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Loblolly Pine (*Pinus taeda* L.) Seedling Growth Response to Site Preparation Tillage on Upland Sites

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Mechanical site preparation has been considered essential to southern pine plantation establishment since the 1950s. Although survival and early growth responses to site preparation are well documented, several factors often contribute to these responses, and the specific contribution of soil tillage is not well established. Soil moisture content, soil resistance to penetration, and loblolly pine (*Pinus taeda* L.) growth were measured on eight sites in the Upper Coastal Plain (UCP) and Piedmont in tilled (T) and nontilled (NT) rows under three conditions: operational site preparation with initial vegetation control (O), operational plus annual fertilization (O+F), and operational plus annual fertilization and complete vegetation control (O+F+V). Tillage reduced average soil resistance to penetration by 9 to 51% across cultural treatments. Soil tillage also reduced volumetric water content. On the most affected site, T rows contained 68% of the water of NT rows in the 0.15- to 0.30-m interval and 53% of the water in the 0.30- to 0.60-m interval. Tillage resulted in positive growth responses on seven of the eight sites, and growth increases occurred across all cultural treatments. After two growing seasons, the largest trees were on a Lucy series soil where the O+F+V treatment resulted in an average stem volume index (SVI) of 8932 cm^3. The smallest trees were on a clayey Faceville series soil where the NT rows in the O treatment had an average SVI of 101 cm^3. Growth responses were poorly correlated with measured differences in average resistance or differences in resistance between T and NT rows in any depth increment (0–0.15, 0.15–0.30, or 0.30–0.60 m); however, soil resistance in the 0- to 0.15-m depth increment demarcated an upper bound for growth. A tillage effect on the volume of soil below a critical soil resistance was helpful for explaining some of the observed responses.

Abbreviations: GLD, ground line diameter; HT, height; NT, nontilled; O, operational site preparation with initial vegetation control; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control; SVI, stem volume index; T, tilled; TDR, time domain reflectometry; UCP, Upper Coastal Plain.

Core Ideas

- **Operational tillage increases pine growth on upland sites of the Upper Coastal Plain and Piedmont.**
- **Growth responses to tillage occur across fertilization and competition control treatments.**
- **Tree size was not well predicted by mean soil resistance.**
- **Soil resistance in the 0- to 0.15-m depth increment delineated an upper bound for tree size two years after planting.**

The southeastern United States is the world's largest industrial wood producer, with approximately 16 million hectares of industrial pine timberland (Prestemon and Abt, 2002; Haynes, 2002; Smith et al., 2004). Wood demand from this region is expected to increase, and the land base dedicated to silvicultural practices is expected to continue to shift from natural forests owned by nonindustrial private landowners to pine plantations (Allen et al., 2005). Thus, the role of intensive forest management to maintain and increase wood production is increasing in significance (Borders and Bailey, 2001; Fox, 2000; Martin and Shiver, 2002).

Since the 1950s, mechanical site preparation has been considered essential to southern pine plantation management (Martin and Shiver, 2002). Mechanical site preparation includes a variety of techniques. Some of these techniques, such as

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shearing and piling, are designed to remove logging debris and make the site more operable and are not intended to impact soil physical conditions. Others, such as bedding or bedding combined with subsoiling (as with a combination plow), are specifically designed to improve soil physical conditions that affect root growth. Regardless of intent, all mechanical site preparation treatments simultaneously affect several factors important to seedling establishment and growth, including soil resistance to penetration, soil water holding characteristics, competing vegetation quantity and species, and nutrient mineralization and availability (Martin and Shiver, 2002; Morris and Lowery, 1988; Pehl, 1983). While survival and increased early growth due to mechanical site preparation has been well documented (e.g., Rahman et al., 2006; Shiver and Fortson, 1979; Tiarks and Haywood, 1996; Wittwer et al., 1986), it is seldom clear how much, if any, of this benefit is due to tillage and improvements in soil physical conditions. Understanding the mechanism of response is important. On sites where response can be attributed to reduced plant competition or increased nutrient availability, less expensive alternatives to mechanical site preparation are available (Allen, 2001).

Tillage treatments can be an important and irreplaceable component of site preparation response when they ameliorate soil physical limitations, such as high resistance to root penetration or poor aeration, whether these limitations occur naturally or result from soil compaction during harvest (Allen et al., 2005; Carlson et al., 2006; Wheeler et al., 2002). Each tillage treatment results in a different volume and configuration of tilled soil (Morris and Lowery; 1988) and will have benefits that depend on both soil conditions and postplanting weather conditions. Rapid root system development during the first year in the field is critical for increasing the chance of good survival and early growth (Adegbidi et al., 2004; Dougherty and Gresham, 1988). Surface tillage treatments, such as disking, can improve root growth by decreasing soil mechanical impedance to root penetration and can improve water infiltration and subsequent soil moisture conditions. Other benefits are incorporation of organic matter and increased mineralization and availability of nutrients. On poorly drained sites, bedding has the potential to lift seedlings in relation to the water table level and provide a well-aerated zone during seedling establishment (Aust et al., 1998; Morris and Lowery, 1988; Wheeler et al., 2002). On upland sites, high resistance to root penetration is considered a major limitation to seedling establishment and growth. Deep tillage by subsoiling or subsoiling combined with surface tillage can reduce resistance to penetration and increase seedling growth. Furthermore, this type of upland tillage can improve water infiltration and reduce runoff, which can potentially reduce moisture stress during dry seasons (Morris and Lowery, 1988; Wheeler et al., 2002).

The benefits of upland tillage have been evaluated on UCP and Piedmont sites. Schilling et al. (2004) reported that root architecture was primarily influenced by subsoiling treatments regardless of surface tillage or machine planting. Their results suggested that machine planting did not differ significantly from combination tillage in terms of young loblolly pine growth. Wheeler et al. (2002) investigated the effects of machine planting, disking, bedding, and combination tillage on the survival and growth of loblolly pine on seven sites in the Piedmont and UCP regions of Georgia. At the end of the third growing season following planting, survival ranged from a low of 75% in the NT treatments to 86% in the disked treatment. Bedding resulted in the most consistent positive response, and there was little advantage to additional subsoil tillage. Overall, growth responses to tillage practices were relatively small and site specific. Another study, conducted by Carlson et al. (2006), examined the effect of surface and subsurface tillage on the survival and growth of loblolly pine on 15 sites in the Southeast. Responses to tillage on upland sites were assessed based on specific soil and site characteristics. Although subsoiling resulted in some positive responses, such as improving survival from 74 to 82% on four Piedmont sites, growth responses were unpredictable and growth was improved by subsoiling on only two of the 15 sites. Surface tillage resulted in the greatest short-term growth responses. Generally, responses were greater for soils with siliceous mineralogy. Soils with kaolinitic or mixed mineralogy did not respond to tillage. The authors suggested that this was because these soils tended to have better structure and lower bulk densities than soils with siliceous mineralogy. Finally, Lincoln et al. (2007) evaluated the effect of five tillage treatments on first-year loblolly pine survival and growth on three different sites in the UCP. Seedling growth was measured at the plot level, and relationships of growth to soil volumetric water content and soil resistance to penetration growth were developed for three intensively monitored seedlings within each plot. Survival was not affected by treatments and ranged from 63 to 99%. These investigators found positive, but small, effects of soil tillage on first year seedling growth, and these were generally achieved with the least intensive tillage treatments. For intensively monitored seedlings, soil resistance to penetration was negatively correlated to measures of growth or size on two of the sites. These relationships explained 35 to 51% of the observed variation; however, the relationships were not robust. Both the measurement of seedling growth and the soil depth interval used to develop these relationships differed by site.

Pine plantation growth responses associated with mechanical site preparation that are due to improved soil physical conditions cannot be replaced by other silvicultural treatments. Although studies of site preparation and tillage effects on tree growth are common, relatively few studies have separated plant benefits due specifically to tillage effects on soil physical properties from other factors. The specific objectives of this study were to (i) isolate and quantify the effects of operational soil tillage on soil water content and soil resistance of upland sites, (ii) test the hypothesis that seedling survival and growth response would be greatest on sites where operational tillage resulted in the greatest reduction in soil resistance, and (iii) develop a relationship between seedling size and soil resistance for the first two growing seasons following planting.

MATERIALS AND METHODS

Site Locations

Eight experimental sites, utilizing a common study design, were established in 2005 in Georgia and Alabama. Five sites were located in the UCP of Georgia on tracts of land owned by MeadWestvaco. Four of these sites were established near the city of Lumpkin in Stewart County, GA and one west of Omaha, GA in Russell County, AL. Three sites were located in the Piedmont region, on tracts of land owned by Plum Creek, one in the proximity of the city of White Plains in Greene County, GA and two near Watkinsville in Oconee County, GA. All sites were established on forests harvested during the year before plot establishment. Seven of the eight sites were well drained. The exception was the site identified as the Gritney soil series (fine, mixed, semiactive, thermic Aquic Hapludult) in Table 1. Field evaluation of this site indicated that it was at the break between somewhat poorly and moderately well-drained soil. There was evidence of a perched water table maintained by lateral flow along a slowly permeable argillic horizon.

In general, the study sites were characterized by soil series that were expected to respond to soil tillage during site preparation, and all of them had been selected by our industrial cooperators for site preparation that included tillage. Only the site identified as the Lucy series (loamy, kaolinitic, thermic Arenic Kandiudult) had coarse-textured surface horizons that were $\geq$0.50 m deep (Arenic) over the argillic horizon. All of the other sites were characterized by soils with surface horizons that were <0.50 m deep over the argillic horizon (Typic). However, significant differences in the A (or Ap) horizon depth and the texture of the horizon immediately below this horizon existed (Table 1).

Study Design and Installation

This study used a design that both minimized site and soil variation within the study area and provided conditions where tree growth and soil measurements were spatially connected while still allowing treatments to be installed under operational conditions. Each of the eight sites was approximately 280 m^2 (14 by 20 m) and was established using a strip-plot design (also known as a split-block design). Sites consisted of three pairs of tilled and adjacent non-tilled rows (blocks) with cultural treatment strips assigned across the rows. Cultural treatment strips were randomly assigned for the first block, and this assignment was carried across the other two blocks (i.e., the cultural treatment assignment was not randomized separately for each block) (Fig. 1). To control tree-growth variability due to genotype, each block consisted of a single loblolly pine clone (LB-SE Q3802, LB-SE L3519, or LB-SE O3621). Strips consisted of three cultural treatments: no culture beyond operational site preparation

Table 1. Characteristics of eight sites used in field experiments of loblolly pine growth response to operational tillage, fertilization and vegetation control.

Location	A horizon depth, m	A horizon/subsurface texture class†	Drainage‡	Soil series	Operational site preparation	Planted §
			Upper Coastal Plain			
Lumpkin, GA	0.05	CL/SC	W	Faceville	11 Mar. 2004-mechanical subsoiling/disking 17 Sept. 2004-chemical aerial	15 Feb. 2005
Russell County, AL	0.15	LS/LS	SP/MW	Gritney	23 Oct. 2004-chemical aerial 15 Nov. 2004-mechanical round pile 15 Dec. 2004-mechanical disking	16 Feb. 2005
Lumpkin, GA	0.20	LS/SL	W	Lucy	11 Mar. 2004-mechanical subsoiling/disking 19 Sept. 2004-chemical aerial	15 Feb. 2005
Lumpkin, GA	0.08	LS/SC	W/MW	Nankin	11 Mar. 2004-mechanical subsoiling/disking 17 Sept. 2004-chemical aerial	15 Feb. 2005
Lumpkin, GA	0.05	LS/SCL	W	Orangeburg	16 Mar. 2004-mechanical subsoiling/disking 28 Sept. 2004-chemical aerial	15 Feb. 2005
			Piedmont			
Watkinsville, GA	0.05	SL/CL	W	Cecil	3 Aug. 2003-clearcut 11 May 2004-chemical aerial 7 Oct. 2004-mechanical round pile and mechanical subsoiling	14 Feb. 2005
Watkinsville, GA	0.25	L/CL	W	Lloyd	25 Sept. 2003-clearcut 15 May 2004-chemical aerial 19 Oct. 2004-mechanical round pile and mechanical subsoiling	14 Feb. 2005
White Plains, GA	0.05	SL/SCL	W	Rion	25 Sept. 2003-clearcut 17 May 2004-chemical aerial 19 Oct. 2004-mechanical round pile and mechanical subsoiling	14 Feb. 2005

† Textures are for A or Ap horizon and horizon immediately below it (e.g. E, BE, BA, Bt).

‡ Drainage class: W, well; MW, moderately well; SP, somewhat poorly.

§ Planted with varieties: LB-SE Q3802, LB-SE L3519, and LB-SE O36321 (CellFor Corp., Atlanta, GA).

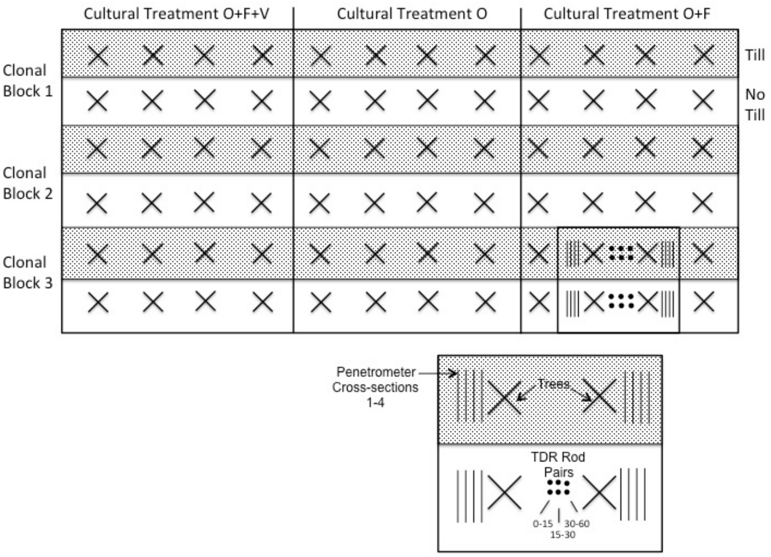


Fig. 1. Example layout of a study site showing clonal blocks, tillage (operational tillage or no tillage), cultural treatments (O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control), and detail of monitoring points.

(excluding tillage) and initial competition control (O), the operational treatment plus annual fertilization (O+F), and the operational treatment plus annual fertilization plus complete competing vegetation control (O+F+V). This was crossed with two tillage treatments: no tillage (nontrafficked rows) (NT) versus operational tillage (T) (Fig. 1). Operational tillage varied among sites, but in all but one case included some degree of both surface and subsoil tillage (Table 1). The three Piedmont sites were subsoiled to a nominal depth of 0.40 to 0.50 m following spot piling using a tractor-mounted subsoiler with a small (0.25 m) wing and hydraulics that allowed the shank to ride over large stumps. All operations were completed in October 2004 following a dry (21 mm of precipitation recorded in nearby Athens, GA) 2-wk period (U.S. Climate Data, 2015). The four well-drained Upper Coastal Plain sites were tilled with a tractor-mounted combination plow configured with a 1.2-m coulter wheel, subsoil shank (nominal depth of 0.50–0.60 m), two coulter disks (0.8-m diam.), and a chopper packer. These operations were completed in mid-March 2004 after two dry weeks (6 mm of precipitation recorded in nearby Columbus, GA). The somewhat poorly drained Gritney site was not subsoiled but was disked with a woods harrow to a nominal depth of 0.15 to 0.20 m in December 2004. Precipitation during the preceding 2-wk period in Columbus, GA totaled 25 mm (U.S. Climate Data, 2015).

Each measurement plot contained eight trees, four on the T row and four on the NT row. A total of 72 trees were planted within each of the eight sites; 36 trees were monitored and utilized for measurements, and the remaining 36 served as single-tree buffers around the measurement trees. The pine seedlings were hand planted at a 1.5-m spacing using dibble bars from 14 to 16 Feb. 2005.

Annual fertilization treatments on O+F and O+F+V plots consisted of N, P, and K at 47, 11, and 49 kg ha^{-1}, respectively. The annual fertilizer application was 93 kg ha^{-1} of urea (46-0-0), 42 kg ha^{-1} of triple superphosphate (TSP; 0-45-0), and 91 kg ha^{-1} of muriate of potash (0-0-60). Macro and micronutrients were also applied in the form of Holly-tone (Espoma Company, Millville, NJ) at 112 kg ha^{-1}. Fertilizer applications were split between spring and summer. Fertilized and vegetation-free plots (O+F+V) were maintained by either direct application of Roundup (glyphosate; Monsanto Company, St. Louis, MO) to foliage of competing vegetation alone or in combination with hand weeding throughout the 2-yr study period. The pesticide Sevin (carbaryl; GardenTech, Palatine, IL) was applied to all seedlings in July and September of the first growing season (2005) to reduce tip-moth (*Rhyacionia frustrana*) infestation.

Soil Measurements

Water content was measured approximately biweekly during the first two growing seasons following planting by time domain reflectometry (TDR) using a Tektronix cable tester (Tektronix, Inc., Beaverton, OR) (Topp and Davis, 1985). Pairs of steel rods (0.05-m spacing) were driven into the soil to three depths: 0.15, 0.30, and 0.60 m. Rods used to measure soil water in the 0- to 0.15-m depth increment were 0.30 m in length but were installed at a 30° angle to the soil surface. Water content in the 0- to 0.30- and 0- to 0.60-m depth increments was measured with rods of these lengths driven vertically into the soil to the respective depths. A total of 18 TDR sets were installed in each of the eight experimental sites. Each set of rods was placed between two measurement trees (i.e., two measurement trees were associated with each of the 18 sets of soil moisture readings at each experimental site) (Fig. 1). Soil water content for the 0- to 0.15-m depth increment was measured directly. Soil water content for the 0.15- to 0.30-m and 0.30- to 0.60-m depth increments was calculated from the integrated measurement (0–0.30 or 0–0.60 m) by adjusting for water content of the shallower depth increments.

Soil mechanical impedance was measured with a Rimik cone penetrometer (Toowoomba, Australia). The shaft was mounted with a 30° angle, 130-mm^2 cone (Standard ASAE S313.3). Measurements were taken for each of the monitored pine tree seedlings, and 0.60-m depth insertions were taken perpendicular to the planting row. Five insertions spaced 0.15 m apart were made for a 0.60-m width perpendicular to the planting row (Fig. 2). A total of 180 insertions were done per site. Penetrometer data were collected four times during the 2-yr study period. Initial measurements were made at 0.20-m distance from the monitored trees, and each new measurement was spaced 0.10 m from the measurements collected during the previous monitoring period.

Penetrometer Data Management

The data stored in the Rimik penetrometer unit consisted of soil resistance values collected at 0.025-m depth increments, covering the 0.60-m depth profile (24 resistance values per insertion). After conducting experimental trials using the hand-held cone penetrometer utilized in this investigation, it was noticed that soil resistances greater than 4500 kPa were often times not recorded since these pressure values were near the load cell limit. For these specific cases, a Visual Basic (VBA; Microsoft, 2002) routine was developed to generate a matrix of missing resistance values at deeper horizons. When reaching the maximum load limit, this program would identify the last point of data recorded, average it with the previous value, and fill in missing deeper data with this average.

To quantify the changes in average site soil penetration resistance associated with tillage, the 0.6- by 0.6-m grid created in the previous step was interpolated using the filled contour plot in SigmaPlot software (SigmaPlot version 9.01; Systat Software, Inc., San Jose, CA). Nonrestrictive rooting volume was estimated using the cross-sectional area of soil with a resistance of <2500 kPa as an index (Taylor et al., 1966; Torreano, 1992).

Seedling Measurements

Survival, height (HT), and ground line diameter (GLD) were periodically measured for the same 36 pine seedlings per site throughout the 2-yr study. Measurements made at the end of the second growing season were used to calculate the SVI using the following relationship:

$$\mathrm{SVI} = \mathrm{HT} \times \mathrm{GLD}^2$$

Statistical Analyses

Soil water content, soil resistance to penetration, and growth measurements were analyzed on a site-by-site basis for tillage, cultural treatments, and tillage × cultural treatment interaction for a strip-plot design using SAS ANOVA procedures (SAS Institute, 2006). To complete these analyses, we assumed that there was little interaction between clones (which were confounded with blocks) and treatments and that incomplete randomization of cultural treatments did not bias the analyses. Where significant differences in water content or resistance occurred, they were separated using Duncan's test at the 0.05 probability level. Where significant differences in HT, GLD, or SVI occurred, they were separated using Tukey's test at 0.05 and 0.10 probability levels. Regression equations were developed between tree size, as measured by SVI at the end of the second growing season, and measures of average soil resistance and differences in soil resistance between T and NT rows. Additionally, linear regressions were developed between measured soil resistances in one depth increment with measured resistances in the depth increment immediately below. These regressions were completed using the regression function in Microsoft Excel (version 14.4.9).

RESULTS

Soil Moisture

Overall, tillage resulted in lower volumetric water content (Table 2), particularly in the two depth increments nearest the surface (0–0.15 and 0.15–0.30 m). Generally, differences in volumetric moisture content between T and NT rows were less in the deepest depth increment (0.30–0.60 m), but differences were still statistically significant. The greatest differences in the Piedmont were measured at the Lloyd (fine, kaolinitic, thermic Rhodic Kanhapludult) site where T rows, on average, contained 68% of the water, by volume, of NT rows in the 0- to 0.15-m interval and 53% of the water, by volume, in the 0.15- to 0.30-m interval. The greatest differences in the Upper Coastal Plain were measured at the Nankin (fine, kaolinitic, thermic Typic Kanhapludult) site where T rows, on average, contained 44% of the water, by volume, of the NT rows in the 0- to 0.15-m depth increment. On most sites, a statistically significant interaction (not shown) between tillage and cultural treatment or tillage, cultural treatment, and depth increment occurred. Most often, average soil water content was lower in fertilized plots without additional vegetation control (O+F) than in the other two cultural treatments (e.g., Faceville [fine, kaolinitic, thermic Typic Kandiudult], Lucy, Orangeburg [fine-loamy, kaolinitic, thermic Typic Kandiudult], Rion [fine-loamy, mixed, semiactive, thermic Typic Hapludult]), particularly with tillage, but this pattern was not consistent. Values presented in Table 2 are averages for dry and wet periods, and differences in water use among cultural treatments that occurred during the growing season are tempered by smaller and nonsignificant differences during wet winter periods.

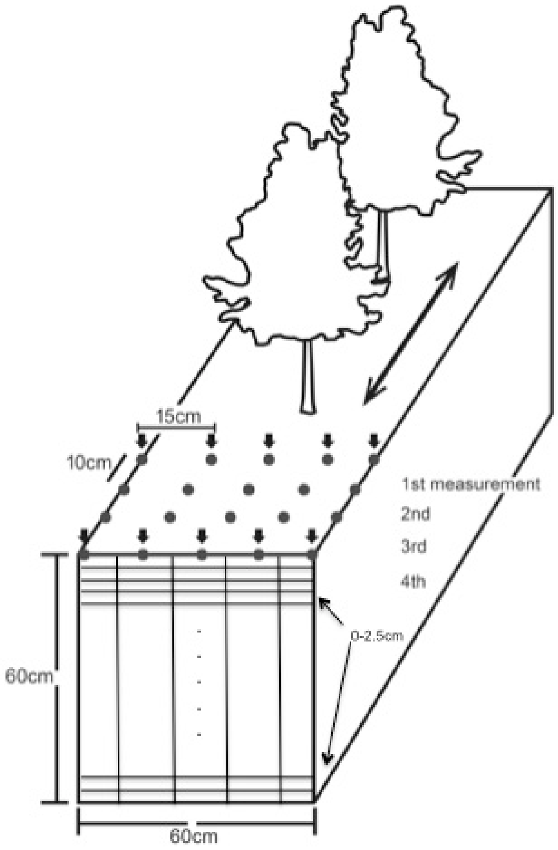


Fig. 2. Location of soil resistance to penetration measurements in relation to planting rows and measurement trees.

Both the total annual precipitation and its monthly distribution were distinctly different for the two growing seasons following planting. Annual precipitation totaled 1588 mm during the first growing season, which was 400 mm greater than the 30-yr average. During the first growing season, monthly precipitation exceeded 30-yr monthly averages from January through August, and March through July precipitation, in particular, was well above normal (99 vs. 52 mm). Drier than normal conditions began in September of the first growing season and, in contrast to the first growing season, March through August precipitation during the second growing season totaled only 34 mm. Patterns of volumetric soil water content presented in Fig. 3 to 5 for three of the eight sites reflect these annual and seasonal differences with generally lower soil water contents during the second growing season. There were no obvious differences in seasonal patterns among treatments with the exception that, as noted above, the depletion of soil water was steeper during the summer on fertilized sites that did not receive additional vegetation control than for the other cultural treatments, particularly on T sites. Differences between T and NT rows were relatively constant across cultural treatments within each site, but the absolute difference varied among sites. The lower volumetric water contents of T versus NT rows of the same cultural treatment largely reflect lower soil bulk densities in T rows; however, differences in volumetric soil water content among cultural treatments within the same tillage treatment most likely reflect differences in gravimetric water content and, hence, may indicate differences in plant water availability. For example, fertilization in the absence of competition control resulted in more rapid water use and lowered available water.

Table 2. Effects of tillage and cultural treatments on average volumetric soil water content for three soil depth increments during two growing seasons following planting. Each value is the average of 17 soil water measurements.

		Depth increment‡					
		0–0.15 m		0.15–0.30 m		0.30–0.60 m	
Site	Culture†	T	NT	T	NT	T	NT
		$\text{m}^3\ \text{m}^{-3}$					
		Upper Coastal Plain					
Faceville	O^{a}§¶	0.16	0.30	0.24	0.37	0.46	0.60#
	O+F^{b}	0.12	0.27	0.18	0.39	0.39	0.48
	O+F+V^{a}	0.13	0.31	0.38	0.37	0.33	0.50
Gritney	O^{a}	0.25	0.32	0.45	0.49	0.60#	0.60#
	O+F^{a}	0.21	0.33	0.44	0.45	0.60#	0.60#
	O+F+V^{b}	0.19	0.32	0.24	0.49	0.52	0.60#
Lucy	O^{a}	0.07	0.13	0.13	0.27	0.23	0.25
	O+F^{a}	0.06	0.13	0.12	0.27	0.28	0.33
	O+F+V^{a}	0.08	0.14	0.17	0.23	0.28	0.26
Nankin	O^{b}	0.07	0.24	0.22	0.37	0.35	0.43
	O+F^{a}	0.09	0.23	0.16	0.42	0.38	0.55
	O+F+V^{a}	0.16	0.25	0.22	0.39	0.36	0.56
Orangeburg	O^{b}	0.14	0.19	0.16	0.26	0.20	0.29
	O+F^{c}	0.09	0.15	0.20	0.30	0.15	0.23
	O+F+V^{a}	0.12	0.19	0.21	0.29	0.22	0.30
		Piedmont					
Cecil	O^{a}	0.19	0.21	0.31	0.42	0.29	0.39
	O+F^{b}	0.17	0.27	0.28	0.38	0.29	0.33
	O+F+V^{a}	0.17	0.23	0.33	0.35	0.36	0.42
Lloyd	O^{a}	0.13	0.23	0.19	0.31	0.18	0.34
	O+F^{b}	0.15	0.17	0.17	0.33	0.16	0.27
	O+F+V^{ab}	0.13	0.20	0.15	0.32	0.21	0.33
Rion	O^{a}	0.19	0.20	0.31	0.30	0.29	0.29
	O+F^{b}	0.15	0.16	0.21	0.25	0.23	0.27
	O+F+V^{a}	0.18	0.23	0.27	0.37	0.28	0.29

† O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control.

‡ Volumetric water content is statistically significant for the tilled (T) and nontilled (NT) treatment comparison across cultural treatments for all sites ($\alpha \leq 0.05$).

§ Cultural treatment means with dissimilar superscripts differ significantly across depth increments using Duncan's significance difference test ($\alpha \leq 0.05$)

¶ At least one higher order interaction (tillage × culture, tillage × depth, or tillage × depth × culture) is significant ($\alpha \leq 0.05$) on every site; significant differences occur among depth increments at all sites (not shown).

Saturated soil conditions occurred on one or more occasions, and these were beyond the calibration limits for the time domain reflectometry (TDR).

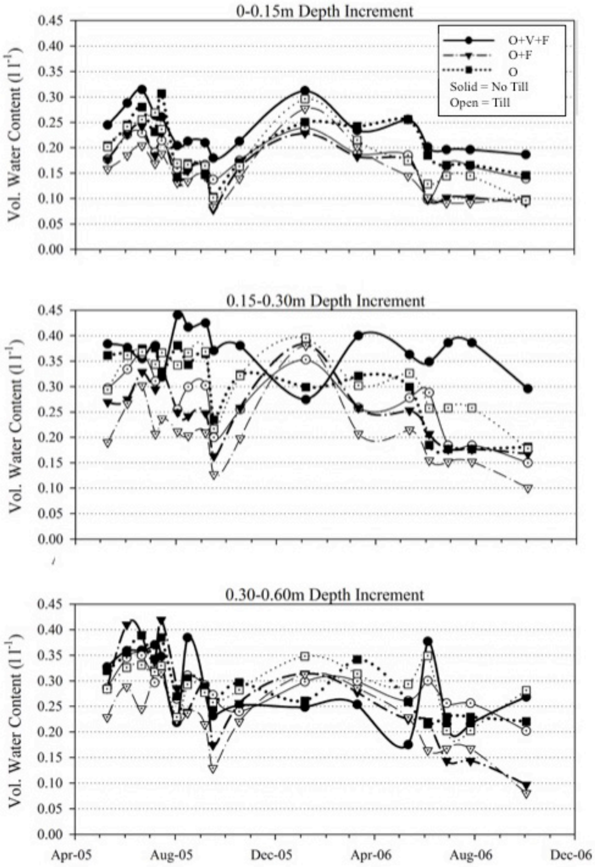


Fig. 3. Seasonal variation in volumetric soil water content during 2 yr following planting at the Rion series study site. O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control.

Soil Resistance

Soil resistance to penetration was decreased by operational tillage for all sites at the 0.05 level of probability (Table 3). Generally, average soil resistances were greater and the reduction in resistance associated with tillage less in deeper depth increments, but there was no interaction between treatment and depth. Reduced penetration resistance in the 0.30- to 0.60-m depth increment indicates that subsoiling extended into this deepest depth increment, as it should have based on nominal tillage depths. Differences in soil resistances among depth increments were significant for all sites except the Orangeburg site at $P \leq 0.01$. For the Orangeburg site, resistance was significantly different among depth increments at $P \leq 0.05$ and, at this site, only the 0- to 0.15- and 0.30- to 0.60-m depth increment differed from one another. Mean soil resistance of the Gritney site, which was the only site that did not include a specific subsoil tillage treatment, increased with depth increment and was obviously lower in T rows than in NT rows within the 0- to 0.15- and 0.15- to 0.30-m depth increments. Clearly, the woods disk used on this site tilled into the 0.15- to 0.30-m depth increment. However, resistances were generally low in the deepest 0.30- to 0.60-m depth increment on this site, and differences between the T and NT treatments were small. In several cases, resistance values were significantly different among cultural treatments across tillage and depth increment, and as previously suggested, these differences were likely due to differences in water use. The fertilization treatment (O+F) at the Orangeburg and Faceville sites had higher soil resistance ($p = 0.03$ and $p = 0.06$, respectively) than the other two treatments, and the operational treatment (O) at the Cecil (fine, kaolinitic, thermic Typic Kanhapludult; $P = 0.05$) site had greater soil resistance than the O+F treatment (Table 3). Greater resistance in fertilized-only (O+F) or operational plots (O) than in plots with vegetation control (O+F+V) is not unexpected since, in most cases, vegetation control should reduce soil water loss through transpiration. However, there is no obvious explanation as to why the operational treatment (O) should have greater resistance than the fertilized treatment (O+F) on the Cecil site.

Linear relationships existed between volumetric water content and resistance to penetration, but both the specific relationship and the reliability of the relationship were site, tillage treatment, and depth specific (Fig. 6). As would be expected, resistance to penetration decreased as soil water content increased.

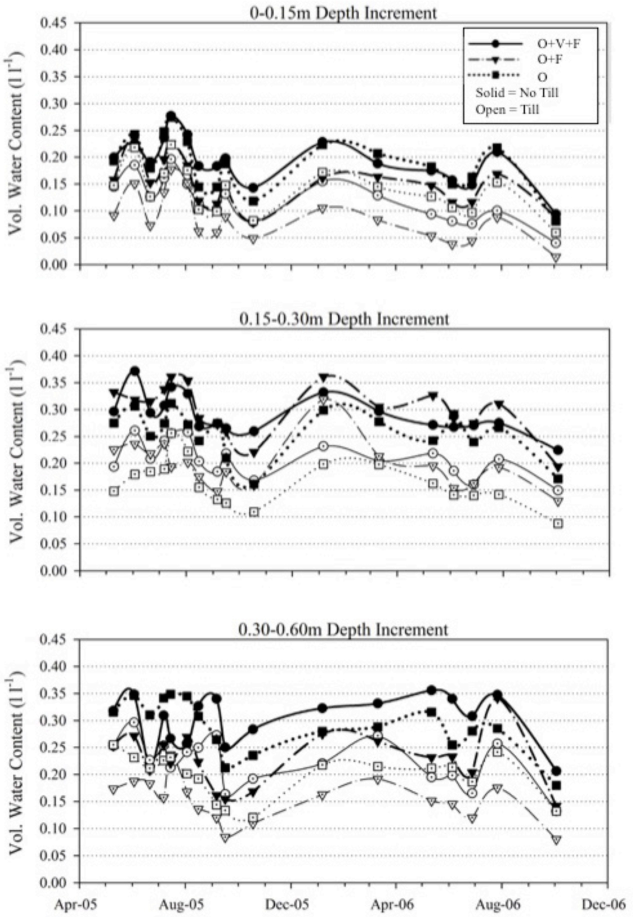


Fig. 4. Seasonal variation in volumetric soil water content during 2 yr following planting at the Orangeburg series study site. O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control.

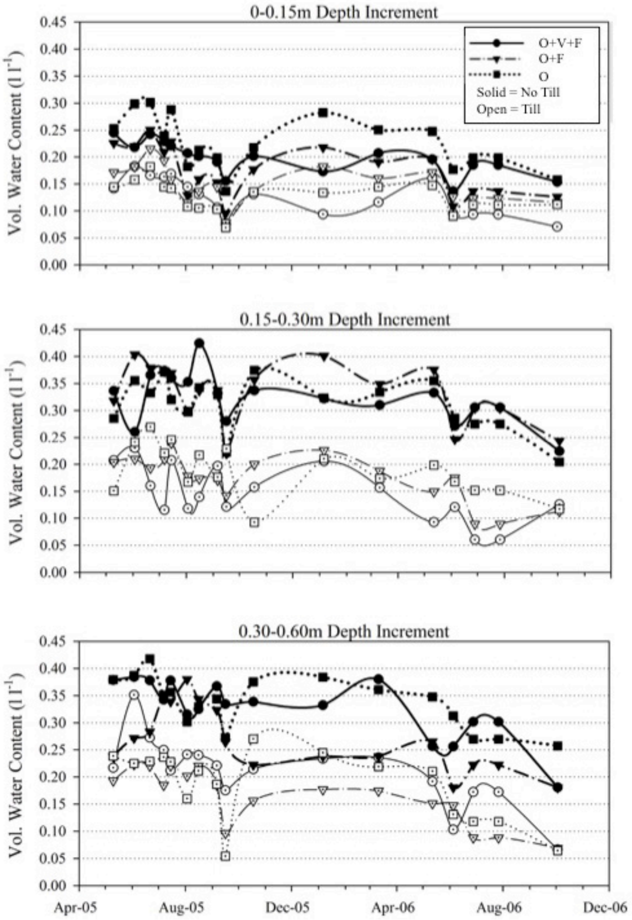


Fig. 5. Seasonal variation in volumetric soil water content during 2 yr following planting at the Lloyd series study site. O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control.

Table 3. Effects of tillage and cultural treatments on average soil resistance for four penetrometer measurements for three soil depth increments. Penetrometer measurements encompassed the range of soil moisture conditions that occurred during the first two growing seasons following planting.

		Depth increment‡					
		0–0.15 m		0.15–0.30 m		0.30–0.60 m	
Site	Culture†	T	NT	T	NT	T	NT
		kPa					
		Upper Coastal Plain					
Faceville	O^{b}§¶	1198	2512	1792	2761	2100	2742
	O+F^{a}	1123	2604	1891	3175	2518	3218
	O+F+V^{b}	998	2293	1474	2511	2143	2813
Gritney	O	1021	1618	1243	1605	1619	1770
	O+F	832	1396	1189	1653	1502	1755
	O+F+V	870	1184	1014	1487	1473	1733
Lucy	O^{a}	1021	1682	1997	2967	3434	4246
	O+F^{ba}	689	1826	1598	2952	2953	3612
	O+F+V^{b}	715	1952	1437	3255	2518	3357
Nankin	O	745	1896	1479	2502	2237	2742
	O+F	821	1789	1502	2661	2075	2825
	O+F+V	927	2360	1281	2665	2086	2749
Orangeburg	O^{b}	1493	3015	2046	3061	2559	2942
	O+F^{a}	1629	3387	2522	3575	3039	3488
	O+F+V^{b}	1336	2632	1707	2574	2275	2567
		Piedmont					
Cecil	O^{a}	1587	3075	2056	3944	3207	4231
	O+F^{b}	1362	2674	1277	3480	3084	4358
	O+F+V^{ab}	1549	2842	1976	3919	2624	4098
Lloyd	O^{b}	946	2225	1410	2928	2501	3191
	O+F^{a}	1046	2344	1615	3390	2695	3307
	O+F+V^{b}	961	1710	1113	2215	2023	2645
Rion	O^{b}	1498	2329	2165	3838	3188	4231
	O+F^{b}	1489	2970	2113	4328	2637	4361
	O+F+V^{a}	2161	3066	2869	4158	4033	4683

† O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation plus annual fertilization and complete vegetation control.

‡ Soil resistance values are statistically different for tilled (T) and nontilled (NT) treatment comparison across cultural treatments ($\alpha \leq 0.05$).

§ Cultural treatments with dissimilar superscripts are significantly different across depth increments using Duncan's test ($\alpha \leq 0.05$); treatments without superscripts did not significantly differ among cultural treatments.

¶ At least one higher order interaction (tillage × culture, tillage × depth, or tillage × depth × culture) is significant ($\alpha \leq 0.05$) on 3 of 8 sites (not shown); significant differences occur among depth increments for all sites.

The regression line between water content and resistance to penetration did not significantly differ among cultural treatments (O, O+F, or O+F+V) within the same tillage treatment for most sites. However, tillage reduced volumetric water content and shifted the range of the regression to lower water contents. It also tended to reduce the negative slope of the regression, such that a change in volumetric water content had a smaller influence on resistance than for NT treatments at the same site.

We also observed a strong linear relationship between average soil resistance measured for each depth increment and the depth increment immediately below it for both T rows and NT rows across the study sites (Fig. 7). This largely explains the lack of interaction among treatments and depth in ANOVA of penetration resistance. Furthermore, it suggests that for these sites, resistance to penetration at depth is correlated with resistance in the surface soil.

Pine Seedling Survival, Height, Diameter, and Stem Volume Index after Two Growing Seasons

Survival was uniformly excellent in this study and was not affected by treatment. Only one seedling of the 288 measurement seedlings died. This excellent survival undoubtedly reflects a combination of abundant rainfall during spring and summer of the first growing season, superior quality seedlings, and quality planting. We would not expect similar results on larger experimental plots or under operational conditions.

The greatest growth occurred on the UCP in the Lucy series site, where tillage combined with fertilization and vegetation control (O+F+V) resulted in an average SVI of 8932 cm^3. The lowest growth was observed in the UCP Faceville site, where the NT rows with the operational site preparation (O) resulted in an average SVI of 101 cm^3. In most cases, growth response to fertilization (O+F) did not differ significantly from the operational treatment (O) (Table 4 and Table 5).

Tillage generally resulted in statistically significant and positive pine growth responses, and this positive response was generally observed across the three cultural treatment levels (Fig. 8). The growth response to tillage was not significant on the Orangeburg (UCP) and Lloyd (Piedmont) soils. On the Orangeburg site, the SVI of trees in the fertilized treatment (O+F) was smaller in T rows than in NT rows but was larger for the other two treatments. This Orangeburg site was one of the more productive sites we studied. It had slightly coarser-textured subsoils than most of the other study sites. The Lloyd site was the only site where trees were smaller in tilled rows across all cultural treatments.

Tillage response tended to be greatest in the fertilized plus vegetation control plots (O+F+V) where growth was also greatest (Table 4). The largest absolute response in SVI was 3878 cm^3 at the Nankin site. Here, trees in T rows were 347% of the SVI and 0.8 m taller than trees planted in NT rows at the end of the second growing season. On a relative basis, the greatest response to tillage was for the Faceville site, and the response was greatest for the O treatment. This site had a shallow fine-textured surface over a sandy-clay subsoil. In the absence of tillage, seedling growth was very poor. For this site, even a small absolute increase in SVI corresponded to a large relative increase. A significant interaction between tillage and cultural treatment occurred on only one site (Nankin). On this site, response to fertilization and vegetation control was much greater when the soil was tilled.

The growth of seedlings in rows that were tilled but that did not receive any further cultural treatment besides operational site preparation was usually less than the growth of seedlings in rows that were not tilled but received fertilizer application and competing vegetation control following planting. Tillage with operational culture (O) outperformed NT treatments (NT) that received fertilization and vegetation control (O+F+V) on only two sites (Rion and Lucy). On the other sites, SVIs of NT treatments that received intensive culture were equal to or greater than T treatments that did not receive intensive culture (Fig. 8).

Neither average soil resistances nor the reductions in soil resistance resulting from tillage were good predictors of seedling size or growth response to treatments across the eight sites and three cultural treatment levels. In Fig. 9, SVI at the end of the second growing season is plotted against the mean soil resistance measurements in the 0- to 0.15-, 0.15- to 0.30-, and 0.30- to 0.60-m depth increments for the two driest measurement dates. The abundance of open symbols at lower resistances in the surface 0 to 0.15 and 0.15 to 0.30 m shows the overall impact of tillage. However, rather than appearing as a linear relationship to tillage, SVI appears to be bounded by an upper resistance line for the 0- to 0.15-m depth increment. Other factors were clearly limiting growth of many seedlings that were planted in soils with low resistance. Small trees occurred even at low average resistances. However, as soil resistance increased, it became a major factor limiting growth. No large trees occurred at the highest levels of soil resistance. We found this pattern existed even when only seedlings that received the highest level of cultural treatment (O+F+V) were included in the regression. A significant linear relationship existed, but it explained only 25% of tree size differences ($SVI_{second} = -1.40$ Res kPa_{0-15}

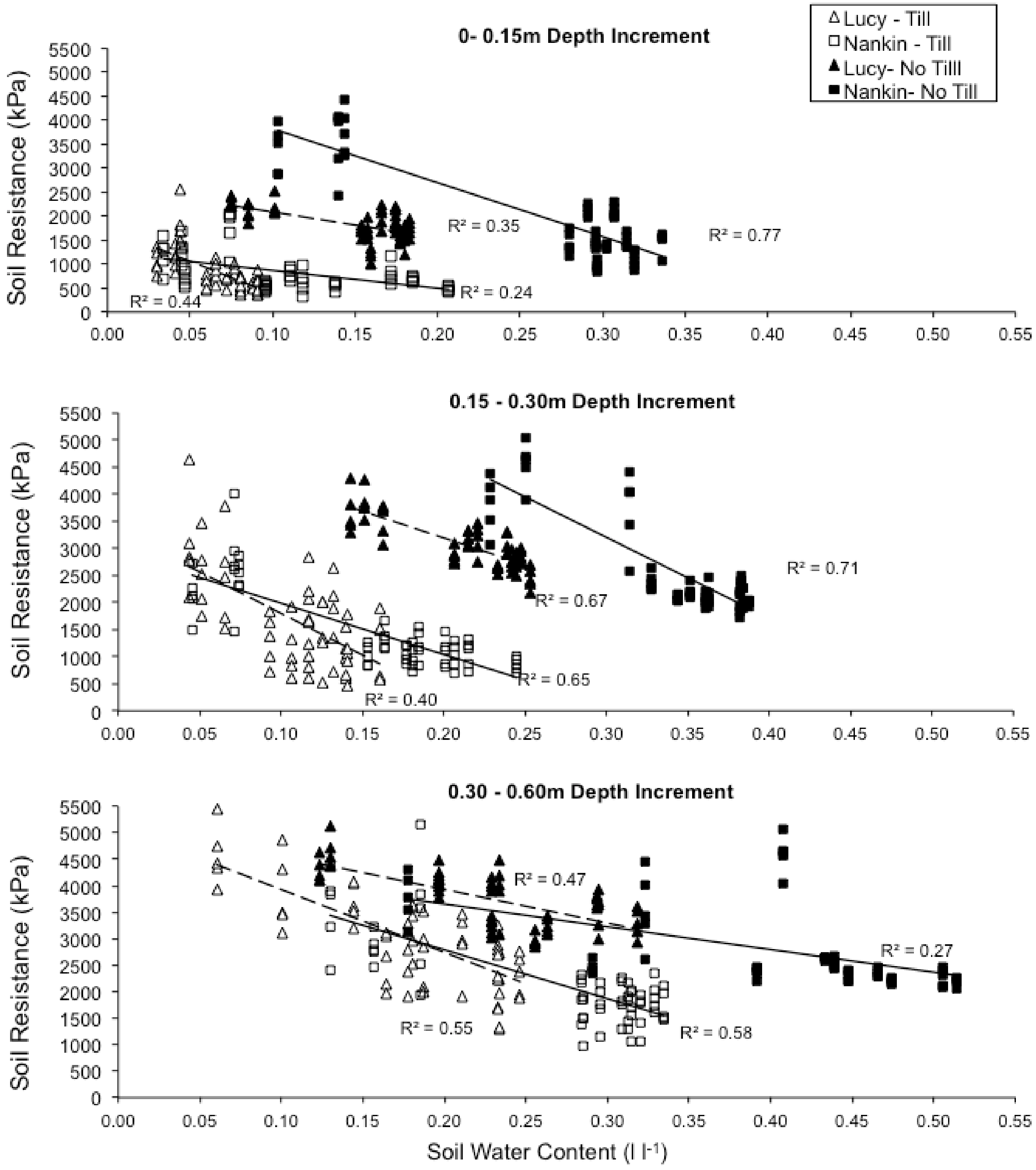


Fig. 6. Relationship between volumetric water content and penetrometer resistance on two of eight experimental sites for tilled (open symbols) and nontilled (filled symbols) by depth increment.

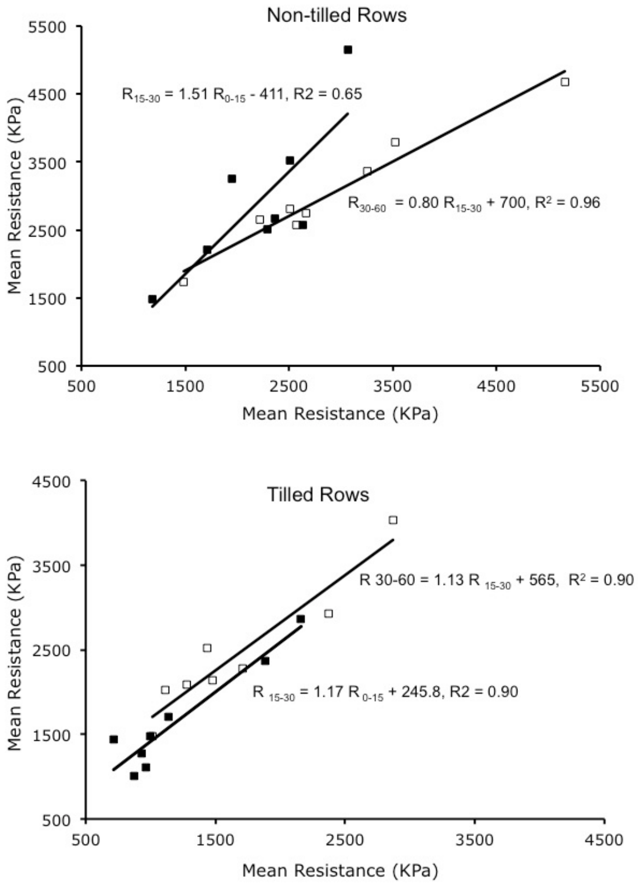


Fig. 7. Relationship between mean penetrometer resistances measured in a depth increment with penetrometer resistance in the next deeper depth increment for nontilled rows and tilled rows. Closed symbols indicate points for the 0.15- to 0.30- versus 0- to 0.15-m relationship; open symbols indicate points for the 0.30- to 0.60-m versus 0.15- to 0.30-m relationship.

+ 6325; R^2 = 0.25). Note that the bounding line evident for the surface 0- to 0.15-m depth increment is less evident for the deeper soil depth increments in Fig. 9.

DISCUSSION

We generally accept that high soil resistance resulting from natural soil conditions or compaction reduces growth, but it has proven difficult to translate this general understanding into guidelines for assessing soil conditions that will improve our ability to predict tree growth response to tillage under field conditions. A variety of factors probably contribute to this, but among the most important are that both the physical conditions of the soils and the amelioration accomplished by tillage treatments vary greatly within and among sites. In this experiment, we attempted to remove some of this variability by using relatively small plots and focusing our efforts on measuring what was accomplished by the tillage treatments rather than the operation itself. Additionally, we controlled variability resulting from different genetics by planting the same three clones at all of our sites in blocks, which allowed us to remove genetic effects along with block effects in the experiment. As long as there was not a strong treatment × genetic (block) interaction, our ability to detect treatment differences was maximized using this approach. Finally, by completely controlling competing vegetation and fertilizing the sites, we partially controlled these common confounding factors in the experiment. Despite these efforts, relationships between average soil resistance to penetration and average tree size (as measured by SVI at the end of the second growing season) explained only a small portion of the variance.

Soil water content affects growth directly through its relationship to soil water potential and plant available water and indirectly through its influence on soil resistance to penetration. This experiment was conducted during a 2-yr period that included drought when low soil moisture would be expected to have a major effect on seedling growth. Generally, volumetric water content in the surface 0- to 0.15- and 0.15- to 0.30-m depth increments was lowered by tillage. On average, it was also lower deeper in the profile (0.30- to 0.60-m depth increment), but there was little difference between T and NT treatments for several of the sites (e.g., Lucy). On most sites, operational tillage included a subsoil shank that exceeded a 0.40-m depth. Where markedly lower water content occurred in the deepest depth increment, it might simply reflect increased macroporosity created by tillage that reached into this depth increment. Alternatively, tillage may have promoted increased root growth at depth, and the lower water contents reflect greater transpirational use of water. Both of these factors probably contributed to the observed reductions in volumetric water content in the deepest depth increment. There was little evidence of increased volumetric soil water content at depth, as would be the case if tillage increased infiltration and delivery of surface water to subsoil horizons. The reduction in volumetric water content did not appear to negatively affect tree growth (the Lloyd site was an exception that will be discussed later). It is possible that roots exploited a greater and deeper soil volume in the tilled soil (Schilling et al., 2004), and they may have been more effective at extracting water. Moreover, reductions in volumetric water content are not equivalent to reductions in plant water availability. Release of water at soil water contents less than field capacity is controlled by particle size distribution. While some mixing of soil horizons can occur during upland forest site preparation that includes piling (Gent et al., 1984; Hoadley, 2014), the influence on particle size distribution within the profile is small compared to the influence on macroporosity. When macropores are created by tillage, the soil water release curve (soil water content plotted against soil water potential) is shifted, but the curve shape is largely retained since particle size distribution, which largely controls the shape of the water retention curve (Ghanbarian-Alavijeh et al., 2010; Zhuang et al., 2001), is not greatly affected. In this study, water availability on a unit volume basis was reduced, but improved rooting conditions that apparently increased root penetration and the volume of soil utilized compensated for the lower availability on a unit volume basis.

Overall, operational tillage resulted in positive growth response, and this response occurred over a wider range of competing vegetation and nutrient availability conditions than is likely

Table 4. Size of loblolly pine two growing seasons following planting in tilled (T) and nontilled (NT) rows receiving three cultural treatments on eight upland sites.

Site	Culture	Height (HT)		Ground line diameter (GLD)		Stem volume index (SVI)†		Tillage response
		T	NT	T	NT	T	NT	
		—cm—		—mm—		—cm^3—		–%–
				Upper Coastal Plain				
Faceville	O	120^{a,c} ‡§	70^{b,c}	25.7^{a,c}	12.0^{b,c}	793^{a,c}	101^{b,c}	785
	O+F	150^{a,c}	93^{b,c}	35.2^{a,d}	19.4^{b,d}	1859^{a,d}	350^{b,d}	531
	O+F+V	175^{a,d}	136^{b,d}	40.0^{a,d}	27.3^{b,d}	2800^{a,d}	1014^{b,d}	276
Nankin	O	144^{a,c}	110^{b,c}	296^{a,c}	20.6^{b,c}	1262^{a,c}	467^{b,c}	270
	O+F	125^{a,c}	77^{b,c}	26.3^{a,c}	14.4^{b,c}	865^{a,c}	160^{b,c}	540
	O+F+V	227^{a,d}	147^{b,d}	49.0^{a,d}	32.7^{b,d}	5450^{a,d}	1572^{b,d}	347
Gritney	O	164^{a,c}	156^{b,c}	31.9^{a,c}	27.6^{b,c}	1669^{a,c}	1188^{B,c}	140
	O+F	198^{a,c}	177^{b,c}	40.4^{a,c}	30.2^{b,c}	3232^{a,c}	1614^{B,c}	200
	O+F+V	231^{a,d}	182^{b,d}	46.9^{a,d}	38.2^{b,d}	5081^{a,d}	2656^{B,d}	191
Orangeburg	O	178^{a,c}	142^{a,c}	43.1^{a,c}	32.9^{a,c}	3307^{a,c}	1537^{a,c}	215
	O+F	140^{a,c}	157^{a,c}	33.1^{a,c}	34.8^{a,c}	1534^{a,c}	1901^{a,c}	81
	O+F+V	222^{a,d}	199^{a,d}	46.5^{a,d}	44.2^{a,d}	4800^{a,d}	3888^{a,d}	123
Lucy	O	235^{a,C}	221^{B,C}	53.0^{a,c}	43.9^{B,c}	6601^{a,c}	4259^{B,c}	155
	O+F	226^{a,C}	187^{B,C}	50.6^{a,c}	36.4^{B,c}	5786^{a,c}	2478^{B,c}	233
	O+F+V	261^{a,C}	245^{B,C}	58.5^{a,d}	49.3^{B,d}	8932^{a,d}	5955^{B,d}	150
				Piedmont				
Cecil	O	153^{a,c}	113^{b,c}	31.3^{a,c}	19.9^{B,c}	1499^{a,c}	447^{B,c}	336
	O+F	162^{a,d}	127^{b,d}	32.0^{a,c}	21.5^{B,c}	1659^{a,c}	587^{B,c}	283
	O+F+V	167^{a,d}	164^{b,d}	36.3^{a,d}	33.3^{B,d}	2201^{a,d}	1819^{B,c}	121
Lloyd	O	120^{a,c}	127^{a,c}	23.3^{a,c}	22.2^{a,c}	651^{a,c}	626^{a,c}	104
	O+F	148^{a,d}	181^{a,d}	32.8^{a,d}	30.5^{a,d}	1592^{a,c}	1684^{a,c}	95
	O+F+V	173^{a,d}	200^{a,d}	36.6^{a,e}	41.7^{a,e}	2317^{a,d}	3478^{a,d}	67
Rion	O	168^{a,c}	138^{b,c}	32.8^{a,c}	27.5^{b,c}	1807^{a,c}	1044$^{b.c}$	173
	O+F	171^{a,c}	118^{b,c}	32.9^{a,c}	25.8^{b,c}	1851^{a,c}	785^{b,c}	236
	O+F+V	175^{b,c}	150^{b,c}	39.5^{a,c}	29.1^{b,c}	2730^{a,c}	1270^{b,c}	215

† SVI = HT (cm) × GLD^2 (cm^2).

‡ Means with dissimilar first letters are significantly different for tillage treatment at the 0.05 (lowercase) and 0.10 (uppercase) level using Tukey's significance difference test. Differences evaluated within each site.

§ Means with dissimilar second letters are significantly different for cultural treatments at the 0.05 (lowercase) and 0.10 (uppercase) level using Tukey's significance difference test. Differences evaluated within each site.

to occur in practice. The O+F treatment created a high nutrient availability condition, which in the absence of additional vegetation control, decreased pine growth on three of the study sites. The O+F+V treatment provided better nutrition and vegetation control than could be operationally accomplished even under very intensive management and probably represents an upper bound to tillage response. It is clear that the response to tillage we measured in the O+F+V treatment was not a result of tillage effects on plant competition but can be directly attributed to changes in soil properties. Both soil physical properties and chemical properties, such as nutrient mineralization and availability, are affected by tillage and, while the fertilization of the O+F+V was intended to minimize this effect, some of the benefit may still be nutritional. Response to tillage in the O and O+F treatments represents the interaction among many factors;resistance to penetration, changes in nutrient mineralization, differences in competing species and plant density, and resulting differences in water and nutrient uptake.

Under controlled conditions, it has been shown that root growth of both agricultural crops (Taylor et al., 1966) and trees (Torreano, 1992) declines linearly from a low resistance maximum, as soil resistance to penetration approaches a critical value that occurs between 2000 and 2500 kPa. Above this critical value, root growth is near zero. It is difficult to apply the concept of a critical resistance value to the dynamic conditions of the field. Root growth-limiting soil resistance can occur during dry periods while other factors, including poor aeration (Kelting et al., 1999), may limit root growth during wet periods, especially on

Table 5. Summary of statistical significance ($P < F$) for loblolly pine growth responses to tillage and cultural treatments after two growing seasons.

Source		df	Height (HT)	Ground line diameter (GLD)	Stem volume index (SVI)
			Upper Coastal Plain		
Faceville	Tillage†	1	0.03	0.02	0.04
	Block/clone‡	2	0.22	0.55	0.75
	Culture§	2	<0.01	0.01	0.02
	Tillage × culture	2	0.78	0.82	0.45
Nankin	Tillage	1	0.02	0.01	0.05
	Block/clone	2	0.05	0.21	0.53
	Culture	2	<0.01	<0.01	<0.01
	Tillage × culture	2	0.08	0.19	0.05
Gritney	Tillage	1	0.05	0.05	0.12
	Block/clone	2	0.06	0.17	0.31
	Culture	2	0.06	<0.01	0.01
	Tillage × culture	2	0.56	0.83	0.56
Orangeburg	Tillage	1	0.42	0.29	0.34
	Block/clone	2	0.94	0.56	0.90
	Culture	2	<0.01	0.01	<0.01
	Tillage × culture	2	0.19	0.15	0.22
Lucy	Tillage	1	0.12	0.12	0.10
	Block/clone	2	0.15	0.88	0.76
	Culture	2	0.10	<0.01	0.01
	Tillage × culture	2	0.76	0.41	0.77
			Piedmont		
Cecil	Tillage	1	0.05	0.06	0.07
	Block/clone)	2	0.26	0.67	0.76
	Culture	2	0.03	<0.01	0.02
	Tillage × culture	2	0.17	0.20	0.76
Lloyd	Tillage	1	0.34	0.98	0.74
	Block/clone	2	0.24	0.59	0.43
	Culture	2	0.01	<0.01	0.01
	Tillage × culture	2	0.67	0.50	0.67
Rion	Tillage	1	0.03	0.02	0.01
	Block/clone	2	0.12	0.65	0.28
	Culture	2	0.66	0.47	0.44
	Tillage × culture	2	0.74	0.82	0.92

† Operational tillage (T) and no till (NT) treatment.

‡ Each block was planted with one of three clones and effects of clone are confounded with blocking.

§ Cultural treatments: O, operational site preparation; O+F, operational site preparation plus annual fertilization; and O+F+V, operational site preparation plus annual fertilization and complete competition control.

Lower Coastal Plain sites. Even during dry periods, when mean soil resistance is above 2500 kPa, roots can exploit zones of low resistance in the soil matrix, particularly macropores left by decaying roots or faunal activity that are not generally measured with a cone penetrometer.

Although root growth was not directly measured in this project, some soil resistance patterns emerge that might affect root growth when the effect of tillage on increasing nonrestrictive soil volume is considered. For example, in Fig. 10 the pattern of resistance within the 0.6 by 0.6 m area perpendicular to the planting row (a surrogate for volume) is presented for each of the four resistance-measuring periods at the Rion site. In this figure, greens and blues are associated with soil resistances lower than the 2000 kPa critical value (Taylor et al., 1966; Torreano, 1992), yellows are near or just above this critical value, and reds are greater than 2500 kPa. Even during the wettest measurement period (lowest panels), most of the soil profile is in red in the NT row. Soil tillage had a significant impact on the volume of soil with acceptable resistances, particularly when the site was dry, and this is one of the sites for which a significant growth response was observed. In contrast, tillage did not result in a significant growth response at the Orangeburg and Lloyd sites. Although average resistance at the Orangeburg site was quite high (Fig. 11), much of the soil volume was near or below the critical soil resistance during wetter periods. The deep topsoil present in the Lloyd site provided an environment conducive to root development even in the absence of tillage (Fig. 12). Only during the driest measurement period was root growth restricted

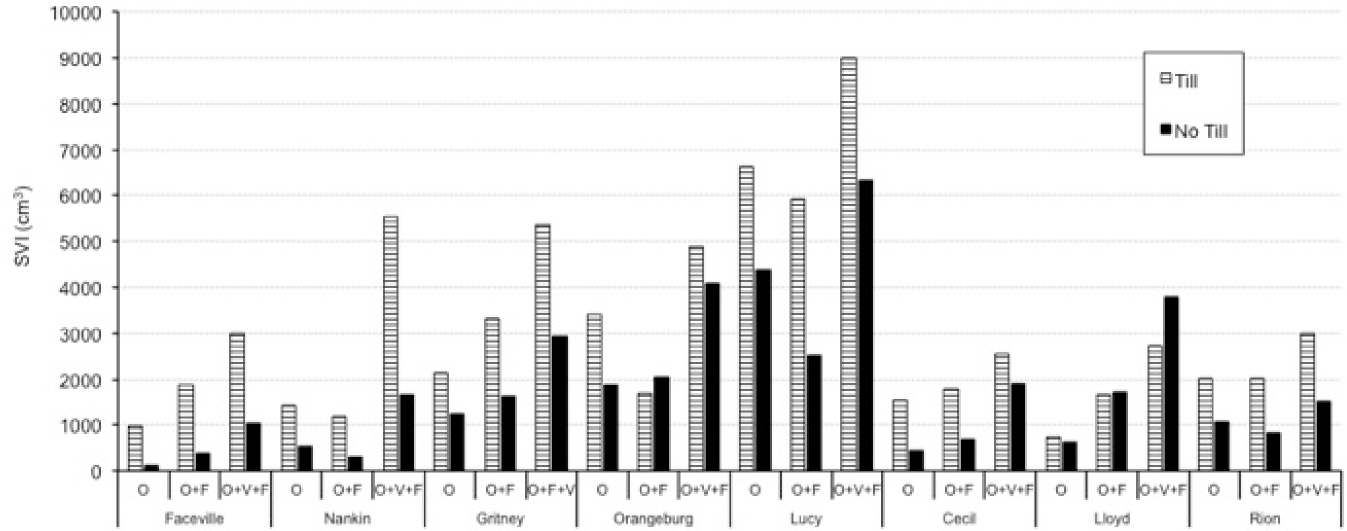


Fig. 8. Mean stem volume index (SVI) of loblolly pine after two growing seasons in tilled and nontilled rows of upland sites by level of cultural treatment (O, operational preparation; O+F, operational preparation plus annual fertilization; O+F+V, operational preparation, annual fertilization, and elimination of competing vegetation).

in most of the profile, and even in this period, resistance to penetration in the surface soil was low. Unlike other sites included in this investigation, there was either no change or a decrease in SVI in tilled rows of this site. Moreover, on the Lloyd site, tillage significantly reduced moisture within the 0.30- to 0.60-m depth increment. Perhaps, at this site, this reduction in water storage was more important from a seedling growth standpoint than reduced soil resistance and increased soil rootability. Pikul and Aase (2003), investigating the effect of subsoiling and subsoiling–disking on water infiltration and storage, showed that the Williams loam soil (fine-loamy, mixed, superactive, frigid Typic Argiustoll) considered in that study could hold only ≈450 mm of water in the top 1.83 m (0.25 m m^{-3}), and water infiltration and drainage data provided evidence that runoff and deep percolation occurred rapidly. Their study showed that subsoiling initially improved infiltration, but no additional water storage was discernable after 15 d. Water loss due to soil loosening has also been investigated in laboratory studies. Foil and Ralston (1967) compared the growth of loblolly pine seedlings after simulating traffic and tillage treatments. Trafficking was simulated by compacting (using a bearing-ratio test machine) and tillage by loosening (using a trowel) soils representing loamy sand, loam, and clay textures. By the end of the first growing season, in the loamy sand soil, loosening reduced height growth compared to undisturbed soil. The growth decline associated with loosening the loamy sand soil was attributed to reduced water (and nutrient) availability resulting from limited lateral root proliferation into zones of air-filled porosity, although considerable vertical growth was noticed. This may have occurred on the Lloyd site in our study.

Quantifying the magnitudes and mechanisms of southern pine growth responses to intensive site preparation has important implications for meeting future silvicultural demands in the South and for allocating limited funds for plantation establishment. In this study, T rows with operational site preparation (O) outperformed NT rows with fertilization and vegetation control (O+F+V) on only one site (Rion). Although both the level of fertilization and vegetation control that we imposed was greater than operational application of these treatments, our results are consistent with the findings of other investigations of tillage and intensive culture of upland sites that have found vegetation control, in particular, to have the greatest effect on early plantation growth (e.g., Carlson et al., 2006).

Soil resistance to penetration is a dynamic property. It changes during the year and over the growing season as soil water content changes. It is also site specific. The four sets of penetration resistance measurements included in this study provide some basis for explaining the response to tillage that we observed on specific sites. On some sites, resistances that were unfavorable at low soil water content were favorable when moisture content increased. Even though tillage reduced soil resistance on these sites, growth response was relatively small. On other sites, soil resistance in NT rows was unfavorable at all measured soil water contents. On these sites, tillage that reduced resistance below the critical levels during one or more of the measurement periods tended to improve growth. Nevertheless, even on the Gritney site, where resistances were low for all four measurements, there was some response to tillage. It also appears that resistance in the surface is more closely associated with a 2-yr growth response than resistance deeper in the profile. The relationship between the upper bound of seedling growth and penetration resistance observed for the surface 0- to 0.15-m depth increment in Fig. 9 is less obvious at the deeper depth increments. Thus, to some extent, these results support results of previous studies that have found greater response to surface tillage than subsoil tillage on upland sites of the Coastal Plain and Piedmont (Carlson et al., 2006).

We found that we could develop reasonable relationships between soil water content and resistance to penetration for some of our study sites and tillage treatments. A previous study by Lincoln et al. (2007) was less successful at developing similar

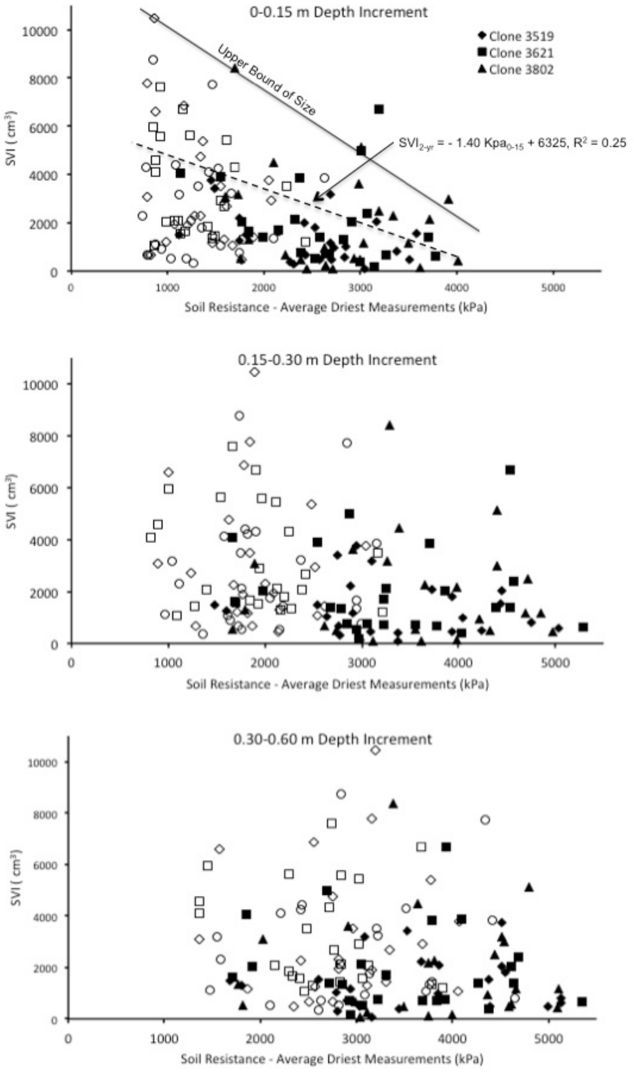


Fig. 9. Relationship between stem volume index (SVI) of loblolly pine after two growing seasons and soil resistance to penetration averaged for the two driest measurement periods by depth increment. Each symbol is the average of two trees. Trees in tilled rows (open symbols) and nontilled rows (filled symbols) are identified to clone by symbol. The regression line shown in the 0- to 0.15-m depth increment is for the O+F+V (operational preparation, annual fertilization and elimination of competing vegetation) cultural treatment.

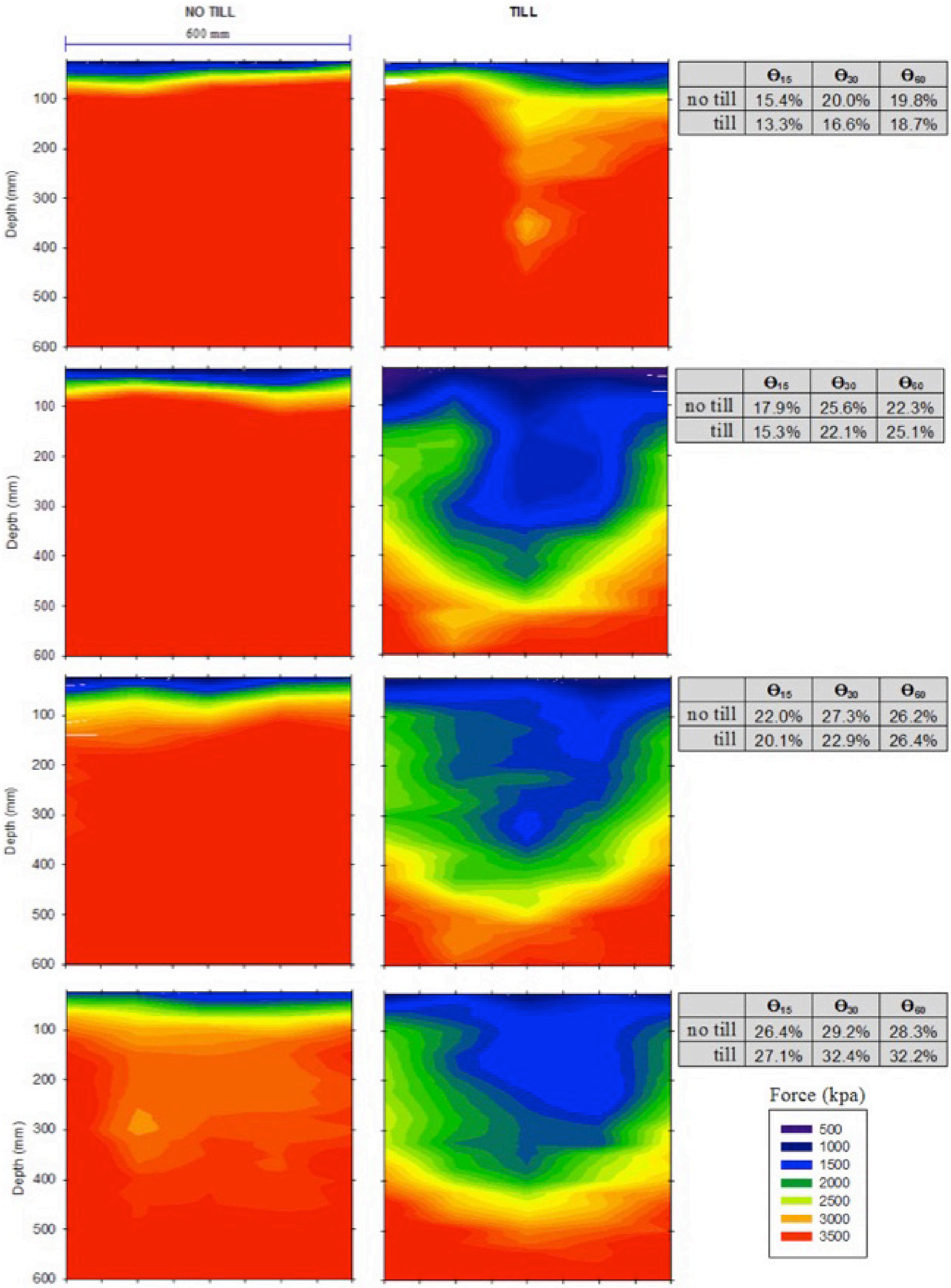
relationships for sites within the same geographic region. This is likely a result of differences in experimental protocol. In the previous study, as in many field experiments, a penetrometer sampling point was selected, and the operator attempted to insert the penetrometer and obtain a reading. When soils were dry, several attempts were made to obtain a reliable measurement. This biased the sample to locations with low inherent resistance, such as pockets containing foliage and litter debris or disturbed and loosened soil locations. In this current study, penetrometer sampling points were located along precisely located transects that were in close proximity to previous sampling transects. If the penetrometer could not be inserted as a result of too great a resistance, we used the resistance recorded at the lowest measured depth for all deeper depths and did not make further attempts to obtain a reading. This avoided bias toward areas of low resistance, which was particularly important when soils were dry and resistant to penetration.

There were advantages and disadvantages to the experimental approach that we used in this research. Most studies of forest site preparation tillage have focused on tillage treatments and how they affect tree survival and growth under operational conditions (e.g., Carlson et al., 2006; Pehl, 1983; Shiver and Fortson, 1979; Wittwer et al., 1986). The large 0.04- to 0.1-ha plots used in these studies invariably include several soil and slope conditions within the research area. While plots of this size capture operational-scale variability and are large enough to be used for growth measurements to be continued throughout the rotation, quantifying soil physical conditions, and relating these conditions to individual tree growth, is problematic. So, as was done by Lincoln et al. (2007), more intensive measurements are usually completed for a small subset of trees within the larger plots.

Our study was designed to focus on the relationship between soil physical properties and tree growth rather than the tillage treatment per se. Although we report seedling response by site and treatment, our ultimate goal was to relate seedling performance to physical measurements of soil conditions across a range of soil and site conditions created by treatments. Toward this end, we utilized small plots that we could carefully monitor and focused on characterizing soil conditions adjacent to individual seedlings. Soil variability was low within the limited area of each research site. Each of the 36 measurement trees on each site was coupled with soil measurements made $\leq$0.75 m from the tree. However, there were several limitations to the approach we utilized. First, in our design, we assumed that there would be minimal interaction between clone and treatment and that the advantage of removing the variability associated with different clones along with block effects would be greater than potential disadvantages. Second, we assumed that the advantages of establishing cultural treatment strips across blocks, which allowed us to minimize buffer distances and keep treatments close together, were greater than potential biases associated with incomplete randomization. Third, the small plot and buffer area sizes limited the number of years seedling measurements would accurately reflect treatments. Finally, while the relationship between soil resistance and maximum 2-yr seedling size developed across all eight sites and presented in Fig. 9 should be robust, too few trees were measured at each site to have confidence in the site-specific growth response to treatment combinations that we observed.

CONCLUSIONS

Operational tillage was found to significantly reduce volumetric soil water content and resistance to penetration and to increase the volume of soil with nonrestrictive rooting volumes in the planting rows. Seedling growth response to tillage treatments was robust and, with one exception, increased growth across all levels of cultural treatments. Despite a consistent response to tillage, seedling size after two growing seasons was not well predicted by either average cone penetrometer soil resistance or by the reduction in average soil resistance in T



	Θ_{15}	Θ_{30}	Θ_{60}
no till	15.4%	20.0%	19.8%
till	13.3%	16.6%	18.7%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	17.9%	25.6%	22.3%
till	15.3%	22.1%	25.1%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	22.0%	27.3%	26.2%
till	20.1%	22.9%	26.4%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	26.4%	29.2%	28.3%
till	27.1%	32.4%	32.2%

Fig. 10. Mean soil resistance for tilled and nontilled treatments for four different moisture conditions at the Rion series site (Piedmont). Mean volumetric water content in the 0- to 0.15- (Θ_{15}), 0.15- to 0.30- (Θ_{30}), and 0.30- to 0.60-m (Θ_{60}) depth increments are provided in the table associated with each measurement.

vs. NT rows. The best regression of individual seedling size was against soil resistance in the 0- to 0.15-m depth increment for seedlings that were fertilized and received vegetation control, and this regression only explained 25% of the observed variation. Instead, an upper bound to seedling size was established by surface soil resistance; as soil resistance increased, the size of the largest seedlings decreased.

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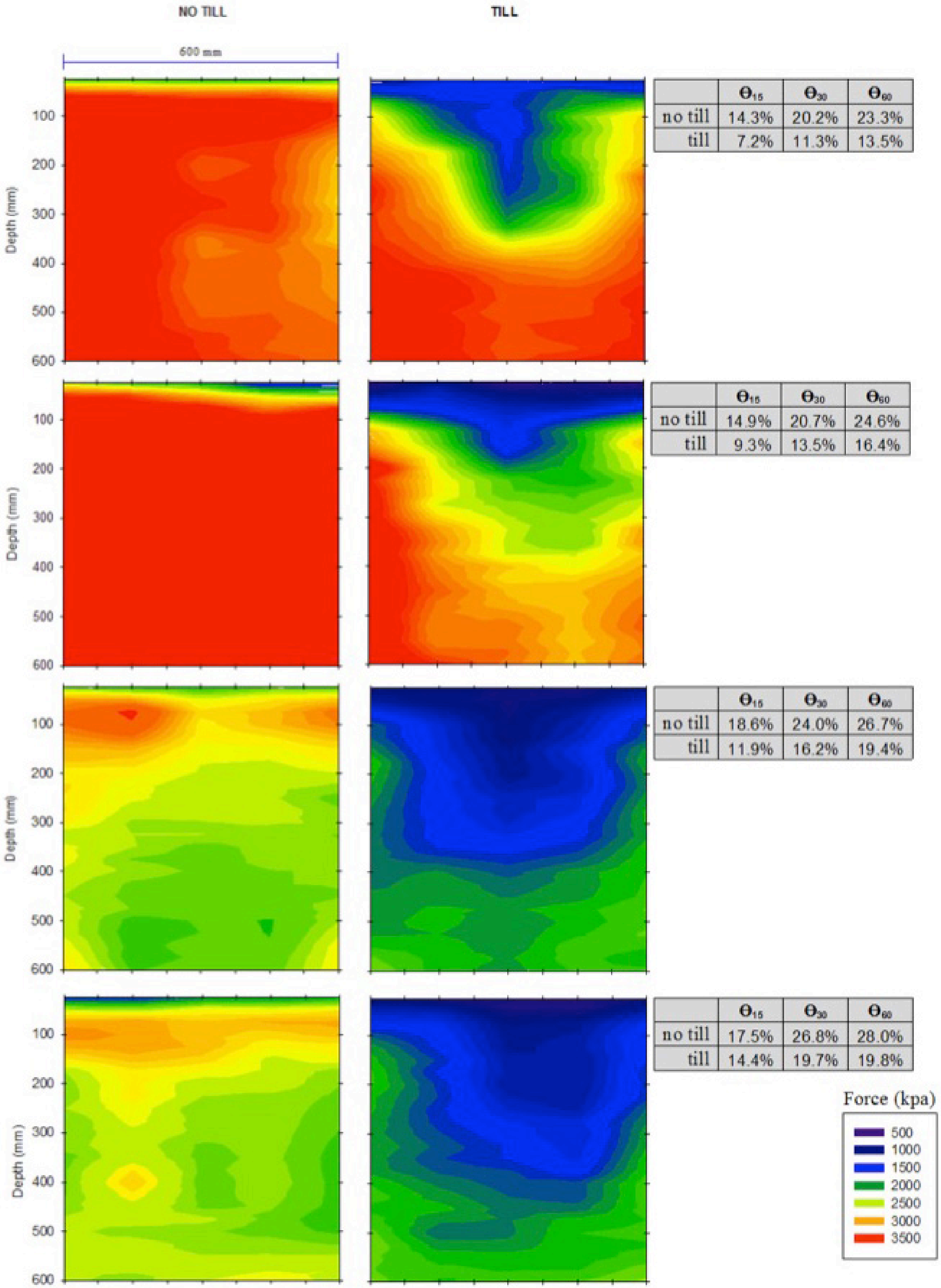

	Θ_{15}	Θ_{30}	Θ_{60}
no till	14.3%	20.2%	23.3%
till	7.2%	11.3%	13.5%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	14.9%	20.7%	24.6%
till	9.3%	13.5%	16.4%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	18.6%	24.0%	26.7%
till	11.9%	16.2%	19.4%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	17.5%	26.8%	28.0%
till	14.4%	19.7%	19.8%

Fig. 11. Mean soil resistance for tilled and nontilled treatments for four different moisture conditions at the Orangeburg series site (Upper Coastal Plain). Mean volumetric water content in the 0- to 0.15- (Θ_{15}), 0.15- to 0.30- (Θ_{30}), and 0.30- to 0.60-m (Θ_{60}) depth increments are provided in the table associated with each measurement.

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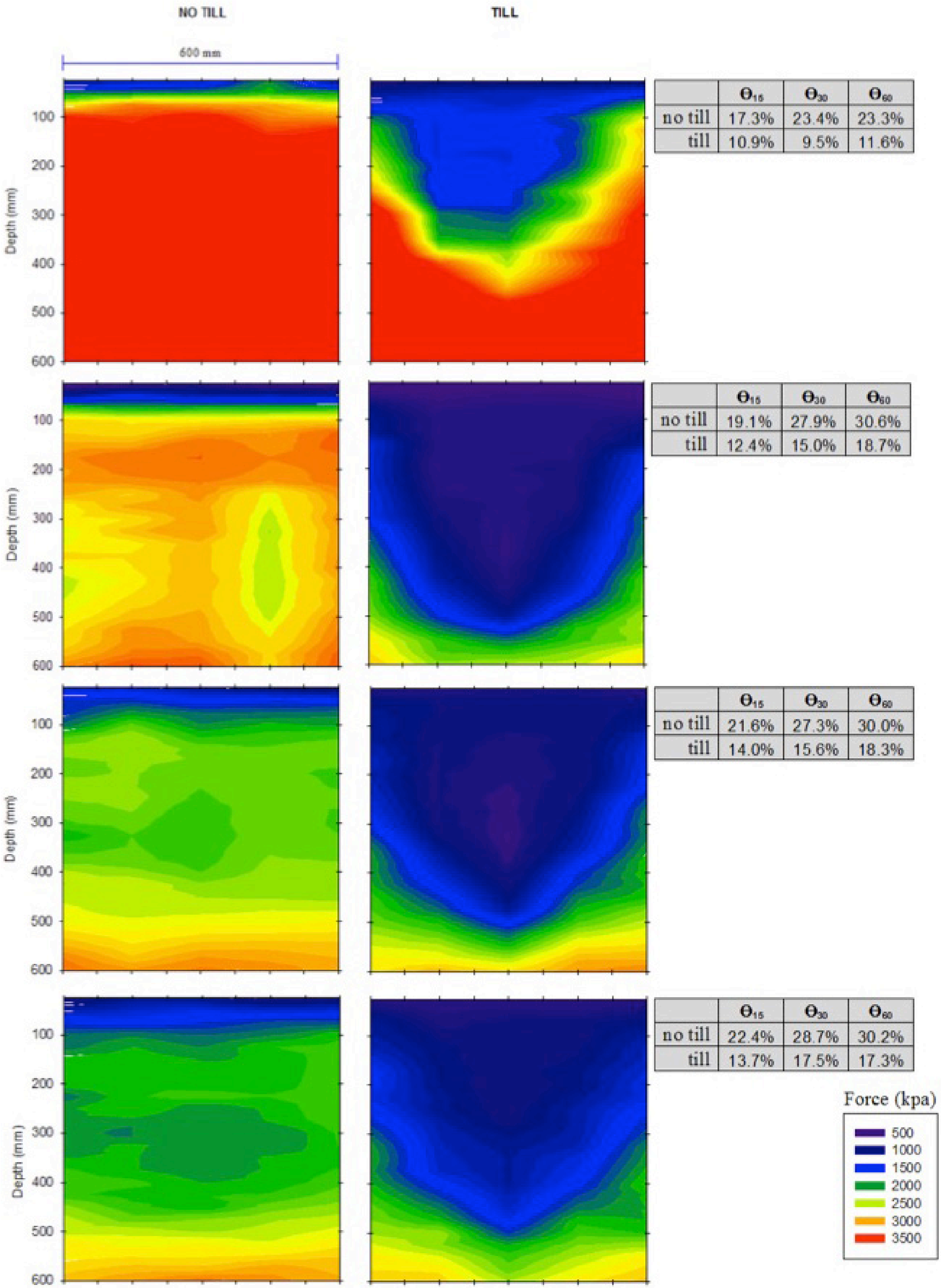

	Θ_{15}	Θ_{30}	Θ_{60}
no till	17.3%	23.4%	23.3%
till	10.9%	9.5%	11.6%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	19.1%	27.9%	30.6%
till	12.4%	15.0%	18.7%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	21.6%	27.3%	30.0%
till	14.0%	15.6%	18.3%

	Θ_{15}	Θ_{30}	Θ_{60}
no till	22.4%	28.7%	30.2%
till	13.7%	17.5%	17.3%

Fig. 12. Mean soil resistance for tilled and nontilled treatments for four different moisture conditions at the Lloyd series site (Piedmont). Mean volumetric water content in the 0- to 0.15- (Θ_{15}), 0.15- to 0.30- (Θ_{30}), and 0.30- to 0.60-m (Θ_{60}) depth increments are provided in the table associated with each measurement.

REFERENCES

Adegbidi, H.G., N.B. Comerford, E.J. Jokela, and N.F. Barros. 2004. Root development of young loblolly pine in Spodosols in southeast Georgia. Soil Sci. Soc. Am. J. 68:596–604. doi:10.2136/sssaj2004.5960

Allen, H.L. 2001. Silvicultural treatments to enhance productivity. In: J. Evans, editor, The forests handbook. Vol. II. Blackwell Science Ltd., Oxford, UK. p. 129–139.

Allen, H.L., T.R. Fox, and R.G. Campbell. 2005. What is ahead for intensive pine plantation silviculture in the South? South J. Appl. For. 29:62–69.

Aust, W.M., G.A. Scheerer, M.D. Tippet, J.A. Burger, and W.H. Mckee, Jr. 1998. Bedding and fertilization ameliorate effects of designated wet-weather skid trails after four years of loblolly pine (*Pinus taeda*) plantations. South. J. Appl. For. 22:222–226.

Borders, B.E., and R.L. Bailey. 2001. Loblolly pine: Pushing the limits of growth. South J. Appl. For. 25:69–74.

Carlson, C.A., T.R. Fox, S.R. Colbert, D.L. Kelting, H.L. Allen, and T.J. Albaugh. 2006. Growth and survival of *Pinus taeda* in response to surface and subsurface tillage in the southeastern United States. For. Ecol. Manage. 234:209–217. doi:10.1016/j.foreco.2006.07.002

Dougherty, P.M., and C.A. Gresham. 1988. Conceptual analysis of southern pine plantation establishment and early growth. South. J. Appl. For. 12:160–166.

Foil, R.R., and C.W. Ralston. 1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Sci. Soc. Am. J. 31:565–568. doi:10.2136/sssaj1967.03615995003100040037x

Fox, T.R. 2000. Sustained productivity in intensively managed forest plantations. For. Ecol. Manage. 138:187–202. doi:10.1016/S0378-1127(00)00396-0

Gent, J.A., Jr., R. Ballard, A.E. Hassan, and D.K. Cassel. 1984. Impact of harvesting and site preparation on physical properties of Piedmont soils. Soil Sci. Soc. Am. J. 48:173–177. doi:10.2136/sssaj1984.03615995004800010032x

Ghanbarian-Alavijeh, B., A. Liaghat, G. Huang, and M.T. Van Genuchten. 2010. Estimation of the van Genuchten soil water retention properties from soil textural data. Pedosphere 20:456–465. doi:10.1016/S1002-0160(10)60035-5

Haynes, R.W. 2002. Forest management in the 21st century: Changing number, changing context. J. For. 100:38–43.

Hoadley, C.W. 2014. Effects of woody biomass retention and distribution patterns on select soil quality indicators in Lower Coastal Plain soils of North Carolina and Georgia. M.S. thesis, Univ. of Georgia, Athens.

Kelting, D.L., J.A. Burger, S.C. Patterson, W.M. Aust, and C.C. Trettin. 1999. Soil quality assessment in domesticated forests–A southern pine example. For. Ecol. Manage. 122:167–185. doi:10.1016/S0378-1127(99)00040-7

Lincoln, M. C., J. R. Britt, B. Cazell, V. Ford, D. Markewitz, R. E. Will, L. A. Morris, and E. A. Carter. 2007. Soil change and loblolly pine (*Pinus taeda)* seedling growth following site preparation tillage in the Upper Coastal Plain of the southeastern United States. For. Ecol. Manage. 242:558–568.

Martin, S.W., and B.D. Shiver. 2002. Impacts of vegetation control, genetic improvement and their interaction on loblolly pine growth in the southern United States–Age 12 results. South. J. Appl. For. 26:37–42.

Microsoft. 2002. Excel Visual Basic. Microsoft Inc., Redmond, WA.

Morris, L.A., and R.F. Lowery. 1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South. J. Appl. For. 12:170–178.

Pehl, C.E. 1983. Site preparation influences on young loblolly pine plantations in East Texas. South J. Appl. For. 7:140–145.

Pikul, J.L., and J.K. Aase, Jr. 2003. Water infiltration and storage affected by subsoiling and subsequent tillage. Soil Sci. Soc. Am. J. 67:859–866. doi:10.2136/sssaj2003.0859

Prestemon, J.P., and R.C. Abt. 2002. The southern timber market to 2040. J. For. 100:16–22.

Rahman, M.S., M.G. Messina, and R.F. Fisher. 2006. Intensive forest management affects loblolly pine (*Pinus taeda* L.) growth and survival on poorly drained sites in southern Arkansas. South J. Appl. For. 30:79–85.

SAS Institute. 2006. SAS version 8.2. SAS Inst., Cary, NC.

Schilling, E.B., B.G. Lockaby, and R. Rummer. 2004. Biomass partitioning and root architecture responses of loblolly pine seedlings to tillage in the Piedmont and Coastal Plain soils. South. J. Appl. For. 28:76–82.

Shiver, B.D., and J.C. Fortson. 1979. Effect of soil type and site-preparation method on growth and yield of flatwoods slash pine plantations. South. J. Appl. For. 3:95–100.

Smith, W.B., P.D. Miles, J.S. Vissage, and S.A. Pugh. 2004. Forest resources of the United States, 2002. General Tech. Rep. NC-241. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Taylor, H.M., G.M. Roberson, and J.J. Parker, Jr. 1966. Soil strength-root penetration relationships for medium to coarse-textured soil materials. Soil Sci. 102:18–22. doi:10.1097/00010694-196607000-00002

Tiarks, A.E., and J.D. Haywood. 1996. Site preparation and fertilization effects on growth of slash pine for two rotations. Soil Sci. Soc. Am. J. 60:1654–1663. doi:10.2136/sssaj1996.03615995006000060008x

Topp, G.C., and J.L. Davis. 1985. Measurement of soil water content using time-domain reflectrometry (TDR): A field evaluation. Soil Sci. Soc. Am. J. 49:19–24. doi:10.2136/sssaj1985.03615995004900010003x

Torreano, S.J. 1992. Effects of soil water availability, aeration and soil mechanical impedance on loblolly pine (*Pinus taeda* L.) root development. Ph.D. diss., Univ. of Georgia, Athens.

U.S. Climate Data. 2015. Climate Columbus - Georgia. http://www.usclimatedata.com/climate/columbus/georgia/united-states/usga0823/2004/12 (accessed 6 Oct. 2015).

Wheeler, M.J., M.A. Jacobson, A.M. Shirley, R.W. Will, and D. Markewitz. 2002. Early loblolly pine stand response to tillage on the Piedmont and Upper Coastal Plain of Georgia: Mortality, stand uniformity, and second and third year growth. South. J. Appl. For. 26:181–189.

Wittwer, R.F., P.M. Dougherty, and D. Cosby. 1986. Effects of ripping and herbicide site preparation treatments on loblolly pine seedling growth and survival. South J. Appl. For. 10:253–257.

Zhuang, J., Y. Jin, and T. Miyazaki. 2001. Estimating water retention characteristic from soil particle size distribution using a non-similar media concept. Soil Sci. 166:308–321. doi:10.1097/00010694-200105000-00002