THE EFFECTS OF TILLAGE INTENSITY ON SOIL PHYSICAL PROPERTIES AND THEIR RELATIONSHIP TO LOBLOLLY PINE SEEDLING GROWTH

By

MARION CHAD LINCOLN

(Under the Direction of Rodney E. Will)

ABSTRACT

The amount of tillage necessary to improve pine seedling growth is important to consider when the expense of soil tillage may not justify gains in growth offered by tillage practices. To determine the relationship between changes in soil attributes associated with differing tillage intensities and growth of loblolly pine seedlings, I measured soil moisture, nitrogen availability, and soil strength on different tillage treatments on three different sites in the Upper Coastal Plain in southwest GA. The five tillage treatments were: no-till, coulter, coulter + subsoil, coulter + bed, and coulter + bed + subsoil. I monitored individual seedlings and measured soil attributes adjacent to these seedlings and correlated these measurements to seedling growth. Tillage increased rootability by decreasing soil strength and increasing porosity and these changes were associated with increased seedling growth. The less intensive tillage treatments may be as effective at improving soil physical characteristics and seedling growth as more intensive tillage treatments.

INDEX WORDS: Soil tillage, Bedding, Subsoiling, Soil strength, TDR, Soil moisture, Loblolly pine, *Pinus taeda*

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MARION CHAD LINCOLN

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MARION CHAD LINCOLN

Major Professor: Rodney E. Will

Committee: Lawrence A. Morris
Daniel Markewitz

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
University of Georgia
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INTRODUCTION

Increasing demands for timber and the desire for increased yields have prompted the use of intensive site preparation in all areas of the southeastern United States (Lantagne and Burger 1987). Mechanical site preparation methods, such as bedding and subsoiling, can improve water status and structure of many soils, and facilitate planting (Berry 1979). The beneficial effects of bedding and ripping are attributed to improved drainage, improved micro-site environment (nutrients, aeration, temperature, and moisture) for root development, increased moisture availability, and reduced competition (Haines et al. 1975). Operations that increase the ability of a seedling to exploit the existing resources in the soil or increase the concentrations of the resources in the soil may increase seedling growth (Wheeler et al. 2002). However, the high cost of mechanical site preparation techniques have caused many forest managers to reconsider the benefits of these practices.

Bedding and subsoiling are often done together, but this intensive tillage operation is expensive. The lower intensity tillage that that occurs during machine planting or bedding alone decreases costs. The tillage practice that results in the greatest gains is most desirable to forest mangers, but these gains may not justify the expense. Moreover, results from operational trials have been highly variable. Improved survival and significant increases in growth are repeated for sites in some studies while other studies show little benefit from tillage on similar sites.

This study was designed to analyze the effects of different levels of soil tillage (coulter only, bedding, subsoiling, and bedding and subsoiling combined) on soil strength, soil nitrogen availability, and soil moisture. The differences in these soil attributes were then correlated to changes in seedling growth. To avoid confounding effects of tillage induced differences in plant competition, weeds were controlled on all plots to eliminate the confounding effects of competition on seedling growth. In addition, it is difficult to separate the effects of soil tillage on physical properties from those on nutrient availability. Therefore, the effects of tillage on fertility were separated from the effects of tillage on soil physical properties by a split plot design in which half the sample trees were fertilized and half were not.

CHAPTER I

LITERATURE REVIEW

Tillage Effects on Seedling Growth

Soil tillage increases overall seedling vigor of loblolly pine throughout the southeastern United States (e.g., Berry 1979; Outcalt 1984; Wittwer et al. 1986; Wheeler et al. 2002). Bedding, the mechanical accumulation of local topsoil onto the planting area, increases growth and survival on poorly drained sites of the lower coastal plain (Haines et al. 1975; McKee and Wilhite 1986; Gent et al. 1986b) and on upland sites (McKee and Wilhite 1986; Wheeler et al. 2002). Subsoiling, which involves pulling a shank of varying depths through the soil, improves growth in mountain soils (Wittwer et al. 1986), while bedding and subsoiling together are sometimes combined in the Upper Coastal Plain and the Piedmont (Wheeler et al. 2002).

Bedding can increase seedling growth with improvements in rooting volume through reduced bulk density and increased macro-porosity (Morris and Lowery 1988). Attiwill et al. (1985) found that increased growth from bedding can also be gained by concentrating organic materials near the root systems of seedlings which can lead to an increase in nitrogen mineralization. Harvey et al. (1997) found that soils within bedded treatments contained nearly triple the total organic matter of non-bedded controls. On an upland site, bedding increased stem volume by 6% in loblolly pine compared to a no-till treatment at age 2 (Wheeler et al. 2002). Bedding in combination with fertilization, weed control or both has been shown to dramatically increase seedling height and diameter (Gent et al. 1986b; Page-Dumroese et al. 1997).

Although increases in available resources have been related to increased seedling growth, bedding may increase growth by allowing roots to acquire necessary resources from larger volumes of soil (Will et al. 2002). On poorly drained sites, bedding is often used to raise the trees above the water table and to provide a greater volume of soil suitable for root expansion. Height and diameter growth of loblolly pine can be dramatically increased on poorly drained, clayey coastal plain soils by bedding (Gent et al. 1986b). McKee and Wilhite (1986) found that the main response to bedding on Lower Coastal Plain sites was drainage that leads to increased root aeration in seedlings.

Subsoiling can loosen soil to a depth of 60 cm or more with the goal of fracturing subsurface soil horizons (Nadeau et al. 1998) and reducing high soil bulk density that tends to reduce root penetration, soil aeration, water infiltration, and percolation. Mixing is minimal with most subsoiling operations. Bulk density reflects changes in soil properties that affect the growth of plants (Stransky 1981), and subsoiling can reduce soil bulk density and aid in root penetration (Harrison et al. 1994). Although subsoiling generally does little to increase the volume of large pores in the soil aside from the soil fracturing caused by subsoiling under proper moisture conditions, it has a greater potential to influence root development than other site preparation operations because of the increased volume of soil exploited by the roots in the first few growing seasons (Morris and Lowery 1988). Subsoiling can also increase plant available water by improving water penetration (Berry 1979). Although the intensity of subsoiling needed may vary by site, some subsoiling is desirable on many sites, especially those where a hardpan may exist (Berry 1979). Wittwer et al. (1986) found subsoiling increased seedling height of loblolly pine on a mountain site at age 2 by 10% and ground line diameter (gld) by 20% while the combination of subsoiling + herbicide increased seedling height by 49% and gld by 50%.

Subsoiling also increased height growth in loblolly pine on a piedmont site at five years by 3.5% and root-collar diameter growth by 9.4% (Berry 1979).

Bedding and subsoiling are often used in combination. This treatment works best in areas that have a combination of a poor belowground rooting environment and lack an A horizon (the top layer of soil). But a combination of treatments does not guarantee additive growth responses. Wheeler et al. (2002) found that bedding treatments resulted in consistent positive growth responses, but adding subsoiling to the bedding treatment did not increase growth. Although bedding increased early growth, it has a diminishing effect on height growth over time (Wilhite and Jones 1981). McKee and Wilhite (1986) found that on a moderately well-drained site, bedding increased tree heights by 33% two years after planting but increased height by only 7% ten years after planting. With other silvicultural treatments such as mid-rotation fertilization, it should be possible to maintain the positive effects of soil tillage on seedling growth throughout the entire stand rotation (Will et al. 2002).

Tillage Effects on Root Growth

Root development is a major factor controlling survival and first year growth of planted pine (Morris and Lowery 1988). Root development is affected by the amount of topsoil available for unimpeded root system expansion (Haines and Davey 1979). The physical condition of the site and genetic growth potential control a seedling’s ability to produce new root growth and exploit soil volume (Carlson 1986). Tillage operations, such as bedding and subsoiling, can improve site conditions to enhance root growth in many situations.

Upland site bedding can improve root growth by reducing soil mechanical impedance, increasing the volume of soil that is exploited, and providing more uniform depth distribution of roots during the first few growing seasons (Morris and Lowery 1988). Harvey et al. (1997) found the most extensive root systems for western white pine (*Pinus monticola*) and Douglas-fir (*Pseudotsuga menziesii*) in bedded treatments as compared to an untreated control. Slash pine (*Pinus elliottii* Engelm. var. *elliottii*) on bedded treatments in the flatwoods of Florida likewise showed improved root growth because the root systems of bedded trees occupied a much greater soil volume and were better distributed around the plant and proliferated deeper into the soil profile than those of control trees. Fifteen-month-old seedlings on beds had nearly three times more lateral roots than control trees (Haines and Haines 1978).

Subsoiling has greater potential to influence seedling root development than other common site preparation operations because roots on subsoiled sites have the potential for increased soil volume exploitation and more uniform depth distribution (Morris and Lowery 1988). Subsoiling improved soil physical conditions and permitted more rapid root growth of a ryegrass/white clover pasture (*Lolium/Trifolium repens*), in which more extensive pasture root lengths were 36% greater below 30 cm depth (Harrison et al. 1994). Subsoiling treatments permitted roots to grow deeper and be more numerous in the A horizon for lodgeploe pine (*Pinus contorta*) compared with the control, but the tillage treatments did not increase height growth (Nadeau et al. 1998).

Tillage Effects on Soil Strength

Root growth and water movement are two of the most important factors affected by soil strength. Soil strength is the capacity of a soil to withstand stress without experiencing failure, whether by rupture or fragmentation and is characterized by soil physical properties such as bulk density, water content and potential, texture, aggregation, cementation, and mineralogy. Among these soil physical parameters affecting soil strength, soil water content and bulk density are most important (Vas and Hopmans 2001). An increase in bulk density can reduce root penetration and development, aeration, percolation, and nutrient availability (Stransky 1981; Grant and Lafond 1993; Chen et al. 1994). When soil bulk density increases, soil strength increases and soil aeration decreases, leading to adverse effects on root and shoot growth (Mitchell et al. 1982; Nambiar and Sands 1992). Poor root growth due to a restrictive soil physical property such as compaction (high bulk density) can be the largest restriction to seedling establishment and growth (Daddow and Warrington 1983; Carlson 1986).

Soil recovery from compaction in the southeastern United States is a slow process because of the absence of freezing and thawing. Also, soils that are high in kaolinite, which are common in the Southeast, lack the natural shrink-swell action of other clays (Mitchell et al. 1982). Compacted soils have fewer and smaller pores, and such conditions can damage or inhibit roots. Loblolly pine roots less than about 5 mm in diameter can be particularly vulnerable to soil compaction (Copeland 1952). Root growth is restricted in fine-textured soil when bulk density exceeds 1.4 Mg/m^3 and in coarser textured soils at 1.6 Mg/m^3 (Gent et al. 1984). Mitchell et al. (1982) observed that roots from soils with bulk density 2.0 Mg/m^3 were consistently restricted to the initial planting hole and were thicker and coarser. In addition, the heights of loblolly pine seedlings after a 19-week growing period were inversely proportional to soil bulk density. Even though roots have the ability to reach and exploit weaker zones of the soil through old root channels and cracks, areas of higher bulk density and soil strength reduce pine height growth (Nambiar and Sands 1992). An increase in bulk density of only 12% from 1.03 Mg/m^3 to 1.17 Mg/m^3 reduced loblolly pine height growth by 39% on a fine loamy sand (Lockaby and Vidrine 1984).

Tillage reduces bulk density. Soil bulk density decreased linearly with an increase of tillage intensity (Chen et al. 1994). While bedding may increase pine growth through promoting root growth due to the mounding of the A horizon (Morris and Lowery 1988), this mounding can also mitigate compaction resulting from harvesting traffic (Zhou et al. 1998). Zhou et al. (1998) found that bedding reduced soil bulk density between 10 to 25 cm in depth, but does not necessarily eliminate the pan or zone of compacted soil that may form below the surface horizons. Subsoiling improves internal structure of many soils and facilitates planting (Berry 1979). The profitability of subsoiling depends on the duration of the beneficial effect of the intervention and the beneficial effects of subsoiling may diminish over time (Ide et al. 1987). Subsoiling of an 8-year-old dryland ryegrass/white clover pasture resulted in a significant decrease (>10%) in soil bulk density (Harrison et al. 1994).

Tillage Effects on Soil Nutrients

Nitrogen availability can often limit the productivity of southern pine plantations, even in areas where large amounts of organic matter are available for mineralization (Vitousek and Matson 1985; Fox et al. 1986). Most NH_4^+ released by mineralization has little chance of being taken up by the small root systems of young pines, and more often than not, the NH_4^+ is used by soil microorganisms, other vegetation, or bacteria that oxidize NH_4^+ to the more mobile NO_3^- (Vitousek and Matson 1985). Organic nitrogen in the soil is released as inorganic N through the microbial oxidation of organic matter. During maintenance and growth, microbes immobilize much of this inorganic N. The difference between microbial release of N (mineralization) and incorporation of N into microbial biomass (immobilization) largely determines the amount of N available for plant uptake (Jansson and Persson 1982; Binkley and Hart 1989). Nitrogen mineralization and nitrification affect the amount and form of inorganic N available for tree growth. Ammonium, the product of mineralization, is tightly held in the soil. Nitrate, the product of nitrification, occurs in dissolved form and can be permanently lost from the soil by leaching or denitrification (Federer 1983). Intensive forest management techniques, such as windrowing and burning, can remove slash, litter, and some soil away from planting areas, potentially resulting in further reductions in nitrogen availability (Morris et al. 1983).

Tillage techniques, such as bedding and subsoiling, can help to concentrate organic matter around the areas to be planted. Attiwill et al. (1985) found a 35% increase in total nitrogen due to increased organic matter in the bedded treatments. Bedding also increases soil temperature (Fox et al. 1986) and the total store of plant-available water in the soil profile, which enhances the activity of soil microorganisms to convert or mineralize nitrogen into inorganic-N that is available for plant uptake (Morris and Lowery 1988). Nitrogen mineralization rates are highest at moisture contents near field capacity and increase with increasing soil temperature. Bedding creates a raised soil surface that is rapidly warmed, which stimulates N mineralization (Attiwill et al. 1985). Zhou et al. (1998) showed a significant increase in total mineral nitrogen and nitrate formation in the first growing season due to bedding. Bedded soils were approximately 30 percent higher in mineral N than nonbedded soils, demonstrating that the increase in mineral nitrogen due to bedding was equal to the application of 250-kg/ha of diammonium phosphate.   Competition can have an adverse effect on the nutrients available to pines, especially in the first year of growth (Burger and Pritchett 1988; Graham et al. 1989). Tillage can reduce competition at planting and allow young trees to access nutrients early in their first growing season (Haines et al. 1975; Lantagne and Burger 1987). However, more aggressive weed control and more effective herbicides may be reducing the importance of tillage on competition control.

Increased nitrogen mineralization in young pine plantations is of no use if the trees on the site are unable to capture the extra nutrients. Will et al. (2002) showed that tillage increased the tree N content in the second growing season. Although the authors found no significant differences in total soil N or total mineralized N due to tillage during the second growing season, the greater uptake of N by the trees was probably due to a greater volume of soil explored by larger root systems and the overall larger tree size in the tilled plots. The potential benefits of higher N mineralization from tillage in the first growing season are mostly unrealized by the trees in young plantations because of their small root systems. The ability of trees to grow larger root systems and capture more available N earlier is accelerated by tillage (Will et al. 2002).

Soil Moisture

Low soil water availability is a primary limitation of forest productivity (Gholz et al. 1990). Water stress in pine seedlings during the first growing season can be the most important factor determining growth (Morris et al. 1993; Torreano and Morris 1998). Torreano and Morris (1998) found that root growth rates were largely determined by soil water availability when soil strength was low and nutrition was maintained at a high level. Low soil water availability can affect seedling growth by limiting root elongation and altering distribution patterns (Ludovici and Morris 1997). The use of site preparation techniques that increase rooting volume and reduce plant competition may increase water availability to seedlings (Morris and Lowery 1988).

Tree growth can be negatively affected by lack of soil aeration. Bedding is typically used on poorly drained soils where aeration is a problem due to high water table (Allen 2000). Bedding also can be used to increase the total quantity of plant-available water. Available water stored between 0.1 and 15 bars is increased by incorporation of organic matter into mineral soils

(Morris and Lowery 1988). However, growth responses to bedding are typically the greatest on poorly drained clays and diminish as soil texture becomes coarser and drainage improves (Allen 2000). Bedding can reduce runoff, which in turn increases infiltration, percolation, and available soil moisture. Subsoiling on the contour can produce a similar effect (Haines and Haines 1978). Haines and Haines (1978) attributed a 30% increase in height after 2.5 years to improved soil moisture and nutrient conditions produced by bedding.

Subsoil compaction can adversely affect root penetration and cause water stress in trees (Nambiar and Sands 1992). Subsoiling can relieve subsoil compaction and aid in root penetration when it results in fracturing and shattering of the soil that reduces mechanical impedance to penetration (Parker and Amos 1982). Subsoiling can increase plant available water in the profile by increasing infiltration through slowly permeable surface layers during rain events and decreasing run-off (Dougherty and Hennessey 1988). Harrison et al. (1994) showed hydraulic conductivities of a subsoiled pasture was significantly greater than that of the undisturbed soil, reflecting the increased pore continuity within the depth of loosening. These improved soil physical conditions permitted more rapid root growth and the development of a more extensive ryegrass/white clover pasture root system with a 30% greater root length below 30cm depth.

Fertilization

Nutrient deficiencies are common in natural pine stands and in plantations in the Southeast. Nitrogen is the most limiting nutrient in many cases (Vitousek and Matson 1985). Phosphorus also can be limiting on many sites in the southeastern Lower Costal Plain (Gent et al. 1986b). Fertilization is an efficient way to treat nutrient poor areas to accelerate stand development and increase financial returns (Ford 1984). In southern pine stands, fertilizers are commonly applied at stand establishment and at midrotation (Allen 1987).

Fertilization at midrotation is commonly used by forest managers to increase growth and maintain gains from earlier cultural treatments. A plantation's potential to use nitrogen typically exceeds the available soil supply resulting in restricted leaf development and growth as trees reach ages between 8-15 (Allen et al. 1990). In established stands, applications of both nitrogen and phosphorus fertilizers have consistently produced large growth responses (Jokela and Stearns-Smith 1993; Allen 1999). Growth gains averaging 25-35% over a six to ten year period following a one time application of 200 kg/ha N or 200 kg/ha N plus 25 kg/ha P are typical (Allen 2000).

Early cultivation combined with fertilization can have long-term positive effects on site quality (Schmidtling 1984). However, fertilization with nitrogen at planting can vary in results because of increased competition from grasses and herbaceous weeds (McKee and Wilhite 1988). Early fertilization with a balanced supply of all nutrients increases stand productivity in some cases. McKeand et al. (2000) found that fertilizer applications at planting increased height by 43% and stem volume by 109% at age 4. Phosphorus broadcast before planting increases the mean size of loblolly pine at age 12 (Haywood and Burton 1990). On poorly drained clay sites, Gent et al. (1986a) recommend N + P fertilization if the additional cost of the N can be paid for by at least a 40% increase in growth response over P alone. Applications of 45-55 kg/ha of elemental N and 28-55 kg/ha elemental P would represent a common fertilizer treatment at time of planting for loblolly pine. A caveat to early fertilization is that increased nitrogen on the site may be ineffective in young stands where competition is controlled because at a normal spacing, seedlings planted at 600 to 850 trees/acre may accumulate only 1.4-2.3 kg of nitrogen after 2 years and over 112 kg/ha may be mineralized naturally over the same period (Vitousek and Matson 1985).

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CHAPTER II

RELATIONSHIP BETWEEN TILLAGE INTENSITY AND INITIAL GROWTH OF LOBLOLLY PINE SEEDLINGS[1]

[1] Lincoln M. Chad, Rodney E. Will, Emily A. Carter, John R. Britt, Lawrence A. Morris.

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Abstract

The amount of tillage necessary to improve pine seedling growth is important to consider when the expense of soil tillage may not justify gains in growth offered by tillage practices. To determine the relationship between changes in soil attributes associated with differing tillage intensities and growth of loblolly pine seedlings, I measured soil moisture, nitrogen availability, and strength across a range of tillage treatments on an Orangeburg soil series near Cuthbert, GA (four replications). I then 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 + bed + subsoil (CSB). Adjacent to three trees per plot (60 trees total), soil moisture was measured every two weeks using TDR, soil nitrogen availability was measured monthly by KCl extractions, and soil strength was measured two times during the year using a cone penetrometer beginning in May 2003. In December of 2003, the 60 trees were excavated to determine tree biomass. Average soil moisture in the upper 60 cm decreased from 28 percent in the NT treatment to 22 percent in the CB and CSB treatments. Nitrate concentrations increased by 33 percent in the bedded treatments (CB and CSB) compared to the NT, C, and CS treatments. From 0 to 200 mm, bedding decreased the average soil strength by 46 percent compared to the other treatments. Subsoiling decreased soil strength at depths deeper than 200 mm. Tillage positively affected relative height growth ($p = 0.0005$) and all the tillage treatments increased relative height growth compared to the NT treatment. Soil strength between 0 and 100 mm ($P=0.002$, $r^2=0.41$) was positively correlated with seedling relative height growth. Soil moisture from 0-300 mm ($P=0.0016$, $r^2=0.44$) was negatively correlated with seedling relative height growth. In contrast, nitrogen availability was not correlated to seedling growth. I calculated that tillage increases rootability by decreasing soil strength and increasing porosity and that these changes are associated with increased seedling growth.

Introduction

Intensive site preparation has become a standard practice for the establishment of pine plantations. Mechanical site preparation methods, such as bedding and subsoiling, can improve water status and structure of many soils, and facilitate planting (Berry 1979). The beneficial effects of bedding or subsoiling can be attributed to improved drainage, improved micro site environment (nutrients, aeration, temperature, and moisture) for root development, increased moisture availability, and reduced competition (Haines et al.1975). Operations that increase the ability of a seedling to exploit the existing resources in the soil or increase the quantities of the resources in the soil will increase seedling growth (Wheeler et al. 2002).

The high cost of mechanical site preparation techniques and inconsistent results have caused many forest managers to reconsider the benefits of these practices. Lower cost treatments, such as fertilization and herbicide application, may reduce the need for tillage if the positive effects of tillage are largely due to increased resource availability. However, if the positive effects of soil tillage are related to changes in soil physical properties and the ability of roots to exploit the soil volume, then it is not easily replaced by other treatments. The goals of this study were to 1) quantify the effects of soil tillage on soil strength, soil moisture, and soil nitrogen availability and 2) determine the relationship between tillage mediated changes in soil attributes and growth of loblolly pine seedlings. Different levels of soil tillage (coulter only, bedding, subsoiling, and bedding and subsoiling combined) were employed to generate a range of responses and to determine the minimum amount of tillage necessary to obtain the desired changes in soil attributes.

Materials and Methods

This study was established on a tract of land owed by MeadWestvaco, located in the Upper Coastal Plain of southwest Georgia. The site was previously in plantation pine and is on an Orangeburg soil (Typic Kandiudult) with 2 to 15 cm of sandy loam topsoil over a clay loam B-horizon. Five treatments were evaluated, no-till (NT), coulter (C), coulter + bed (CB), coulter + subsoil (CS), and coulter + subsoil + bed (CSB). Prior to tillage treatments, all plots received an aerial herbicide treatment of 5.7 L (6 qts.) Accord SP™ and 28 g (1oz) Escort™ in a total aqueous solution of 143 L ha^{-1} (fifteen gallons

ac^{-1}) in July 2002. The plots were operationally hand planted in January 2003 with a second-generation open pollinated Atlantic Coast loblolly pine family at a normal spacing of 1500 trees ha^{-1} (605 trees ac^{-1}). The rows were 3.7 m (12 ft) apart and the seedlings were planted at a 1.8 m (6 ft) spacing along the rows. A broadcast herbaceous weed control treatment of 850 g ha^{-1} (12 oz ac^{-1}) of Oustar™ was aerially applied in March 2003 at 95 L ha^{-1} (10 gallons ac^{-1}). To ensure uniform and complete weed control, spot applications using glyphosate were done throughout the year to control herbaceous and woody competition.

The randomized complete block design consisted of four blocks each containing five randomly selected treatment plots. The plots are 7 rows wide with 30 trees per row (1.5 ha). Tillage treatments were implemented using a Savannah Forestry Equipment, LLC model 420 two-disk heavy-duty subsoil plow pulled by a Caterpillar D-7R tractor in November, 2002. This plow consisted of a linear arrangement of a 1.2 m coulter wheel followed by a 7.5 cm wide subsoil shank in front of two 80 cm diameter opposed notched disk blades. The plow configuration creates a continuous bed up to 50 cm in height, 1.7 m wide, and subsoils at a depth up to 60 cm deep. 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 no-till treatments were hand planted at the same spacing as the tillage treatments.

Before the first growing season (2003), three trees of differing size were chosen in each plot (60 trees total) to for intensive monitoring and measurement. Two sets of time domain reflectometry (TDR) rods were installed on the row adjacent to each of these trees from 0-30 cm and 0-60 cm depth. Volumetric soil water content was measured at approximately 2-week intervals throughout the first growing season. Seedling height and ground line diameter were measured at 4-week intervals. Additionally, we measured 2M KCl extractable ammonium and nitrate concentration once per month (Mulvaney 1996). Soil strength was measured with a Rimik CP 20 Cone Penetrometer in May and August. Nine insertions were made to a depth of 600 mm and recorded in 25 mm increments in an area of a square meter around each tree. At the end of the first growing season, all 60 measurement trees were excavated to measure stem, foliage, and root biomass.

We tested the effects of tillage type on soil strength, soil moisture, and nitrogen availability by analysis of variance (ANOVA), using a split-plot analysis when appropriate, i.e., when soil depth (soil strength) and date (soil moisture) were included in the analysis. We then tested the relationship between the tillage-mediated differences in these soil attributes on seedling relative height growth (absolute height growth/initial height) using linear regression. The responses of the three seedlings per plot were averaged before analyses as the plot served as the experimental unit.

Results

Soil Moisture

Volumetric soil moisture varied throughout the growing season with generally reduced moisture in summer due to lower precipitation and greater evapotranspiration (date effect P <0.0001)(Fig.2-2). Between 0 to 600 mm, the volumetric moisture content of the soils in the NT treatment was consistently higher than in the tillage treatments, with the bedded (CB and CSB) treatments having the lowest moisture content (tillage effect P =0.0002) (Fig.2-2). Tillage effects were generally consistent throughout the year (date x tillage treatment P=0.11). Average volumetric soil moisture content ranged from 28 percent in the NT treatment to 22 percent in the CSB treatment (Fig.2-2). Moisture content from 0 to 300 mm was similar to 0 to 600 mm with treatment and date significant, but there was a date x tillage interaction (P<0.0001) probably due to less consistent moisture contents of the tillage treatments resulting from greater variation in periodic wetting and drying.

Soil Strength

Soil strength changed with soil depth (depth effect P<0.0001). In the NT plots, soil strength increased between 100 to 200 mm and then decreased at deeper depths, probably reflecting a root restrictive layer in the soil profile across the site (Fig.2-1). Overall, the tillage treatments reduced soil strength (tillage effect P<0.0001), but depth to which the different tillage treatments was effective depended on tillage type (tillage x depth interaction P<0.0001). The bedding treatments (CB and CSB) reduced average SOIL STRENGTH from 1411 kPa in the NT treatment to 463 kPa in the beds between 0 and 100 mm. At greater soil depths, the subsoil treatments were more effective at reducing soil strength. Between 500 to 600 mm, the CSB treatment was most effective with an average soil strength of 922 kPa compared to 1462 kPa of the NT. The C treatment was less effective than the more intensive tillage treatments at reducing soil strength, but this treatment reduced soil strength at all depths compared to the NT treatment. The results for August 2003 were similar to May with tillage treatment, depth, and tillage x depth significant ($P<0.0001$).

Soil Nitrogen Concentration

Tillage treatment ($P=0.006$) and date ($P<0.0001$) significantly affected soil Nitrate N concentration (Fig.2-3). Average nitrate N levels throughout the year ranged from a high of 3.2 ug/g in the CB treatment to 1.8 ug/g in the CS treatment. The higher nitrate N levels in the bedded treatments was most likely due to increased organic matter and top soil that are localized around the seedlings and a soil surface that was more rapidly warmed (Morris and Lowery 1988). Higher nitrate levels in mid summer, were expected because of higher temperatures. Tillage treatments did not significantly affect ammonium N concentration ($P=0.60$).

Seedling Growth

A positive relationship existed between seedling height and root biomass ($P<0.0001$ and $r^2=0.46$) and seedling height and stem biomass ($P<0.0001$ and $r^2=0.60$) across tillage tretments. The regression equations are: height = 46.089+0.3851*(root biomass) and height = 43.139+0.6495*(stem biomass) where height is seedling height in cm and biomass is in grams. During the 2003 growing season, seedlings in the tilled treatments grew taller than the seedlings in the NT treatment resulting in a significant date x treatment interaction ($P<0.0001$) (Fig.2-4). Seedling height increased from 22.5 to 52.3 cm in the NT treatment and from 19.1 to 69.5 cm on the CSB treatment (Fig.2-4). Planting depth differences caused a difference in initial heights between treatments of up to 6 cm. Because of the differences among the initial heights of seedlings within treatments (from 16 cm in the CB treatment to 23 cm in the NT) and due to the small differences in initial heights between tillage treatments, we used relative height growth (seedling height growth / initial height) as our estimate of seedling response. Relative height growth increased as a result of tillage ($P=0.0005$) (NT=1.4; C=2.9; CS=3.1; CB=3.5; CSB=2.9).

Relative height growth increased as soil strength decreased in the upper portion of the soil profile (0-400 mm). From 400 to 600 mm the relationship between soil strength and relative height growth was not significant. As soil strength in the 0 to 100 mm zone decreased from 1900 to 500 KPa, relative height growth increased from 1.6 to 3.5 with 41 percent of the variation in relative height predicted by soil strength (Fig.2-5). This relationship was also significant ($P<0.05$) from 100 to 200 mm ($r^2=0.37$), 200 to 300 mm ($r^2=0.31$), and 300 to 400 mm ($r^2=0.22$). As average volumetric water content between 0 to 300 mm decreased from 29 percent to 19 percent, relative height growth increased from 1.6 to 3.5 ($P=0.002$, $r^2=0.44$)(Fig.2-6). The relationship at 0 to 600 mm was not as strong ($P=0.01$, $r^2=0.29$). Nitrate N, both ammonium ($P=0.72$) and nitrate ($P=0.26$), were not significantly related to relative height growth (Fig.2-7).

Discussion

The purpose of soil tillage in plantation site preparation is to improve soil physical attributes and to facilitate seedling establishment and growth. The data in this study indicate a correlation between soil strength and seedling growth. As soil strength decreased seedling growth increased. This correlation was most likely due to improved soil physical conditions that enabled roots to better capture and exploit soil resources (Will et al. 2002). Subsoiling was successful at reducing soil strength at depths deeper than 400 mm, but as other studies have shown, adding subsoiling to other tillage treatments did not increase growth (Wheeler et al. 2002).

As volumetric water content decreased, relative height growth increased. The decrease in volumetric water content in the tilled treatments did not necessarily translate into less available water for the seedlings as the amount of soil water available to plants is a function of rooting volume as well as water infiltration and retention characteristics of the soil (Morris and Lowery 1988). The decrease in volumetric water content in this study was most likely caused by an increase in large voids in the soil and increased macro-porosity created by the tillage treatments (Harrison et al. 1994). Increased macro-porosity probably allowed the roots to more fully utilize the site, and this may have translated into improved relative height growth (Shiver and Fortson 1979, Will et al. 2002).

Although tillage increased nitrate N, this increase did not relate to increased relative height growth. Increased levels of N in the soil may not always be necessary to improve early seedling growth. Morris and Lowery (1988) stated that increased N mineralization may not be important in young stands because over 100 lb/ac of N may be mineralized in the first two years after site preparation while pine seedlings accumulate only three to five lb/ac when planted at normal densities. These increased levels of nitrate N may be useful to the trees when they grow larger and the site becomes more fully exploited. Also, in this study, near-complete weed control eliminated any vegetation competing for available N that could be expected to have an adverse effect on seedling growth (Burger and Pritchett 1988).

The results obtained in this study indicate that tillage treatments decreased soil strength, decreased volumetric soil moisture, and increased nitrogen availability. The change in soil strength resulting from tillage is probably the most meaningful predictor of seedling response to tillage intensity. In areas with high soil strength, particularly in the upper portion of the soil profile, tillage will increase seedling growth. On this soil, adding subsoiling to bedding did not cause any additional benefit, and minimal tillage, i.e., the coulter only, provided almost as much benefit as the more intensive treatments. The effects of tillage will probably provide an additive benefit to weed control as we found a tillage response in the absence of competing vegetation.

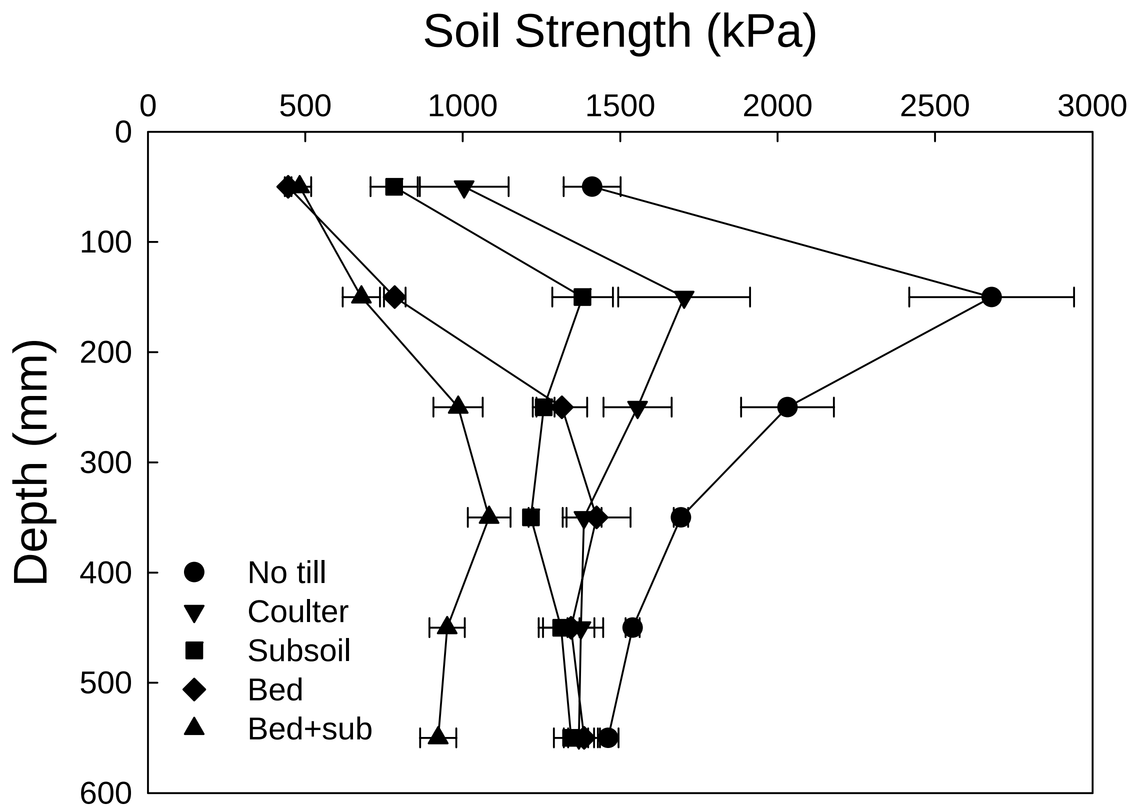

Figure 2-1. The response of soil strength to soil depth and tillage treatment for a one-year-old loblolly pine stand in southwest Georgia measured in May 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

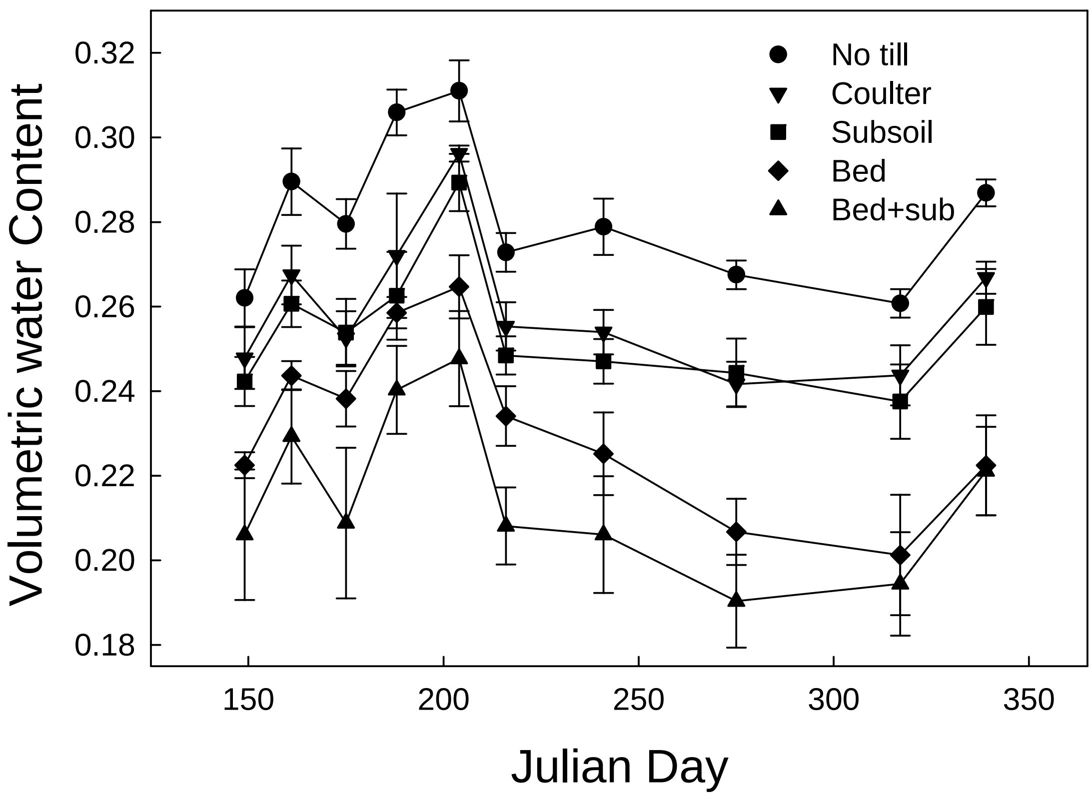

Figure 2-2. Average volumetric water content from 0 to 600 mm of the tillage treatments for a one-year-old loblolly pine stand in southwest Georgia measured in 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

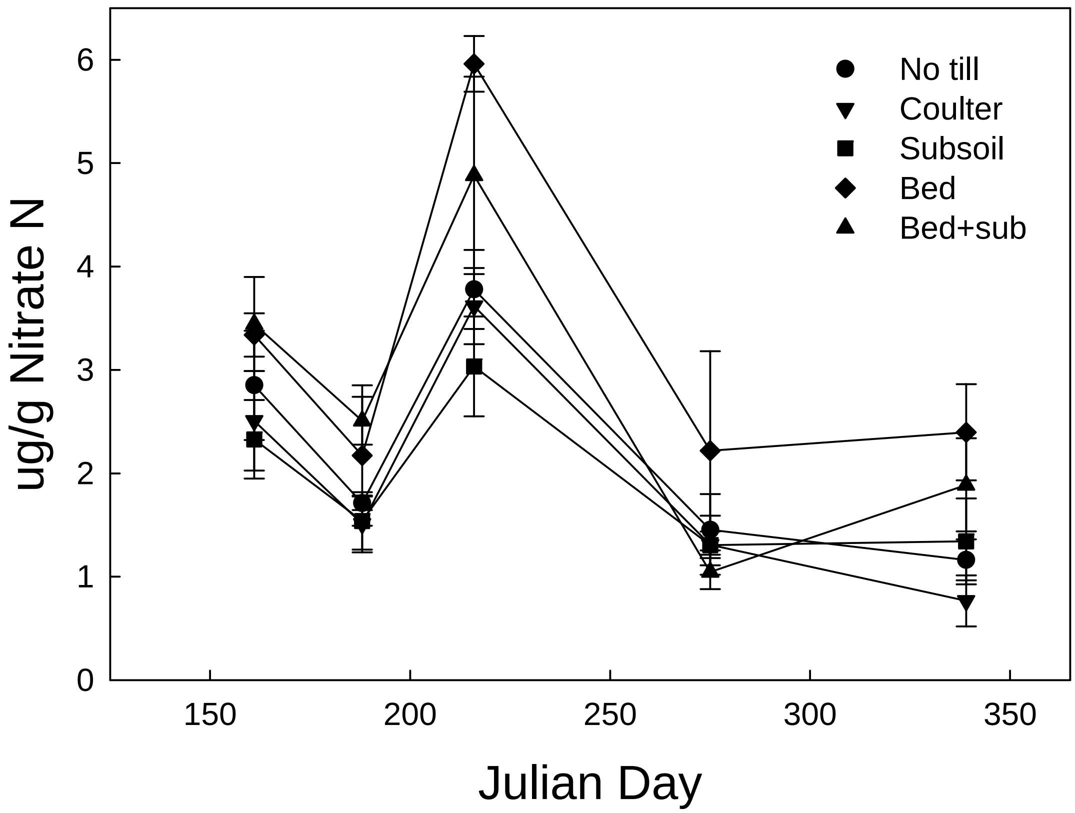

Figure 2-3. Nitrate N concentration of the tillage treatments for a one-year-old loblolly pine stand in southwest Georgia measured in 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

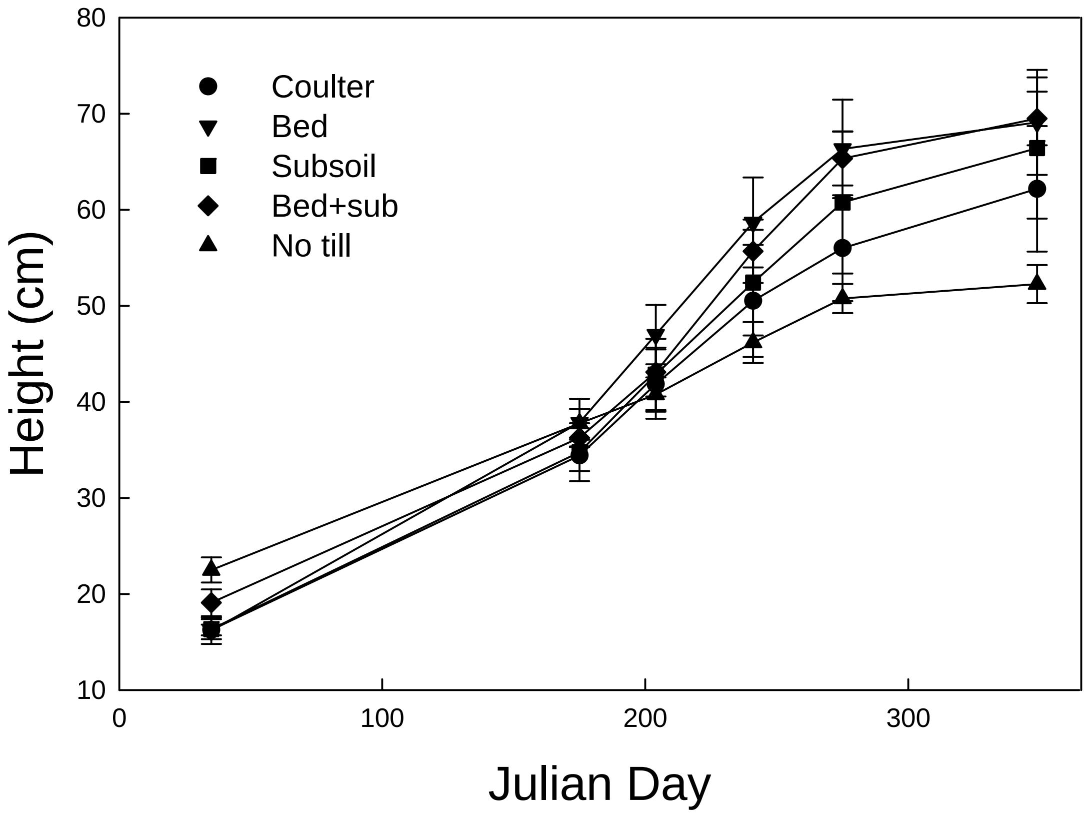

Figure 2-4. Height growth of loblolly pine seedlings by tillage treatment for a one-year-old loblolly pine stand in southwest Georgia measured in 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

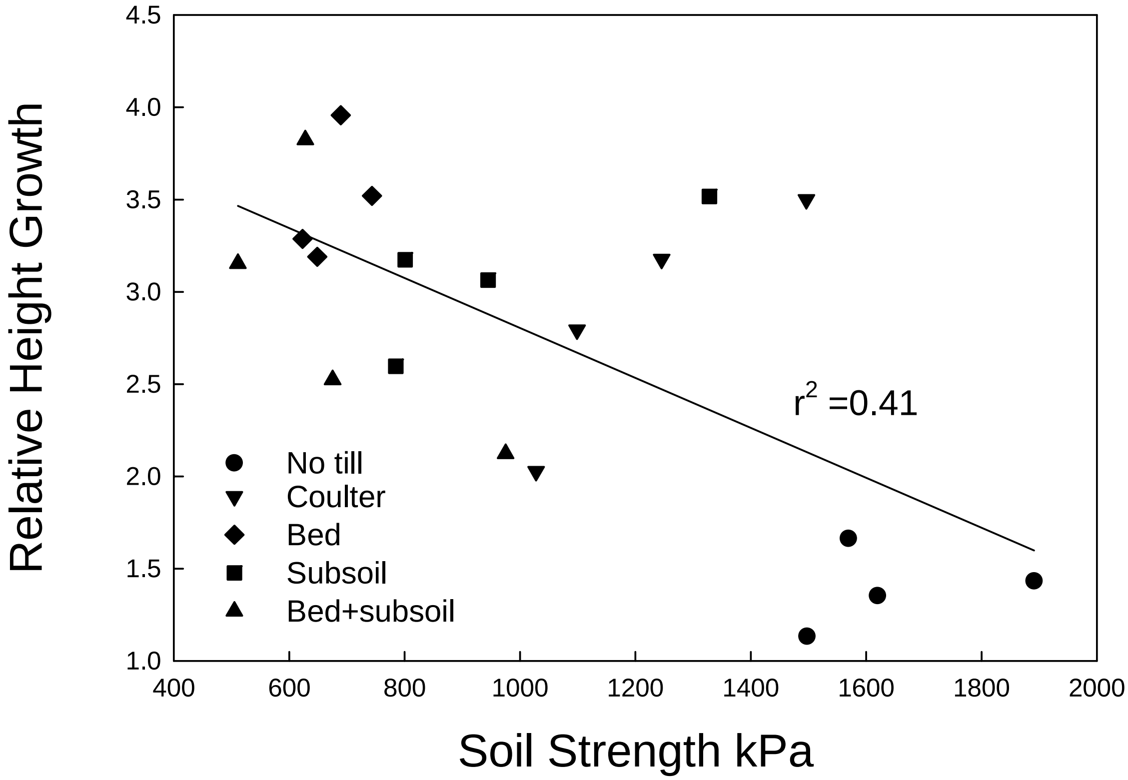

Figure 2-5. Regression of soil strength from 0 to 100 mm as related to relative height growth for a one-year-old loblolly pine stand in southwest Georgia measured in 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

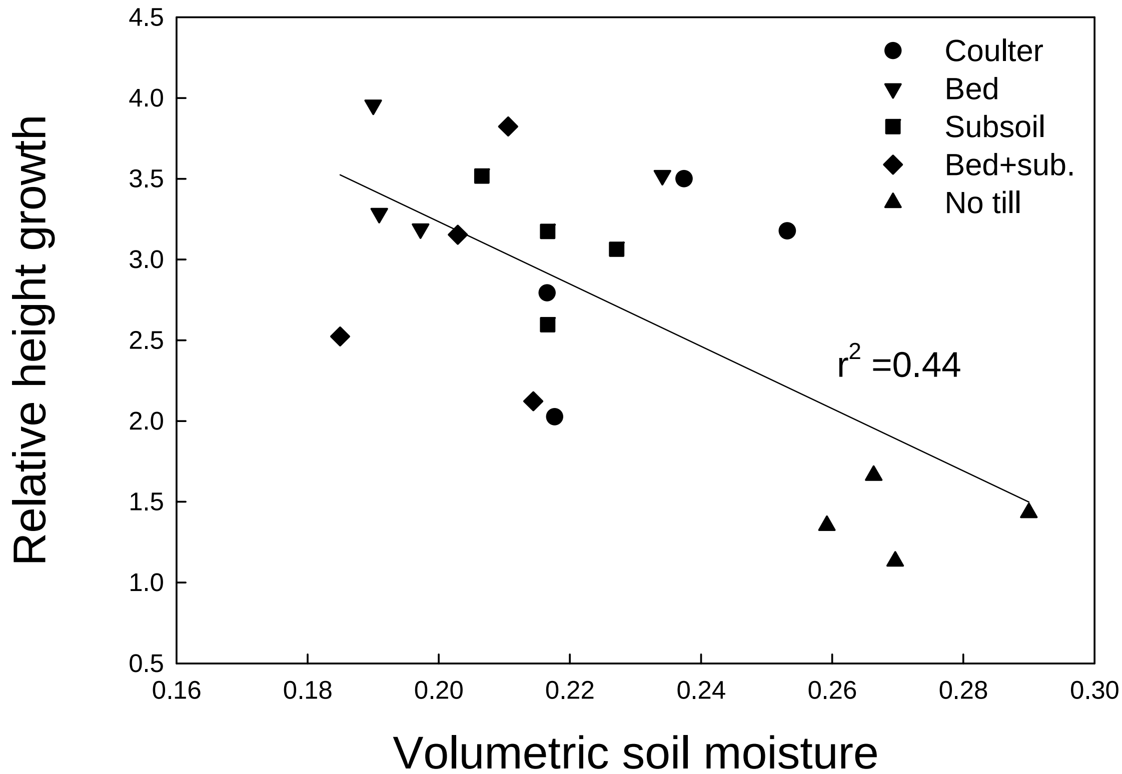

Figure 2-6. Regression of average soil moisture from 0 to 300 mm as related to relative height growth for a one-year-old loblolly pine stand in southwest Georgia measured in 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

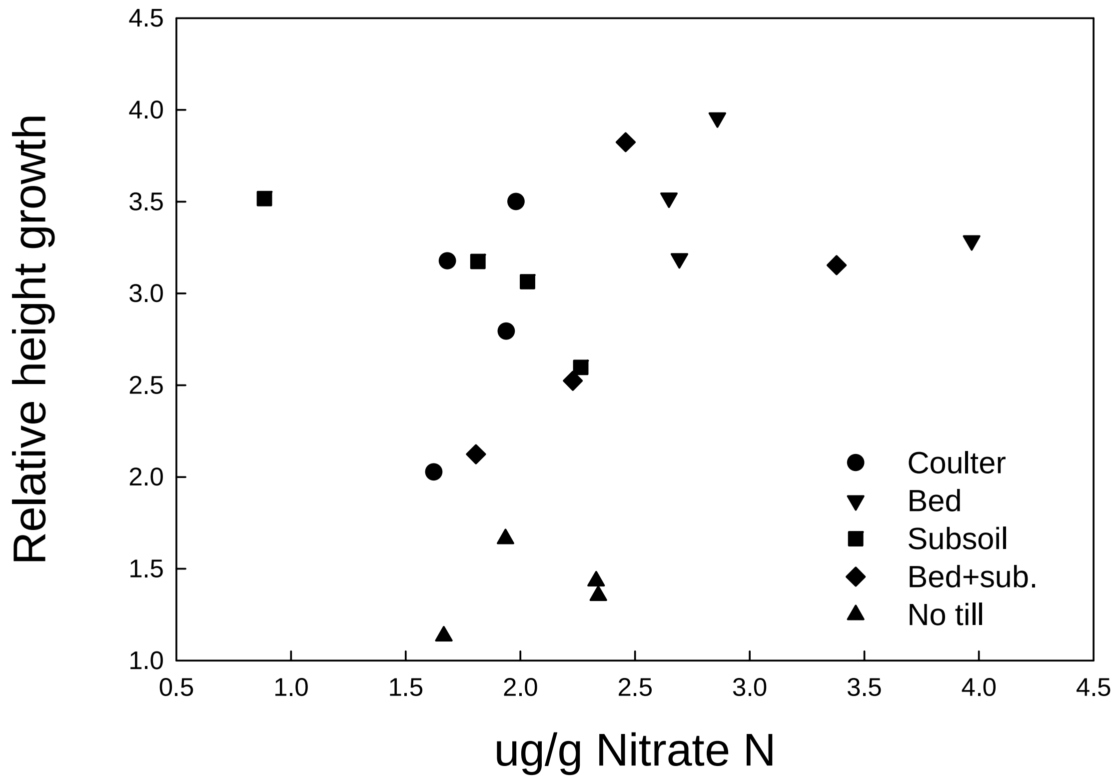

Figure 2-7. Regression of nitrate N levels of individual tillage treatments as related to relative height growth for a one-year-old loblolly pine stand in southwest Georgia measured in 2003. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

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Will, R.E., M.J. Wheeler, D. Markewitz, and others. 2002. Early loblolly pine stand response to tillage on the piedmont and upper coastal plain of Georgia: Tree allometry, foliar nitrogen concentration, soil bulk density, soil moisture, and soil nitrogen status. Southern Journal Applied Forestry 26(4): 190-196.

CHAPTER III

THE EFFECTS OF TILLAGE INTENSITY ON SOIL PHYSICAL PROPERTIES AND THEIR RELATIONSHIP TO SEEDLING GROWTH [2]

[2] Lincoln, M. Chad, Rodney E. Will, Lawrence A. Morris, Daniel Markewitz, Emily A. Carter, and John R. Britt. To be submitted to Canadian Journal of Forest Research.

Abstract

Soil tillage can be a very important tool to be utilized by forest managers to improve growing conditions in order to increase pine seedling growth. Some of the advantages of soil tillage such as competition control and improved N availability to seedling can be achieved by less expensive chemical site treatments. But, the improvements in soil physical properties caused by soil tillage cannot be replaced by other treatments. To determine the relationship between changes in soil attributes associated with differing tillage intensities and growth of loblolly pine seedlings, I measured soil moisture and strength for a range of tillage treatments on two sites (one site with a clay subsoil and no topsoil and one site with a loamy sand topsoil over a clay loam subsoil) in southwest GA (three replications on each site) 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 + bed + subsoil (CSB). Adjacent to six trees per plot (90 trees total per site), volumetric water content (VWC) was measured every two weeks using TDR and soil strength (soil strength) was measured four times during the year using a cone penetrometer. In December following the first growing season, the 90 trees were excavated to determine tree biomass. Average VWC in the upper 30 cm decreased by approximately 10% from the NT treatment to the more intensive treatments at both sites. Tillage increased ground line diameter (gld) at the plot level ($p = 0.05$) on both sites. On both sites as soil strength increased, gld decreased. Soil strength between 40 and 50 cm ($p = 0.03$, $r^2 = 0.40$) was negatively correlated with seedling relative gld growth at the clay site. Soil strength between 10 and 40 cm ($p < 0.02$, $r^2=0.35$) was negatively correlated with seedling gld at the sandy site. At the clay site, the relatively low intensity C treatment was most effective at increasing gld and on the sandy site, the NT treatment (machine planted) was similar to the other

more intensively tilled treatments (CSB and CB). These results indicate that less intensive tillage treatments may be as effective at improving soil physical characteristics and seedling growth as more intensive tillage treatments.

Introduction

Increasing demands for timber and the desire for increased yields per hectare have prompted the use of intensive site preparation in all areas of the southeastern United States (Lantagne and Burger 1987). Mechanical site preparation methods, such as bedding and ripping, can improve water status and structure of many soils, and facilitate planting (Berry 1979). The beneficial effects of bedding and ripping are attributed to improved drainage, improved micro-site environment (nutrients, aeration, temperature, and moisture) for root development, increased moisture availability, and reduced competition (Haines et al. 1975). These improvements increase the ability of a seedling to exploit the existing resources in the soil or increase the concentrations of the resources in the soil and in turn increase seedling growth (Wheeler et al. 2002).

The high cost of mechanical site preparation techniques have caused many forest managers to reconsider the benefits of these practices, especially when the benefits of site preparation can be captured through other less expensive treatments such as fertilization or competition control (Lantagne and Burger 1987; McKee and Wilhite 1988; McKeand et al. 2000). While competition control and fertilization increase the concentration of resources available to crop trees, they cannot substitute for the tree’s natural ability to capture resources through root expansion. Site preparation techniques such as bedding and subsoiling potentially increase the rootable soil volume for planted pine (Nadeau et al.1998; Morris and Lowery 1988).

Bedding is often needed on wet sites where root growth is limited by waterlogging (Haines et al. 1975; McKee and Wilhite 1986; Gent et al. 1986). Improved growth from subsoiling can be large in mountainous, rocky areas where subsoiling breaks up shallow hard pans and impervious subsoil layers (Wittwer et al. 1986). Tillage also may be effective on upland soils where lack of topsoil and restrictive subsoil may limit nutrient availability and seedling root growth (McKee and Wilhite 1986; Wheeler et al. 2002).

High soil strength, the capacity of a soil to withstand stress without experiencing failure, whether by rupture or fragmentation, is a potential limitation to growth that can only be addressed by soil tillage. Root growth and water movement are two of the most important factors affected by soil strength. Soil strength is a function of soil physical properties such as bulk density, water content and potential, texture, aggregation, cementation, and mineralogy. Among these soil physical properties affecting soil strength, soil water content and bulk density have the strongest influence (Vas and Hopmans 2001). An increase in bulk density can reduce root penetration and development, aeration, water infiltration rate, saturated hydraulic conductivity, and nutrient availability, which can decrease root and shoot growth (Stransky 1981; Mitchell et al. 1982; Nambiar and Sands 1992; Grant and Lafond 1993; Chen et al. 1994). Poor root growth due to increased bulk density and soil strength that results from compaction can be the largest restriction to seedling establishment and growth (Daddow and Warrington 1983; Carlson 1986). Soil moisture plays a particularly important role in determining soil physical conditions. First, it is a major factor influencing soil strength. At low moisture content, much greater force is required to push a penetrometer into the soil (Shaw 1942). Additionally, the availability of soil water is important for seedling growth (Gholz et al. 1990). Water stress in pine seedlings during the first growing season can be the most important factor determining growth (Morris et al. 1993; Torreano and Morris 1998). Torreano and Morris (1998) found that root growth rates were largely determined by soil water availability when soil strength was low and nutrition was maintained at a high level. Low soil water availability can affect seedling growth by limiting root elongation and altering distribution patterns (Ludovici and Morris 1997). The use of site preparation techniques that increase rootable soil volume and reduce plant competition may increase water availability to seedlings (Morris and Lowery 1988).

Tillage can increase nutrient acquisition by concentrating nutrients near the tree (Morris and Lowery 1988) or by increasing the ability of roots to exploit the soil volume. While fertilization can supplant the effects related to increased nutrient concentration, nutrient uptake is a function of availability and soil volume exploitation. Will et al. (2002) showed that tillage increased pine tree N content in the second growing season. The authors found no significant differences in total soil N or total mineralized N due to tillage during the second growing season and concluded the greater uptake of N by the trees was due to a greater volume of soil explored by larger root systems and the overall larger tree size in the tilled plots. The potential benefits of higher N mineralization from tillage in the first growing season are mostly unrealized by the trees in young plantations because of their small root systems. In contrast, the ability of trees to grow larger root systems and capture more available N earlier is accelerated by tillage (Morris and Lowery 1988; Will et al. 2002).

Potential greater improvements resulting from tillage must be considered relative to the expense of tillage. Bedding and subsoiling are often done together using a 3-in-1 plow, but this intensive tillage operation is expensive compared to bedding alone or the minimal tillage that may occur during machine planting. The goal of this study was to determine the effects of different intensities of soil tillage (coulter only, bedding, subsoiling, and bedding and subsoiling combined) on soil strength and soil moisture and to relate these changes to 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 on soil physical properties with tillage effects on competition and (2) isolating effects associated with improved fertility by comparing fertilized trees to nonfertilized trees. As the effects of tillage vary with soil type, the potential range in the tillage response on upland sites were determined on two contrasting sites (one with a clay subsoil and one with a sandy clay loam subsoil).

Materials and Methods

This study was established on two tracts of land, one owned by MeadWestvaco Corporation and the other by Rayonier Inc. Both tracts are located in the Upper Coastal Plain of southwest Georgia. The clay site (MeadWestvaco) is located southeast of Cuthbert, GA, (Latitude 31.77N, Longitude –84.79W) and has a Greenville soil series (Fine, kaolinitic, thermic Rhodic Kandiudult) that is highly eroded and compacted with no topsoil over a clay B-horizon. The sandy site, (Rayonier) is located west of Lumpkin, GA (Latitude 32.05N, Longitude –84.79W) and has an Orangeburg soil series (Fine-loamy, kaolinitic, thermic Typic Kandiudult) with a loamy sand topsoil averaging 15 to 40 cm in depth over a sandy clay loam B-horizon. Both sites were harvested in 2002. Before harvesting both sites supported loblolly pine plantations. Both study sites were operationally harvested 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 at each site were established and tillage treatments were randomly assigned within each plot.

Prior to tillage treatments, the clay site received an aerial herbicide treatment of 0.95 L Chopper™ (BASF Corporation, Research Triangle Park, N.C. 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} in October 2003. The plots at the clay site were operationally hand-planted in February 2004 with a full-sib Atlantic Coast loblolly pine family. The rows were 3.7 meters apart with seedlings planted at a 1.8-meter 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-meter 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-meter 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™ + 5.68 L Glypro Plus™ in June 2003 in a 57 L ha^{-1} aqueous solution. A broadcast herbaceous weed control treatment of 56.7 g Oust™ (E.I. du Pont de Nemours and Company, Wilmington, DL. Active ingredient sulfometuron methyl 75.0%) and 56.7 g Escort™ (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. The rows were 3.7 meters apart and the seedlings were planted at a 0.9-meter spacing to ensure full stocking. An additional herbaceous weed control treatment of 0.12 L

Arsenal^{TM} (BASF Corporation, Research Triangle Park, N.C. 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}. Spot application using glyphosate was done 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 and 30 trees per row for the sandy site. 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 1.2m 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 of 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 of differing 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 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} (Table 3-1). 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 ½ of the total dose of micronutrients. The second dose in July consisted of $^{2}/_{3}$ of the total dose of N-P-K and ½ of the total dose of micronutrients. The fertilizer was applied evenly to a 1.8 x 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 90 trees per site, soil moisture and soil strength 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 moisture was measured approximately every two weeks from early May until September and monthly from September until December. Soil strength was measured with a Rimik CP 20 Cone Penetrometer (Toowoomba, Queensland) in May, August, October, and December. Nine insertions were made to a depth of 600 mm and recorded in 25 mm increments in an area of a square meter around each tree (fig. 3-1). 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 first growing season in mid-December, all 90 of the trees that were intensively measured at each site were harvested to determine stem, foliar, and root biomass. Individual trees were harvested with a tree spade attached to a Bobcat™ skid-steer loader (Bobcat, West Fargo, ND). Trees were excavated to a depth of 60 cm and were separated into stems, branches, foliage, and root on site. Stems, braches, and foliage were dried at 60^{o} C and weighed. Roots were frozen until they were separated into less than 2 mm, 2 to 5 mm, and greater than 5 mm diameter classes. After separation, each diameter class of roots was dried at 60^{o} C to a constant weight and then weighed. At time of harvest, heights and ground line diameters of all trees in plots were measured.

Each site was analyzed separately. The effects of tillage treatments on 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 plot (approximately 65 seedlings) representing the experimental unit (n=3). The effects of tillage type on soil strength and soil moisture were tested using split-plot ANOVA. Measurements surrounding the six trees per plot were averaged to obtain a plot level estimate (experimental unit). 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 strength 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. No differences existed for seedling growth rates or in the relationship between soil strength, soil moisture, and seedling growth between the fertilized and nonfertilized trees. Therefore all six trees per plot were averaged to serve as the experimental unit.

Results

Soil Moisture

Clay Site

When averaged across the eight sampling dates, soil volumetric water content (VWC) from 0 to 30 cm soil depth ranged from a high of 0.34 in the NT treatment down to 0.17 cm^3/cm^3 in the CSB treatment. This large and consistent difference resulted in a significant tillage effect ($p = 0.004$) (Fig. 3-2). Differences among the tilled treatments were not significant when considered throughout the year. Volumetric water content from 0 to 60 cm soil depth was generally higher than 0 to 30 cm, ranging from 0.34 for the NT down to 0.23 for the CSB and had a similar tillage effect due to the high VWC in the NT treatment ($p = 0.0004$) (Fig. 3-2). For both depths, no interaction between treatment and date existed but VWC fluctuated throughout the season (date effect, $p <0.0001$) caused by fluctuations in precipitation.

Sandy Site

As with the clay site, VWC varied throughout the growing season with generally reduced moisture in mid-summer due to lower precipitation and greater evapotranspiration (date effect $p < 0.0001$). Between 0 and 30 cm soil depth, VWC was generally lower than at the clay site, ranging from 0.20 to 0.13 for the different treatments (tillage effect, $p = 0.05$). However, unlike on the clay site the C treatment was the highest throughout most of the year with the bedded treatments having the lowest moisture content, and the NT treatment intermediate (Fig. 3-3). A significant date x tillage interaction ($p = 0.002$) occurred in the 0 to 30 cm depth range probably due a temporary decrease of the C treatment relative to the other treatments on Julian date 273. From 0 to 60 cm soil depth, VWC was higher than in the 0 to 30 cm depth (Fig. 3-3). As with the 0 to 30 cm layer, the effect of tillage was significant ($p = 0.002$). The VWC of the CSB, CB, and NT treatments were significantly lower than the CS or the C treatments. A significant treatment x date interaction ($p = 0.3$) did not occur for the 0 to 60 cm interval.

Soil Strength

Clay Site

Soil strength (soil strength) measurements were not possible on the NT plots at the clay site because the soil strength of the soil surface surpassed the upper limit of the penetrometer's capacity (5000 kPa). Therefore, soil strength between 0 and 10 cm in the NT plots was conservatively estimated to be 5000 kPa for any comparisons with the tilled treatments. Estimates below 10 cm in the NT treatment were also not possible. When including the NT treatment estimate of 5000 kPa, tillage had a significant ($p < 0.0001$) effect on soil strength from 0 to 10 cm. Soil strength varied throughout the year from 0 to 10 cm (date effect, $p < 0.0001$) and tillage effects on soil strength changed throughout the year (treatment x date effect, $p = 0.02$). On all dates, the NT treatment had significantly higher soil strength than the tilled treatments in the 0 to 10 cm soil layer (see Fig. 3-4 for soil strength in 0 – 10 cm for all treatments except the NT). However, differences among the other treatments varied with date, but in general, the bedded treatments had lower soil strength than the nonbedded treatments. In

May, the CSB, CB, and CS had significantly lower soil strength than the C treatment. In October the CSB and the CB treatments had significantly lower soil strength than the than C treatment. In December, the CB treatment was significantly ($p < 0.05$) lower than the CS treatment. When the estimated soil strength of the NT was dropped from the analysis that included soil depths below 10 cm, the tillage treatments did not significantly affect soil strength ($p = 0.42$). On all dates, soil strength increased with soil depth ($p < 0.0001$). A significant date x depth interaction ($p = 0.01$) existed, because soil strength varied less with soil depth as the year progressed (Fig. 3-4).

Sandy Site

Soil strength varied throughout the year (date effect, $p < 0.0001$), with soil strength in December generally lower than the other three dates. Soil strength increased with depth ($p < 0.0001$) but the soil strength near the soil surface increased during the year and the soil strength lower down decreased during the year (date x depth effect, $p < 0.0001$). The bedded treatments (CSB and CB) had the lowest soil strength, followed by NT, CS, and C (tillage effect, $p = 0.003$) (Fig. 3-5). Because of a significant date x tillage interaction ($p < 0.0001$), each date was analyzed separately. In May (tillage effect, $p = 0.002$), the bedded treatments had the lowest soil strength, and were significantly lower than the C, NT and CS treatments. The C treatment had the highest soil strength and was significantly greater than the NT and CS treatments. In August (tillage effect, $p = 0.01$), the bedded treatments had significantly lower soil strength than all other treatments. In October (tillage effect, $p = 0.006$), the trends were similar to the previous sampling months with the bedded treatments being significantly lower in soil strength than the

CS, NT, and C treatments. In December (tillage effect, $p = 0.001$), the bedded treatments once again had significantly lower soil strength than the CS, NT, and C treatments.

Plot level tree size and survival after first growing season

At the plot level (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, $p = 0.12$) (Fig. 3-6 and 3-7). At the clay site, ground line diameter (gld) ranged from a height of 15.1 mm in the C treatment to a low of 11.9 mm in the NT treatment ($p = 0.05$) (Fig. 3-6). In contrast to the clay site, the gld of the bedded trees on the sandy site were larger (21.5 mm) than the C treatment (16.4 mm) ($p = 0.05$) (Fig. 3-7). Although differences in survival were not significantly affected by tillage treatments ($p = 0.36$) 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 at 65, 63, and 63 respectively. Survival at the sandy site was over 99% on all treatments.

Seedling Biomass

On both sites, seedling hgt and gld after the first growing season were correlated to total biomass (biomass of the shoot and roots combined). Across all tillage treatments, a positive relationship existed between hgt and total biomass, with 53% ($p = 0.002$) of the variation in biomass explained by hgt on the clay site (Fig. 3-8) and 75% ($p < 0.0001$) at the sandy site (Fig. 3-8). A positive relationship ($p < 0.0001$) also existed for gld, with 74% of the variation in biomass explained by gld on the clay site (Fig. 3-8) and 77% at the sandy site (Fig. 3-9). The relationship between stem volume index ($gld^2 * hgt$) and total biomass explained 83% of the variation in total biomass at the clay site and 80% at the sandy site (Fig. 3-8 and 3-9). Results were similar for regressions comparing hgt, gld, and volume index to stem biomass after the first growing season. The r^2 values were 0.61, 0.74, and 0.87 for relationships between stem biomass and hgt, gld, and volume index for the clay site and 0.90, 0.84, and 0.94 for relationships between stem biomass and hgt, gld, and volume index for the sandy site.

Size and growth of harvest trees

When analyzed with fertilizer application as a split-plot factor, there were no significant effects of fertilization or interactions involving fertilization on the size or growth of measurement 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 all further analyses. 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). Relative hgt growth was not significantly affected by tillage treatments. Relative hgt and gld growth were the measurements of choice because of significant differences (p = 0.07) in initial height between tilled and untilled plots related to planting depth (deeper in the tilled treatments) and large variability of the seedling sizes within treatments (Table 3-2). On the sandy site, gld of the seedlings in the C treatment were significantly (p =0.02) smaller than the other treatments (Table 3-2). There were no significant differences in hgt among tillage treatments.

Relationship between seedling growth and soil properties

Clay Site

When just the tilled plots were considered (NT not included), the correlations between the average soil strength for soil layers deeper than 40 cm and relative gld were negatively related. As soil strength decreased from 3100 to 1900 kPa in the 40 to 50 cm zone, rgld increased from 1.7 to 2.4 with 40% ($p = 0.03$) of the variation in rgld explained by soil strength (Fig. 3-10). This relationship was also significant ($p = 0.06$) 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 strength 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 3-2) and by far the highest soil strength in the surface horizons. If a soil strength of 5000 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. 3-11). The relationship between VWC from 0 to 30 cm and rgld was not significant ($p = 0.1$). In the case of VWC, data were available for the NT treatments. The correlation is stronger for VWC than for soil strength in large part because the NT treatments could be included and had the highest VWC and lowest rgld of all treatments.

Relationship between seedling growth and soil properties

Sandy Site

Ground line diameter and hgt at the end of the first growing season were used to correlate soil strength to seedling growth. The soil strength between 10 and 40 cm was negatively correlated to seedling size at the end of the first growing season. As soil strength 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 to 30 cm depths also (hgt $p = 0.05$, $r^2 = 0.27$; gld $p = 0.02$, $r^2 = 0.35$). As soil strength decreased from 2000 to 1400 kPa in the 30 to 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. 3-12). In contrast to the clay site, there was no relationship between VWC and gld or hgt at either soil depth interval (0 to 30 cm or 0 to 60 cm).

Discussion

Volumetric Water Content and Soil Strength

The lower soil moisture content in the tilled treatments (bedding in particular) of the clay site were similar to Lincoln et al. (*In press*), which was conducted on a similar upland site with an Orangeburg soil series that has 2 to 15 cm of sandy loam topsoil over a clay loam B-horizon. The lower VWC throughout the year in the tilled treatments was most likely caused by an increase in large voids in the soil and increased macro-porosity created by the tillage treatments (Harrison et al. 1994; Morris and Lowery 1998). The sandy site was similar to the clay site in that the bedded treatments were drier than the other tillage treatments; however, the NT treatment was lower in VWC than the C and CS treatments. The reason for the higher VWC in the C and CS treatments at the sandy site may have been due to the depression on the soil surface left by the plow, which could cause water to collect along the tilled surface and more infiltration along the planting row. This would not occur on the NT treatment at the sandy site because of the slight mounding caused by the machine planter. A slight depression was also caused by the C and CS treatments at the clay site, but this did not lead to higher VWC. Another possible explanation would be the differences in macro-porosity among the tillage treatments. Bedding decreased VWC and probably increased macro-porosity at both sites. On the clay site that had good fracturing of the soil, the C and CS treatment probably also increased macro-porosity. In contrast, the C and CS treatments may not have been as effective on the sandy site that may have already had sufficient macro-porosity.

Water availability is a function of seedling rooting volume and water infiltration and retention characteristics of the soil (Morris and Lowery 1988). Soil tillage that increases porosity leads to changes in the soil water retention curve and increases in hydraulic conductivities (Ahuja et al. 1998). Our moisture readings were volumetric. A further examination of gravimetric moisture contents and moisture retention curves may be necessary to determine the water available to the seedlings. Will et al. (2002) compared VWC of bedding and bedding + subsoiling to control plots for a range of upland sites. They also found that bedding decreased VWC, but their study did not contain a C or CS treatment to compare the response on clay vs. sandy sites. Page-Dumroese et al. (1997) found higher available water in bedding treatments compared to the controls, although these differences were small. This finding indicates that changes in soil structure with bedding may increase plant available water even if VWC declines.

Bedding decreased soil strength at both sites because mounding and concentrating the surface horizon in most cases mitigates compaction resulting from harvesting traffic (Zhou et al. 1998) and increases macro-porosity, which decreases bulk density (Terry et al. 1981; Morris and Lowery 1988). The reduction in soil strength below the beds was a function of our sampling methodology. All measurements were made from the surface down. The beds were very effective at reducing soil strength to 60 cm depth at the sandy site because the bed height combined with the topsoil depth was often sufficient to avoid areas of higher soil strength deeper in the soil profile. At the clay site, the NT treatment had soil strength dramatically greater than the tilled treatments. The soil at the clay 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 strength and increase growth. At the sandy site, the soil strength of the NT was intermediate and the coarse textured soil with high macro-porosity and resultant low inherent soil strength caused there to be little effect of the C and CS on soil strength.

At the clay site, the CS treatment had the highest soil strength at depths greater than 30 cm on the first sampling date (May). This higher soil strength at depth was most likely caused by the subsoiling shank not penetrating the soil to the full 60 cm as it was designed and may have caused an area of higher soil strength at about 30 cm where the shank did not penetrate to a full 60 cm depth. Evidence for this is that when the spatial variation in penetration resistance was examined, higher soil strength at 30 cm depth occurred in the center of the CS treatment than 50 cm to either side of center. According to Morris and Lowery (1988), subsoiling does little to increase the volume of large pores or reduce mechanical impedance when soils are plastic. The higher soil strength at 30 cm in the CS treatment was not apparent in October or December and may have been alleviated by water infiltration or root penetration deeper into the soil profile over time.

Upland site bedding can improve root growth by reducing soil mechanical impedance (Morris and Lowery 1988) and surface bulk density (Terry et al. 1981; Zhou et al. 1998), but bedding may have a diminishing effect on height growth over time (Wilhite and Jones 1981).

Subsoiling, when done under the correct moisture conditions, can improve the internal structure of many soils and facilitate planting (Berry 1979), but as with bedding the beneficial effect of subsoiling may diminish over time (Ide et al. 1987). The porosity increases caused by soil tillage degrade over time because of natural cycles of wetting and drying (Ahuja et al. 1998), so the length of time that a tillage treatment is effective may be related to local amounts of precipitation and the resulting soil reconsolidation.

Growth

At both sites, the tillage effects on the growth of the measurement trees were similar to that at the plot level. Therefore, the sub-samples of trees that were chosen for intensive measurement was representative of the plot level response. This study resulted in significant differences among tillage treatments in growth at the end of one growing season at both sites. However, the effectiveness of the different treatments depended on site. Bedding increases early seedling growth by increasing rooting volume through reduced bulk density and increased macro-porosity (Morris and Lowery 1988) and by concentrating organic material near the root systems of seedlings (Attiwill et al. 1985). Bedding increased growth on the sandy site but not the clay site. This could be because the clay site lacked topsoil and incorporated organic materials. Bedding on fine textured soils can be effective when conditions at the soil surface (such as presence of organic material) are favorable for improvement (Wheeler et al. 2002; Lincoln et al. *In press*). Subsoiling provided no added benefit to growth at either site. This result is similar to Wheeler et al. (2002) and Lincoln et al. (*In Press*). Lincoln et al. (*In press*) found that in areas with high soil strength, adding subsoiling to bedding did not cause any additional benefit in seedling growth, and minimal tillage, i.e., the coulter only, provided almost as much benefit as the more intensive treatments.

At the clay site, the relatively low intensity C treatment was most effective at increasing gld at the plot level. The minimal tillage offered by the C treatment appeared to be all that was necessary to break through strong clay surface and foster growth in the first year. On the sandy site, the NT treatment (machine planted) was similar to the other more intensively tilled treatments and may be all that is needed on sites with a thick, sandy surface horizon. The machine planter used as the NT treatment may have provided more soil tillage than the C treatment. In contrast to the clay site, the C treatment at the sandy site provided little benefit in growth, probably because of the minimal amount of tillage offered by the coulter wheel only being pulled through the sandy topsoil of this site.

Fertilization did not affect seedling growth in the first growing season, probably because of low nutrient demand of the small trees coupled with limited root systems. Most NH_4^+ released by mineralization or fertilization has little chance of being utilized by the small root systems of young pines, and more often than not, the NH_4^+ is immobilized by soil microorganisms, other vegetation, or bacteria that oxidize NH_4^+ to the more mobile nitrate which can be rapidly lost from the soil before being utilized by seedlings (Vitousek and Matson 1985).

Effect of soil physical properties on growth

Clay Site

In soils with an eroded and compacted surface horizon, like the clay site, 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 strength in the 0 to

10 cm depth compared to the NT treatment and these reductions were correlated to 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 treatments were dropped from the analysis, individual tillage treatments did not significantly affect soil strength, but soil strength at depths deeper than 40 cm were correlated with seedling growth. It is important to point out that the tillage effects on soil strength were plot-level estimates while the correlations between soil strength and seedling growth were based on individual trees. Tillage probably resulted in better micro site differences in soil strength that in turn increased growth. It is also a bit misleading to disregard the plot-level effects of tillage on soil strength because they were not statistically significant since soil strength varied by approximately 700 kPa among the tilled treatments. It is also possible that the correlation between soil strength in the deeper soil layers and rgld on the clay site was a spurious correlation or that soil strength below 40 cm was related to some other factor associated with greater growth as the importance of rooting volume below 40 cm during the first year is questionable (Nambiar and Sands 1992).

As VWC decreased, seedling rgld growth increased on the clay site. The decrease in VWC in the tilled treatments did not necessarily translate into less available water for the seedlings as the amount of soil water available to plants is a function of rooting volume as well as water infiltration and retention characteristics of the soil (Morris and Lowery 1988). Increased macro-porosity probably allowed the roots to more fully utilize the site, and this may have translated into improved relative height growth (Shiver and Fortson 1979, Will et al. 2002).

Effect of soil physical properties on growth

Sandy Site

On the sandy site, a reduction in soil strength in the upper 50 cm was positively related to hgt and gld growth. The effect of tillage on soil strength was related to the increased growth clearly indicating that tillage was having the desired effect on soil physical properties and growth. In contrast to the clay site, there was no relationship between VWC and seedling size. This seems to indicate that the negative relationship found between VWC and growth on sites with finer textures (see above, Lincoln et al. In press) are related to changes in the macro-porosity that accompany tillage. Finer textured soils with high micro-porosity may have the ability to hold enough water for plants even though macro-porosity and soil drainage increases (Page- Dumroese et al. 1997).

The goal of this study was to determine the effects of different intensities of soil tillage (coulter only, bedding, subsoiling, and bedding and subsoiling combined) on soil strength and soil moisture and to relate these changes to seedling growth. Based on these results and those from Lincoln et al. (In Press), bedding on sites with a minimal amount of topsoil can be beneficial because of the advantages of consolidating topsoil around seedling roots. The coulter only treatment in highly eroded, compacted, fine texture sites may be most effective at establishing seedlings due to the fracturing of the soil surface without smearing or increasing bulk density at depth. Machine planting, if possible, on these compacted fine textured soils, may provide enough tillage to lower surface soil strength and improve seedling growth. Machine planting may be the best alternative, i.e., good growth response for minimum amount of tillage, on sites with adequate topsoil because the tillage provided by the machine planter may be sufficient to improve seedling survival and growth.

Table 3-1. Macro and micro-nutrient percentages in Holley-tone fertilizer.

Element	Concentration %	Application rate
Total N	0.4	0.04
P2O5	0.6	0.06
K2O	0.4	0.04
Ca	0.3	0.03
Mg	0.05	0.005
S	0.5	0.05
B	0.02	0.0002
Cl	0.1	0.001
Co	0.005	0.000005
Cu	0.05	0.0005
Mn	0.05	0.0005
Fe	0.1	0.01
Mo	0.005	0.000005
Na	0.1	0.001
Zn	0.05	0.0005

Table 3-2. Height and ground line diameter of the harvested loblolly pine trees at the clay site located southeast of Cuthbert, GA and for a sandy site west of Lumpkin, GA at the end of the first growing season. Initial hgt and gld were measured in May 2004. The hgt and gld were measured in December 2004. (NT = No till; C = Coulter; CS = Coulter + Subsoil; CB= Coulter + Bed; CSB = Coulter + Subsoil + Bed).

Clay site	Initial hgt		Initial gld		hgt		gld		Relitive hgt growth		Relitive gld growth	
	cm	(s.e.)	mm	(s.e.)	cm	(s.e.)	mm	(s.e.)		(s.e.)		(s.e.)
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												
	cm	(s.e.)	mm	(s.e.)	cm	(s.e.)	mm	(s.e.)		(s.e.)		(s.e.)
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

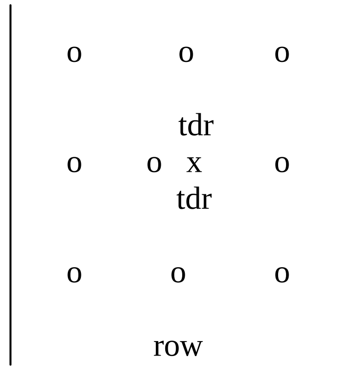


Figure 3-1. Pattern of penetrometer insertion around individual intensively measured loblolly pine seedlings. (o = penetration point; x = seedling; tdr = 30 and 60 cm time domain reflectometry rods).

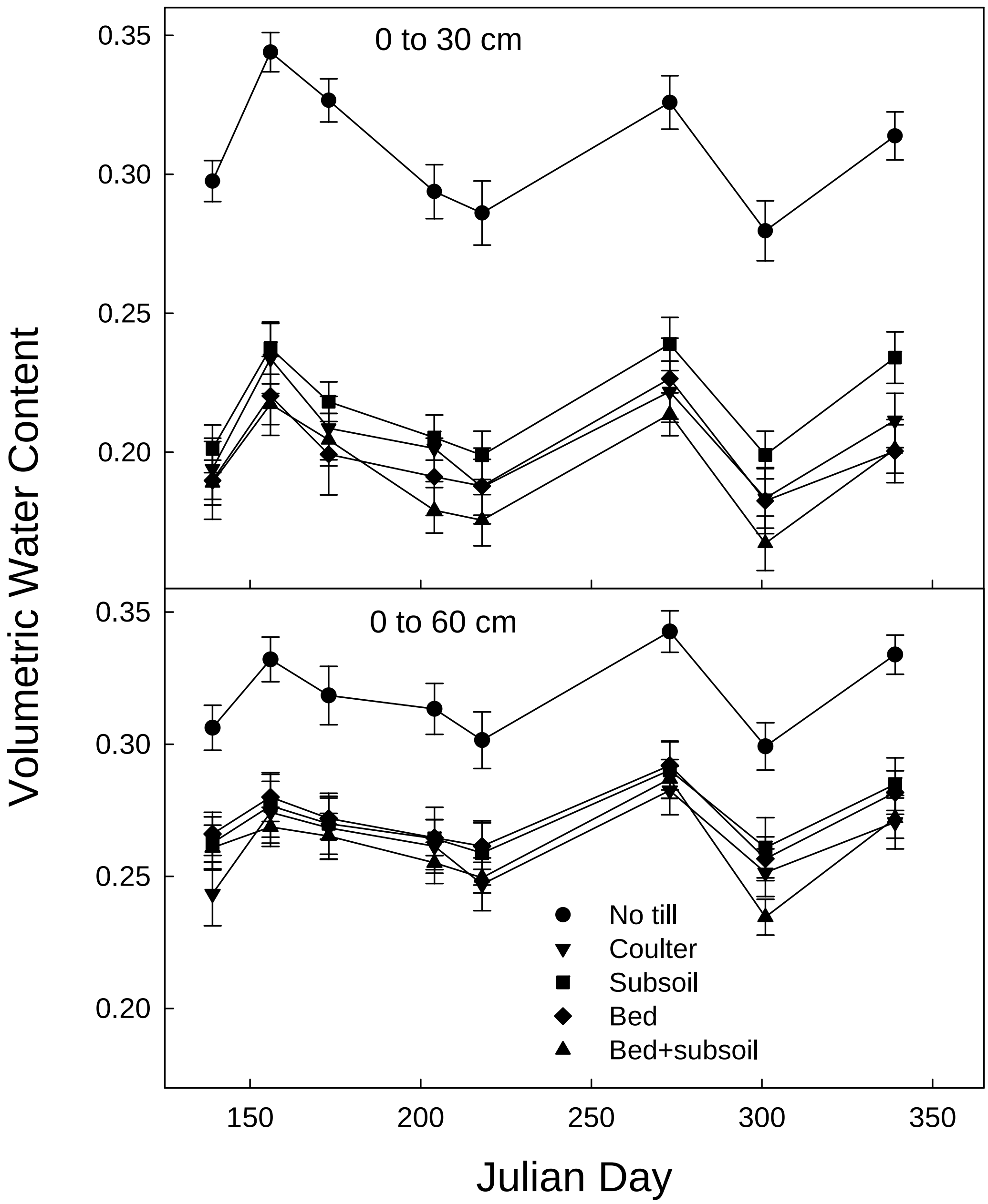


Figure 3-2. Soil volumetric water contents throughout the growing season between 0 to 30 and 0 to 60 cm soil depth for the different tillage treatments at the clay site planted with loblolly pine seedlings southeast of Cuthbert, GA. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

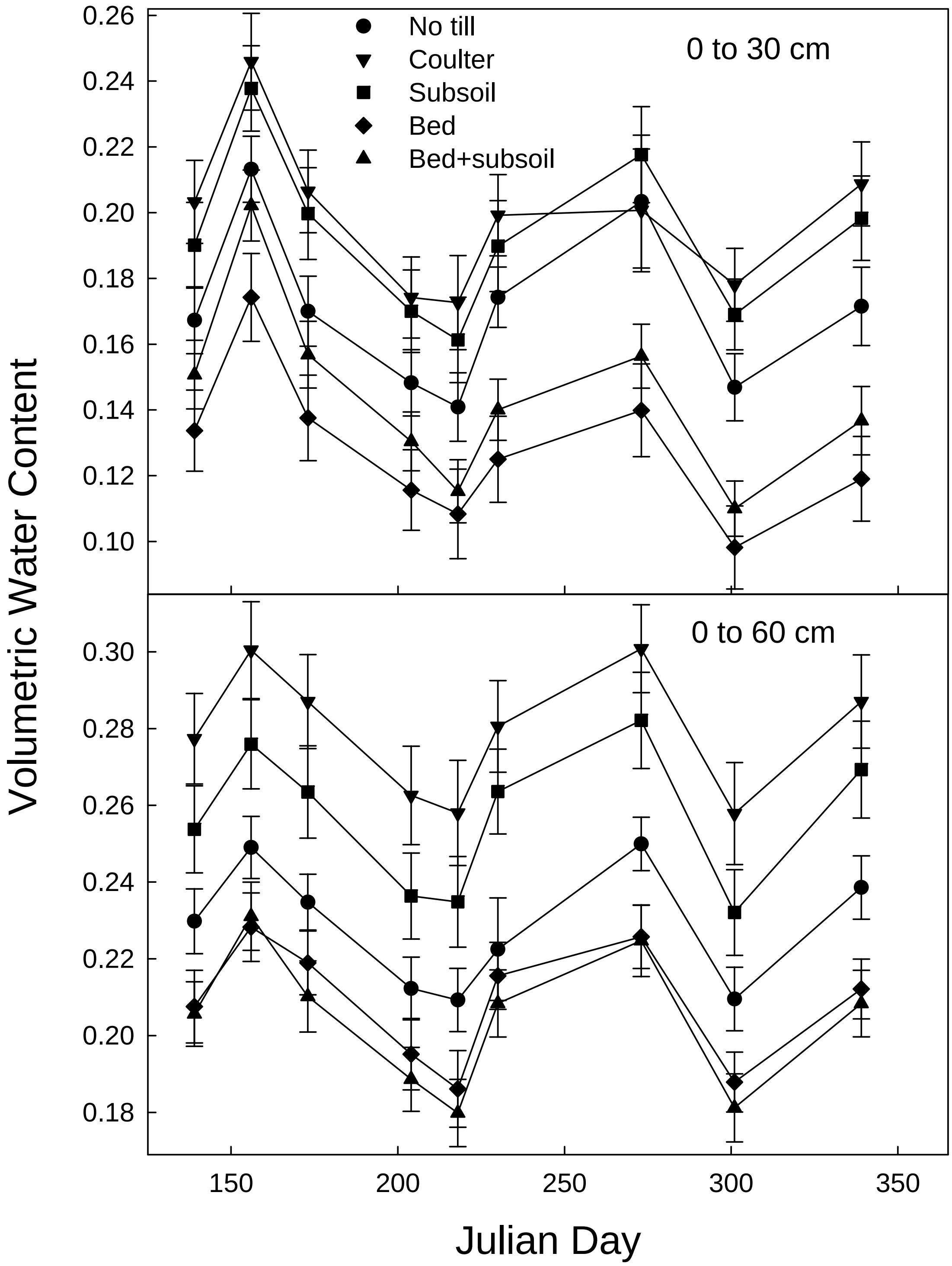


Figure 3-3. Soil volumetric water contents throughout the growing season between 0 to 30 and 0 to 60 cm soil depth for the different tillage treatments at the sandy site planted with loblolly pine seedlings west of Lumpkin, GA. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

Figure 3-4. Soil strength between 0 and 600 mm for May, October, and December 2004 at the clay site planted with loblolly pine seedlings southeast of Cuthbert GA. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

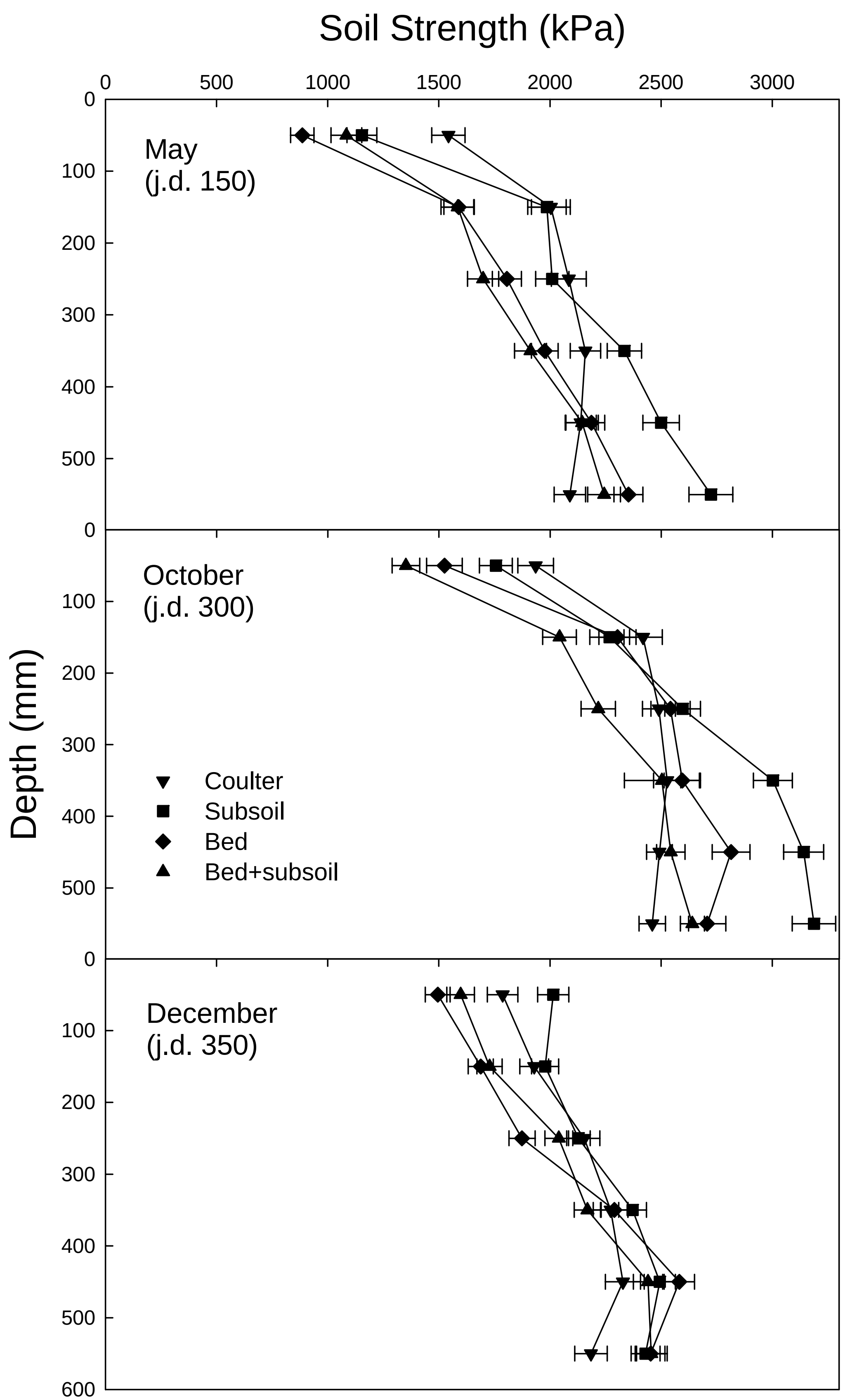
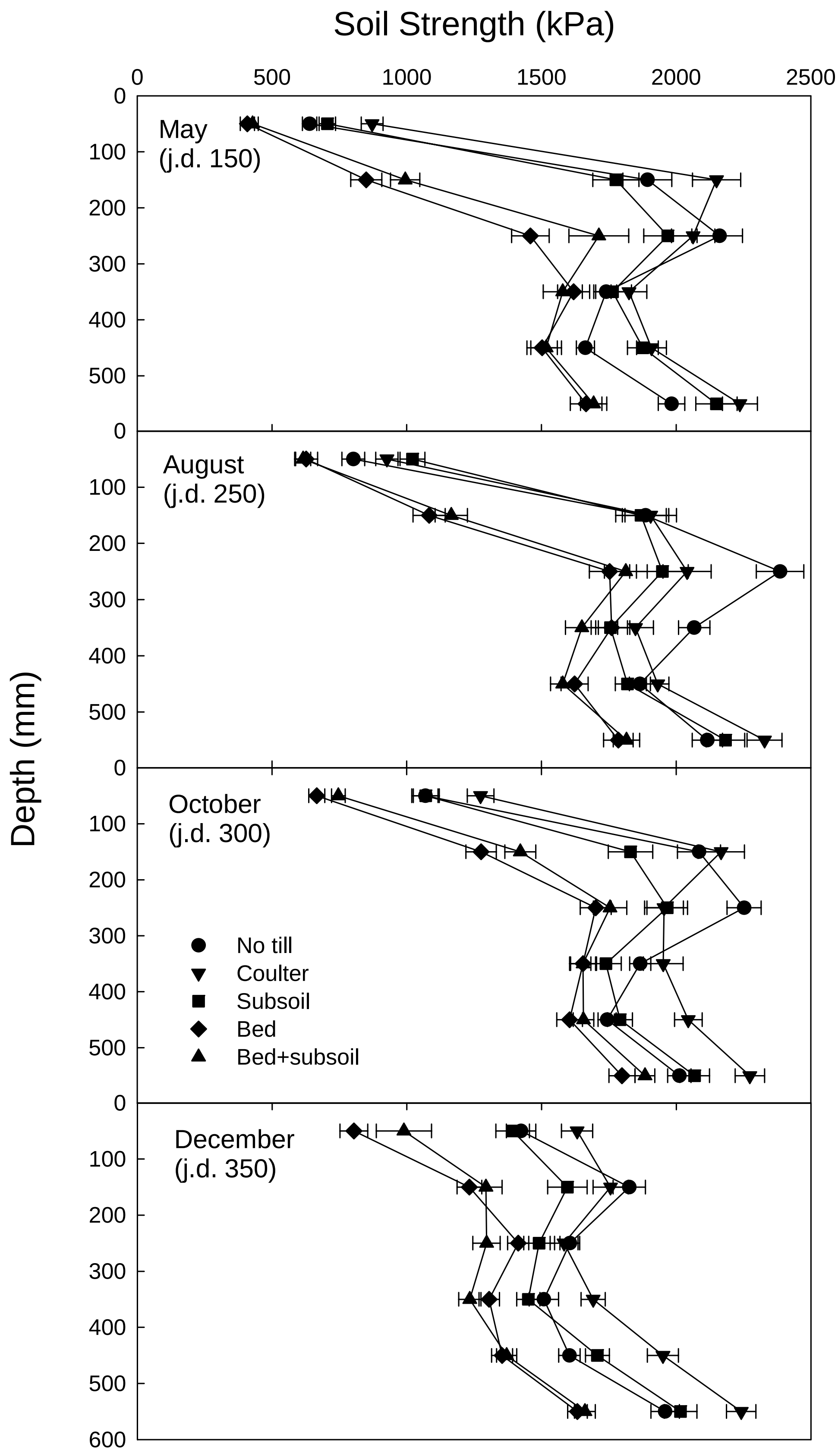

Soil Strength (kPa)
0
500
1000
1500
2000
2500
3000
Depth (mm)
0
100
200
300
400
500
600
May
(j.d. 150)
October
(j.d. 300)
December
(j.d. 350)
Coulter
Subsoil
Bed
Bed+subsoil

Figure 3-5. Soil strength 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. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).



Soil Strength (kPa)
0
500
1000
1500
2000
2500
Depth (mm)
0
100
200
300
400
500
600
May
(j.d. 150)
August
(j.d. 250)
October
(j.d. 300)
December
(j.d. 350)
No till
Coulter
Subsoil
Bed
Bed+subsoil

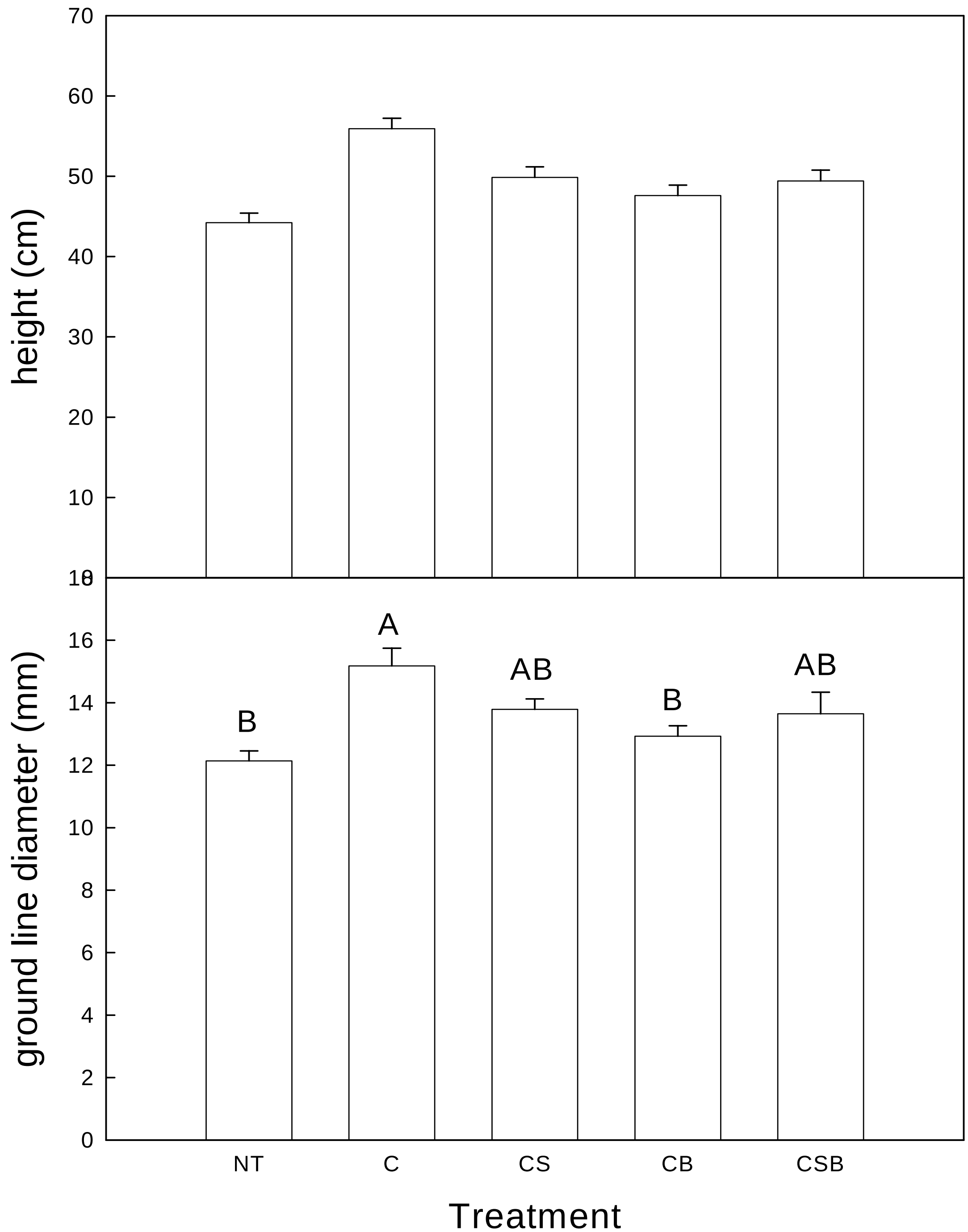


Figure 3-6. Height and ground line diameters of loblolly pine seedlings grown in a range of tillage treatments on the clay site southeast of Cuthbert GA following the first growing season. Means represent the average of the three blocks with each plot comprised of approximately 65 trees. Vertical bars 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, and CSB = coulter + subsoil + bed).

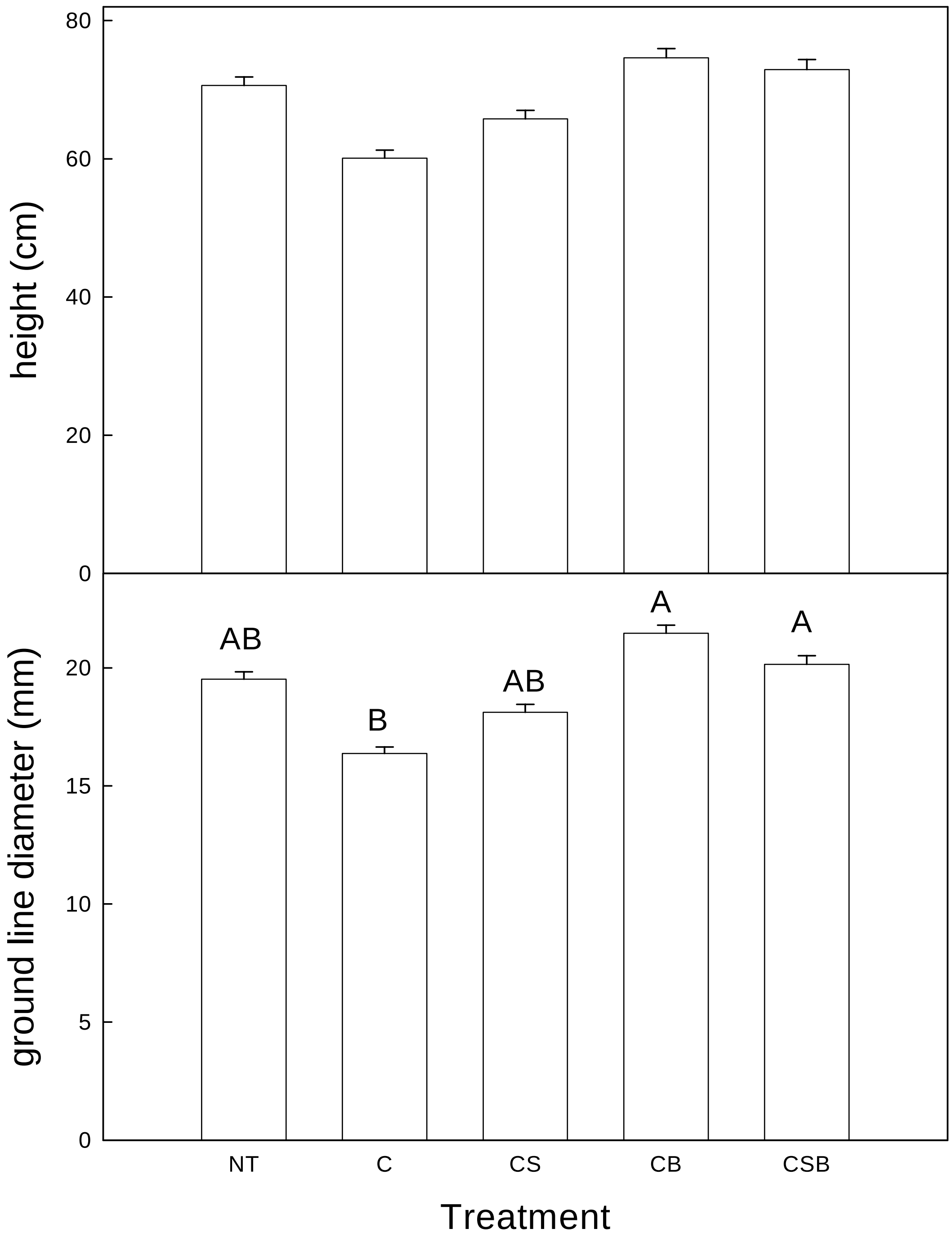


Figure 3-7. Height and ground line diameters of loblolly pine seedlings grown in a range of tillage treatments on the sandy site west of Lumpkin, GA following the first growing season. Means represent the average of the three blocks with each plot comprised of approximately 65 trees. Vertical bars represent 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, and CSB = coulter + subsoil + bed).

Figure 3-8. Relationship between seedling total biomass (total above ground biomass + total below ground biomass) and height (hgt), ground line diameter (gld), and volume index ($hgt*gld^2$) of one-year-old loblolly pine trees at the clay site southeast of Cuthbert GA. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).

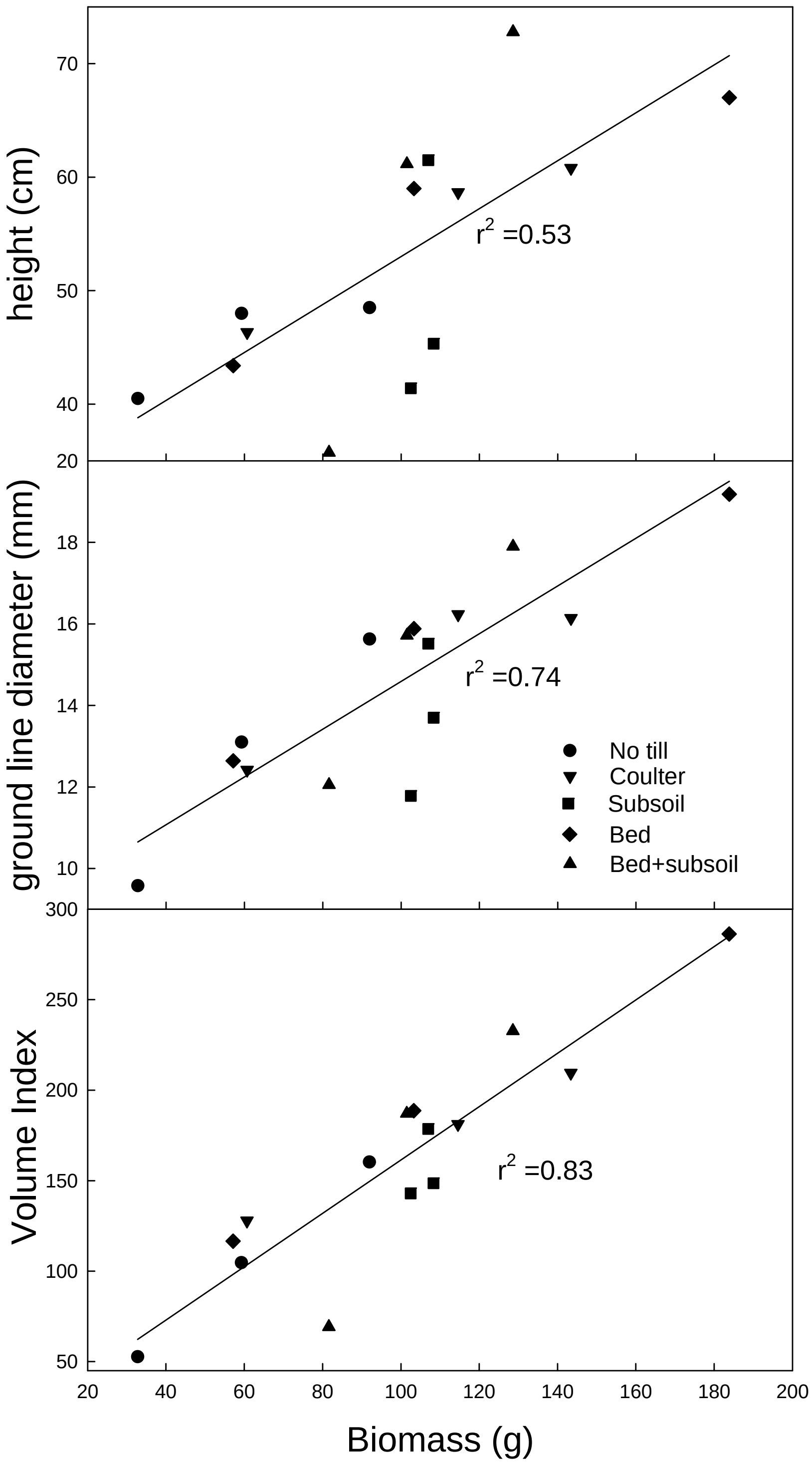
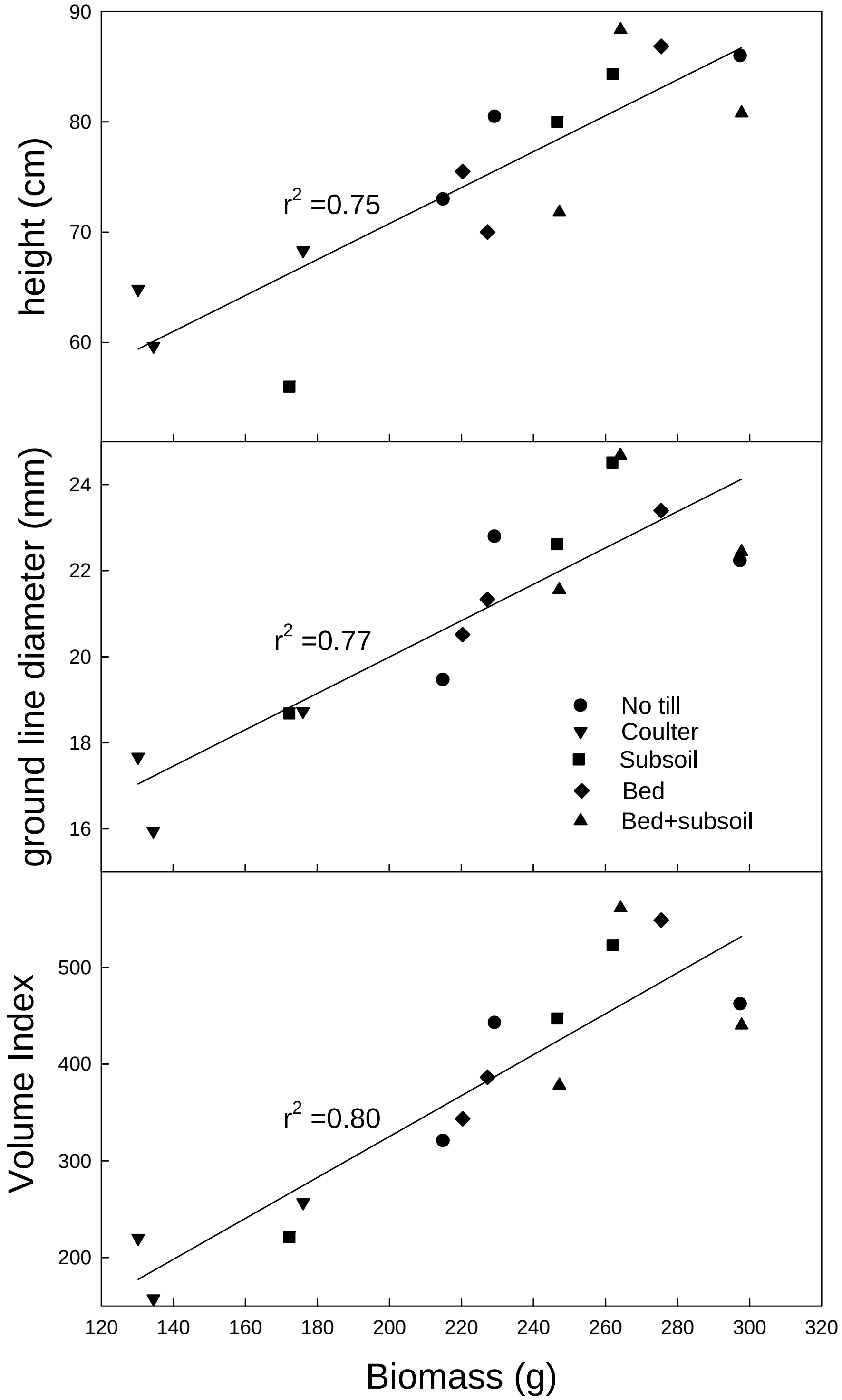

height (cm)
70
60
50
40
20
r2 =0.53
ground line diameter (mm)
18
16
14
12
10
r2 =0.74
No till
Coulter
Subsoil
Bed
Bed+subsoil
300
250
200
150
100
50
Volume Index
r2 =0.83
20
40
60
80
100
120
140
160
180
200
Biomass (g)

Figure 3-9. Relationship between seedling total biomass (total above ground biomass + total below ground biomass) and height, ground line diameter, and volume index ($hgt*gld^2$) of one-year-old loblolly pine trees at the sandy site west of Lumpkin, GA. (bed, subsoil, and bed + subsoil treatments included the coulter treatment).


height (cm)
ground line diameter (mm)
Volume Index
Biomass (g)
r2 =0.75
r2 =0.77
r2 =0.80
No till
Coulter
Subsoil
Bed
Bed+subsoil
90
80
70
60
24
22
20
18
16
500
400
300
200
120
140
160
180
200
220
240
260
280
300
320

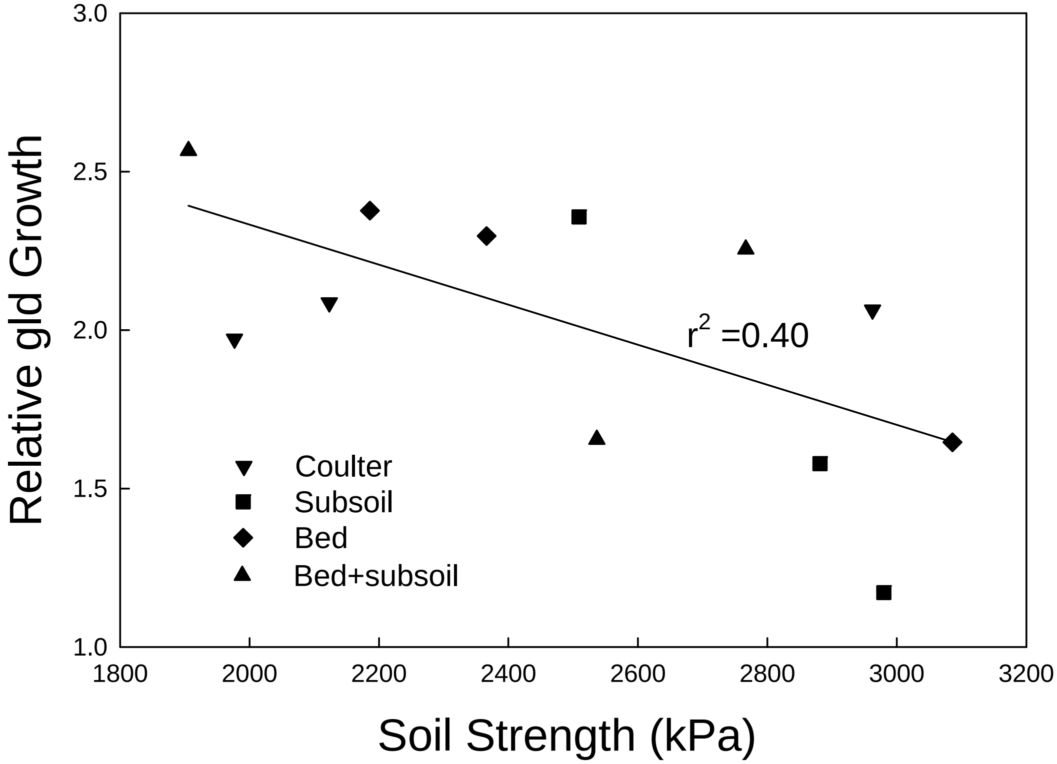


Figure 3-10. Correlation between relative ground line diameter (gld) growth of loblolly pine seedlings and soil strength between 40 and 50 cm on the clay site southeast of Cuthbert GA following the first growing season. The no till treatment could not be measured because the surface soil strength exceeded the maximum limit of the penetrometer.

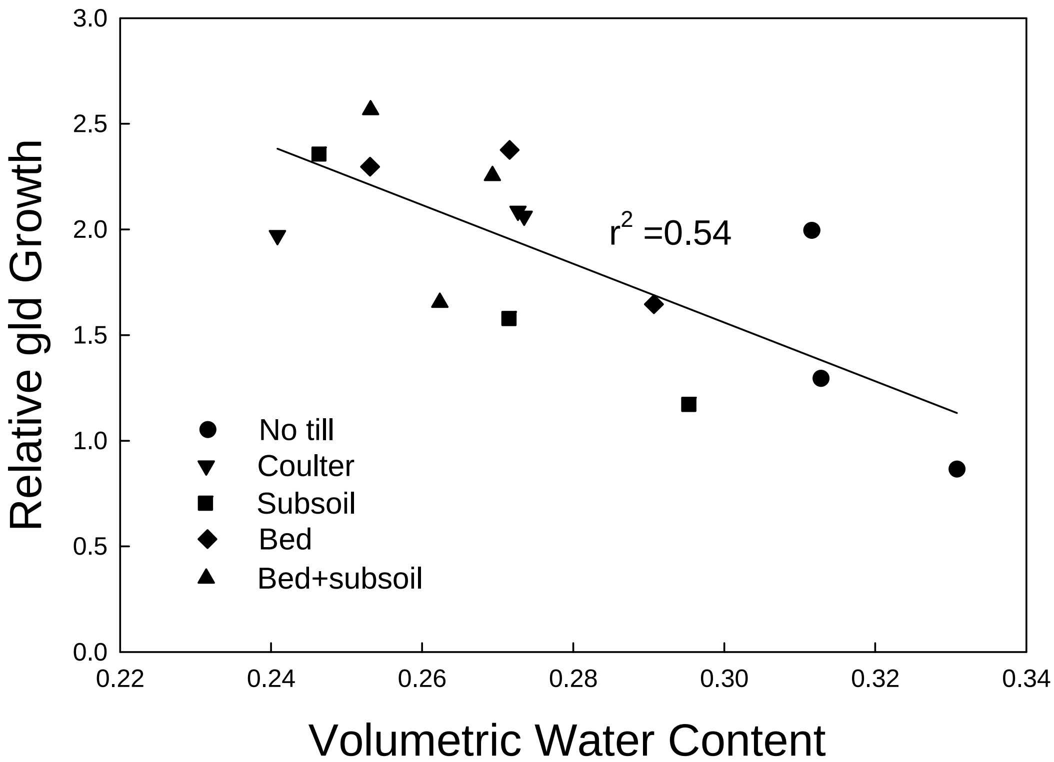


Figure 3-11. Correlation between relative ground line diameter (gld) growth of loblolly pine seedlings and volumetric water content between 0 and 60 cm on the clay site southeast of Cuthbert GA following the first growing season.

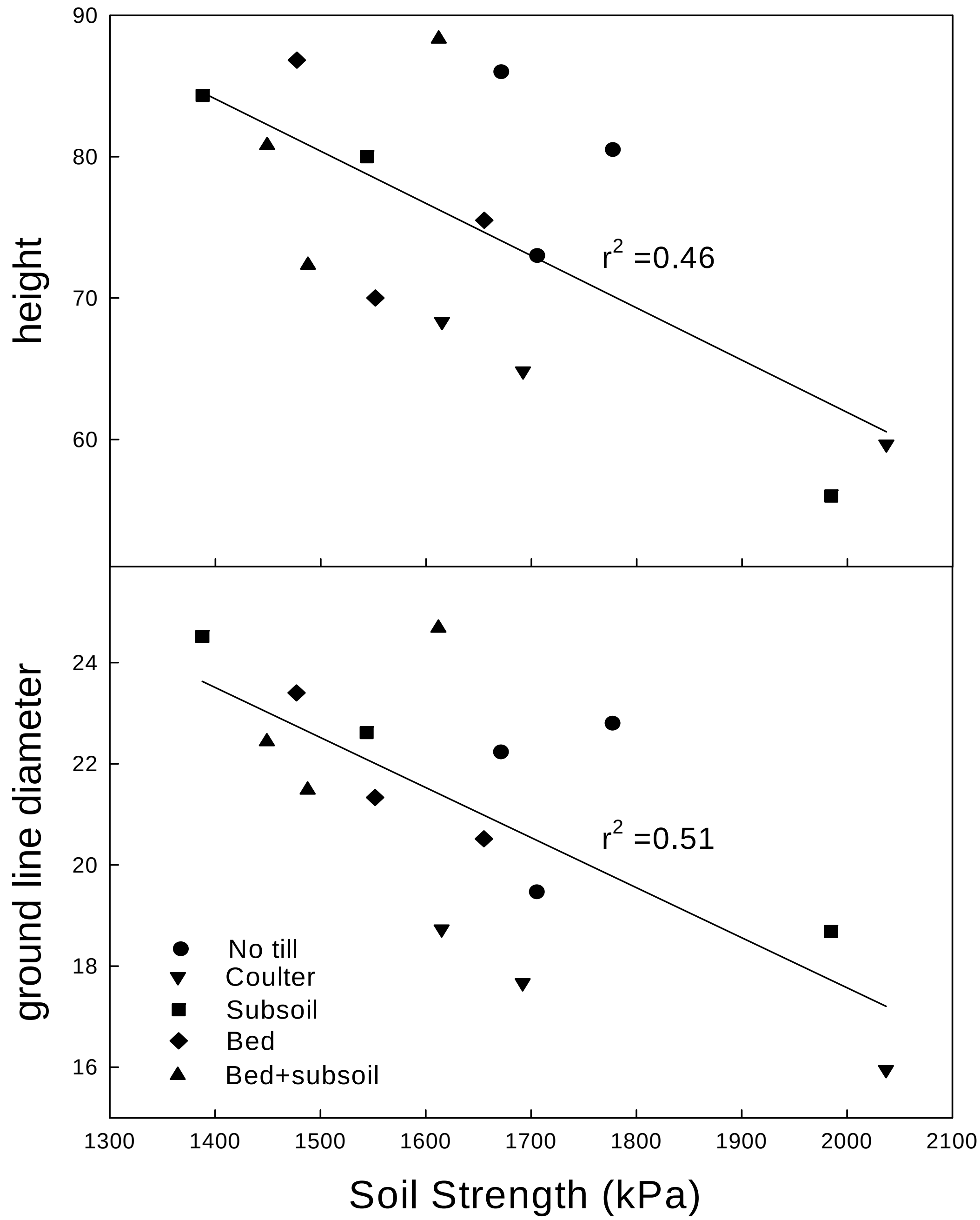


Figure 3-12. Correlation between soil strength from 30 to 40 cm and ground line diameter (gld) and height (hgt) of loblolly pine on the sandy site west of Lumpkin, GA following the first growing season.

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CONCLUSIONS

The goal of this study was to determine the effects of different intensities of soil tillage (coulter only, bedding, subsoiling, and bedding and subsoiling combined) on soil strength and soil moisture and to relate these changes to seedling growth. Tillage mediated changes in soil physical properties were clearly important; soil strength was related to absolute and relative seedling gld growth. Growth in the first growing season was not a function of nutrient availability since fertilization did not have an effect on tree response. The ability of a seedling to capture resources through root expansion is most likely the most important factor relating to growth in the first year.

Based on these results, bedding on sites with a minimal amount of topsoil can be beneficial because of the advantages of consolidating topsoil around seedling roots. The coulter only treatment in highly eroded, compacted, fine texture sites may be most effective at establishing seedlings due to the fracturing of the soil surface without smearing or increasing bulk density at depth. Machine planting, if possible, on these compacted fine textured soils, may provide enough tillage to lower surface soil strength and improve seedling growth. Machine planting may be the best alternative, i.e., good growth response for minimum amount of tillage, on sites with adequate topsoil because the tillage provided by the machine planter may be sufficient to improve seedling survival and growth.