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ScienceDirect
Forest Ecology and Management 242 (2007) 558–568
Forest Ecology and Management
www.elsevier.com/locate/foreco

Soil change and loblolly pine (*Pinus taeda*) seedling growth following site preparation tillage in the Upper Coastal Plain of the southeastern United States

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Received 13 October 2006; received in revised form 23 January 2007; accepted 23 January 2007

Abstract

To determine the relationship between changes in soil physical properties due to tillage and growth of loblolly pine (*Pinus taeda* L.) seedlings, we measured soil moisture and penetration resistance for a range of tillage treatments on two Upper Coastal Plain sites in Georgia and correlated these measurements to the growth of individual seedlings. The five tillage treatments were: no-till (NT), coulter only (C), coulter + subsoil (CS), coulter + bed (CB), and coulter + subsoil + bed (CSB). The effects of tillage on soil penetration resistance and volumetric water content were isolated from the potentially confounding effects of tillage on competition and soil fertility by completely eliminating all competing vegetation and by comparing tree response with and without periodic nutrient additions. At the site with a clay B-horizon at the surface, the tillage treatments increased relative height and relative diameter growth compared to the NT treatment during the first season, decreased soil penetration resistance, and decreased volumetric soil moisture (VWC). At the sandy site with a loamy sand topsoil averaging 15–40 cm in depth over a sandy clay loam B-horizon, bedding, subsoiling and the minimal tillage associated with machine planting increased seedling growth compared to the C treatment. Soil penetration resistance and VWC were greatest in the C treatment, intermediate in the NT treatment, and lowest in the treatments receiving bedding. Soil penetration resistance between 40 and 50 cm ($p = 0.03$, $r^2 = 0.40$) was negatively correlated with seedling relative diameter growth at the clay site. Soil penetration resistance between 10 and 40 cm ($p < 0.02$, $r^2 = 0.35$) was negatively correlated with seedling diameters at the sandy site. Overall, the positive effects of soil tillage on growth were relatively small (i.e., increases in height and diameter of about 20%). Most of the positive benefits of tillage on growth and soil physical properties were captured with less intensive treatments such as machine planting (sandy site) or the coulter only (clay site).

Keywords: *Pinus taeda*; Loblolly pine; Tillage; Bedding; Subsoiling; Upper Coastal Plain

1. Introduction

Mechanical site preparation is a common silvicultural treatment used in plantation forest management in all areas of the southeastern United States (Lantagne and Burger, 1987). Benefits of mechanical site preparation include improved drainage, improved micro-site environment (nutrients, aeration, temperature, and moisture) for root development, and reduced competition (Haines et al., 1975). Many upland sites of the Coastal Plain have thin topsoil above a restrictive subsoil that may inhibit seedling root growth and limit nutrient availability (McKee and Wilhite, 1986; Wheeler et al., 2002). Additionally, soil compaction caused by trafficking of heavy equipment is a problem on many of these sites. Between 25 and 50% of a site is

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0378-1127/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.foreco.2007.01.069

trafficked during harvest (e.g., Hatchell et al., 1970; Aust et al., 1998). Upland sites of the Coastal Plain are particularly susceptible to compaction damage because harvesting can be conducted on these sites during wet periods when they are suspended in other locations (Miller et al., 2004).

On upland sites, tillage, such as bedding and subsoiling, have several potential mechanisms by which they increase seedling growth. The primary mechanism is to increase the easily rooted soil volume and allow the seedlings to more efficiently exploit existing soil resources (Will et al., 2002; Nadeau et al., 1998; Morris and Lowery, 1988; Wittwer et al., 1986). However, site preparation tillage also increases the concentrations of resources available to the tree through increased mineralization and decreased interspecific competition (Attiwill et al., 1985; Haines et al., 1975; Lantagne and Burger, 1987). Generally, the relative contributions of the potential mechanisms by which site preparation increases growth have not been quantified. Several recent studies of site preparation tillage on upland sites reported only small increases (Wheeler et al., 2002) or no increase (Schilling et al., 2004) in seedling growth when the benefits of tillage were isolated from the effects plant competition. Given the relatively high cost of upland soil tillage, which averages between \$92 and \$120 per acre when subsoiling is included (Smidt et al., 2005), its use may not be justified if some of the previously reported growth increases (e.g., Lantagne and Burger, 1987; McKee and Wilhite, 1988; McKeand et al., 2000) can be captured through other less expensive treatments such as fertilization or competition control.

If tillage increases seedling growth by improving soil physical properties irrespective of the other benefits, then upland tillage may be an important silvicultural tool. To appropriately use this tool, seedling growth responses need to be quantified across a range of soil physical properties related to the implementation of different tillage intensities. In particular, soil strength, or the capacity of soil to withstand stress without experiencing failure by rupture or fragmentation, can limit root growth and water movement (Daddow and Warrington, 1983; Carlson, 1986). In addition to the direct effects of soil moisture on seedling growth (Morris et al., 1993; Torreano and Morris, 1998; Gholz et al., 1990), soil moisture is inversely related to soil strength (Shaw et al., 1942) such that low soil moisture may limit root elongation and alter distribution patterns (Ludovici and Morris, 1997). Therefore, understanding the relationship between tillage mediated changes in soil strength and soil moisture in relation to seedling growth is necessary to evaluate the potential importance of mechanical tillage on upland sites.

The overall goal of this study was to determine the effects of different intensities of soil tillage (no-till, coulter-only, coulter + bedding, coulter + subsoiling, and coulter + bedding + subsoiling) on soil penetration resistance, a measure of soil strength, and soil moisture and to relate these changes to loblolly pine (*Pinus taeda* L.) seedling growth. The effects of tillage on soil physical properties were isolated from tillage effects that could be met by other silvicultural treatments by (1) eliminating competing vegetation on all plots to prevent confounding tillage effects of soil physical properties with tillage effects of competition control and (2) eliminating the effects associated with available nutrient concentrations by comparing the effects of tillage among fertilized trees that were not nutrient limited. As the effects of tillage vary with soil type, the potential range of tillage response on upland sites was determined on two contrasting sites. While these results are generally applicable to plantation forest systems, loblolly pine represents a particularly good model system. Loblolly pine is the most important economic species in the southeastern United States, composing the majority of the 13 million ha of pine plantations in that region (Fox et al., 2006). In addition, loblolly pine is known to respond well to changes in soil physical properties and resource availability (e.g., Fox et al., 2006; Will et al., 2006; Wheeler et al., 2002).

2. Methods

This study was established on two tracts of land, one owned by MeadWestvaco Corp. and the other by Rayonier Inc. Both tracts are located in the Upper Coastal Plain of Georgia. The clay site (MeadWestvaco) is located southeast of Cuthbert, GA (latitude 31°77′N, longitude −84°79′W) and has a Greenville soil series (Fine, kaolinitic, thermic Rhodic Kandiudult) that is highly eroded and compacted with a clay-rich B-horizon at the surface. Sand, silt, and clay percentages are 53, 14, 33 (0–10 cm), 36, 16, 48 (10–20 cm), 31, 16, 44 (20–50 cm), and 30, 39, 31 (50–100 cm). The sandy site (Rayonier) is located west of Lumpkin, GA (latitude 32°05′N, longitude −84°79′W) and has an Orangeburg soil series (fine-loamy, kaolinitic, thermic Typic Kandiudult) with a loamy sand topsoil averaging 15–40 cm in depth over a sandy clay loam B-horizon. Sand, silt, and clay percentages are 87, 7, 6 (0–10 cm), 84, 9, 8 (10–20 cm), 61, 9, 30 (20–50 cm), and 49, 27, 24 (50–100 cm). Existing loblolly pine plantations were operationally harvested from both sites in 2002. Five site preparation treatments were evaluated on each site, no-till (NT), coulter (C), coulter + bed (CB), coulter + subsoil (CS), and coulter + subsoil + bed (CSB). Three blocks of treatments were established at each site with tillage treatments randomly assigned to plots.

Prior to tillage treatments, October 2003, the clay site received an aerial herbicide treatment of 0.95 L Chopper™ (BASF Corporation, Research Triangle Park, NC; active ingredient Isopropylamine salt of Imazapyr 27.6%), 2.84 L Glypro Plus™ (Dow Agrosciences, Indianapolis, IN; active ingredient glyphosate 41.0%), and 0.59 L RedRiver 90 surfactant (Brewer International, Vero Beach, FL) in a total aqueous solution of 57 L ha^{-1}. The plots at the clay site were operationally hand-planted in February 2004 with a full-sib family Atlantic Coast loblolly pine family (same male and female parents, both originating on the Atlantic Coastal Plain). The rows were 3.7 m apart with seedlings planted at 1.8 m spacing along the rows. A broadcast herbaceous weed control treatment of 340 g ha^{-1} of Oustar™ (E.I. du Pont de Nemours and Company, Wilmington, DL; active ingredients hexazinone 63.2% and sulfometuron methyl 11.8%) was applied in 1.8 m bands along the rows in March of 2004. A second herbaceous weed control treatment consisting of 340 g ha^{-1} of Oustar™ was applied on 1.5-m bands in April 2004. To ensure uniform and complete weed control, hand spraying using glyphosate was done throughout the 2004-growing season to eliminate herbaceous and woody competition.

The sandy site received a broadcast herbicide treatment of 0.95 L Chopper^{TM} + 5.68 L Glypro Plus^{TM} in June 2003 in a 57 L ha^{-1} aqueous solution. A broadcast herbaceous weed control treatment of 56.7 g Oust^{TM} (E.I. du Pont de Nemours and Company, Wilmington, DL; active ingredient sulfometuron methyl 75.0%) and 56.7 g Escort^{TM} (E.I. du Pont de Nemours and Company, Wilmington, DL; active ingredient metsulfuron methyl 60.0%) was applied via skidder in October of 2003 in a 76 L ha^{-1} aqueous solution. The sandy site plots were hand-planted in January 2004 with three different loblolly pine clones with each block receiving a different clone. This distribution of genotypes to different blocks allowed us to eliminate genetic variation within blocks and remove genetic differences from the test of tillage effects as part of the blocking variable while still assessing the consistency of tillage effects on a variety of genotypes. The rows were 3.7 m apart and the seedlings were planted at a 0.9 m spacing to ensure full stocking. The plots (0.15 ha) were 7 rows wide with 30 trees per row. An additional herbaceous weed control treatment of 0.12 L Arsenal^{TM} (BASF Corporation, Research Triangle Park, NC; active ingredient Isopropylamine salt of Imazapyr 28.7%), 56.7 g Spyder (Riverdale, Burr Ridge, IL; active ingredient sulfometuron methyl 75.0%), and 28.3 g Escort^{TM} in a 121 L ha^{-1} aqueous solution was broadcast in April of 2004. In December 2004, every other tree was removed to achieve an operational planting density of 1500 trees ha^{-1}. *Note*: the clay site was operationally planted at 1500 trees ha^{-1} so no trees were removed from that site. Glyphosate was spot applied throughout the year to eliminate herbaceous and woody competition.

The randomized complete block design on each site consisted of three blocks each containing five randomly assigned treatment plots. The plots (0.15 ha) were 7 rows wide with 15 trees per row for the clay site (105 trees per plot) and 30 trees per row for the sandy site (210 trees per plot). Tillage treatments were installed using a Savannah Forestry Equipment (Savannah, GA), LLC model 420^{TM} two-disk heavy-duty subsoil plow pulled by a Caterpillar^{TM} (Peoria, IL) D-7R tractor in January 2004 for the clay site and in June 2003 for the sandy site. This plow consists of a linear arrangement of a 1.2 m diameter coulter wheel followed by a 7.5 cm wide, 60 cm long subsoil shank and then two 80 cm diameter opposed notched disk blades. The plow creates a continuous 1.7 m wide bed up to 50 cm in height and subsoils to a depth of 60 cm. To install the non-bedded tillage treatments, the disks were elevated to avoid soil contact. To install the non-subsoiled tillage treatments, the subsoil shank was removed from the plow. The NT treatments were hand planted at the same spacing as the tillage treatments. On the clay site, the NT plots were dibbled into flat ground to simulate normal hand planting while on the sandy site, a machine planter was run through the plots and then the seedlings were hand planted in the planting slit. Although the machine planter created some minimal tillage in the NT treatment on the sandy site, this was done to simulate the most common operational treatment on these types of sites.

Before the first growing season (2004), six trees representing the full range of initial seedling size were chosen in each plot (90 trees total per site) to be intensively measured. From the six intensively measured trees per plot, three trees were randomly chosen for fertilization. The total fertilizer application rate was 93 kg ha^{-1} N (ammonium nitrate), 4 kg ha^{-1} P (triple superphosphate), and 12 kg ha^{-1} K (potash). Macro- and micronutrients were also applied in the form of Holly-tone (Espoma Company, Millville, NJ) at 454 kg ha^{-1}. The fertilization was a split application with the first dose in May consisting of 1/3 of the total dose for N–P–K and 1/2 of the total dose of micronutrients. The second dose in July consisted of 2/3 of the total dose of N–P–K and 1/2 of the total dose of micronutrients. The fertilizer was applied evenly to a 1.8 m × 3.7 m area surrounding each tree.

For all six intensively measured seedlings in each plot, height and ground line diameter were measured at the beginning and end of the 2004-growing season. Near each of these 90 trees per site, soil moisture and soil penetration resistance were periodically measured. Soil moisture was measured using time domain reflectometry (TDR) with a Techtronics model 1502B analog cable tester (Techtronics, Beaverton, OR). Pairs of 0.3 cm diameter TDR rods were installed before the growing season in the tilled areas along the rows and left in place throughout the year from 0 to 30 and 0 to 60 cm soil depth. Soil moisture was measured approximately every 2 weeks from early May until September and monthly from September until December. Soil penetration resistance was measured with a Rimik CP 20 Cone Penetrometer (Toowoomba, Queensland) in May, August, October, and December. Nine insertions equally spaced in a 1 m^2 area around each seedling were made to a depth of 600 mm and recorded at 25 mm intervals. Data within each 100 mm depth increment from all nine measurements per tree were averaged to calculate an estimate for each 100 mm layer of soil.

At the end of the growing season, heights and ground line diameters of all trees in the internal measurement plots (approximately 65 trees) were measured to determine plot-level seedling size at the end of the first growing season.

Each site was analyzed separately. The effects of tillage treatments on plot-level seedling heights and diameters following the first growing season were analyzed using a randomized complete block design ANOVA with the average of all seedlings within each measurement plot (approximately 65 seedlings) representing the experimental unit, i.e., block ($n = 3$). The effects of tillage type on soil penetration resistance and soil moisture were tested using split-plot ANOVA. No differences existed for seedling growth rates or in the relationship between soil penetration resistance, soil moisture, and seedling growth between the fertilized and nonfertilized trees. Therefore measurements pertaining to all six trees per plot were averaged to serve as the experimental unit to assess the effects of tillage. Tillage served as the whole-plot factor while date and soil depth (in the case of soil strength) served as the split-plot factors.

To determine how soil moisture and soil strength affected seedling growth, the relationship between soil penetration resistance and soil moisture and final seedling height (hgt), final ground line diameter (gld) or relative ground line diameter growth (rgld; absolute gld growth/initial gld) were tested using regression analysis. On the clay site, rgld growth was chosen for the analyses because of differences ($p = 0.07$) in initial height based on planting depth between tilled and untilled plots (deeper in tilled treatments) and large variability in initial seedling sizes. Because of the uniformity of the clones used on the sandy site and the lack of a significant difference in initial height, final hgt and gld (December 2004) were used for the analyses at the sandy site. Soil penetration resistance and volumetric soil moisture used in this analysis were obtained by averaging all measurements made during the year.

3. Results

3.1. Soil moisture

3.1.1. Clay site

When averaged across the eight sampling dates, volumetric soil water content (VWC) from 0 to 30 cm soil depth ranged from a high of 0.34 $cm^3 cm^{-3}$ in the NT treatment down to 0.17 $cm^3 cm^{-3}$ in the CSB treatment (Fig. 1). This consistently greater VWC in the NT compared to plots receiving tillage resulted in a significant tillage effect ($p = 0.004$). However, differences among the tilled treatments were not significant. Volumetric water content from 0 to 60 cm soil depth was generally higher than 0–30 cm, ranging from 0.34 $cm^3 cm^{-3}$ for the NT to 0.23 $cm^3 cm^{-3}$ for the CSB and had a similar tillage effect due to the high VWC in the NT treatment ($p = 0.0004$) (Fig. 1). For both depth increments, no interaction between tillage and sampling date existed because while VWC fluctuated throughout the season (date effect, $p < 0.0001$) differences were consistent among treatments.

3.1.2. Sandy site

Volumetric water content varied throughout the growing season with generally reduced moisture in mid-summer (date effect, $p < 0.0001$). The 0–30 cm VWC was generally lower than at the clay site, ranging from 0.20 to 0.13 $cm^3 cm^{-3}$. Volumetric water content varied among the tillage treatments (tillage effect, $p = 0.05$) but, unlike on the clay site, VWC was the highest in C treatment, was lowest for the bedded treatments and was intermediate for the NT treatment (Fig. 2). A significant date × tillage interaction ($p = 0.002$) occurred in the 0–30 cm depth range due a temporary decrease of the C treatment relative to the other treatments on Julian date 273 (September 29). Volumetric water content was higher within the 0–60 cm depth increment than in the 0–30 cm depth (Fig. 2) and differed among tillage ($p = 0.002$). The VWC of the CSB, CB, and NT treatments were significantly lower than the CS or

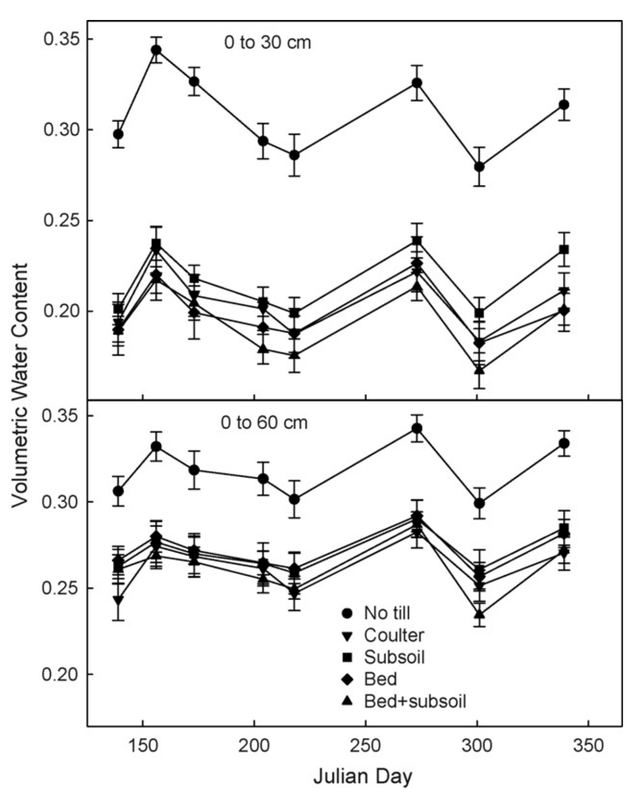

Fig. 1. Soil volumetric water contents ($cm^3 cm^{-3}$) throughout the growing season in the 0–30 and 0–60 cm soil depth increments for the different tillage treatments at the clay site planted with loblolly pine seedlings southeast of Cuthbert, GA on a Greenville soil series (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

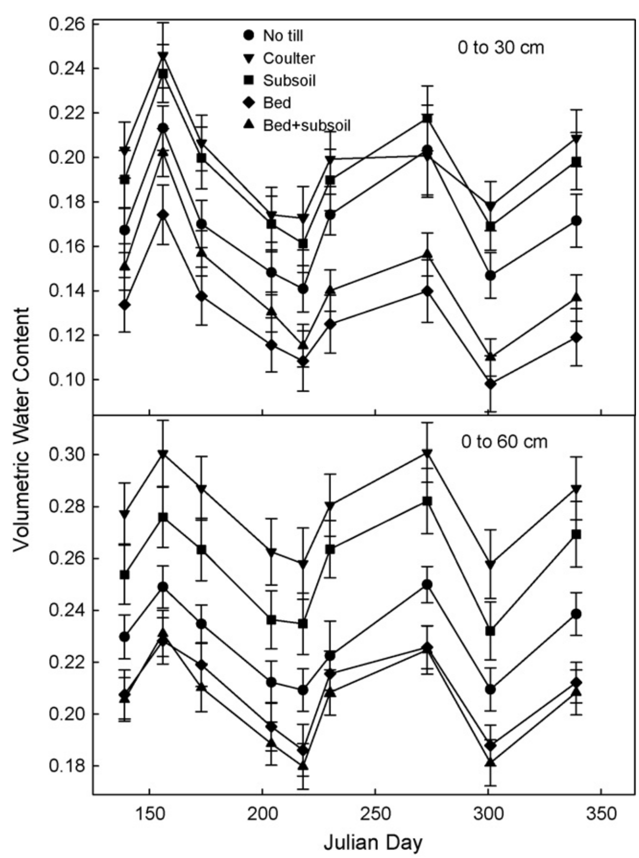

Fig. 2. Soil volumetric water contents ($cm^3 cm^{-3}$) throughout the growing season in the 0–30 and 0–60 cm soil depth increments for the different tillage treatments at the sandy site planted with loblolly pine seedlings west of Lumpkin, GA on an Orangeburg soil series (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

the C treatments. Unlike the 0–30 cm depth, the effects of treatment were consistent throughout the year (treatment × date interaction, $p = 0.30$).

3.2. Soil penetration resistance

3.2.1. Clay site

It was not possible to measure soil penetration resistance on the NT plots at the clay site because the soil penetration resistance of the soil surface exceeded the upper limit of our penetrometer's capacity (5000 kPa) on all sampling dates. Therefore, soil penetration resistance between 0 and 10 cm in the NT plots was conservatively estimated to be 5000 kPa (the penetrometer maximum). We did not include the NT treatment in comparisons at deeper depths.

Soil penetration resistance in the surface 10 cm varied during the year ($p < 0.0001$) and tillage effects on soil penetration resistance changed throughout the year (treatment × date interaction, $p = 0.02$). On all dates, the NT treatment had significantly higher soil penetration resistance than the tilled treatments in the 0–10 cm soil layer (see Fig. 3 for soil penetration resistance in 0–10 cm for all treatments except the NT). While, differences among the tilled treatments varied with date, the bedded treatments generally had lower soil penetration resistance than the non-bedded treatments. In May, the CSB, CB, and CS had significantly lower ($p < 0.05$) soil penetration resistance in the 0–10 cm interval than the C treatment. In October the CSB and the CB treatments had significantly lower soil penetration resistance than the than C treatment. In December, the CB treatment was significantly lower than the CS treatment.

Analysis of the four tillage treatments (NT dropped) and all depths indicated that differences in soil penetration resistance among treatments were non-significant ($p = 0.42$). On all dates, soil penetration resistance increased with soil depth ($p < 0.0001$). A significant date × depth interaction ($p = 0.01$) occurred, because soil penetration resistance varied less with soil depth as the year progressed (Fig. 3).

3.2.2. Sandy site

Soil penetration resistance varied throughout the year (date effect, $p < 0.0001$), with soil penetration resistance in December generally lower than the other three dates. Soil penetration resistance increased with depth ($p < 0.0001$). The bedded treatments (CSB and CB) had the lowest soil penetration resistance, followed by NT, CS, and C (tillage effect, $p = 0.003$) (Fig. 4). Because of a significant date × til- tillage interaction ($p < 0.0001$), each date was analyzed separately. In May (tillage effect, $p = 0.002$), the bedded treatments had the lowest soil penetration resistance, and were significantly lower than the C, NT and CS treatments. The C treatment had the highest soil penetration resistance and was significantly greater than the NT and CS treatments. In August (tillage effect, $p = 0.01$), October (tillage effect, $p = 0.006$) and December (tillage effect, $p = 0.001$), the bedded treatments had significantly lower soil penetration resistance than all other treatments.

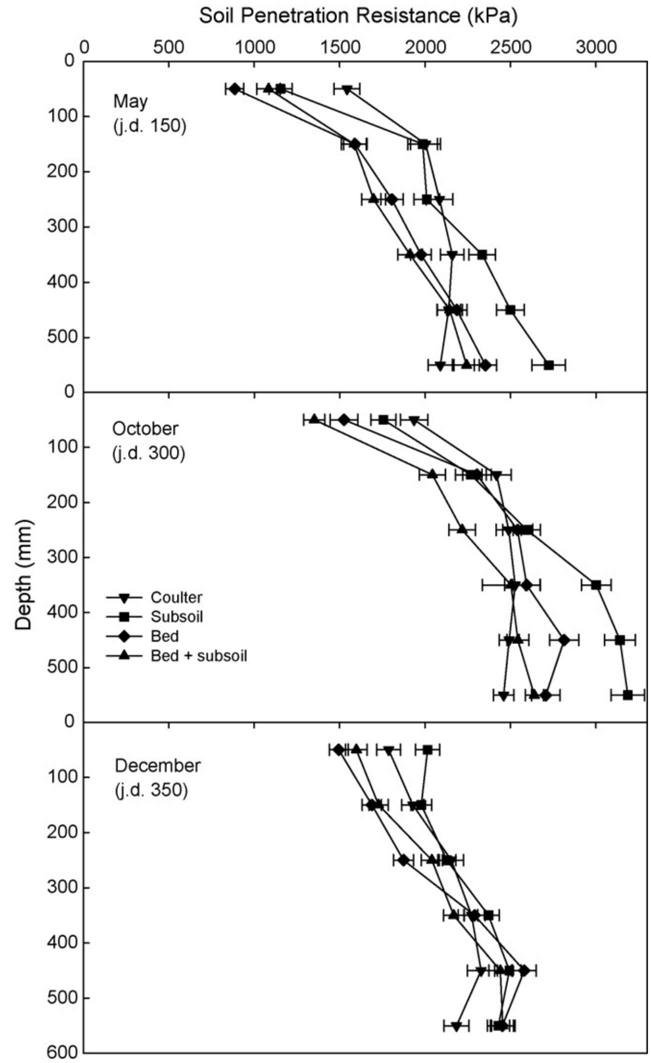

Fig. 3. Soil penetration resistance between 0 and 600 mm for May, October, and December 2004 at the clay site planted with loblolly pine seedlings southeast of Cuthbert GA on a Greenville soil series (bed, subsoil, and bed + subsoil treatments included the coulter treatment). Soil penetration resistance of the no-till treatment exceeded the upper limit of the penetometer (5000 kPa) and could not be measured.

3.3. Plot-level survival and tree size after first growing season

Survival was not significantly affected by tillage treatments on either site. On the clay site, the C treatment had the best survival at 81%, followed by the CB treatment at 73%. The CS, CSB, and NT all had similar survival rates of 65, 63, and 63%, respectively. Survival at the sandy site was greater than 99% in all treatments.

When comparing the seedling means based on all trees within the measurement plot (each plot mean comprised approximately 65 measurement trees), the tillage treatments did not significantly affect height (hgt) on either site at the end of the first growing season (clay site, $p = 0.27$; sandy site, $p = 0.12$) (Figs. 5 and 6). At the clay site, ground line diameter (gld) ranged from 15.1 mm in the C treatment to 11.9 mm in the NT treatment ($p = 0.05$) (Fig. 5) with the C treatments

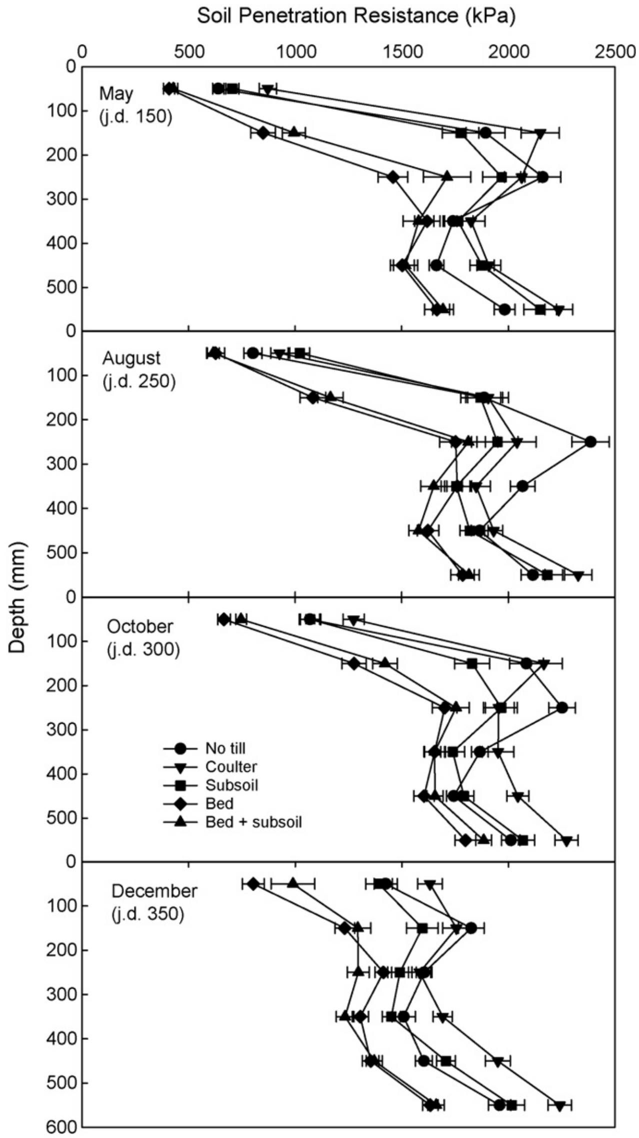

Fig. 4. Soil penetration resistance between 0 and 600 mm for May, October, August, and December 2004 at the sandy site planted with loblolly pine seedlings west of Lumpkin GA on an Orangeburg soil series (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

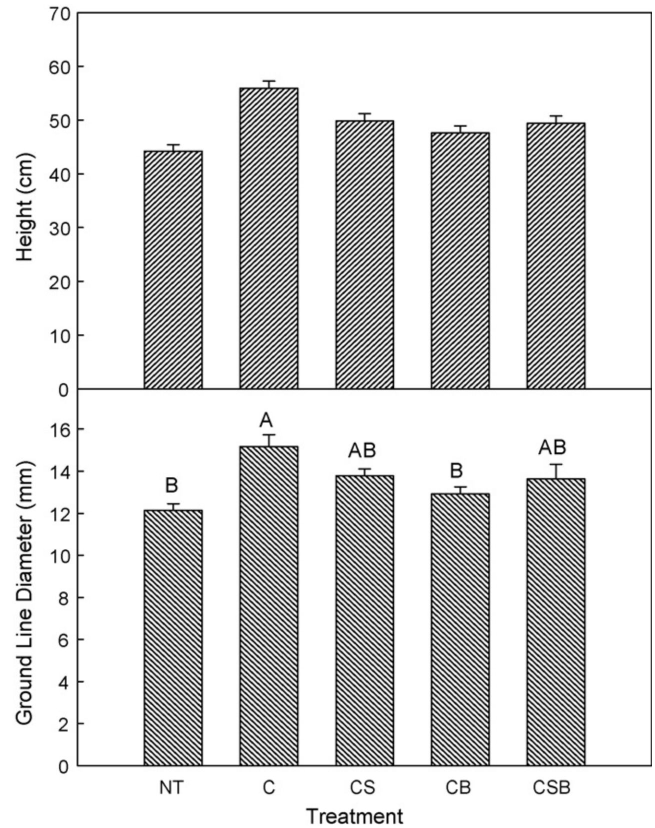

Fig. 5. Height and ground line diameters of loblolly pine seedlings grown in the various tillage treatments on the clay site southeast of Cuthbert GA (Greenville series) following the first growing season. Means represent the average of the three blocks with each plot comprising approximately 65 trees. Vertical bars represent standard error. Different letters indicate a significant difference based on Duncan's multiple range tests (NT: no-till; C: coulter; CS: coulter + subsoil; CB: coulter + bed; CSB: coulter + subsoil + bed).

significantly greater than the NT and CB treatment. In contrast, gld of the C treatment on the sandy site was significantly smaller (16.4 mm) than the CB and CSB treatments ($p = 0.05$) (Fig. 6).

3.4. Size and growth of intensively measured trees

There were no significant effects of fertilization or interactions involving fertilization on the size or growth of intensively measured trees. Likewise, the relationships between tree size or growth and soil physical properties of fertilized and nonfertilized trees were similar. Therefore, all six trees per plot were pooled for analyses.

In general, the growth of the intensively measured seedlings was similar to the more extensive sampling at the plot level. On the clay site, the seedlings in the CSB, CB, and C treatments grew larger on a relative basis in gld than in the NT treatments ($p = 0.08$) (Table 1). Relative hgt growth was not significantly affected by tillage treatments. Relative gld growth was used to correlate to soil penetration resistance and VWC because of significant differences ($p = 0.07$) in initial height between seedlings in the tilled and untilled plots related to planting depth (deeper in the tilled treatments) and large variability of the seedling sizes within treatments (Table 1). On the sandy site, gld of the seedlings in the C treatment was significantly ($p = 0.02$) smaller than the other treatments (Table 1). There were no significant differences in hgt among tillage treatments.

3.5. Relationship between seedling growth and soil properties

3.5.1. Clay site

We found that between 30 and 40% of the variation in individual seedling diameter growth could be explained by soil penetration resistance. As soil penetration resistance decreased from 3100 to 1900 kPa in the 40–50 cm zone, rgld increased from 1.7 to 2.4 with 40% ($p = 0.03$) of the variation in rgld explained by soil penetration resistance (Fig. 7). This relationship was also significant ($p = 0.06$) for soil penetration

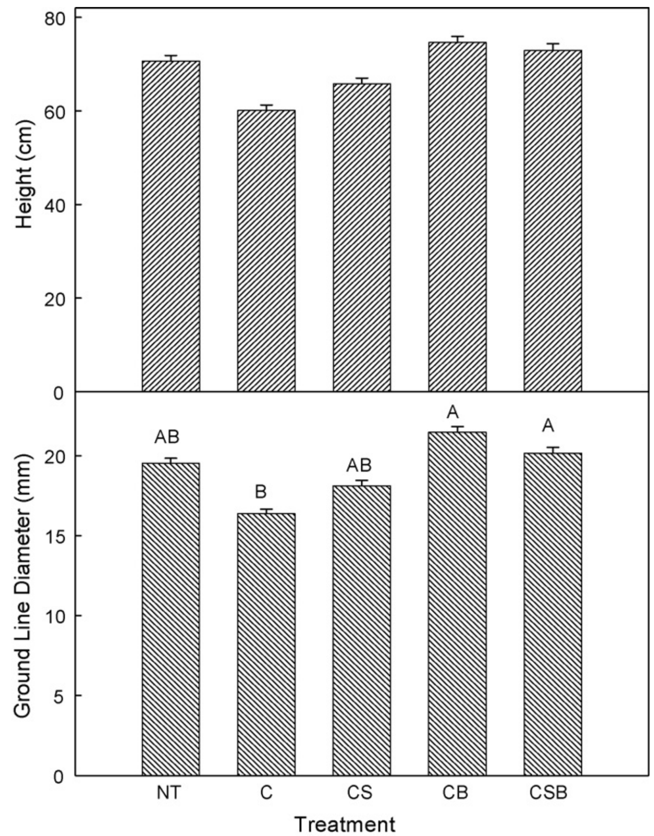

Fig. 6. Height and ground line diameters of loblolly pine seedlings grown in a range of tillage treatments on the sandy site west of Lumpkin, GA (Orangeburg series) following the first growing season. Means represent the average of the three blocks with each plot comprising approximately 65 trees. Vertical bars represent standard error. Different letters indicate a significant difference based on Duncan's multiple range tests (NT: no-till; C: coulter; CS: coulter + subsoil; CB: coulter + bed; CSB: coulter + subsoil + bed).

resistance from 50 to 60 cm ($r^2 = 0.31$). The correlation is less robust than it would be if data from the NT plots could be included (soil penetration resistance on NT plots surpassed the maximum limit of the penetrometer, i.e., 5000 kPa). On this site, the NT plots had the lowest rgld (Table 1) and by far the highest soil penetration resistance in the surface horizons. If a soil penetration resistance of 5000 kPa is assumed for the NT plots for the 0 to 10 cm layer, the correlation is significant ($p = 0.05$) with 27% of variation explained. A similar relationship existed between VWC and rgld. As average VWC from 0 to 60 cm increased from 0.24 to 0.33, rgld decreased from 2.4 to 1.1 ($p = 0.002$, $r^2 = 0.54$) (Fig. 8). The relationship between VWC from 0 to 30 cm and rgld was not significant ($p = 0.1$).

3.5.2. Sandy site

Ground line diameter and hgt at the end of the first growing season were used to correlate soil penetration resistance to seedling growth. The soil penetration resistance between 10 and 40 cm was negatively correlated to seedling size at the end of the first growing season. As soil penetration resistance decreased from 2000 to 1400 kPa in the 30–40 cm layer, gld increased from 17 to 23 mm ($p = 0.006$, $r^2 = 0.51$) and hgt increased from 60 to 85 cm ($p = 0.005$, $r^2 = 0.46$) (Fig. 9). Similarly, as soil penetration resistance between 10 and 20 cm increased, hgt ($p = 0.05$, $r^2 = 0.27$) and gld ($p < 0.02$, $r^2 = 0.35$) decreased. This relationship held true for 20–30 cm depth interval also (hgt $p = 0.05$, $r^2 = 0.27$; gld $p = 0.02$, $r^2 = 0.35$). In contrast to the clay site, there was no relationship between VWC and gld or hgt at either soil depth interval (0–30 cm or 0–60 cm).

4. Discussion

4.1. Volumetric water content and soil penetration resistance

Bedding decreased VWC at both sites, probably as a result of increased large voids in the soil and increased macroporosity (Harrison et al., 1994; Morris and Lowery, 1988). In contrast, the C and CS treatments had lower VWC than the NT treatment on the clay site while the NT treatment had lower

Table 1
Height (hgt) and ground line diameter (gld) of the intensively measured loblolly pine trees at the clay site located southeast of Cuthbert, GA (Greenville series) and for the sandy site west of Lumpkin, GA (Orangeburg series) at the end of the first growing season

Treatment	Initial	hgt	Initial	gld	hgt		gld		Rel hgt growth		Rel gld growth	
	cm	S.E.	mm	S.E.	cm	S.E.	mm	S.E.		S.E.		S.E.
Clay site												
NT	20.2	0.8	5.2	0.3	46.0	4.2	12.8	1.4	1.2	0.2	1.4	0.3
C	18.6	0.9	5.1	0.3	54.9	5.8	14.9	1.3	2.1	0.4	2.0	0.3
CS	17.4	0.6	4.9	0.3	49.9	6.2	13.8	1.6	1.8	0.3	1.7	0.2
CB	16.3	0.7	4.8	0.2	56.6	5.1	15.9	1.5	2.6	0.4	2.3	0.3
CSB	17.9	0.9	4.8	0.3	58.3	6.1	15.5	1.2	2.2	0.4	2.2	0.2
Sandy site												
NT	25.0	1.1	7.6	0.4	79.8	3.8	21.5	1.1	2.3	0.2	1.9	0.2
C	24.8	1.7	7.2	0.4	64.3	3.5	17.5	0.7	1.7	0.2	1.5	0.1
CS	23.6	1.7	7.2	0.4	73.4	3.9	21.9	1.1	2.4	0.3	2.1	0.2
CB	28.1	1.7	6.8	0.2	77.4	4.9	21.8	1.2	1.9	0.2	2.2	0.2
CSB	23.6	0.8	6.8	0.3	80.5	4.4	22.9	1.0	2.4	0.2	2.4	0.2

Tillage treatments were: NT: no-till; C: coulter; CS: coulter + subsoil; CB: coulter + bed; CSB: coulter + subsoil + bed. Rel hgt growth and Rel gld growth represent the growth during the first growing season divided by the initial height or diameter. S.E. represents the standard error of the mean based on three replicates that each comprise the mean of six subsamples.

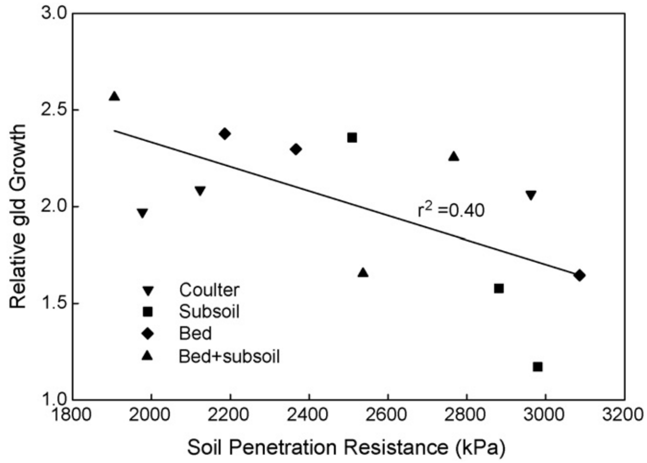

Fig. 7. Correlation between relative ground line diameter (gld) growth of loblolly pine seedlings and soil penetration resistance in the 40–50 cm depth increment on the clay site southeast of Cuthbert GA (Greenville series) during the first growing season. The no-till treatment could not be measured because the surface soil penetration resistance exceeded the maximum limit of the penetrometer (5000 kPa). The bed, subsoil, and bed + subsoil treatments included the coulter treatment.

VWC than the C and CS treatments on the sandy site. On the clay site that had good fracturing of the soil, the C and CS treatment probably increased macro-porosity in a similar way as the bedded treatments. In contrast, C and CS treatments apparently did not fracture the soil as effectively on the sandy site as indicated by higher VWC than the NT treatment. Without adequate fracturing, the depression left by the coulter and subsoil shank probably caused water to collect along the tilled surface and increase infiltration along the planting row.

Lower soil moisture content in the tilled treatments (bedding in particular) was similar to results from another site (Lincoln et al., 2006), which was conducted on an Orangeburg soil series that has 2–15 cm of sandy loam topsoil over a clay loam B-horizon. Will et al. (2002) also found that bedding decreased

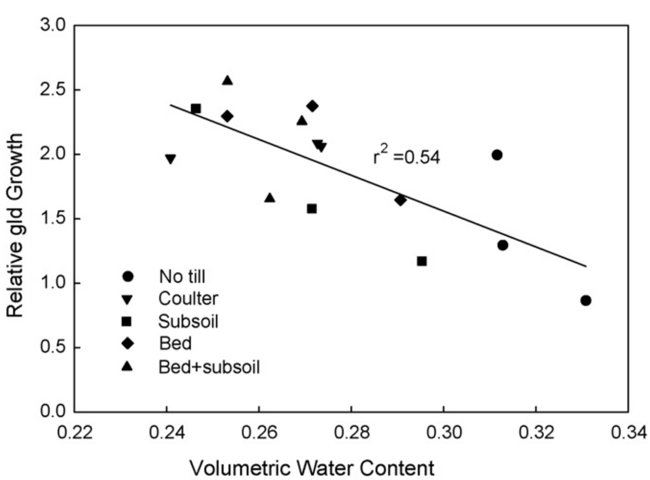

Fig. 8. Correlation between relative ground line diameter (gld) growth of loblolly pine seedlings and soil volumetric water content in the 0 and 60 cm depth increment on the clay site southeast of Cuthbert GA (Greenville series) during the first growing season. The bed, subsoil, and bed + subsoil treatments included the coulter treatment.

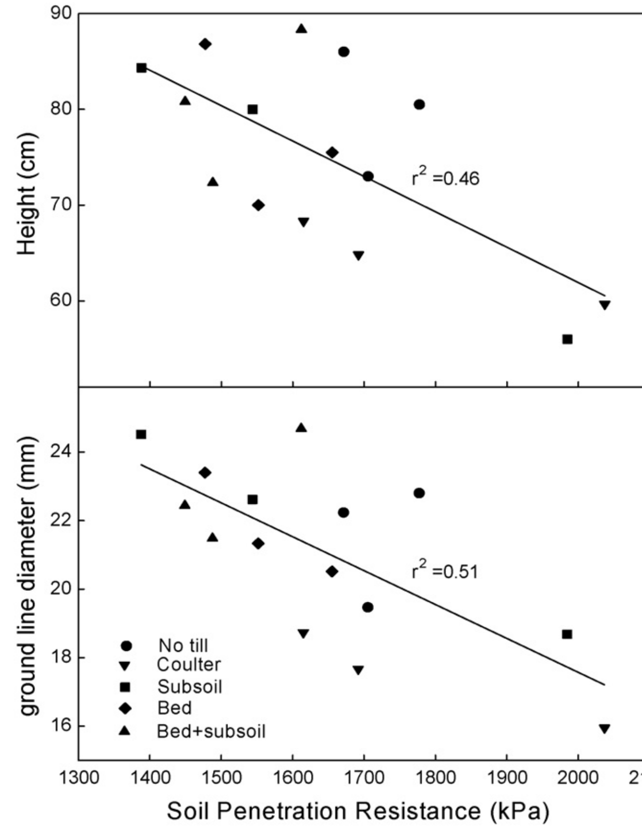

Fig. 9. Correlation between soil penetration resistance in the 30–40 cm depth increment and ground line diameter (gld) and height (hgt) following the first growing season for loblolly pine on the sandy site west of Lumpkin, GA (Orangeburg series). The bed, subsoil, and bed + subsoil treatments included the coulter treatment.

VWC compared to untilled areas, but their study did not contain a C or CS treatment to compare the variable response on clay versus sandy sites.

The potential for water uptake by seedlings is a function of seedling rooting volume as well as water infiltration and retention characteristics of the soil. Our moisture readings were volumetric and did not directly measure plant available water. Thus, we cannot quantify the effect of treatments on available water. However, the similarity in patterns of VWC and the relatively consistent absolute change between measurement dates suggest that available water was relatively similar. Page-Dumroese et al. (1997) found higher available water in bedded treatments compared to the controls, although these differences were small.

In a soil that is otherwise not altered, soil strength decreases with increases in soil moisture potential or soil water content. In this study, tillage created large pores and fractures within the soil and incorporated organic debris such as leaf and pine needle litter and branches that created low resistance in tillage treatments while simultaneously reducing volumetric soil water holding capacity. As a result, decreased soil VWC was associated with decreased soil penetration resistance when assessed across tillage treatments. In addition, although differences in volumetric water content existed among treatments and during the growing season, differences in penetration resistance among treatments were not well related to these differences (Morris et al., 2006).

On the clay site, soil penetration resistance was significantly reduced by all the tillage treatments. The soil at this site lacks an A-horizon and was heavily compacted from prior harvests and farming. Because soil recovery from compaction in the southeastern United States is a slow process (Mitchell et al., 1982), even minimal tillage such as the C treatment on this site can be enough to substantially decrease soil penetration resistance and increase growth. In contrast, soil penetration resistance of the NT treatment at the sandy site was intermediate. Subsoiling treatments that did not include bedding were ineffective at decreasing soil penetration resistance in this coarser-textured soil.

On the clay site, the CS treatment had the highest soil penetration resistance at depths over 30 cm. This is somewhat counterintuitive. This higher soil penetration resistance at depth was likely caused by the subsoiling shank not fully penetrating the soil to the full 60 cm design depth resulting in compaction at the bottom of the shank. To evaluate this, we analyzed the spatial pattern of soil penetration resistance within each sample and determined that penetration resistance was higher at 30 cm depth directly below the furrow created by the subsoiling shank than it was 50 cm cm to either side of the slit, providing evidence for some compaction associated with the subsoiling treatment. By October, the higher soil penetration resistance at 30 cm in the CS treatment was not apparent, indicating that water infiltration or root penetration deeper into the soil profile over time alleviated some of the compaction associated with subsoiling. Under operational conditions, this type of shallower-than-design tillage appears to be the norm for difficult clay-textured soils.

4.2. Tillage effects on plot-level seedling growth

The effectiveness of tillage depended on site. At the sandy site, seedlings in the two bedded treatments were significantly larger than those in the C treatment (the treatment with the lowest growth). On the clay site in comparison, the C treatment grew best. Bedding may have increased growth on the sandy site but not the clay site because the clay site lacked topsoil and incorporated organic materials. Bedding is particularly effective when topsoil and organic matter are present at the soil surface and are incorporated within the bed (Wheeler et al., 2002; Lincoln et al., 2006). In addition, on clay-textured soils, large chunks of soil with large voids can be created during bedding resulting in many unfavorable locations for planting. On the clay site, the minimal tillage offered by the C treatment appeared to be all that was necessary to break through the strong clay surface and enhance growth in the first year. On an Orangeburg soil with similar surface properties, Lincoln et al. (2006) also found that the coulter-only treatment provided almost as much benefit as the more intensive treatments. In contrast to the clay site, the C treatment at the sandy site reduced growth, probably because of compaction resulting from the coulter wheel being pulled through the sandy topsoil of this site. On the sandy site, the growth in the NT treatment (machine planted) was similar to the other more intensively tilled treatments and this may be all the tillage that is needed on sites with a thick, sandy surface horizons.

4.3. Relationship of soil physical properties to individual tree relative growth

Fertilization, applied to half of the intensively measured trees, did not increase growth. This indicates that on these two sites, nutrient availability following harvesting was enough to meet demand during the first growing season. Given the complete control of interspecific competition, plant use would be expected to be fairly low and emphasizes the importance of vegetation management for allowing crop trees to acquire available resources.

Sites like the clay study site that have eroded surface soils and an exposed clay-rich Bt horizon are relatively common throughout the Upper Coastal Plain and Piedmont of the southeastern United States. At such sites, any tillage that breaks up a strong soil surface horizon may be successful at increasing growth and survival in the first year. On the clay site, all tillage types were effective at reducing soil penetration resistance in the 0 to 10 cm depth compared to the NT treatment and these reductions were associated with increased rgld growth. First-year survival at the clay site was not significantly affected by tillage. Perhaps enough soil fracturing at the soil surface from hand planting allowed for seedling establishment, albeit slower growth. When the NT treatment was dropped from the analysis, tillage treatments did not significantly differ in the effect on soil penetration resistance. However, growth of individual plots receiving tillage was correlated to soil penetration resistance. Similarly, growth was correlated to soil penetration resistance at the sandy site. These results indicate that tillage or other activities that decrease soil penetration resistance as well as inherently lower soil strength are related to increased growth.

As VWC decreased, seedling rgld increased on the clay site. These results indicate that in our study water availability on a soil volume basis was of less importance to growth than the changes in soil strength and increases in macroporosity related to tillage. Increased macroporosity and reduced soil penetration resistance that is linked to decreased VWC probably allowed the roots to more fully utilize the site, translating into improved growth (Shiver and Fortson, 1979; Will et al., 2002). In contrast to the clay site, there was no relationship between VWC and seedling size on the sandy site. This seems to confirm that the negative relationship found between VWC and seedling growth observed on tilled sites (Will et al., 2002; Lincoln et al., 2006) does not represent a causative relationship.

5. Conclusions

The goal of this study was to determine the effects of different intensities of soil tillage on soil penetration resistance and soil moisture and to relate these changes to seedling growth. Since we isolated tillage mediated effects on soil properties from those related to competition control or fertility, we are confident that tillage does have a positive influence on seedling growth, albeit relatively small and inconsistent across different sites. In particular, treatments that reduce soil penetration resistance can be expected to increase seedling growth. Across the range of soil penetration resistance we measured, we found that plots with the lowest soil penetration resistance had seedling growth rates approximately 50–60% greater than plots with the highest soil penetration resistance. While there were inherent difference in soil penetration resistance among plots, tillage generally did reduce soil penetration resistance and contribute to the measured growth differences. Volumetric soil water content was negatively correlated to seedling growth at one of the two sites, probably as an ancillary result associated with greater macroporosity. Based on these findings, the challenge is to employ the most efficient tillage method to reduce soil penetration resistance.

Any method that fractured the eroded, compacted surface horizon at the clay site was adequate to increase growth such that the minimal tillage associated with the coulter-only treatment was most effective. In contrast, the coulter-only tillage treatment at the sandy site tended to increase soil penetration resistance and decrease seedling growth probably because the coulter compacted the soil as it moved through the sandy surface horizon. However, the minimal tillage associated with the machine planting at the sandy site resulted in seedling growth similar to the more intensive treatments.

Overall, we recommend employing the least intensive tillage necessary to fracture the surface and decrease soil penetration resistance on these Upper Coastal Plain sites. While bedding has been effective in previous studies on upland soils (Lincoln et al., 2006; Wheeler et al., 2002), this may be more intensive than necessary to achieve the potential growth gains associated with tillage mediated changes in soil physical properties, especially when the benefits of bedding on competition and soil fertility can be achieved by herbicides and fertilization. Similarly, the positive effects of subsoiling on early seedling growth are either negligible or too small to warrant the relatively large expense (Lincoln et al., 2006; Wheeler et al., 2002; Schilling et al., 2004). Ultimately, the decision as to whether to till and the choice of tillage method will depend on the inherent soil penetration resistance of the site, the texture of the surface horizon, and the moisture conditions of the soil at the time of tilling. In the case of our study, fairly low intensity tillage was sufficient on these Upper Coastal Plain sites.

Acknowledgements

The Georgia TIP3 program funded this project. MeadWestvaco and Rayonier allowed use of these sites for research and provided equipment and personnel. The assistance of the faculty and staff of the University of Georgia was greatly appreciated.

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