with gains in MAP. Although not always significant, a similar trend was observed in the Bt1 horizon of the Ruston soil. It is conceivable that as non-pine vegetation recovered and planted pines grew, roots and their ectomycorrhizal networks were the primary source of these soil porosity changes. Shifts in MIP, therefore, were secondary to these initial changes in the fraction of soil porosity attributed to macropores as reported by Kramer and Boyer (1995).

The understory vegetation associated with the Beauregard soil at site 2 is dominated by grasses while that associated with the Ruston soil at site 1 is primarily composed of forbs and woody shrubs (Haywood 2007). Probable differences in understory vegetation rooting between the two sites in this study provide insight regarding why the two soil types had dissimilar responses to vegetation management treatment. It is likely that soil perturbation in the A horizon by grass roots was greater on the Beauregard soil compared to the Ruston soil because the root systems of grass are generally shallower and more fibrous than those of forbs and woody shrubs (Jackson and others 1996). On the C plots of the Beauregard soil where grasses were not chemically controlled by herbicides during establishment, fibrous grass roots may have maintained relatively higher levels of A horizon perturbation and organic matter enrichment. In this situation, an increase in MAP and a decrease in MIP would be expected as the grass fibrous root network expanded. Curiously, the opposite was observed on the Beauregard C plots with greater MIP and no difference in MAP attributable to grass root system expansion.

An evaluation of A horizon PAWHC provides an explanation for this observation. On the Beauregard soil, greater PAWHC on the C plots compared to the H plots indicates that the fraction of MIP capable of storing plant-available water was greater on the C plots compared to the H plots. This result implies that a larger fraction of large micropores existed in the A horizon on the C plots compared to the H plots. A critical component of this theory is grass and other plant roots that may have increased the fraction of MIP capable of containing plant-available water. Changes in MIP pore size distribution could have occurred directly by root system expansion or indirectly by the breakdown of macropores, established by roots, into large micropores (Kramer and Boyer 1995).

This mechanism of change in MIP and PAWHC, however, does not explain why lower Bt1 PAWHC in the Beauregard soil was greater on the C plots compared to the H plots. For this horizon, we speculate that clay mobilization rather than roots changed the distribution of micropore size within MIP. This was possible because the H plots had less understory vegetation than the C plots throughout the soil sampling period. This condition lessened soil perturbation by understory rooting. With less soil perturbation, relatively large, vertical, continuous soil pores could have been maintained which enabled the vertical movement of soil water containing fine clay particles from the A and upper Bt1 horizons (Bouma and Dekker 1978). The static nature of large soil macropores on the H plots would have allowed the vertical translocation of fine clay particles and their deposition on the surface of structural aggregates and inside soil pores in the lower Bt1 horizon (Buol and other 2011). With deposition of clay in the lower Bt1 horizon on the H plots, the fraction of small micropores would have increased, and the fraction of MIP capable of storing plant-available water would have decreased. To investigate this theory, the long-term monitoring of soil physical properties at this location will continue, and an assessment of lower Bt1 horizon micromorphological responses to vegetation management treatments will be considered if treatment effects on lower Bt1 PAWHC persist.

Tree Physiology and Soil Physical Property Relationships

A detailed synthesis of long-term loblolly pine production at seven locations concluded that water availability was not the main driver of loblolly pine productivity across this species' natural range (Jokela and others 2004). In support, earlier work by Cregg and others (1990) demonstrated that increases in available soil water induced by 50 and 75 percent reductions in basal area had little effect on loblolly pine water relations on a sandy loam soil in Oklahoma. Adaptation to the dry climate of the western edge of the southern pine region was also observed by Blazier and others (2004). In their study, two sources of loblolly pine, one each originating from a wet and dry location, had equivalent rates of gas exchange and stemwood production on a droughty Oklahoma soil. Others have also observed that water availability in the western edge of the southern pine range did not influence loblolly pine gas exchange unless trees were experiencing prolonged drought (Gravatt and others 1997; Tang and others 2003, 2004).

Our results indicate that the marginalization of water availability as a control of pine production in the Southeast may be due to an overriding effect of the soil physical environment on root system growth. We found that relationships between soil physical properties and longleaf pine tree vigor were primarily apparent in the absence of water deficit (i.e., PWP values > -0.6 MPa) (table 3). Patterns of significance in our regression analyses also indicate that maintenance of some level of understory vegetation may alleviate harsh soil physical conditions. On soil types similar to those in our study, therefore, the physical environment of the soil and the amount and distribution of understory vegetation could have a marked effect on pine vigor as measured by photosynthesis rate and predawn water potential.

Two observations suggested that when moisture was adequate on the C plots, the A horizon maintained a level of control on A_{net} by affecting plant-available water storage. These observations

Table 3--Significant partial coefficients of determination (*R^2*) and probabilities of a greater *F*-value (Pr > *F*) for multiple regressions between two dependent variables (rate of upper-crown net photosynthesis in the afternoon (A_{net}), predawn needle water potential (PWP)), and 14 independent variables (year, depth to the argillic horizon (DAH), and soil bulk density (BD), microporosity (MIP), macroporosity (MAP), and plant-available water holding capacity (PAWHC) of the A and upper and lower Bt1 horizons). When partial *R^2* values were significant, correlation coefficients (*r*) are reported. Regressions were conducted by site (sites 1 and 2), water status (dry and moist), and vegetation management treatment for data with DAH within one standard deviation of the mean DAH of each site

Soil type[a]	Water status	Vegetation management treatment	Dependent variable	Observations (no.)	Significant independent variable	Partial R^2	Pr > *F*	*r*
Ruston	Moist	Control	A_{net}	13	none			
			PWP	13	none			
		Herbicide	A_{net}	14	upper Bt1 BD	0.4651	0.0072	0.6820
				14	upper Bt1 MIP	0.2323	0.0143	-0.4820
			PWP	14	lower Bt1 MIP	0.3853	0.0179	0.6207
				14	A BD	0.1992	0.0423	-0.4463
				14	DAH	0.2300	0.0055	-0.4796
	Dry	Control	A_{net}	9	lower Bt1 BD	0.4917	0.0353	0.7012
			PWP	9	none			
		Herbicide	A_{net}	12	year	0.6726	0.0011	-0.8201
			PWP	12	none			
Beauregard	Moist	Control	A_{net}	15	A MIP	0.7506	<0.0001	0.8664
			PWP	15	none			
		Herbicide	A_{net}	16	A PAWHC	0.4181	0.0068	-0.6466
			PWP	16	upper Bt1 BD	0.4633	0.0037	-0.6807
	Dry	Control	A_{net}	1	none			
			PWP	1	none			
		Herbicide		6	none			
			PWP	6	A MIP	0.7708	0.0214	-0.8780

[a]Site 1 is mostly Ruston fine sandy loam with some Malbis fine sandy loam and Gore very fine sandy loam. Site 2 is mostly Beauregard s loam with some Malbis fine sandy loam.

were a positive correlation between A horizon MIP and A_{net} on the C plots (table 3), and greater A horizon PAWHC and MIP on the C plots compared to the H plots (fig. 3). Absence of a significant MIP-A_{net} correlation on the H plots indicates that this relationship may be important when understory vegetation, grass in particular, is competing with pines for water at young ages (Haywood 2007).

In contrast, on the Beauregard H plots we observed negative relationships between A_{net} and A PAWHC and between PWP and upper Bt1 BD (table 3). One interpretation of these negative relationships is that with the translocation of clay and silt from the A horizon to the argillic horizon, A horizon MIP decreased and A horizon MAP increased (Buol and other 2011). These possible soil porosity responses to clay translocation would naturally reduce A horizon PAWHC. With clay illuviation into the upper Bt1, the BD of this soil layer may have grown closer to creating a barrier to root elongation, restricting pine root system expansion and reducing the effective root-zone. If this were the case, PWP would have become more negative due to root-zone restriction and an increase in upper Bt1 BD. Subsequently, an indirect, negative relationship between A_{net} and A horizon PAWHC would develop.

The relationship between physiological function and BD in the upper Bt1 differed between the two sites, and we believe that these findings reflect the distinct textural differences between the Beauregard and Ruston soils. For example, while both soil types contain equivalent amounts of clay in the A, E, and Bt1 horizons, their silt and sand fractions differ. The Ruston soil contains approximately 46 percent less silt and 54 percent more sand than the Beauregard soil (National Cooperative Soil Survey 2013). Also, the E and Bt1 horizons of the Ruston soil are fine sandy loam and clay loam in texture, respectively, whereas comparable horizons of the Beauregard soil are both silt loam in texture (National

Cooperative Soil Survey 2013). As with the Beauregard soil, clay content in the Bt1 horizon of the Ruston soil could have been correlated with the formation of extreme bulk densities that limited the effective root-zone. However, we speculate that the sand content of the Ruston soil maintained the integrity of macropores and allowed the creation of micropores by the formation of clay coatings (i.e., cutans) on the surface of sand particles and clay bridges between sand particles (Buurman and others 1998). Furthermore, this positive effect of sand on soil porosity and, subsequently, root system expansion superseded any negative effects of high BD on root elongation in the Ruston soil. Because a decrease in MIP implies there was an increase in MAP, this concept is supported by the negative relationship between A_{net} and upper Bt1 horizon MIP (table 3). We attribute the absence of a significant positive correlation between pine vigor variables and upper Bt1 MAP to the inherently high variability of MAP.

With the illuviation of clay in the fine sandy loam layer that is below the clay loam layer in the Ruston soil, the formation of cutans and clay bridges could have favored the fraction of MIP capable of storing plant-available water. Positive correlation between PWP and lower Bt1 MIP reflects this phenomenon (table 3). However, absence of a similar significant relationship between PWP and PAWHC in the lower Bt1 MIP suggests that there are aspects of clay illuviation other than its effect on MIP and PAWHC that also affect pine vigor.

SUMMARY

This report summarizes 8 years of soil physical property responses to the manipulation of understory vegetation on two common forest soils in the West Gulf Coastal Plain. This long-term soil monitoring effort will continue, and the mechanisms of soil change will be explored as warranted. We also describe a short-term study of the relationship between pine vigor and the soil physical environment. Results demonstrate temporal changes in porosity fractions and bulk densities that potentially favor pine root system expansion and represent the natural recovery of Beauregard silt loam and Ruston fine sandy loam soils after disturbance. Differences in soil porosity fractions in response to two extremes in vegetation management suggest that temporal changes in soil physical properties were correlated with the reestablishment of understory vegetation after pine seedlings were planted. In the A horizon, it is possible that soil perturbation by grass and other plants indirectly benefited pine vigor by increasing the water-holding capacity of soil micropores. Soil physical property changes in the upper and lower Bt1 horizon may have been due to clay illuviation. Inconsistent relationships between pine vigor variables and subsoil physical properties between the two soils suggest that in addition to clay illuviation, factors such as subsoil sand content play a role in pine vigor. These results provide insight regarding soil variables of probable importance to root system expansion and pine vigor and the sensitivity of pine vigor to differences in understory vegetation and subsoil texture on the West Gulf Coastal Plain.

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