TILLAGE EFFECTS ON LOBLOLLY PINE SEEDLING GROWTH, SOIL NITROGEN, FOLIAR NITROGEN, AND SOIL ELECTRICAL RESISTIVITY IN THE UPPER COASTAL PLAIN OF SOUTHWEST GEORGIA

By

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(Under the Direction of Daniel Markewitz)

ABSTRACT

Relationships between site preparation tillage and growth were assessed through three growing seasons for five treatments in two different *Pinus taeda L.* plantations within the upper Coastal Plain of southwest Georgia. Results revealed that minimum tillage often had the greatest growth response. A coulter only treatment produced the greatest response at a clay rich site. On a sandy site, the control was as productive as bedded treatments. Soil electrical resistivity was used at the sandy site to assess soil moisture utilization with tillage over a 2x8x2 m soil volume. Resistivity was linearly correlated with soil moisture in the top 30 cm; in the control plots and the interbed areas of bedded plots, R^2 ranged from 0.58 to 0.74; in bedded plots and the bedded areas of the bedded plot, R^2 ranged from 0.12 to 0.53. Near infrared reflectance spectroscopy predicted total foliar and soil N with some success ($R^2 > 0.9$).

INDEX WORDS: Coastal Plain, Coulter, Foliar Nitrogen, Near Infrared Reflectance Spectroscopy, *Pinus taeda L.,* Soil Nitrogen, Soil Electrical Resistivity, Soil Moisture, Tillage

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The southeast USA produces more timber than any other country in the world (Wear and Greis 2002). Increasing demands for timber and the desire for increased yields per hectare have prompted the use of intensive site preparation in pine plantation management throughout 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, and reduced competition (Haines et al. 1975). Site preparation operations that increase the ability of a seedling to utilize the existing resources in the soil or increase the concentrations of the resources in the soil will likely also increase seedling growth (Wheeler et al. 2002). Operationally, however, growth gains and the future economic value of these gains must exceed the cost of implementation. The high cost of mechanical site preparation techniques, particularly in relation to upland tillage operations, may limit the practice of these techniques.

Typically, in upland tillage practices, bedding and subsoiling are performed simultaneously with a 3-in-1 plow; however, this tillage technique requires more energy, is more intensive and, consequently, costs go up. Lower intensity tillage, such as that which occurs during machine planting or bedding alone, would cost less than the more intensive treatment. The most desirable tillage technique is clearly that which provides the greatest growth response for the lowest cost. This implies that, although the greatest volume growth gains may be achieved with the most intensive treatment, these gains per unit cost may not exceed those achievable with lower intensity tillage techniques.

The research results reported in this thesis largely focuses on a study designed to assess growth response to varying intensities of tillage treatment (Lincoln et al. in press). In Cuthbert and Lumpkin, Georgia, four tillage treatments and a control were implemented in three replicate blocks at both locations. The four tillage treatments, in order of decreasing intensity, were: coulter + bed + subsoil (CBS), coulter + bed (CB), coulter + subsoil (CS), and coulter only (C)—all compared to a non-tilled (NT) control.

Growth response at the end of the first growing season for both locations was reported by Lincoln et al. (in press). Lincoln et al. (in press) showed that at Cuthbert, the site with a clay B-horizon at the surface, the tillage treatments increased relative height and relative growth diameter in comparison to the control during the first growing season. It was also shown that at the sandy site, Lumpkin, two bedding treatments and the control increased pine growth relative to the C and CS treatments. Additionally, Lincoln et al. (in press) reported on measures of soil penetration to resistance and volumetric water content (VWC) to a depth of 60 cm. Lincoln et al. (in press) found that on the clay site, beds were drier overall. Most of the benefits of tillage on growth were obtained with the less intensive treatments such as machine planting or the C treatment, but all tillage treatments produced a greater response than the growth responses from the control.

Based on these results, there was interest in continuing growth measurements in order to quantify changes in growth gains or losses during early years of seedling establishment. Furthermore, the measured decline in VWCs under the treatments with higher growth posed an interesting dilemma; were the soils drier due to increased porosity from tillage or due to greater utilization of soil moisture by the seedlings? As such, two objectives of this component of the research were to 1) continue to quantify growth response to tillage by direct growth measures, as well as foliar and soil N quantification and 2) assess tree rooting volume using soil electrical resistivity—which is effected by soil moisture.

Quantification of tree growth response is straightforward and the following response to tillage over these years was hypothesized to be:

H1: Tree volume growth will increase with increasing tillage intensity and growth gains observed after the first growing season will continue to increase due to greater resource utilization such as moisture and nitrogen. However, foliar N, would not be effected by tillage.

In contrast to measuring tree growth and chemical quantification, the estimation of rooting volume is difficult. Time domain reflectometry (TDR) techniques that were used by Lincoln et al. (in press) are excellent to quantify VWC at point locations (Topp and Davis 1985), but it would require large numbers of probes to estimate soil moisture drawdown over a larger volume to estimate rooting. The depth to which these probes can be inserted and measured also has a practical limitation; as such, three dimensional (3D) electrical resistivity measurements were utilized for this purpose. This is a relatively novel usage of this technology in the realm of forestry that has been unapplied previously.

Soil electrical resistivity is a measurement of the difficulty of electrical current to flow throughout a given volume of soil. For this research, a 3D volume was measured. Electrical resistivity consists of injecting a continuous current into the ground through two current electrodes and then measuring the resulting potential difference in two other electrodes. Voltage and current measurements are obtained from an array of electrodes placed on the ground surface (Ojelabi et al. 2002; Seaton and Burbey 2002). The assignment of current and potential electrodes at each point is determined by a specific electrode configuration moving along the electrode grid. Based on Ohm's law, an apparent resistivity value is then calculated from knowing the intensity of the injected current, the difference in voltage, and the geometric positions of electrodes as determined by the array (AGI 2004). The true resistivity values (ohm-m) are then determined by inversion of the apparent resistivity values (Loke and Barker 1996).

The 3D soil electrical resistivity method was applied to the most extreme tillage treatment and the control at the Lumpkin site—which was sandy and well-drained. The measurements were performed five times over a 16 month period during 2005 and 2006. It was hoped that measuring changes in soil electrical resistivity over the two growing seasons would capture differences in soil moisture drawdown around the trees that could be used to estimate rooting volume. It was hypothesized that:

H2: Under intensive tillage treatments, soils in proximity to trees will demonstrate increases in soil electrical resistivity over time over a larger volume in response to increased tree rooting volume with tillage and greater plant soil water utilization.

In addition to the above studies, a limited investigation of the use of near infrared reflectance (NIR) spectroscopy for analysis of foliar and soil N was undertaken. NIR reveals information on chemical bonds based on the vibrational movements of the constituents of molecules within the samples of interest. NIR spectroscopy has previously been used to perform compositional analysis of agricultural commodities such as animal forage, corn, cotton, grains, and silage; it has also found increased usage in other industries and research disciplines (Barton 2002). Analysis of pine foliage has also been performed (Gillon et al. 1999) while use of NIR spectroscopy for soil analysis has been limited (Sorenson and Dalsgaard 2005). The main objective of this component of the research was to demonstrate the potential, if any, of NIR spectroscopy for expanding spatial and temporal analysis of foliar and soil N through this more rapid low cost approach. Based on the findings of similar studies, it was hypothesized that:

H3: NIR spectra can be used to predict foliar and soil N concentrations across growing seasons and the two research sites, respectively.

Given the three hypotheses, the desired outputs from this research were to 1) quantify growth responses of tillage on loblolly pine seedlings after three growing seasons 2) relate soil VWC and soil electrical resistivity to assess increases in tree rooting volume with tillage, and 3) correlate soil extractable, total soil, and foliar N to NIR spectra.

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CHAPTER II

LOBLOLLY PINE GROWTH AND FOLIAR AND SOIL NITROGEN CONCENTRATION RESPONSES TO TILLAGE[1]

[1] Adams, B. L. and D. Markewitz. To be submitted to the *Southern Journal of Applied Forestry*.

Abstract

Growth responses to tillage in loblolly pine (*Pinus taeda*) plantations vary greatly across the southeastern United States. This study addresses the minimum tillage required to produce the greatest growth response on upland sites within the upper Coastal Plain of Georgia. The objective is to determine which of four treatments will produce the greatest growth response—compared to a non-tilled control. The hypothesis was that the growth response will increase with increasing tillage intensity. Two loblolly pine plantations, one classified as a Greenville soil series near Cuthbert, GA and the other classified as an Orangeburg soil series near Lumpkin, GA, were planted in early 2004 utilizing four treatments: coulter + bed + subsoil (CBS), coulter + bed (CB), coulter + subsoil (CS), and coulter only (C), compared to a non-tilled (NT) control. Loblolly pine growth and foliar nitrogen (N) concentrations were determined annually over the first three and two growing seasons, respectively. Soil N concentrations were measured four times, May, June, August, and December during the first (2004) growing season. At Cuthbert, all tillage treatments produced some positive growth response compared to the non-tilled control—but the coulter only treatment had the greatest growth response. In contrast, at the end of 2005, the C treatment at Lumpkin was the worst performer—while there were no statistical differences in the best growers which were the bedded (CB, CBS) treatments and the non-tilled controls. At the end of 2006, the statistically highest growth response was the CB treatment. Extractable soil N was not statistically different across treatments. These results from the upper Coastal Plain of Georgia did not support a simple linear response of increasing growth with increasing tillage intensity.

Introduction

In intensive pine plantation management, the objective of site preparation (i.e. tillage, fertilization, etc.) is to maximize nutrient and water availability for tree growth (Allen et al. 1990). Tillage affects physical and chemical processes simultaneously and strongly affects the ability of the roots to access nutrients and water. The cause and effect relationships that occur with tillage treatments are important to understand and manipulate, if possible, so that plantation managers get the greatest growth response from the seedlings with the minimum investment of site preparation.

Two common tillage practices, bedding and subsoiling, are often used in combination; although, results are mixed. Bedding is the mechanical accumulation of local topsoil onto the planting area; in the flatwood regions and the lower Coastal Plain, bedding has been shown to be effective in raising seedlings above waterlogged conditions—thus improving growth and survivability substantially (Haines et al. 1975; McKee and Wilhite 1986; Gent et al. 1986). Additionally, bedding has shown limited success on upland sites (McKee and Wilhite 1986; Wheeler et al. 2002). Subsoiling is performed with a shank fitted with a wing to lift the soil as it is pulled behind a tractor or plow; it was shown by Wittwer et al. (1986) that subsoiling improves growth in mountain soils. Subsoiling has been shown to increase rooting volume of some annual crops on upper Coastal Plain sites (Vepraskus et al. 1986). Subsoiling may be desirable on many sites where a hardpan exists to allow for root expansion (Berry 1979).

In addition to the combining of bedding treatments, there have been many studies that focus on nutrient management practices; typically these practices have focused on soil nitrogen (N) and phosphorus (P) availability. Tillage practices, such as bedding, used in combination with fertilization, weed control or both has been shown to dramatically increase seedling height and stem diameter (Gent et al. 1986). In other cases, the effect of site preparation treatments such as windrowing, bedding, or burning have been studied relative to rates of N mineralization, decomposition, or other mechanisms of nutrient release; increases in organic matter from bedding can lead to an increase in nitrogen mineralization (Morris and Lowery 1988).

Water availability has also been studied relative to its inherent site availability and more rarely has been manipulated (Albaugh et al. 1998); drainage is typically dictated by the soil type. However, water availability can be affected indirectly with subsoiling; it can increase total storage of plant available water in the profile by increasing surface filtration or infiltration through slowly permeable subsurface layers and thus decrease run-off (Berry 1979; Morris and Lowery 1988).

Despite the successes of bedding in the flatwoods and lower Coastal Plain regions, the effects of bedding or tillage in upland environments remains less clear (McKee and Wilhite 1986; Wheeler et al. 2002). This uncertainty to tillage response in upland sites is true relative to growth, soil N, and soil moisture. When compared to a control, the effects of tillage treatment can result in three outcomes: initial effects can stay the same, over time become more pronounced, or disappear over subsequent growing seasons. For example, Wilhite and Jones (1981) found that, although bedding increased early growth, it has a diminishing effect on height growth over time. Ideally, one tillage method or combination of methods would make the most N available and also provide optimum moisture conditions across all sites; realistically, the method of tillage will need to be site specific depending on the local pre-existing site conditions and climate. Plantation managers are interested in determining the minimum tillage that produces the greatest growth response—the smallest investment that produces the greatest return. To address the uncertainty in response to tillage in upland soils and to assess the minimum tillage requirements, a series of experiments were undertaken (Wheeler et al. 2002; Will et al 2002). The first of these studies was initiated as collaboration with Rayonier Inc. Early results from Lincoln et al. (in press) demonstrate positive growth responses on the clay site in the first growing season, and based on these early results, the current study is focused on following up growth responses through the third growing season.

The specific objectives of this study are to 1) determine which of the four treatments yields the greatest growth response, 2) evaluate effects on soil extractable and total N concentration, and 3) assess changes in foliar N. It was hypothesized that growth response would continue to increase with increasing tillage intensity; that soil extractable N and total N would be greatest under bedding treatments (i.e., CBS and CB) and that foliar N would not vary with tillage treatments since excess N would simply be utilized to grow more leaves rather than increase foliar N.

Materials and Methods

Research sites

This study was established on two tracts of land on the Upper Coastal Plain of southwest Georgia. The first site is owned by MeadWestvaco Corporation and is located six miles southeast of the town of Cuthbert (31°77′ N, 84°79′ W) off of Morgan Road in Randolph County, Georgia. The soil at this site is classified as a Greenville series (fine, kaolinitic, thermic Rhodic Kandiudult) that compacted with a clay-rich B-horizon exposed at the surface. Resistance to penetration exceeded 5000 KPa (Lincoln et al. in press). Plinthite and ironstone are also prevalent. According to the Randolph County Soil Survey (Phillips et al. 1928), the Greenville soils have apparently been influenced to some extent by the underlying siliceous limestone. The soil map divides the location of the loblolly pine plantation into two Greenville soils, a sandy loam which comprises 11.4%, and a clay loam which comprises 7.2% of the land area of Randolph County.

The second site is owned by Rayonier Inc. and is located on Georgia Highway 27 approximately ten miles west of the town of Lumpkin ($32^{o}05'$ N, $84^{o}79'$ W) in Stewart County, Georgia. The soil is classified as an Orangeburg series (fine-loamy, kaolinitic, thermic Typic Kandiudult) with a loamy sand topsoil averaging 14 to 40 cm in depth over a sandy clay loam B-horizon; this site is well drained. According to the Stewart County Soil Survey (Long et al. 1916), the Orangeburg series are typically well-drained soils, and annual crops are more susceptible to drought. The Soil survey indicates that the Orangeburg sandy loam comprises 12.4% of the land area of Stewart County.

Complete details of each site establishment are reported in Lincoln et al. (9n press). Briefly, both sites utilized a complete randomized block design with three replicate blocks of five treatments (Anderson and McLean 1974). The four tillage treatments were: coulter + bed + subsoil (CBS), coulter + bed (CB), coulter + subsoil (CS), and coulter (C), all compared to a non-tilled (NT) control. While both sites represent complete randomized blocks, a full factorial design was not implemented. Thus, there was no independent bedding or subsoiling treatments. The lack of a full factorial design is a function of the equipment used in that removing the coulter wheel was not practical.

Site-preparation was performed at Cuthbert in January of 2004 and at Lumpkin in June of 2003. At both sites, tillage treatments were implemented using a Savannah Forestry Equipment (Savannah, Ga), LLC model 420 two-disk heavy-duty 3-in-1 plow pulled by a Caterpillar (Peoria, Il), D-7R tractor. This plow has a linear arrangement of a 1.2 m coulter wheel; followed by a 7.5 cm wide subsoil shank then two 80 cm diameter opposed notched disk blades. The plow 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 non-tilled control treatment was hand planted at the same spacing as the tillage treatments.

The loblolly seedlings at Cuthbert were operationally hand-planted in February 2004 with a full-sib Atlantic Coast loblolly pine family. The rows were 3.7 m apart with seedlings planted 1.8 m apart in the rows. At Lumpkin, loblolly seedlings were hand-planted in January 2004 with three different loblolly pine clones where each block received a different clone. The rows were 3.7 m apart and the seedlings were planted 0.9 m apart in order to ensure full stocking.

Soil Sampling and Measurements

For descriptive purposes, soils were sampled from a single augur hole in each of the three blocks on each site. In June 2004, samples were collected with a 10-cm diameter hand-auger from six different depths; 0-10, 10-20, 20-50, 50-100, 100-150, and 150-200 cm. The samples were composited for each hole for each of the six depths. The samples were stored at 4^{o}C until they could be processed within 72 hours. Processed samples were air-dried and passed through a two mm sieve where rocks and chunks of organic matter were removed. Samples for each hole of the six depths were analyzed for soil pH (Thomas 1996). Mehlich I (Sparks 1996) extractable P and cations (Kuo 1996) were analyzed by flow analysis on an Alpkem FS 3000, (O I Analytical, College Station, Tx) and an Atomic Absorption Spectragraph (Perkin Elmer, Waltham, MA). Additionally, textural analysis was performed using the hydrometer method described by Gee and Bauder (1986).

To assess tillage treatment effects on soil N concentration, soil samples were taken near three seedlings in each of the 15 plots for both sites. Samples were collected with a punch tube in March, June, August and December of the first growing season (2004). The soil samples were stored at 4^{o}C until they could be processed within 72 hours. Field moist samples were extracted with 2M potassium chloride (KCl) using a 10:1 liquid to solid ratio where 50 grams of extractant was added to 5 grams of soil in a 250 ml erlenmeyer flask (Mulvaney 1996). After extraction, the supernatants were stored in clean plastic vials at 4^{o} C until analyzed for NH_4^+ and NO_3^- using an Alpkem FS 3000 (OI Analytical, College Station, Tx). Within plot samples were averaged prior to statistical analysis such that n = 3 for both locations.

Seedling Growth Measurements

Ground line diameter and tree height were taken at the end of the first three growing seasons (2004, 2005 and 2006). Ground line diameters were measured with a digital caliper (Mitutoyo Co., China). Heights were measured with a telescoping fiberglass pole (Forestry Suppliers, Inc., Jackson MS). At Cuthbert, each plot was 7 by 20 rows with an internal measurement plot of 5 by 18 rows. At Lumpkin, each plot was 7 by 15 rows with an internal 5 by 13 row measurement plot. The first growing season measurements were made in December of 2004. For the Cuthbert plots, n = 84-94 trees, and for the Lumpkin plots, n = 64-68 trees. The second growing season measurements were made in January of 2006, and for both locations only the first nine trees were measured in each of the five rows, n = 45 trees. In January of 2007, n = 84-94 trees for each plot at Cuthbert, and at Lumpkin, n = 64-68 trees for each plot.

Foliar Nitrogen

Foliar samples were taken in December of 2004 from three trees in each of the 15 plots at each site. Needles were sampled from the most recent flush of the growing season. Unfortunately, the same three trees were destroyed for biomass evaluation at the end of the first growing season, so they could not be re-sampled in the future. In early January 2006 (i.e., the end of the second growing season) each tree within the five measurement rows—excluding the buffer trees at the end of each row—were sampled. All samples within each plot were composited and then dried at 61^{o}C until being crushed in a Certiprep 8000-D mixer mill (SPEX, Metuchen, N.J.) for analysis by dry combustion for total N using a NC 2100 Dry combustion Analyzer (CE Instruments, Lakewood N.J.).

Mortality

This study only presents the results of average height and ground line diameter for the live trees—which does not directly account for mortality. During the first growing season, Lincoln et al. (in press) reported that at Cuthbert, the C treatment had the best survival rate at 81%, followed by the CB treatment at 73%. The CS, CBS, and NT had similar survival rates of 65%, 63%, and 63% respectively. Because the Lumpkin site was double planted to ensure optimum planting density, survival rate approached 100%.
At the Cuthbert site, there were only four additional trees that died between the second (2005) and the third (2006) growing season. Similarly, at the Lumpkin site, only four trees died through the second growing season. During the third growing season, only one tree died of natural causes; however, Rayonier Inc. thinned a small number of suppressed seedlings. Provided there are no plights, i.e. tip moth infestation, severe draught etc., mortality is typically highest in the first growing season.

Statistical Analysis

Growth parameters, soil extractable NH_4^+ and NO_3^-, and foliar N were all analyzed as a one-way ANOVA treating repeated measures as a split plot. In all cases n = 3 and each location was analyzed separately.

Results

Soil Characterization

Based on the two meter soil profiles, the pH for the Lumpkin site overall was lower than the pH measurements for the Cuthbert site (Table 2-1). At Lumpkin, pH ranged from 4.0 at depth to 4.3 between 10-50 cm. Cuthbert, which ranged from 4.2 at depth to 5.2 between 20-50 cm, was less acidic than Lumpkin. In both locations, the lowest pH values occurred at depth (Table 2-1).

Textural differences were also readily apparent between the sites; overall, the Cuthbert site contained a higher percentage of clay material throughout the profile; and the Lumpkin site contained a higher percentage of sand. Based on the textural analysis, the Cuthbert site is either a clay or clay loam and the Lumpkin site is a sandy clay loam (Table 2-1).

The effective cation exchange capacity (ECEC) is much higher at Cuthbert than at Lumpkin. Even the highest values at Lumpkin are lower than the lowest ECEC values at Cuthbert (Table 2-1). Additionally, Cuthbert has a very high base saturation to 50 cm. Lumpkin has its highest base saturation between 20-50 cm. At both locations, the base saturation is identical below a meter (Table 2-1).

Soil Nitrogen Concentration Analysis

It was hypothesized that tillage treatments would increase extractable N concentrations due to an enhanced mineralization of organic matter. At Cuthbert, the range of extractable N values was greater than at Lumpkin, but there were no major differences between N concentrations across sampling months or among treatments (Figure 2-1). At Lumpkin, average N concentrations 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 (Figure 2-1).

Seedling Growth Responses to Tillage

The growth parameters, ground line diameters (Figure 2-2), tree heights (Figure 2-3), and volume indexes (Figure 2-4) across tillage treatments at the end of the second growing season (2005) and the end of the third growing season (2006) (Table 2-2) were assessed. Volume index was estimated using diameter^2 x height (i.e., D^2H).

At Cuthbert, for all growth parameters, all the tillage treatments exceed the NT control and the C only treatment produced the greatest average responses at the end of both the second and third growing seasons. Within the CBS treatment (i.e., the most intensive tillage regime), average response for volume index was not statistically different from the C only treatment (Table 2-2). The NT control treatment was consistently the worst performer. Growth responses for NT at the end of the second growing season for ground line diameter, height, and volume index was 22, 24, and 52%, respectively, below the average responses of the C only treatment. At the end of the third growing season, the NT control treatments were 18, 20 and 40% less, respectively, when compared to the C only treatment.

At Lumpkin, the treatment that produced the highest average growth was the CB treatment for both the second and third growing seasons. At the end of the second growing season, however, there were no statistical differences for volume ($p < 0.05$) among the bedded treatments, CBS and CB, and the NT control treatment, although all three of these treatment responses were statistically greater than the CS and C treatments. At the end of the third growing season, the CB was statistically greater than the NT for ground line diameter ($p < 0.05$) and volume ($p < 0.05$), while tree height ($p < 0.05$) on both the bedded treatments produced greater responses than the NT control (Table 2-2).

The poorest growth responses were observed in both the CS and the C treatments—which were statistically less than the NT control at the end of the both the second and third growing season for all growth parameters (Table 2-2). Compared to the highest averages, which for both years was the CB treatment, the C treatment had the lowest average growth; volume index was 51 and 41% less at the end of the second and third growing season, respectively.

Foliar Nitrogen Analysis

At Cuthbert the average foliar N concentration across treatments in the first growing season (2004) was ~1.8 % while that at Lumpkin was ~1.4 %. By the end of the second growing season (2005), foliar N concentration at Cuthbert had declined ($P < 0.05$) in all treatments to an average value of ~1.3 %. During this decline the highest values corresponding to tillage treatments CBS and CB in 2004 became the lowest values in 2005, and conversely the lowest value for C became the highest values in 2005. This response might reflect a dilution of foliar N in the productive CBS and CB treatments. At Lumpkin, differences in foliar N were not statistically significant and only the CS treatment showed a declining pattern (Figure 2-5).

Discussion

Soil-site Characterization

The soils at the Cuthbert and Lumpkin experimental sites are representative of soils for the region. Prior to the establishment of the current stand, it is known that both sites were loblolly pine plantations due to decaying pine stumps that occur in rows—typical of a plantation (Rusty Cobb, 2004, Personal Communication). The high base saturation at this site may also reflect more recent agricultural inputs—a response observed on other sites (Richter and Markewitz 2001). The Cuthbert site is likely located on land with an agricultural history—as evidenced by the presence of a dilapidated farmhouse structure, barn structure, and the remnants of a well. In which case, agricultural liming may have influenced the high base saturation observed. The Greenville soils in this area, however, have apparently also been influenced and derived to some extent by the underlying siliceous limestone (Phillips et al. 1928). Surface soils at this site appear to be exposed Bt horizons based on clay content and color (2.5YR 3/6). In places, this exposed Bt horizon presented an extremely hard surface pan during the most recent plantation establishment. In contrast to Cuthbert, the Lumpkin site retains a thick (~40 cm) sandy loam surface and, thus, does not appear to be eroded—nor is there any evidence of previous agricultural activity at the site or on any of the surrounding lands.

Soil Nitrogen Concentration

Increased levels of N in the soil may not always be necessary to improve early seedling growth. Increased N mineralization may not be as important in young stands because >100 kg/ha of N may be mineralized in the first two years after site preparation, while pine seedlings accumulate only 3.5 to 5.5 kg/ha when planted at normal densities (Morris and Lowery 1988).

However, these increased levels of N potentially become useful to the trees when they grow larger and their roots are able to access a larger soil volume (Morris and Lowery 1988).

At Cuthbert, the highest average N concentrations in the bedded treatments. Bedding, which concentrates organic materials and surface soil into localized areas (Attiwill et al. 1985) and creates a surface that is more rapidly warmed, may provide the greatest stimulation to N mineralization (Morris and Lowery 1988). These higher N concentrations in mid-summer might be expected due to the increased mineralization associated with higher temperatures.

Seedling Growth Responses

Comparing both the Cuthbert and Lumpkin sites, the effect of tillage treatment diminishes with improved drainage conditions on these two upper Coastal Plain sites. As Allen (2001) points out, growth responses to bedding are typically the greatest on poorly drained clays and the effects diminish as soil texture becomes coarse and drainage improves; these two sites seem to follow suit. Cuthbert is a highly eroded and poorly drained clay site, and by the end of the second growing season, tillage treatments produced growth responses statistically greater than the NT control. In contrast, the Lumpkin site is not eroded and retains a sandy loam surface soil; overall, it is well drained. At this site, the NT control treatment performed nearly as well as the most extensive treatment through the first three growing seasons; the differences at the end of 2005 were not statistically significant. At Cuthbert, all the initial treatment responses seem to disappear after the third growing season—with only the NT treatment lagging. At Lumpkin, only the CB treatment seems to retain its growth advantage through the third growing season.

Foliar Nitrogen

There appears to be no distinguishable influences of tillage on foliar N concentration. Previous research has demonstrated that tillage can increase nutrient acquisition by concentrating nutrients near the tree or by increasing the ability of roots to utilize a larger soil volume (Morris and Lowery 1988). However, Will et al. (2002) also did not find any influence of tillage on foliar N concentration.

Nitrogen responses

High levels of growth in both Cuthbert and Lumpkin were not associated with higher levels of soil extractable N or foliar N (Figure 2.1 and 2.5). Similar findings were reported by Wheeler et al. (2002) and Will et al. (2002) for both soil and foliar N concentrations. As trees grow and N demand increases during a rotation it is possible that bedding, which tends to concentrate organic materials and surface soil into localized areas around trees (Attiwill et al. 1985) might demonstrate some increased benefit.

Similarly, if tillage allowed for trees to grow larger and deeper roots these might enable access to a larger soil volume (Morris and Lowery 1988).

Conclusions

It was originally hypothesized that increasing tillage intensity would be correlated with increased growth. This hypothesis was not supported at either the Cuthbert site or the Lumpkin site. At Cuthbert, the site responded positively to tillage treatments; however, the most intensive treatment (i.e., CBS) did not produce the greatest growth response. In fact, at the end of the third growing season at Cuthbert, no tillage response was statistically different, and they all outperformed the NT control plots. At the Lumpkin site, where surface soils are more coarsely textured, tillage treatments did not produce an increased growth response relative to the NT control. In fact, at Lumpkin, tree growth in the NT treatments were not statistically different than the most intensive CBS treatments—while the C treatment produced poorer growth than the NT control treatments. Interestingly, the C tillage treatment produced the worst response at Lumpkin, yet it produced the greatest response at Cuthbert. In both cases, growth responses did not effect changes in soil N availability or foliar N concentrations.

In short, from the tillage experiments at both these two sites it was shown that using the 3-in-1 plow—which included coulter, bedding, and subsoiling—was not justified by growth responses through the third growing season. At sites like Cuthbert, where surface soils are severely eroded or compacted, minimal tillage to break the surface pan appears sufficient to enhance tree growth. At sites like Lumpkin, which contain a sandy cap and are well drained, no treatment appears to be necessary.

Table 2-1. Soil chemical and particle size analysis for soil profiles from Cuthbert and Lumpkin, GA. Samples were collected in June 2004. Values are mean (±1 SD) for three profiles. The table contains the pH of solution in 0.01M $CaCl_2$, as well as the textural analysis, effective cation exchange capacity (ECEC), and base saturation (BASE). Cuthbert soils are characterized as a Rhodic Kandiudult and Lumpkin soils as a Typic Kandiudult.

	Depth	pHs	ECEC	BASE	Sand	Clay
	cm		**cmol$_c$ kg^{-1}**	----------------------	**%**	---------------------
Cuthbert	0-10	4.8 ± 0.1	8.7 ± 3.0	96.3 ± 1.0	52.7 ± 18.5	33.3 ± 16.1
	10-20	5.1 ± 0.4	8.2 ± 1.6	96.7 ± 1.4	36.0 ± 1.0	48.0 ± 2.0
	20-50	5.2 ± 0.3	6.8 ± 1.3	96.9 ± 1.2	31.0 ± 5.6	44.3 ± 6.4
	50-100	4.6 ± 0.2	2.9 ± 1.2	82.4 ± 8.9	30.0 ± 7.2	30.7 ± 22.2
	100-150	4.4 ± 0.2	1.4 ± 0.4	28.0 ± 9.5	36.0 ± 6.6	31.0 ± 10.4
	150-200	4.2 ± 0.1	1.3 ± 0.2	16.4 ± 6.8	38.7 ± 2.3	32.0 ± 7.0
Lumpkin	0-10	4.1 ± 0.2	1.0 ± 0.1	40.2 ± 5.5	86.7 ± 2.5	6.0 ± 3.5
	10-20	4.3 ± 0.2	0.9 ± 0.1	44.1 ± 7.9	83.7 ± 1.2	7.7 ± 1.5
	20-50	4.3 ± 0.0	2.4 ± 0.7	73.5 ± 9.1	60.7 ± 9.8	30.3 ± 12.4
	50-100	4.2 ± 0.1	2.3 ± 0.1	70.7 ± 0.8	48.9 ± 8.8	24.3 ± 6.1
	100-150	4.1 ± 0.1	1.5 ± 0.3	29.7 ± 6.5	46.7 ± 8.3	17.7 ± 16.8
	150-200	4.0 ± 0.1	1.7 ± 0.2	13.9 ± 6.9	48.0 ± 6.1	27.3 ± 10.1

Table 2-2. Loblolly pine growth measurements for the end of the 2nd (2005) and 3rd (2006) growing seasons for tillage experiments in Cuthbert and Lumpkin, GA. Treatments are NT=no-till; C=coulter only; CS=coulter+subsoil; CB=coulter + bed; and CBS=coulter+bed+subsoil. Values with the same letter in the same row are not statistically different. Gld=groundline diameter and volume index is estimated as diameter^2 x height (i.e., D^2H). Superscripts indicate pairwise comparisons—as indicated by Duncan's multiple range test.

Site: Year: Measurement			Tillage Treatment					Overall
			CBS	**CB**	**CS**	**C**	**NT**	**P value**
Cuthbert	**2005**	gld (mm)	26.8 ^{ab}	25.4 ^{b}	26.5 ^{ab}	28.8 ^{a}	22.3 ^{c}	**< 0.1**
		height (cm)	107.3 ^{ab}	102.2 ^{b}	103.6 ^{ab}	116.2 ^{a}	88.5 ^{c}	0.1379
		volume (cm^3)	1696.0 ^{a}	1455.7 ^{ab}	1485.5 ^{ab}	1959.2 ^{a}	953.1 ^{b}	**< 0.1**
	2006	gld (mm)	41.3 ^{ab}	39.6 ^{b}	40.6 ^{b}	43.1 ^{a}	35.3 ^{c}	**< 0.1**
		height (cm)	181.9 ^{ab}	172.5 ^{b}	173.4 ^{b}	188.4 ^{a}	149.9 ^{c}	0.1013
		volume (cm^3)	7119.5 ^{a}	6450.6 ^{a}	6376.8 ^{a}	7554.0 ^{a}	4516.0 ^{b}	0.1155
Lumpkin	**2005**	gld (mm)	33.9 ^{ab}	35.4 ^{a}	28.8 ^{c}	26.9 ^{c}	32.6 ^{b}	**< 0.05**
		height (cm)	142.6 ^{ab}	145.2 ^{a}	125.2 ^{c}	118.0 ^{c}	135.6 ^{b}	**< 0.05**
		volume (cm^3)	2853.3 ^{a}	3060.9 ^{a}	1738.1 ^{b}	1493.6 ^{b}	2399.9 ^{a}	**< 0.05**
	2006	gld (mm)	45.9 ^{ab}	47.6 ^{a}	40.6 ^{c}	38.3 ^{d}	44.6 ^{b}	**< 0.05**
		height (cm)	196.3 ^{a}	199.3 ^{a}	174.9 ^{c}	166.1 ^{d}	187.9 ^{b}	**< 0.05**
		volume (cm^3)	7186.2 ^{ab}	7694.3 ^{a}	5166.8 ^{c}	4555.0 ^{c}	6441.5 ^{b}	**< 0.05**

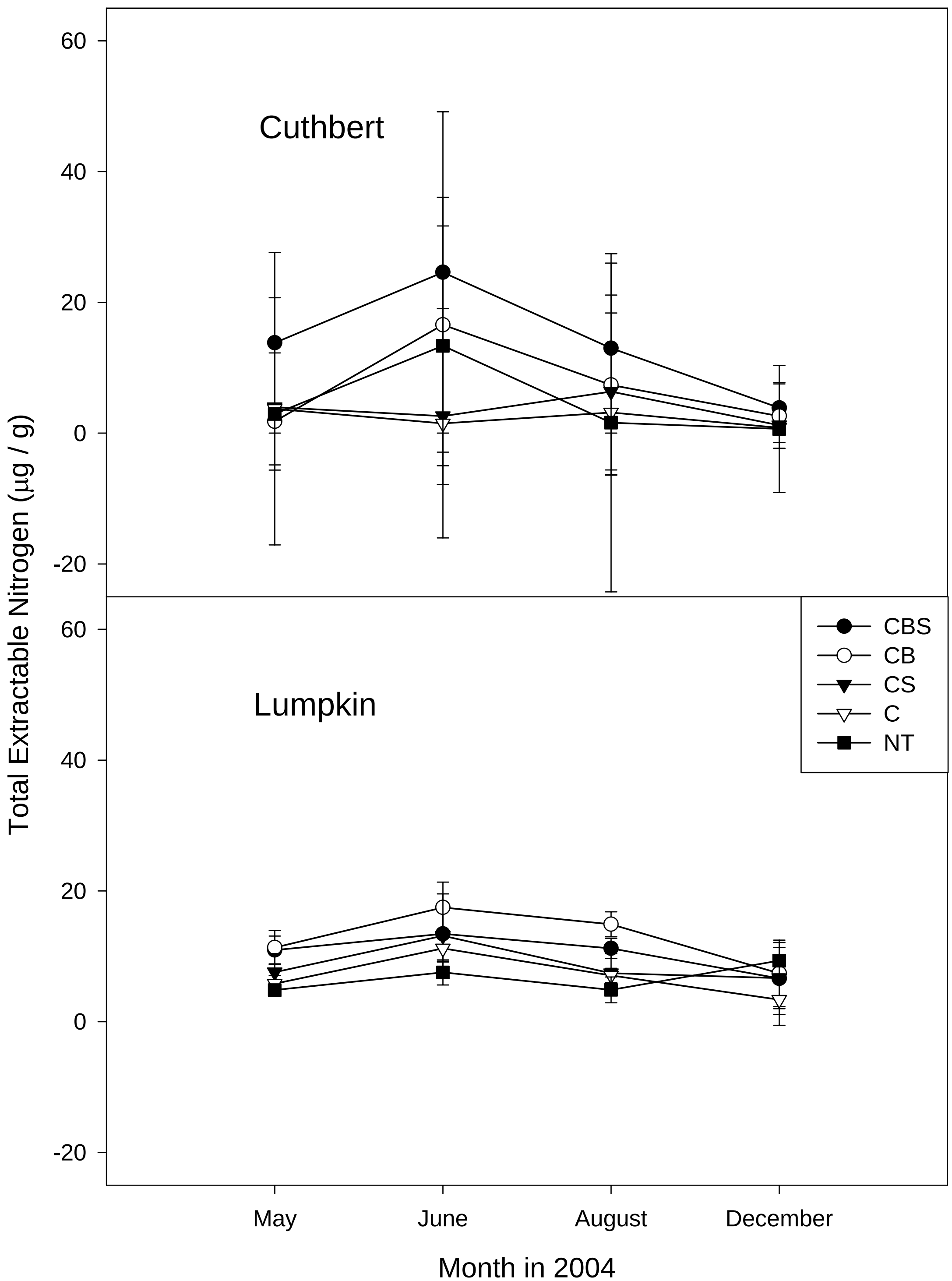

Figure 2-1. Total Extractable Nitrogen (i.e., the sum of extractable NH_4-N and NO_3-N) for Cuthbert and Lumpkin, GA measured through the first growing season. Treatments are NT=no-till; C=coulter only; CS = coulter+subsoil; CB=coulter + bed; and CBS=coulter+bed+subsoil. Values are means ±1 SD (n = 3 replicate blocks).

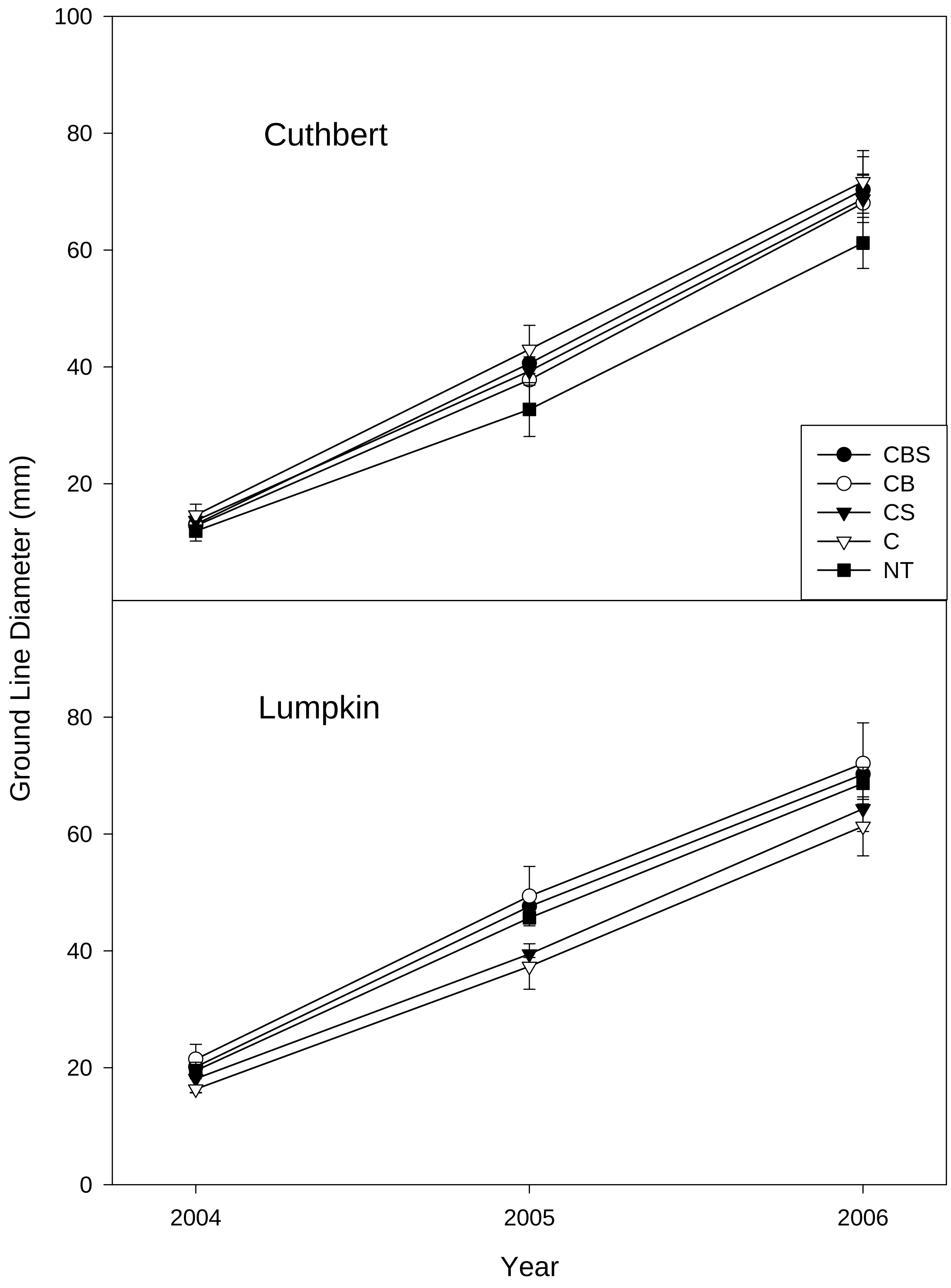

Figure 2-2. Ground Line Diameter (mm) for loblolly pine trees in Cuthbert and Lumpkin, GA measured after the first, second and third (2004-2006) growing seasons. Treatments are NT=no-till; C=coulter only; CS=coulter+subsoil; CB=coulter+bed; and CBS=coulter+bed+subsoil. Values are mean±1 SD (n = 3 replicate blocks).

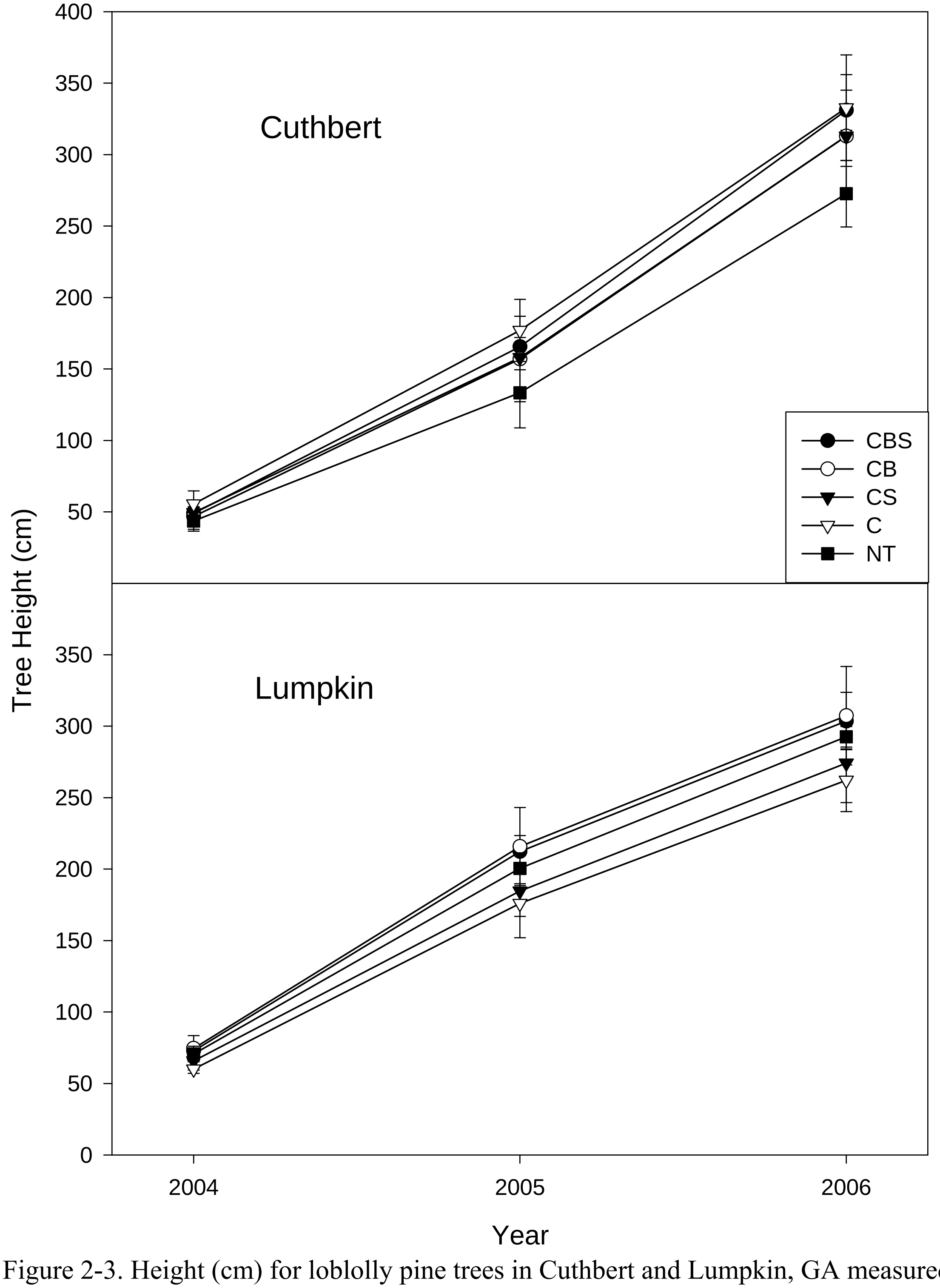

Figure 2-3. Height (cm) for loblolly pine trees in Cuthbert and Lumpkin, GA measured after the first, second and third (2004-2006) growing seasons. Treatments are NT=no-till; C=coulter only; CS=coulter+subsoil; CB=coulter + bed; and CBS=coulter+bed+subsoil. Values are mean±1 SD (n = 3 replicate blocks).

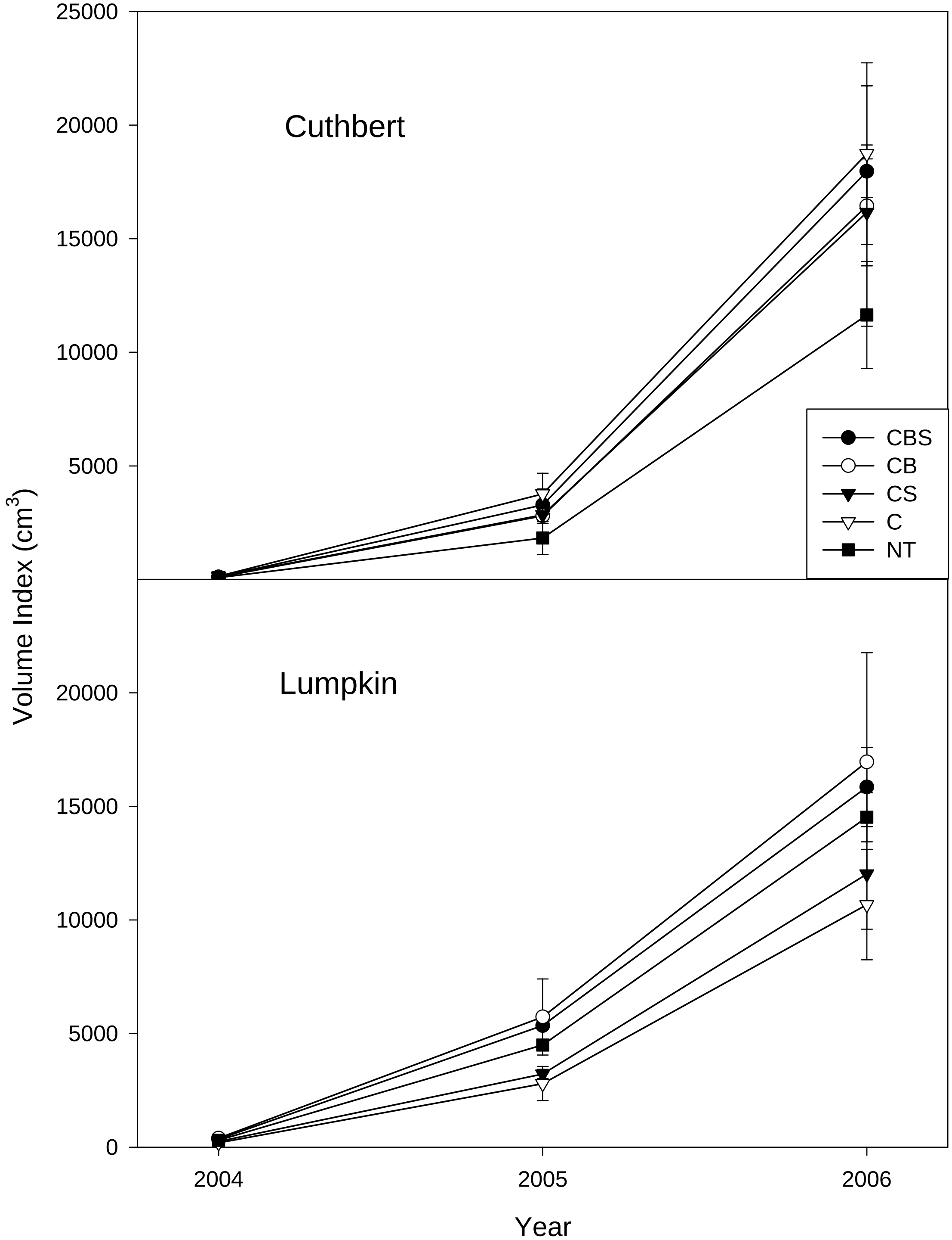

Figure 2-4. Volume index (cm^3) for loblolly pine trees in Cuthbert and Lumpkin, GA measured after the first, second and third (2004-2006) growing seasons. Treatments are NT=no-till; C=coulter only; CS=coulter+subsoil; CB=coulter + bed; and CBS=coulter+bed+subsoil. Values are mean±1 SD (n = 3 replicate blocks).

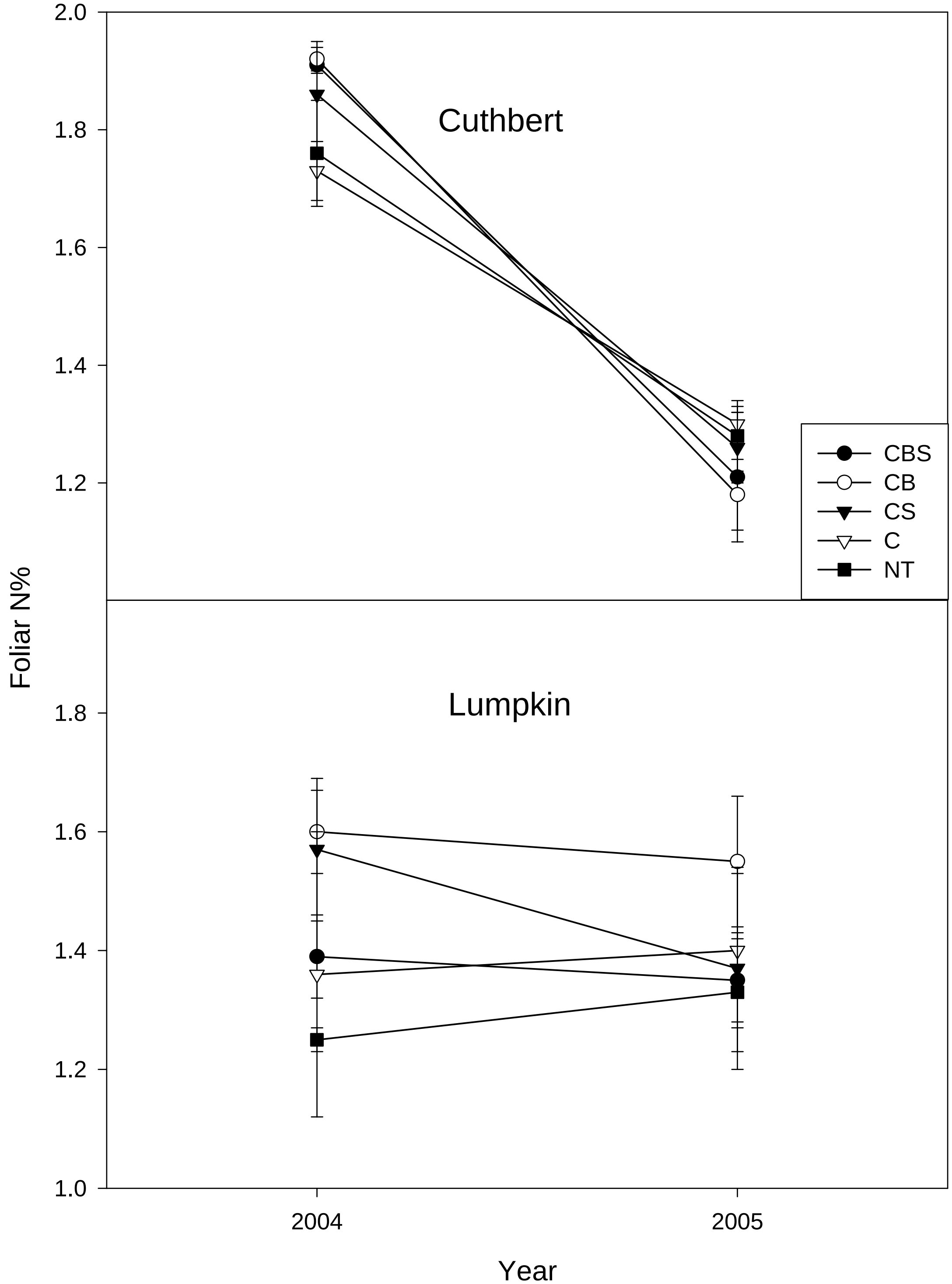

Figure 2-5. Foliar nitrogen for loblolly pine trees in Cuthbert and Lumpkin, GA after the first (December 2004) and second (January 2006) growing seasons. Treatments are NT=no-till; C=coulter only; CS=coulter+subsoil; CB=coulter + bed; and CBS=coulter+bed+subsoil. Values are mean±1 SD (n = 3 replicate blocks).

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CHAPTER III

THREE-DIMENSIONAL SOIL MOISTURE PROFILING WITH ELECTRICAL RESISTIVITY ACROSS TILLAGE TREATMENTS IN A LOBLOLLY PINE PLANTATION IN SOUTHWEST GEORGIA[2]

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Abstract

Soil tillage (e.g., bedding or subsoiling) for site preparation in loblolly pine (*Pinus taeda L.*) plantations in the Piedmont and upper Coastal Plain of the Southeast USA can increase growth. Poor root growth due to high soil bulk density can limit overall plant growth and survival. Direct quantification of the effect of tillage on soil rooting volume, however, has not been possible. For this research, 3D soil electrical resistivity (SER) imaging was used in an effort to directly estimate plant rooting volume. SER is sensitive to soil moisture conditions and thus it might be possible to quantify changes in soil moisture drawdown through a soil volume in response to tillage. An existing tillage experiment, planted in 2004, was used to assess soil moisture drawdown in a 2x8x2 m soil volume between a non-tilled (NT) control treatment and a more extensive coulter+bedding+subsoil (CBS) treatment (n = 3). Volumetric water content (VWC) for the 0-30 cm layer was measured using time domain reflectometry (TDR) and soil electrical resistivity over the soil volume was measured using a 28 probe configuration spaced 1 m apart with an electrical resistivity meter. SER measures were taken on five dates over 2005 and 2006; moisture measures were taken on four dates. Resistivity was well correlated with VWC. For each of the NT treatments, R^2 ranged from 0.58 to 0.66 and in CBS treatments, R^2 ranged from 0.33 to 0.53. For CBS treatments, the strength of this relationship varied between bed R^2 ranged from 0.12 to 0.40 and interbed $R^2 = 0.50$ to 0.74 locations. When compared to the CBS treatments on each date, the average resistivity model values over the entire soil volume was higher in the NT controls than in the CBS treatments, although these differences were not significant ($p > 0.05$). Using 3D resistivity, greater moisture utilization could not be inferred in CBS relative to NT.

Introduction

Soil tillage (i.e., bedding, disking, subsoiling) for site preparation in loblolly pine plantations in the Piedmont and upper Coastal Plain of the Southeast USA has been shown to increase growth (Morris and Lowery 1988; Allen et al. 1990; Wheeler et al. 2002). In contrast to bedding of poorly drained sites that facilitates pine growth through increasing surface soil aeration (Aust et al. 1998), the mechanisms that improve growth in upland sites are less clear (Will et al. 2002). Tillage in upland sites may improve aeration, or reduce bulk density and mechanical resistance to root penetration (Foil and Ralston 1967; Morris and Lowery 1988). Similarly, tillage may improve the availability of water or nutrients (Fox et al. 1986). It is difficult to isolate the specific mechanism driving growth response. In a recent study comparing the Piedmont and Coastal plain of Georgia, Will et al. (2002) concluded that, rather than affecting growth by increasing water or nutrient availability on a soil volume or weight basis, tillage probably improved growth by increasing the ability of seedlings to utilize a larger volume of soil—thus acquiring greater total amounts of necessary resources earlier in the seedling's life.

Early in seedling establishment, poor root growth due to high soil bulk density can limit overall plant growth and survival (Daddow and Warrington 1983; Carlson 1986). Disking, bedding, and subsoiling can all reduce mechanical resistance of surface soils to root growth (Gent and Morris 1986). Subsoiling, in particular, can potentially increase the depth of root penetration (Wittwer et al. 1986). After seedling establishment, the continued ability of plant roots to utilize soil resources will affect subsequent growth. Various approaches have been implemented to estimate water utilization by plant roots and relate conditions for belowground growth with aboveground growth (Colbert 2001; Morris et al. 2006). Direct quantification of soil rooting volume has not been possible.

For this research, however, it was proposed using three dimensional (3D) soil electrical resistivity imaging in an effort to directly estimate plant rooting volume by soil moisture draw down. With this approach, it might be possible to quantify moisture draw down in proximity to planted pine seedlings through a soil volume. Soil electrical resistivity is sensitive to soil moisture conditions (Turession 2006) and some success in imaging soil utilization around corn plants has been achieved (Panissod et al. 2001).

In this study, an existing tillage experiment in a loblolly pine (*Pinus taeda L.*) plantation on the upper Coastal Plain of southwest Georgia was used to assess soil moisture drawdown between a non-tilled (NT) control treatment and a more extensive coulter + bedding + subsoil (CBS) treatment (Lincoln et al. in press). Point sample measurements were taken with time domain reflectometry (TDR) probes at this site, and results indicated that soils were drier in the beds of the CBS treatment relative to the NT control although average tree heights in the CBS were taller—but not statistically. These results are consistent with those of an earlier tillage study in five locations throughout the Piedmont and upper Coastal Plain of Georgia (Wheeler et al. 2002; Will et al. 2002) that also demonstrate drier beds with larger growth responses.

Given the above results it was hypothesized that decreased resistance to root penetration with tillage increased soil rootability and plant rooting volume. As such, in the CBS treatment, soils in proximity to seedling roots will demonstrate larger increases in soil electrical resistivity over time over a larger volume in response to increased tree rooting volume with tillage and greater soil water utilization by seedlings.

Materials and Methods

Site Establishment

This study was established in early 2005 during the second growing season of a loblolly pine (*Pinus taeda*) plantation owned by Rayonier Inc. on the upper Coastal Plain of southwest Georgia. The plantation is located approximately ten miles west on Georgia Highway 27 outside of the town of Lumpkin (32^{o} 05′N, 84^{o} 93′W) in Stewart County, Georgia. The tillage study at this site was implemented to determine growth response across four tillage treatments against a control. The soils at the site are classified as an Orangeburg series (fine-loamy, kaolinitic, thermic Typic Kandiudult) with a loamy sand topsoil averaging 14 to 40 cm in depth over a sandy clay loam B-horizon; this site is well drained. According to the Stewart County Soil Survey (Long et al. 1916), the Orangeburg series are typically well-drained soils—making annual crops more susceptible to drought. The Soil Survey indicates that the Orangeburg sandy loam comprises 12.4% of the land area of Stewart County. While there has been at least one pine plantation rotation prior to the current rotation, it is likely that the area was a natural forest prior to this time; there is no evidence of an agricultural history at the Lumpkin site—or on the surrounding lands.

Site-preparation was performed in June 2003; tillage treatments were implemented using a Savannah Forestry Equipment (Savannah, GA), LLC model 420 two-disk heavy-duty 3-in-1 plow pulled by a Caterpillar (Peoria, IL), D-7R tractor. This plow consists of a linear arrangement of a 1.2 m coulter wheel; followed by a 7.5 cm wide subsoil shank then two 80 cm diameter opposed notched disk blades. The plow 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 non-tilled (NT) treatments were hand planted at the same spacing as the tillage treatments.

Details of the site description are reported in Lincoln et al. (in press). In brief, the tillage treatments utilized different arrangements of the 3-in-1 plow including; coulter + bed + subsoil (CBS), coulter + bed (CB), coulter + subsoil (CS), coulter (C), and the non-tilled (NT) control. At establishment, the study site received an aerially applied broadcast herbicide treatment. In October of 2003, a broadcast herbaceous weed control treatment was applied via skidder.

Loblolly seedlings were hand-planted in January of 2004 with three different loblolly pine clones; each block received a different clone. All tillage treatments, including the control, were hand planted at the same spacing. The rows were 3.7 m apart and the seedlings were planted 0.9 m apart in order to ensure full stocking. At the end of the first growing season (2004), trees were thinned to 1500 trees ha^{-1} by removing every other tree. The experimental design of the original study was a randomized complete block with three replicates of five treatments (Anderson and McLean 1974). Only the most extreme tillage treatment and the non-tilled control were utilized in the soil electrical resistivity study. As such, this soil electrical resistivity survey was a complete randomized block design with three replicate blocks of two treatments. The extreme tillage treatment utilized in this study was a coulter + bed + subsoil (CBS), and the control was non-tilled (NT).

Resistivity Measurements

Measurements of soil electrical resistivity were initiated in March of 2005 and were repeated in June 2005, November 2005, March 2006 and June 2006. Resistivity measurements were made with a 28-electrode SuperSting R8 Resistivity / Induced Polarization (IP) meter (Advanced Geosciences Inc., Austin, TX).

The probe array was a grid in the shape of a rectangle, with three transects of nine electrodes, spaced one meter apart, with the 28th electrode being placed outside the rectangle in the middle row (Figure 3-1). The probe array was perpendicular to the tillage rows and crossed three tillage rows. In every survey, 3-5 trees were present within the rectangular electrode grid. The electrodes (i.e., metal stakes) are attached in sequence such that the bottom transect electrodes, numbered 1-9, proceed left to right, the middle row, numbered 10-18, proceeds back right to left, and the top row, numbered 19-27, returns again proceeding left to right. The 28th electrode was positioned outside the long end of the rectangle in the middle transect one meter to the right of the middle electrode (Figure 3-1) preventing any confusion when taking notes and orienting the graphs for analysis. After the survey was complete, and moisture measurements were taken, pin flags were left at each electrode location to ensure that the same area was resampled during subsequent measurements. During all dates of soil electrical resistivity measurements, n = 3, except in March 2005 when one CBS plot is missing, and in March 2006 when one NT plot is missing.

Data analysis from the SuperSting is achieved with 3D EarthImager v 2.0 © 2003 software (Advanced Geosciences Inc., Austin, TX). The Earthimager software allows the user to write custom programs for resistivity surveys. A specific coordinate program was written for the Supersting to take points in a longitudinal rectangular shape with one-meter spacing as described previously. The custom AGI array combines non-standard dipole-dipole and gradient configurations (Figure 3-2). According to Stummer et al. (2004), combined dipole-dipole and gradient arrays have an optimal resolution.

Resistivity Data Processing

Essentially, the apparent resistivity data is in the form of a large text file. The Earthimager v 2.0 © 2003, allows the user to invert the apparent resistivity data for 3D models of electrical resistivity within the subsurface (Figure 3-3 to 3-8). As with most data processing, the largest responsibility of the user is to remove noisy data and extraneous values. The data were inverted to obtain a root mean square misfit between measured and predicted apparent resistivity between five and 10%; typically this was achieved in less than four iterations. The resistivity allowable range of soil resistivities was 500-2500 ohm-m. The inversion method was the smooth model inversion, with eight X and Y mesh divisions per electrode interval (giving each cubes $1/8^{th}$ m on a side) and the surface survey mesh utilized a depth factor of one. The forward modeling method was finite difference. The type of boundary condition was a mixed; the matrix equation solver was a conjugate gradient.

Soil Volumetric Water Content

Time domain reflectometry (TDR) was used to measure the soil volumetric water content (VWC) (Topp and Davis 1985). Soil VWC measurements were not taken in March of 2005; measurements were collected on all other dates for all other plots except for the missing resistivity NT treatment in March 2006. Soil VWC measurements were made at each of the 28 electrode points after the resistivity survey using a Moisture Point Model MP-917 (Environmental Sensors Inc., Ontario, Canada), with a 30 cm diode probe after resistivity electrodes were removed. TDR probes were placed within 5 cm distance of the electrode hole. Pin flags were left at each electrode location to ensure that the same area was resampled for subsequent measurements.

Bulk Density

Bulk density samples, for each of the six plots, were collected during the first growing season (2004) using the method described by Blake and Hartge (1986). A 7.5 cm diameter by 7.5 cm tall brass core was driven into the ground to collect known volumes of soil. Four depth zones in the middle of the layer were sampled: 0-15, 15-30, 30-45, and 45-60 cm. The samples were stored at 4^{o}C until they could be emptied from the cores. Samples were labeled, emptied into paper bags, and dried at 105^{o}C for two days before they were weighed; large rock or woody fragments were removed.

Data Analysis

ANOVA was used to determine differences in resistivity averaged over the entire soil volume between tillage treatments (Tables 3-3). The five dates were treated as a split plot repeated measure (Anderson and McLean 1974). Additionally, the soil volume was divided into two depth zones—shallow and deep—for analysis. This depth for separation was based on the depth of the subsoiling shank which cut approximately 60 cm into the soil. ‘Shallow’ represents all depths above 60 cm, and everything deeper than 60 cm was classified as 'deep.' ANOVA was used to determine differences in the overall resistivity between the two depths for both treatments, as well as resistivity between the two depths within each treatment, over five dates.

The soil VWC and the soil electrical resistivity measurements were analyzed using regression (Figure 3-9 and 3-10). Resistivity is treated as the dependent variable, y, and moisture is treated as the independent variable, x, in a simple linear regression. TDR readings of soil VWC were taken with a 30 cm diode probe—providing a single integrated measure over the upper soil layer. In contrast, the soil electrical resistivity models reveal more spatial resolution, depending on the programmed mesh size, as well as multi-depth layers. The resistivity data were processed at the highest 8 mesh resolution which produced three layers to a depth of 37.5 cm below the surface. An average was taken over the upper three resistivity layers to estimate the average resistivity over the same depth as VWC. Thereafter, based on the gridpoints of the resistivity model, the four measures surrounding the location of the TDR diode were averaged to get a soil electrical resistivity value for correlation with VWC.

In each plot, there were 28 pairs (model resistivity and moisture) of points on each date; the 28th electrode was not considered, since the quality of the soil resistivity estimates was uncertain due to the geometry of this probe relative to the rectangle. The models of soil electrical resistivity for each plot for all four dates (June and November 2005, and March and June 2006) were analyzed by treatment (i.e., CBS only and NT only) and within the CBS treatment, by location. Location was defined as being outside the tillage row (interbed) or inside the tillage row (bedded). The objective was to more specifically test the effects of tillage on the resistivity vs. moisture relationship.

Results

Soil Moisture and Bulk Density

Average volumetric water content measured with TDR in the upper 30 cm was found to be higher in the NT treatments and lower in the CBS tilled treatments on all dates of collection (Table 3-1). However, the differences were not statistically different ($p > 0.1$). The CBS treatments were further divided into interbed areas and bedded areas to more fully assess the effect of tillage. On all four dates within the CBS tilled treatments, the average soil VWC was higher in the interbed areas and lower in the bedded areas (Table 3-2). Only in November 2005 was the difference in soil moisture content statically significant ($p < 0.05$).

In the surface depths (0-15cm), the average bulk density values, $n = 3$ for each depth, were lower in the CBS plots relative to the NT plots (Table 3-3). Below 15 cm, bulk density increased to similar values in deeper layers for both the NT and CBS treatments. Additionally, there seems to be a hardpan in the 15-30 cm depth as indicated by the higher bulk density (1.7 g cm^{-3}) for both treatments (Table 3-3).

Soil Electrical Resistivity and Soil Moisture

Linear regressions—with untransformed data—for moisture and resistivity by plot over all dates provided R^2 values between 0.33 and 0.66 (Figure 3-9). Soil resistivity values are extracted from the soil resistivity models at the grid nodes surrounding the original electrode positions (as shown in Figure 3-1). Raw R^2 values were used rather than adjusted R^2 values, and only one value for resistivity in plot 3 (a CBS tillage treatment) in November 2005 was manually removed after post processing because it was an outlier. For all six of the regressions, three replicate blocks for each treatment, slopes were negative—thus indicating a decrease in resistivity with increasing moisture (Figure 3-9). Regressions in the NT plots exhibited higher R^2 values than regressions from the CBS plots, and resistivity values were higher in the NT plots (Table 3-1).

Given the higher correlations in the NT plots (i.e., higher R^2), the three CBS plots were further divided into interbed areas and bedded areas for both resistivity and moisture (Figure 3-10). Two thirds of the data, for each plot, were classified into interbed points and one third of the data were classified as bedded points—based on where the points were located. The soil electrical resistivity values were then correlated with their respective moisture contents. The hypothesis was that changes in porosity and/or decreased bulk density due to tillage were complicating the resistivity vs. moisture relationship. As with the overall correlations of the NT and CBS treatments, the slopes were negative and the undisturbed interbed areas did, in fact, have higher R^2 values compared to the bedded counterparts (Figure 3-10).

In all cases above, the regressions indicated that resistivity is responsive to changes in soil moisture as well as apparently being responsive to changes in bulk density. Although these relationships are only established for the 30 cm depth, there is sufficient evidence (Turesson 2006) to indicate that resistivity is reflective of soil moisture at depth, and can be used to infer patterns of rooting through soil moisture drawdown (Panissod et al. 2001).

Soil Electrical Resistivity with Tillage Treatment

Although there was some tendency to observe higher resistivity values in proximity to trees, these patterns were not sufficiently strong to allow for estimation of rooting volume as originally proposed. As such, differences were analyzed within the entire measured 2x8x2 m volume—under the assumption that differences in plot root volume and soil moisture utilization would still be measurable. The average resistivity value over the entire soil volume was higher, on all dates, in the NT control treatments than in the CBS tilled treatments (Table 3-4). However, these differences were not significant ($p < 0.1$) and there was no interaction with date. The average resistivity values ranged from ~800 to 1800 ohm-m and generally increased from March 2005 to June 2006. The variance among dates was matched by the within soil volume variance for any given date (Figures 3-3 to 3-8). In fact, within the soil volume on any specific date under any tillage, the variance ranged from ~500 to 2500 ohm-m.

To further refine the analysis, soil profile was divided by depth into 'shallow' and 'deep' based on the approximate depth of the subsoil tine. The objective was to focus more specifically on that soil that had been disturbed and had increased airspaces—the hypothesis being that with greater disturbance, there would be higher root proliferation and higher (i.e., drier) resistivity values. However, essentially, there are no differences in the shallow profile averages and the deeper profile averages over all treatments or between respective tillage treatments for any particular date (Table 3-4). For the NT control treatments, there were no statistical differences between shallow and deep ($p > 0.1$) and in March and June of 2005, the resistivity values were very slightly higher in the deeper depths, and in the three subsequent dates, the averages were very slightly higher in the shallow depth (Table 3-4). In the CBS treatments, there were statistical differences found between shallow and deep depths for March and June of 2006 ($p < 0.1$) and for all dates in the CBS treatments, the resistivity values were very slightly higher in the shallow depths (Table 3-4).

Discussion

The purpose of soil tillage in forest site preparation is to improve soil chemical and physical attributes and to facilitate maximum seedling establishment and growth. As Carr (1982) points out, a granulated soil will have more water-filled large pores with high capillary conductances and less water filled small pores with low capillary conductances than the natural soil from which it was derived. Ignoring the effect of ion concentration on soil waters, this is strictly a consideration of soil structure as it relates to moisture drawdown and volumetric water content. While resistivity may be a useful tool in undisturbed landscapes to relate moisture draw down, it looses potential predictive ability in disturbed landscapes probably due to decreased bulk density and increased pore space (Figure 3-10). As Morris and Lowery (1988) suggest, subsoiling can increase total storage of plant available water in the profile by increasing infiltration through slowly permeable surface layers during rain events and decreasing run-off, yet effects of this phenomenon could not be determined with soil electrical resistivity measurements.

Soil Moisture

The average volumetric water content on the NT control treatments for each date are higher than the volumetric water content on the CBS tilled treatments; thus, the bedded treatments are drier. This phenomenon has been shown in other research (Morris and Lowery 1988; Wheeler et al. 2002; Lincoln et al. (in press). In other tillage studies dealing with moisture and bedding treatments, the bedded areas were dryer than the non-bedded areas; this, likely, is related to increased pore space and decreased bulk density. With beds being drier, it is counter intuitive, to hypothesize greater growth, as found by Wheeler et al. (2002) or in the current study, unless it is the trees that are utilizing soil moisture—causing the beds to be drier.

Soil Electrical Resistivity with Tillage Treatment

It was hypothesized that plants on bedded treatments had improved growth due to reduced physical resistance of root growth and thus would utilize a greater soil volume. Furthermore, measures of 3D soil electrical resistivity images should reflect these moisture changes and could be used to demonstrate plant utilization of a greater soil volume. Utilizing a similar approach, Panissod et al. (2001) demonstrated some success in measuring soil moisture changes in an agricultural case study where 2D resistivity transects were taken perpendicularly to corn rows planted 0.8 m apart. Both a 1 m and a 0.2 m spacing of electrodes were tested; greater success achieved with the closer spacing. Below corn crops, hemispherical patterns of higher resistivity were observed (Panissod et al. 2001)—no doubt indicating soil moisture draw down due to utilization by corn roots.

In the current study, a wider spacing was used due to the larger and longer lived nature of pine trees. A 3D approach was used to for the estimation of soil volume. Unfortunately, contrary to the hypothesis, higher resistivity values were not observed in proximity to plants nor any clear pattern in annual drawdown (Figures 3-3 to 3-8). Although, there were localized areas—representing the bedded rows—in the CBS plots with high resistivity values, overall, the highest values for resistivity values occurred in the NT plots (Table 3-1). However, within the CBS plot, the interbed areas of the CBS tilled plot had overall lower average resistivity values (i.e., higher VWC) when compared to the bedded areas of the CBS tilled plots which had higher resistiviy values and lower VWC (Table 3-2).

Within the NT control plots, better correlations between VWC and soil electrical resistivity were observed. This can partially be attributed to lower pore space and higher bulk density.

CBS Tilled Plots / Disturbed Soils

Lincoln et al. (in press) found that soil VWC on beds is typically lower than in non-bedded areas. Generally, this was the case in this study—although differences were not statistically significant. The soil VWC values taken from the NT control treatments were not higher than those taken from the CBS tilled treatments; the upper range was the same for both, however, in the CBS treatments, there were a larger number of moisture values below 10 %.

Additionally, clayey soils tend to retain a blocky structure much longer than a sandy soil after disturbance; these correlations of soil electrical resistivity and soil VWC might even be expected to be lower in a clayey soil than in a sandy soil. However, due to typical higher ion concentrations in clays, a clayey undisturbed soil might reveal even stronger relationships between electrical resistivity and moisture than those relationships observed at an undisturbed sandy site with relatively the same soil VWC.

Disturbed vs. Undisturbed

An overall consideration of the interbed areas and bedded areas of the CBS plot indicate that the variability becomes larger with soil disturbance, and the relationship between soil VWC and soil electrical resistivity breaks down.

Although it is clear that in the bedded areas, the average moisture values are much less, and that the average resistivity values are higher than in the interbed areas; yet differences are not statistically different for either moisture or resistivity between the interbed areas or the bedded areas. Given the relationship between the two variables, and having shown that this relationship is strong, but breaks down as disturbance increases, then there must be another factor or factors that influence this relationship by either influencing moisture readings, the resistivity values, or a combination of the two.

Conclusions

It is no large breakthrough that soil electrical resistivity and soil moisture are related. It was hypothesized that soils in proximity to seedling roots would have show increases in resistivity due to soil moisture utilization. However, the relationship between the two breaks down as soil disturbance increases. Clearly there is a difference in the R^2 values between the NT and the CBS treatments as well as the interbed and bedded R^2 points within the CBS treatment. The graphs of soil moisture content vs. soil electrical resistivity show more scatter for the CBS tilled treatment than the NT control as well as the bedded areas within the CBS tilled plot when compared to the interbed areas of the same plot. This is most likely because tillage and disturbance causes decreases in bulk density and introduces mixture of different sized air spaces—effecting resistivity measures in different ways based on the wetting and drying processes of the soil.

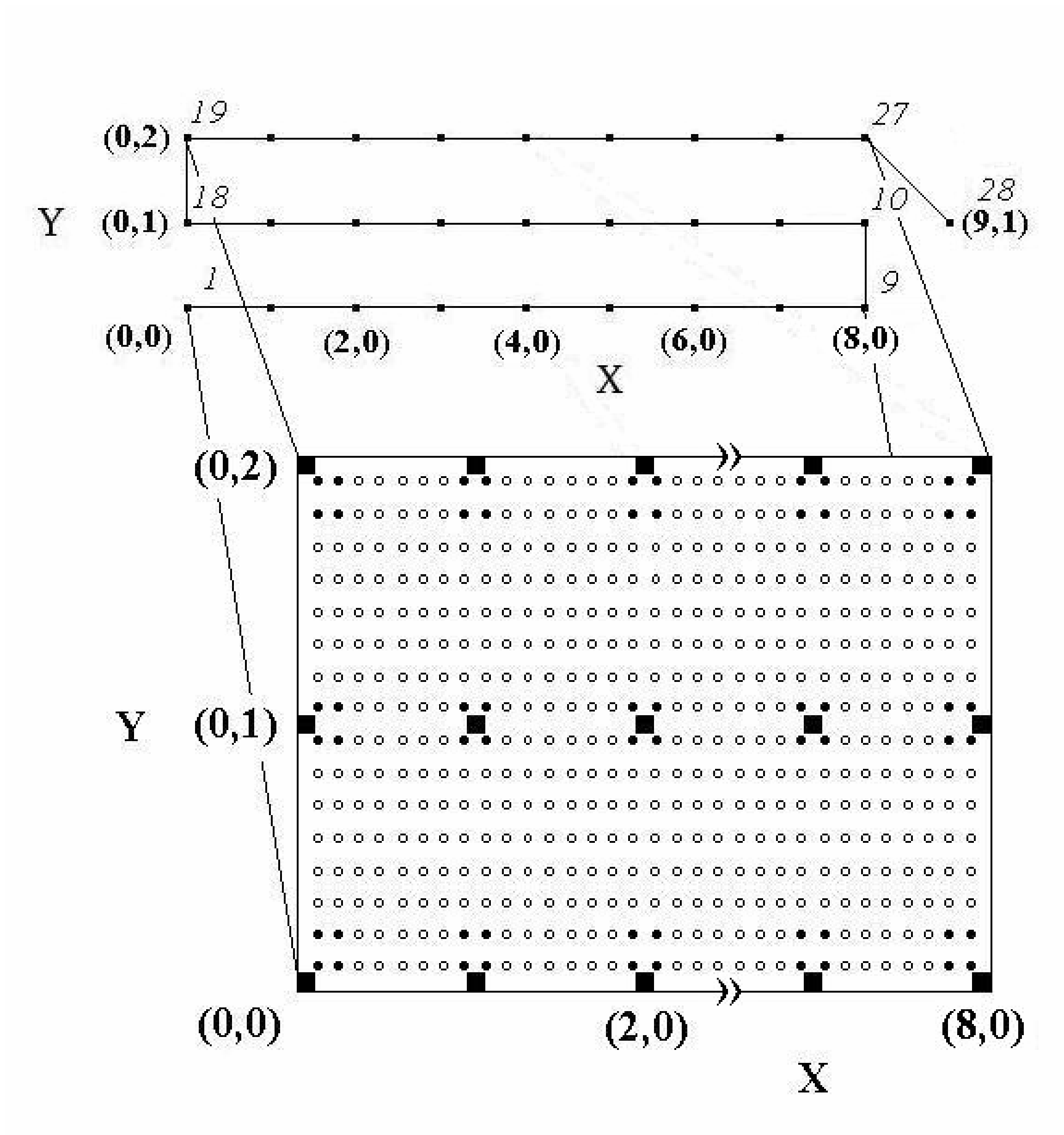

Figure 3-1. Bird's eye view of electrode geometry and mesh for soil electrical resistivity. In the top graphic, electrode geometry is represented with squares. The direction of the resistivity cable connects each electrode dot. Coordinates are in parenthesis (x, y), and electrode numbers are in italic font to the right of and above their respective electrode position. In the bottom graphic, each open dot represents the coordinates whereby a resistivity value has been obtained from inversion of the apparent resistivity data. The squares represent electrode geometry as well as moisture sampling positions. The four nearest resistivity values, filled dots, were used when comparing moisture to resistivity.

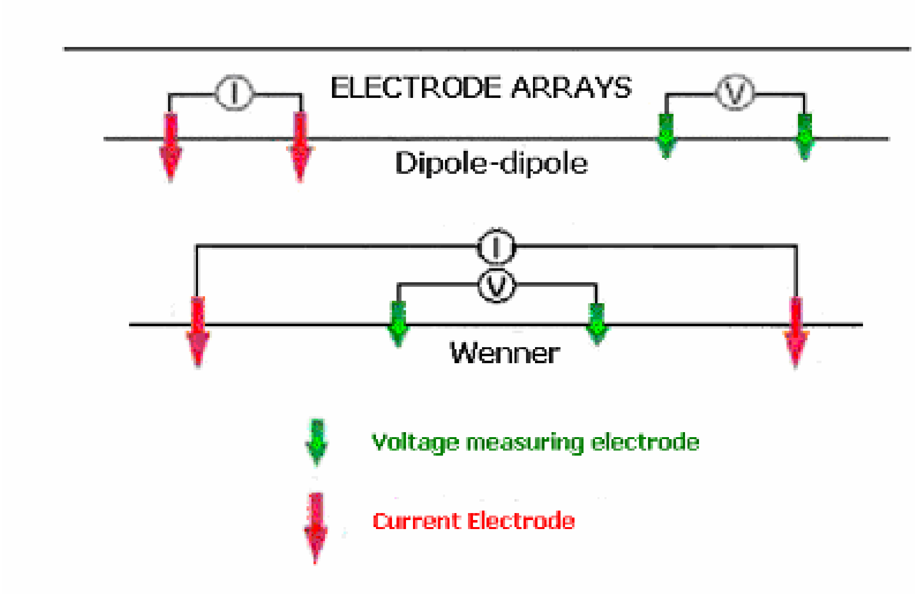

Figure 3-2. Typical electrode arrays for soil electrical resistivity soundings. Note that with the AGI SuperSting electrodes are placed in the ground at equidistant spacing, and the current configuration is computer controlled. This allows for the repeated soundings with different arrays for a single placement of probes.

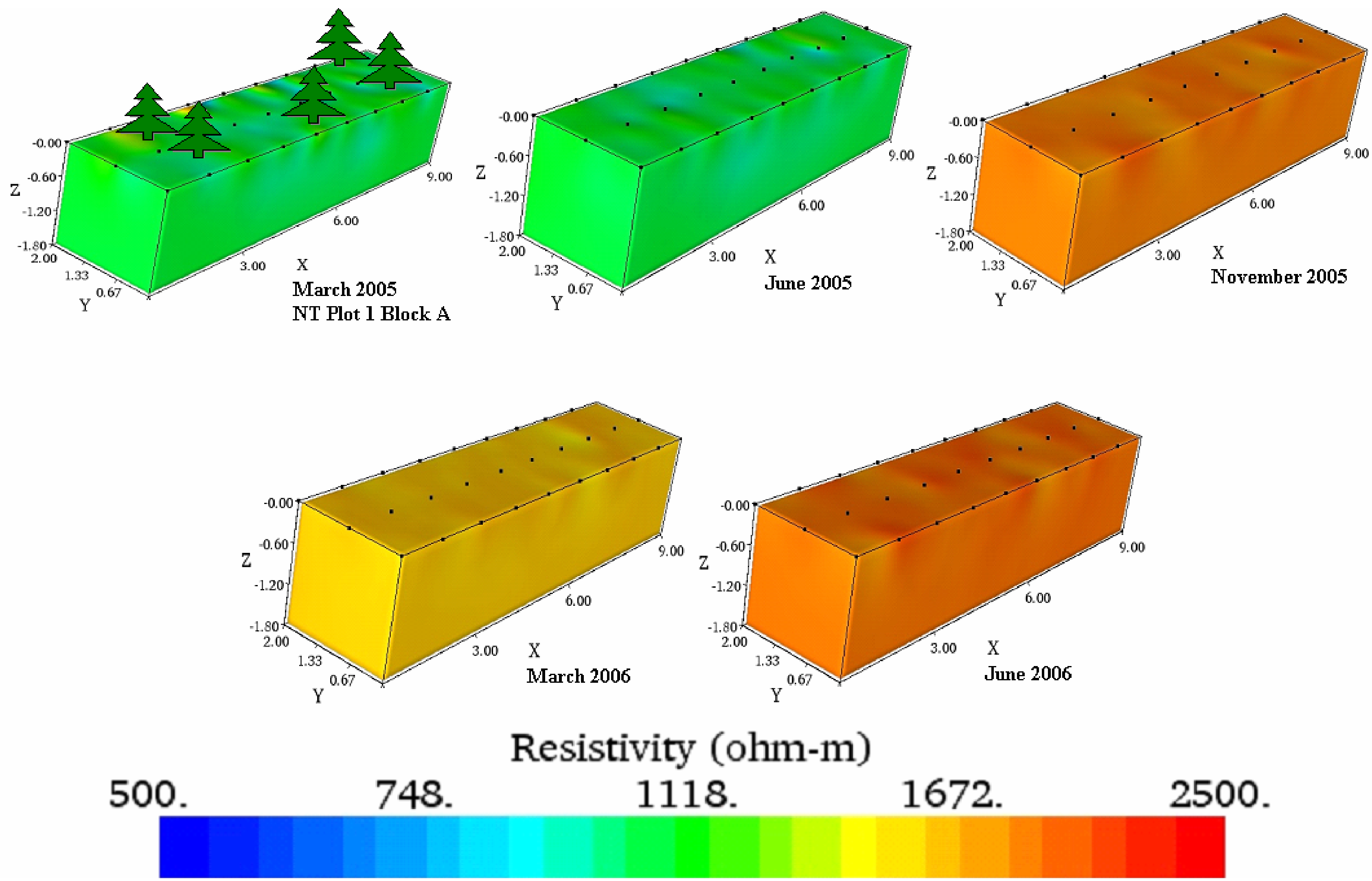

Figure 3-3. Soil electrical resistivity models for NT treatment Plot 1 over five dates. Black dots represent electrode locations, and trees represent locations of loblolly pine seedlings and are shown as a reference only in the first graph and are not to scale.

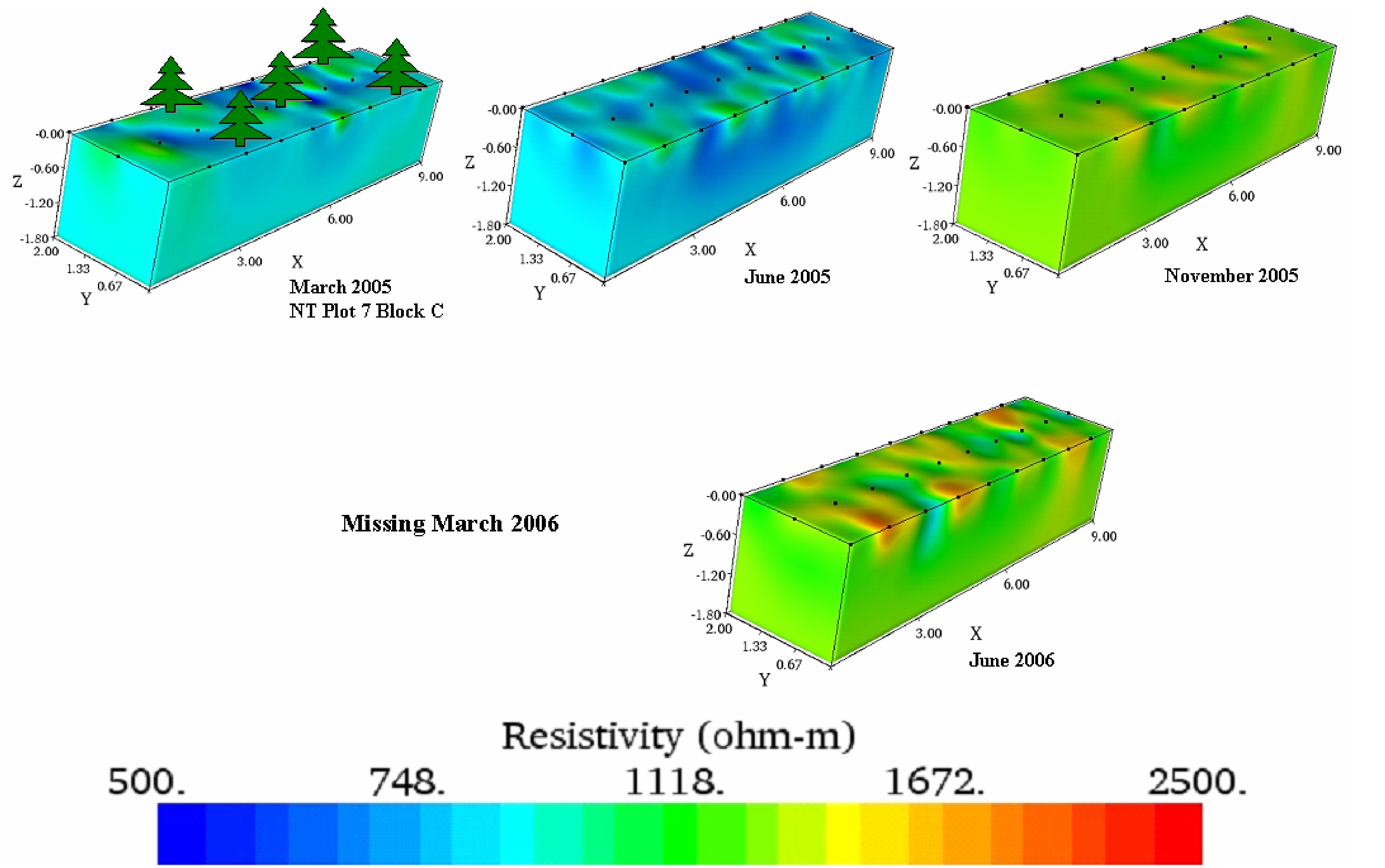

Figure 3-4. Soil electrical resistivity models for NT treatment Plot 7 over four dates. Black dots represent electrode locations, and trees represent locations of loblolly pine seedlings and are shown as a reference only in the first graph and are not to scale.

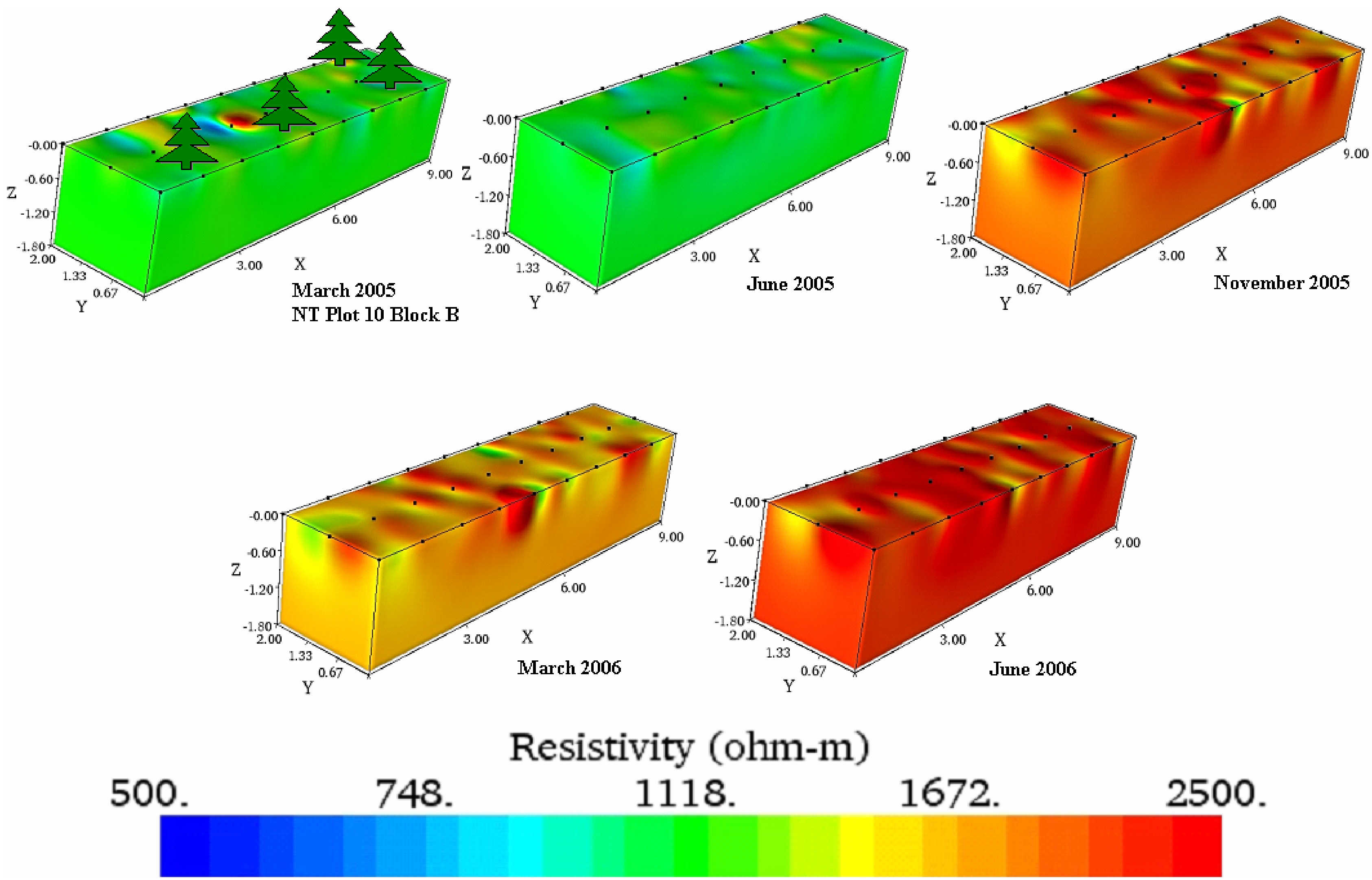

Figure 3-5. Soil electrical resistivity models for NT treatment Plot 10 over five dates. Black dots represent electrode locations, and trees represent locations of loblolly pine seedlings and are shown as a reference only in the first graph and are not to scale.

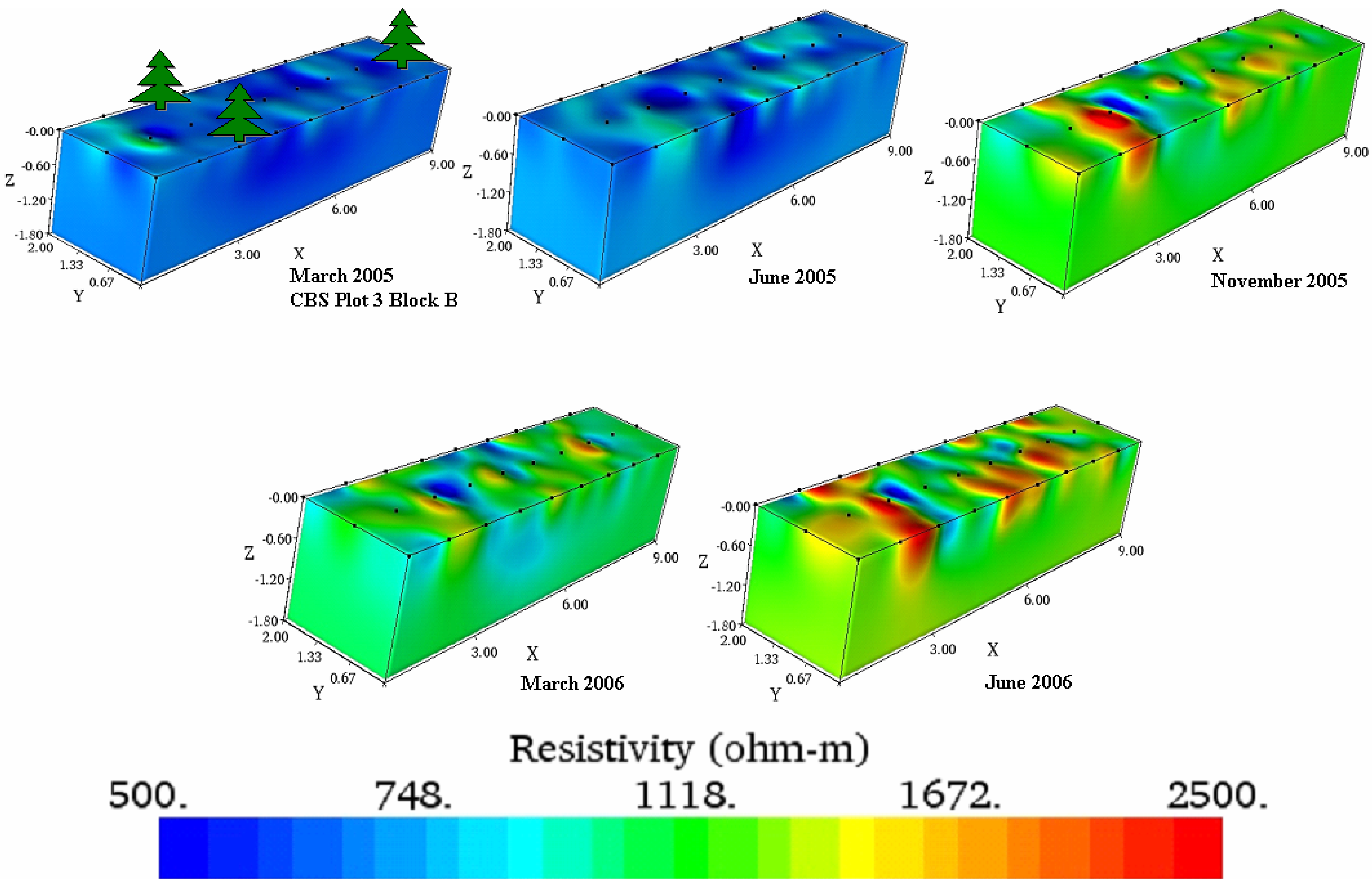

Figure 3-6. Soil electrical resistivity models for CBS treatment Plot 3 over five dates. Black dots represent electrode locations, and trees represent locations of loblolly pine seedlings and are shown as a reference only in the first graph and are not to scale.

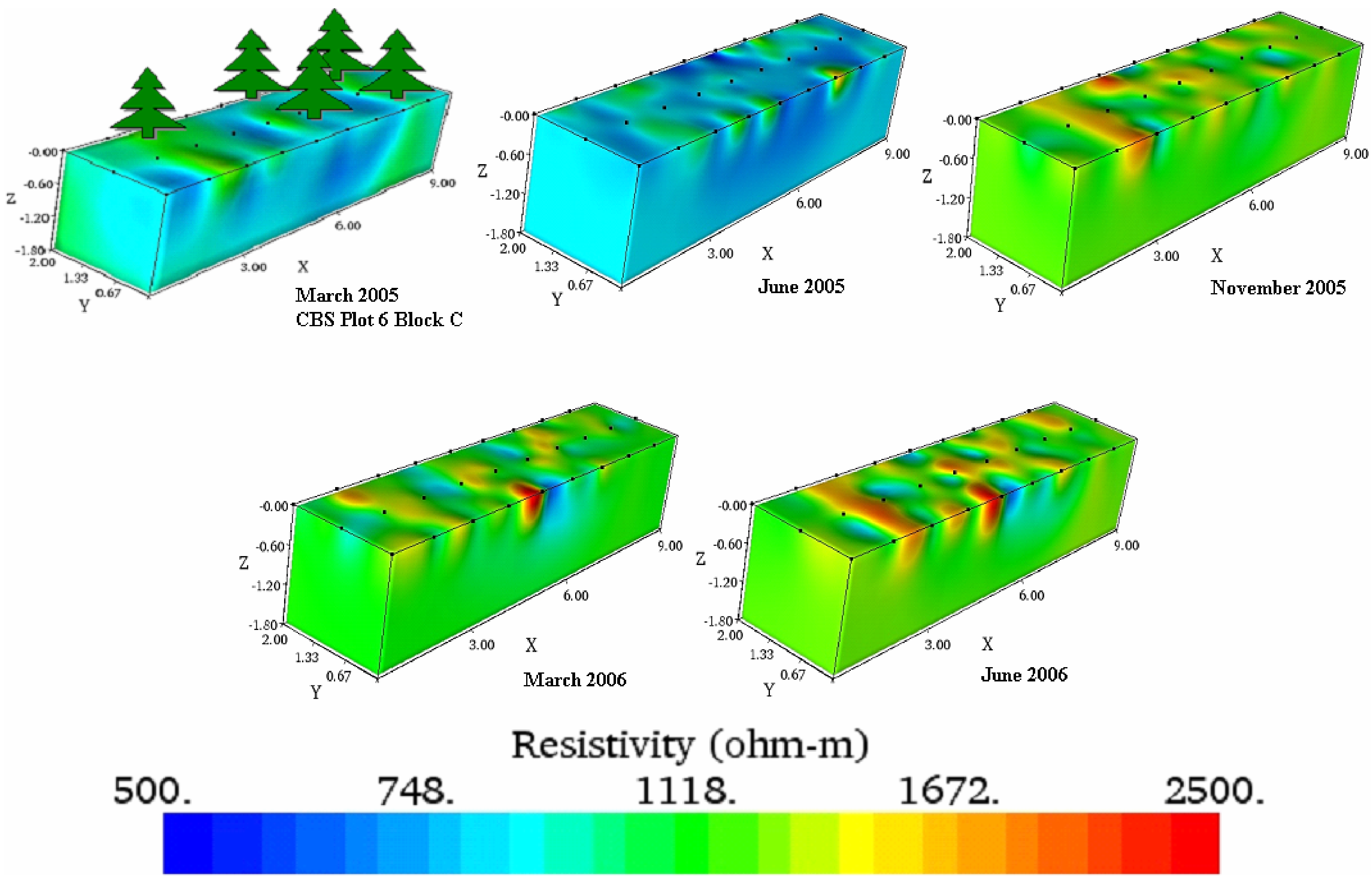

Figure 3-7. Soil electrical resistivity models for CBS treatment Plot 6 over five dates. Black dots represent electrode locations, and trees represent locations of loblolly pine seedlings and are shown as a reference only in the first graph and are not to scale.

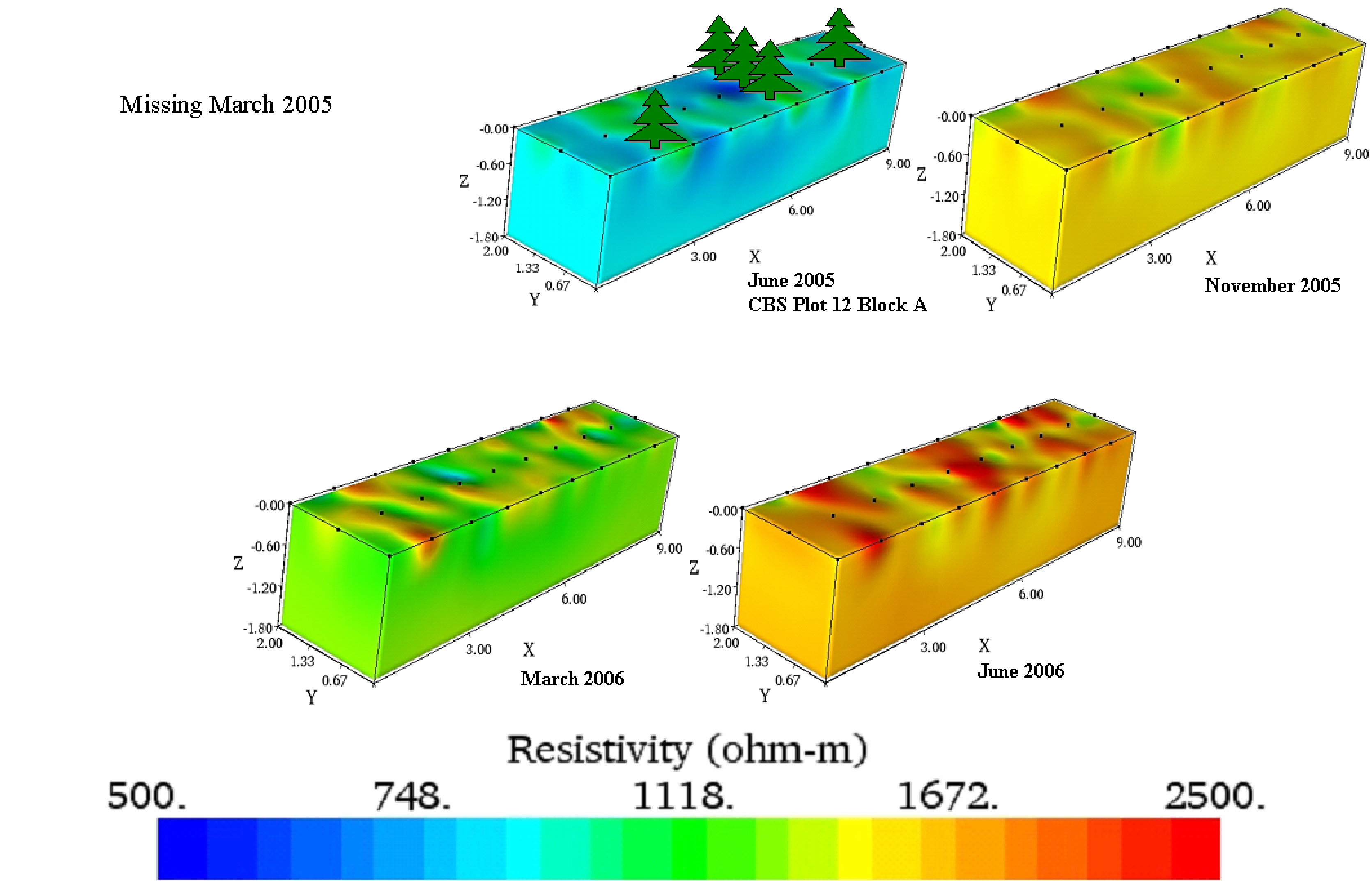

Figure 3-8. Soil electrical resistivity models for CBS treatment Plot 12 over four dates. Black dots represent electrode locations, and trees represent locations of loblolly pine seedlings and are shown as a reference only in the first graph and are not to scale.

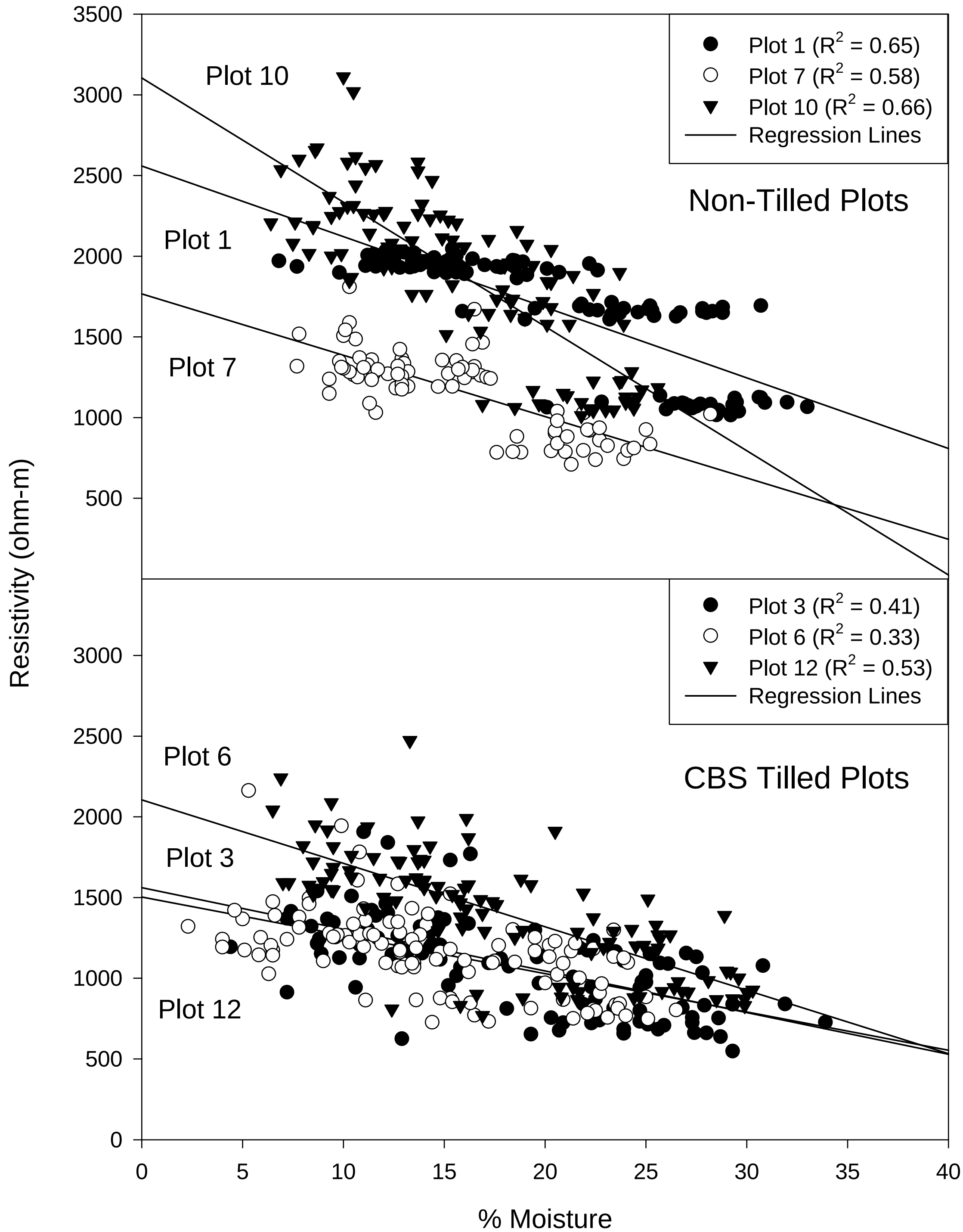

Figure 3-9. Non-Tilled Plots (top) and CBS Tilled Plots (bottom) of volumetric water content vs. soil electrical resistivity. Data was taken in June 2005, November 2005, March 2006, and in June 2006. (In March 2006, a NT plot was missing).

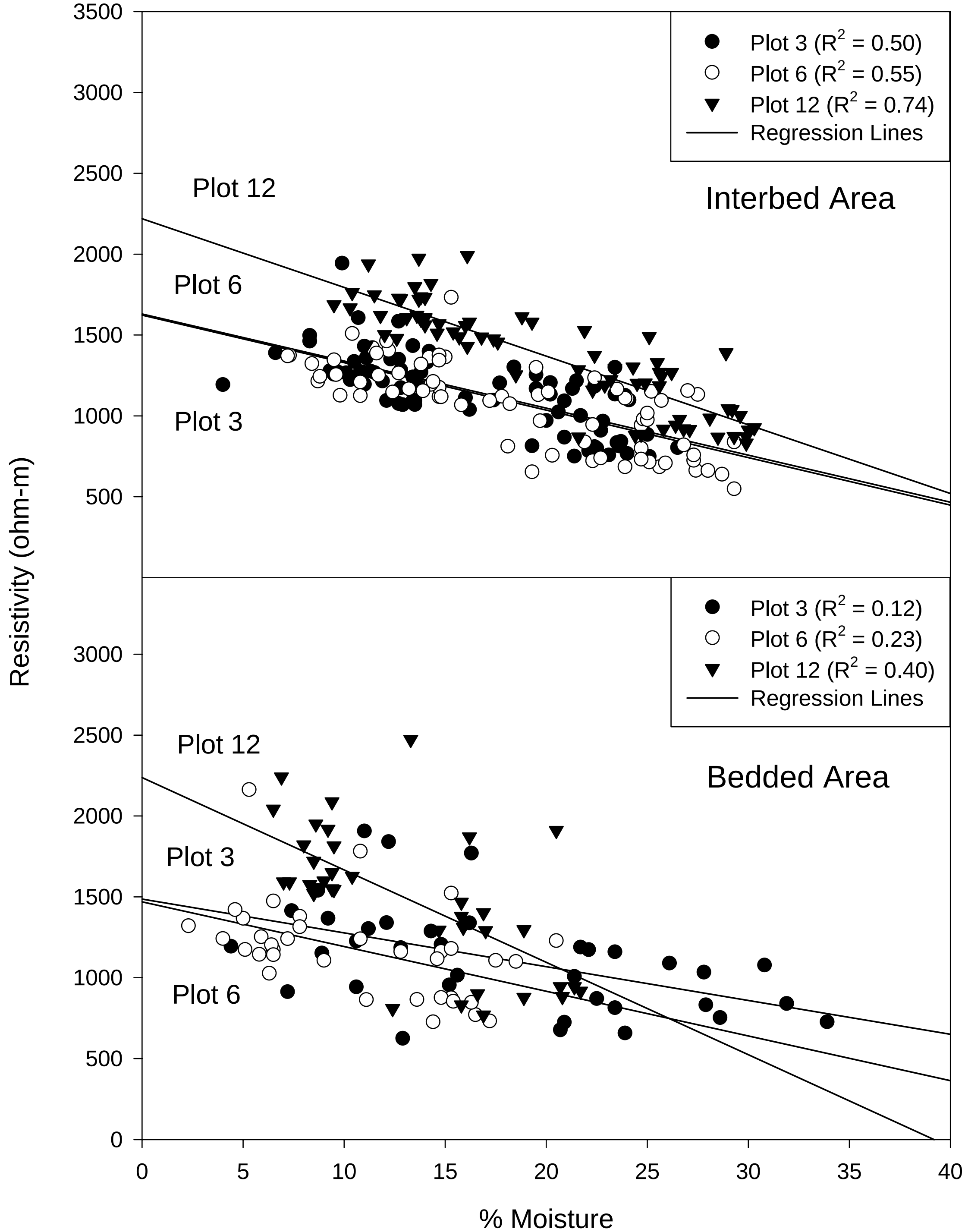

Figure 3-10. Interbed points (top) and bedded points (bottom) of soil volumetric content vs. soil electrical esistivity within the CBS plot. Data was taken in June 2005, November 2005, March 2006, and in June 2006.

Table 3-1. Average (± 1SD) volumetric water content (%) for 0-30 cm soils and soil electrical resistivity (ohm*m) within a non-till control (NT) and a coulter+bedding+subsoiling (CBS) tillage treatment in a loblolly pine plantation in Lumpkin, GA. (In March 2006, a NT plot was missing). The site was planted in 2004.

Variable	Treatment	Averages			
		Jun 2005	**Nov 2005**	**Mar 2006**	**Jun 2006**
Moisture Content	**NT**	24.2 ± 3.2	14.4 ± 1.7	21.7 ± 4.1	11.7 ± 1.7
	CBS	23.2 ± 2.7	12.1 ± 1.6	21.2 ± 2.4	10.9 ± 1.4
Resistivity ohm*m	**NT**	1024 ± 144	1787 ± 437	1729 ± 95	1897 ± 520
	CBS	824 ± 95	1355 ± 188	1197 ± 150	1498 ± 276

Table 3-2. Average (± 1SD) volumetric water content (%) for 0-30 cm soils and soil electrical resistivity (ohm*m) of interbed points and bedded points within in the CBS and a coulter+bedding+subsoiling (CBS) tillage treatment in a loblolly pine plantation in Lumpkin, GA (In March 2006, a NT plot was missing). The site was planted in 2004. Bold values indicate statistically significant differences
($p < 0.05$).

Variable	Treatment	Averages			
		Jun 2005	**Nov 2005**	**Mar 2006**	**Jun 2006**
Moisture content	**interbed**	25.1 ± 2.4	**13.8 ± 1.5**	22.6 ± 2.2	11.8 ± 1.0
	bedded	19.4 ± 5.1	**9.1 ± 2.8**	18.3 ± 3.7	9.1 ± 3.1
Resistivity ohm*m	**interbed**	830 ± 107	1352 ± 183	1166 ± 120	1449 ± 232
	bedded	813 ± 69	1360 ± 197	1259 ± 211	1597 ± 363

Table 3-3. Bulk density estimates from Cuthbert and Lumpkin, GA. (n = 3 for each depth) Samples collected June 2004. Values are mean (± 1 SD) for three plots.

Depth	NT	CBS
0-15cm	1.50 ± 0.1	1.25 ± 0.2
15-30cm	1.71 ± 0.1	1.70 ± 0.1
30-45cm	1.49	1.49 ± 0.2
45-60cm	1.50 ± 0.1	1.58 ± 0.1

Table 3-4. Average (± 1SD) soil electrical resistivity (ohm-m) for a 2x2x8 m volume under a non-tilled (NT) control and a coulter+bedding+subsoil (CBS) tillage treatment in a loblolly pine plantation in Lumpkin, GA. The plantation was established in 2004. (In March 2005 a CBS plot was missing, and in March 2006, a NT plot was missing). Values are mean±1 SD; numeric values in bold indicate a significant difference ($p < 0.1$) for shallow and deep in March and June 2006 for CBS.

Treatment	**Soil Depth**	**Average Resistivity**				
		Mar 2005	**Jun 2005**	**Nov 2005**	**Mar 2006**	**Jun 2006**
NT	**ENTIRE**	1037 ± 137	998 ± 154	1771 ± 431	1712 ± 74	1884 ± 552
CBS	**ENTIRE**	795 ± 206	802 ± 92	1333 ± 191	1162 ± 134	1438 ± 269
BOTH	**Shallow**	960 ± 89	900 ± 75	1562 ± 249	1355 ± 165	1670 ± 339
	Deep	963 ± 95	900 ± 75	1542 ± 250	1334 ± 178	1651 ± 330
NT	**Shallow**	1034 ± 140	996 ± 157	1781 ± 442	1719 ± 82	1887 ± 565
	Deep	1040 ± 134	1000 ± 151	1761 ± 419	1706 ± 65	1880 ± 540
CBS	**Shallow**	799 ± 209	803 ± 84	1342 ± 181	**1174 ± 132**	**1453 ± 269**
	Deep	791 ± 203	800 ± 89	1324 ± 201	**1152 ± 136**	**1423 ± 269**

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CHAPTER IV

NEAR INFRARED REFLECTANCE SPECTROSCOPY FOR MEASUREMENT OF FOLIAR AND SOIL NITROGEN IN LOBLOLLY PINE PLANTATIONS[3]

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Abstract

Near Infrared Reflectance Spectroscopy (NIRS) is used widely for the analysis of organic constituents in a wide range of agricultural commodities such as animal forage, corn, cotton, grains, and silage. There is growing interest in NIRS technology in the field of soil science, and calibrations for NIRS have been developed for many soil attributes. One difficulty with NIRS is an apparent need for local calibrations. As such, the objective of this study was to develop calibrations at two different sites in the upper Coastal Plain of Georgia with contrasting soils. Calibrations of NIRS were developed for 1) foliar N, 2) extractable NH_4^+ and NO_3^-, and 3) soil total N. The goal is to facilitate the future measurement and availability of these data for pine plantation fertilization decisions. Two loblolly pine plantations, one classified as a Greenville soil series near Cuthbert, GA and the other classified as an Orangeburg soil series near Lumpkin, GA, were planted with loblolly pine in early 2004. Soil samples were taken in December 2004 and March 2005 and foliage in December 2004 and 2005. Foliar N in 2004 was well predicted (R^2 = 0.96 and a ratio of predicted deviation (RPD) = 4.34) but 2005 foliar N concentration was poorly predicted with the 2004 calibration. Extractable (2M KCl) soil NH_4^+ and NO_3^- were not well predicted individually or at low concentrations (< 2 μg/g) but the sum of extractable N obtained an R^2 = 0.52. When NIRS was used to predict total soil N, obtained with dry combustion techniques, R^2 = 0.92 and an RPD = 2.28 was achieved. NIRS clearly demonstrates promise for foliar and soil N analysis in pine plantations but additional work on the robust nature of calibrations is necessary.

Introduction

Near infrared reflectance spectroscopy (NIRS) is a rapid non-destructive technique that analyzes intact samples. These samples may be dried prior to analysis or analyzed "as is," in either case, the sample is preserved for further or future analysis. Reflectance is a useful tool in determining properties of chemical bond lengths and both diffuse reflection and transmission measurements are used. Diffuse reflectance is used more widely (Skoog et al. 1998) while transmission is primarily used for liquids (Barton 2002). NIR spectroscopy is used widely for the analysis of organic constituents in a wide range of agricultural commodities such as animal forage, corn, cotton, grains, and silage (Burns and Cziurczak, 1992; Williams and Norris, 2001). Typically, it is implemented for the large scale analysis of grain. NIRS has found increased usage in other industries and reseach disciplines (Barton 2002) and there is growing interest in NIRS technology in the field of soil science (Eshani et al. 1999; Ludwig et al. 2002).

There are many techniques available for soil chemical and physical analysis (Sparks 1996), but virtually all are time and cost intensive. A number of investigations have responded by trying to develop rapid, low cost approaches, which have included the utilization of NIRS in the laboratory (Eshani et al. 1999; Ludwig et al. 2002). NIRS analysis in the laboratory enables the evaluation of soil characteristics with minimal sample preparation and a sample spectrum can be captured in under two minutes. NIRS has been related to organic matter (OM), carbon (C), nitrogen (N), moisture content, cation exchange capacity, clay content, and $CaCO_3$ among others (Ben-Dor and Banin 1995; Dalal and Henry 1986, Dunn et al. 2002; Morra et al. 1991). Typically, however, calibrations need to be site specific or need to use a wide variety of soils in the process of calibration (Malley 1998).

The major interest in our particular research is to develop NIRS calibrations for the upper Coastal Plain soils of our study site—particularly soil extractable N since it is the common limiting element to pine plantation productivity. The bands representing N-H and N-O bonds are quantified by NIRS and should represent N in the soil in its two available forms—ammonium (NH_4^+) and nitrate (NO_3^-). NIRS is performed in the infrared region between ~780 and 2500 nm (Skoog et al. 1998). Covalent chemical bonds between less-dense atoms such C, N, O, and H, with primary absorbances in the infrared region, have strong vibrational overtones and combination bands that absorb light in the near infrared region. Since every type of bond has a different natural frequency of vibration, and since even two of the same type of bond in two different compounds are in slightly different environments, no two molecules with a different structure have exactly the same infrared absorption pattern—or infrared spectrum (Skoog et al. 1998). The near infrared region of the electromagnetic spectrum is useful because a linear relationship between absorbance and concentration (i.e., the Beer-Lambert-Bouguer relationship) is exhibited in the majority of biological and agricultural applications, and thus, the approach can be used for quantitative estimation (Eshani et al. 1999).

Shenk et al. (1979) state that four criteria must be met for meaningful NIRS predictions: (i) selection of calibration samples representative of the population to be predicted, (ii) accurate laboratory analysis of the calibration samples, (iii) choice of the correct mathematical treatment of the NIR data for optimum information extraction, and

(iv) choice of wavelengths relevant to the total population of samples. The objective of this study was to carry out these steps for measurement of soil extractable N to facilitate the future measurement and availability of these data for pine plantation fertilization decisions. It was hypothesized that NIR can be used to predict foliar and soil N concentrations across years and the two research sites, respectively. Foliar N analysis was also included since these are used for fertilizer decisions and NIRS has worked well with plant tissues previously (Barton 2002). At two different sites, calibrations of NIRS were developed for 1) foliar N representing the first and second growing seasons, 2) extractable NH_4^+ and NO_3^-, and 3) soil total N obtained via dry combustion.

Materials and Methods

Research Sites

This study was established on two tracts of land on the Upper Coastal Plain of southwest Georgia. The first site is owned by MeadWestvaco Corporation and is located six miles southeast of the town of Cuthbert (31^{o}77′ N, 84^{o}79′ W) off of Morgan Road in Randolph County, Georgia. The soil at this site is classified as a Greenville series (fine, kaolinitic, thermic Rhodic Kandiudult) that compacted with a clay-rich B-horizon exposed at the surface. Resistance to penetration exceeded 5000 KPa (Lincoln et al. in press). Plinthite and ironstone are also present. According to the Randolph County Soil Survey (Phillips et al. 1928), the Greenville soils may have been influenced to some extent by the underlying siliceous limestone. The soil map divides the location of the loblolly pine plantation into two Greenville soils, a sandy loam which comprises 11.4%, and a clay loam which comprises 7.2% of the land area of Randolph County.

The second site is owned by Rayonier Inc. and is located approximately ten miles west on Georgia Highway 27 outside of the town of Lumpkin (32^o05′ N, 84^o79′ W) in Stewart County, Georgia. The soil is classified as an Orangeburg series (fine-loamy, kaolinitic, thermic Typic Kandiudult) with a loamy sand topsoil averaging 14 to 40 cm in depth over a sandy clay loam B-horizon; this site is well drained. According to the Stewart County Soil Survey (Long et al. 1916), the Orangeburg series are typically well-drained soils, and annual crops are more susceptible to drought. The Soil Survey indicates that the Orangeburg sandy loam comprises 12.4% of the land area of Stewart Country.

Both sites utilized a complete randomized block design with three replicate blocks of five treatments (Anderson and McLean 1974). The four tillage treatments were: coulter + bed + subsoil (CBS), coulter + bed (CB), coulter + subsoil (CS), and coulter (C) all compared to a non-tilled (NT) control plot.

Site-preparation was performed at Cuthbert in January of 2004 and at Lumpkin site preparation was performed in June of 2003. At both sites, tillage treatments were implemented using a Savannah Forestry Equipment (Savannah, GA), LLC model 420 two-disk heavy-duty 3-in-1 plow pulled by a Caterpillar (Peoria, Il), D-7R tractor. This plow has a linear arrangement of a 1.2 m coulter wheel; followed by a 7.5 cm wide subsoil shank then two 80 cm diameter opposed notched disk blades. The plow 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. At each site, the non-tilled treatments were hand planted at the same spacing as the tillage treatments. However, at Lumpkin, trees were double planted and then thinned after establishment. During the first growing season (2004), both sites were fertilized using the same method. Site details are described by Lincoln et al. (in press).

First Year Fertilization Schedule

During the first growing season (2004), a small subset of trees (n = 3 per plot) were fertilized. 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 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 Hollytone (Espoma Company, Millville, N.J.) at 454 kg ha^{-1}. The fertilizer was applied evenly to a 1.8 x 3.7 m area surrounding each tree. After the first growing season, there was no subsequent fertilizations.

Soil Sample Collection and Sample Preparation

On each of the plots, the three fertilized trees were paired with three trees that were not fertilized; in statistical analysis, these treatments were treated as a split plot (Lincoln et al. in press). Samples were collected in May, June, August and December of 2004. Three samples from 0-15 cm depth were collected around each of the six trees in each plot using a 2 cm punch tube. These samples from each tree were composited and sieved < 2 mm to remove rocks and root. These samples were used for extractable N analysis. In March 2005, soil samples were collected from CBS, CB and NT plots using a hand auger. A subsample was ground in a Certiprep 8000-D mixer mill (SPEX, Metuchen, N.J.) to homogenize the sample and provide maximum surface area. these samples were used to obtain total N via dry combustion to compare to NIR.

Extractable Nitrogen

For NIRS calibration with extractable N, only the soils collected in December 2004 were considered. The soil samples were stored at 4^{o}C until they could be processed within 72 hours. Processed samples were air-dried and passed through a two mm sieve where rocks and chunks of organic matter were removed. Extraction took place in 2M potassium chloride (KCl) using a 10:1 liquid to solid ratio where 50 grams of extractant was added to 5 grams of soil in a 250 ml Erlenmeyer flask (Mulvaney 1996). After extractions were performed, the supernatants were stored in clean plastic vials at 4^{o} C and, within 72 hours, they were analyzed using an Alpkem FS 3000, (O I Analytical, College Station, TX) for NH_4^+ and NO_3^-.

Foliar Tissue Collection and Sample Preparation

Foliar samples were taken in December of 2004 and January of 2006—representing first growing season and second growing season, respectively. In the first growing season (2004), pine needles from the most recent flush of the season were taken from the three unfertilized trees that were sampled for extractable N in each plot. Foliar samples were not composited; each tree was analyzed individually. Because these six trees in each plot were destructively sampled at the end of the first growing season for allometric analysis (Lincoln et al. in press), the sampling method was different for the second growing season (2005). In January 2006, 40-55 trees from the interior sampling rows of each plot were sampled from one fascicle of needles at its most recent flush. The samples were composited such that thirty samples were collected (i.e., one composite from each plot at both locations).

For both growing seasons, the needles were stored in a drying oven between 59-61°C until it was determined, by weighing and comparing weights, that the foliar tissue had stopped loosing moisture; typically, this was two full days. Afterwards, the foliar tissue samples were cut and crushed in a Certiprep 8000-D mixer mill (SPEX, Metuchen N.J.). The samples were then ready to be weighed for total N analysis via dry combustion, and NIRS analysis.

Combustion Analysis for Soil Total and Foliar Tissue N

Analysis for total N of soils and foliar tissue was performed on a dry combustion NC 2100 analyzer (CE Instruments, Lakewood, N.J.). Combustion was performed for soil N on samples taken in March 2005 as well as the foliar samples taken at the end of the first growing season (2004), and the second growing season (2005). Soil samples from March 2005 consisted of 30 samples from the Lumpkin site, and 10 samples from Cuthbert. Foliar samples in 2004 consisted of 40 samples—representing one per tree—for both Cuthbert and Lumpkin. For 2005, there were 15 foliar samples from each site. All samples were analyzed with a subset done for NIRS.

Near Infrared Reflectance Spectroscopy

NIRS scans were collected for a subset of soil and foliar tissue samples, 40 soil samples (March 2005), 40 foliar samples for the first growing season (2004), and 30 foliar samples for the second growing season (2005). The samples were analyzed for NIR on a FOSS Model 5000 scanning spectrometer (Foss NIRSystems Inc., Alberta, Canada) in a climate controlled environment of 40% relative humidity at a temperature of 20^{o}C; samples were conditioned in this environment for 48 hours prior to scanning. NIR spectra were collected at two nanometer (nm) intervals over the wavelength range of 1100-2500 nm (Figure 4-1).

The resulting wavelengths of spectral data are subject to noise—caused by fluctuating electromagnetic fields, or any number of uncontrollable events. Following the NIR scans, smoothing with the Savitzky-Golay algorithm was used to filter out noise which causes spectra shifts not relating to the desired information contained within the spectra (Næs et al. 2002). After smoothing and estimation of the second derivative, data was analyzed using partial least squares (PLS) regression—a form of multivariate analysis (Næs et al. 2002). All mathematical treatments were performed using Unscrambler® (version 9.2) software (Camo Processes As., Oslo, Norway).

The calibration approach typically utilized for NIRS involves collecting spectral responses over many wavelengths for a set of well characterized samples, developing a calibration for a selected constituent using a data reduction technique such as partial least squares (PLS) regression and then using the calibration to predict the constituent in a test set. PLS is similar to principal component analysis; in both methods, the total amount of data is reduced by obtaining explanatory principal components (PCs), or factors.

However, PLS obtains these components by maximizing covariance between the independent variables (i.e. spectra) and the dependent variable (i.e. constituent of interest); because of this, the principal components are more directly related to the variability in the dependent variable (Næs et al. 2002). Previously obtained total N concentrations, from dry combustion analysis, was entered as the dependent variables.

Cross validation was used and the method was systematic; seven segments and four samples per segment were used with a full model size with no more than 10 PCs. The PCs are used to predict the independent variables; the fewer factors necessary, the stronger the predictive model. The Ratio of Predicted Deviation (RPD) is calculated using the standard deviation (STDEV) of the reference values of the predicted data divided by the root mean standard error of prediction (RMSEP), STDEV/RMSEP. This term describes how well the model can be used for prediction. For calibrations, the RPD is calculated using the STDEV of the reference of the calibration data divided by the standard error of cross validation (SECV) which is obtained when the calibration data is used to validate itself (Barton 2002). Regardless of the mathematical treatment and multivariate analysis, the spectral data is only as useful as the accuracy of the measurement of the independent variable. All combinations of trials are mentioned, but only the successful trials are discussed in depth. In each case, multiple attempts to predict data were performed; although only the best outcomes are presented.

Results

Foliar Nitrogen

NIRS and foliar N concentrations for the 2004 samples, including both Lumpkin and Cuthbert, were well correlated (Figure 4-2). The relation was strongly, positively linear (R^2 = 0.96) over the range of 1.3 to 2.4% foliar N using six PCs. These foliar N concentrations are relatively high for mature seedlings, but reflect the young age of the seedlings. Pritchett (1979) highlights the approximate critical range for foliar N for Slash pine (*Pinus elliottii)* and Radita pine (*Pinus radiate) as* 1.0-1.4%. Foliar samples collected in 2005, however, were not well predicted by the 2004 calibration. In an effort to improve these calibrations twenty foliar samples from 2005 were added to the existing 2004 calibration of 40 foliar samples for a total of 60 foliar samples used to predict the remaining 10 samples from 2005. Unfortunately, there were still very poor predictions of 2005 foliar N. Performing location specific calibrations within the individual sites for the same year did not strongly improve these 2005 predictions.

Extractable Soil Nitrogen

Soil extractable NH_4^+-N and NO_3^--N were not well correlated with NIRS. However, when the sum of soil extractable N data (i.e., NH_4^+-N + NO_3^--N) for both sites are combined into a single regression, (Figure 4-3), the R^2 value is 0.52. Individually, the relationships within the Lumpkin samples (R^2 = 0.25) are not as strong as the relationship within the Cuthbert samples (R^2 = 0.57); this could partly be due to the fact that the range of total N values was not as great for Lumpkin as Cuthbert. This concern about the limit of detection at the lower end of the range led to an investigation of the relationship between NIRS and total soil N.

Total Soil Nitrogen

Soil samples from March 2005 were measured for total N by dry combustion and subsequently analyzed by NIRS. Despite only having 10 samples for Cuthbert, predictions were relatively good. In the calibration model, six samples obtained an RPD = 0.97, R^2 = 0.79 using two PCs; no data was removed from the calibration. In the prediction, four samples obtained a RPD = 2.97, R^2 = 0.88 using two PCs (Figure 4-4).

At Lumpkin, 22 samples were utilized for calibration, and eight samples were utilized for prediction; no data was removed in the calibration model. The calibration model obtained a RPD = 1.32, R^2 = 0.98 and for predictive purposes, RPD = 3.22 for prediction and R^2 = 0.92. Seven PCs were utilized for both the calibration and the prediction (Figure 4-5).

Predictions from one site to another were generally poor, such that Lumpkin samples were poor at predicting samples from Cuthbert, and vice versa. The combined analysis for the two sites, with a total of 40 samples from March 2005, were more successful. Thirty random samples were selected for the calibration model and the remaining 10 samples were used for prediction. The calibration RPD = 1.98, and R^2 = 0.93; for prediction, RPD = 2.28 with an R^2 = 0.92 was obtained using five PCs for both the calibration and the prediction (Figure 4.6).

Discussion

Foliar Nitrogen

NIRS has previously been applied to analysis of C, N and P contents in pine needles (Gillon et al. 1999) and in pine wood (Schimleck and Workman, 2004). In the Gillon et al. (1999) study, calibrations between NIRS and foliar N of *Pinus halipensis* had $R^2 > 0.94$. This study examined local vs. global calibrations and found few differences but did not test calibrations across years. In studies of wood properties in loblolly pine across the southeast US, calibrations were also excellent but global calibrations were typically updated with some data from each new site prior to attribute estimation on site (Jones et al. 2005). In a study determining the robustness of calibrations across growing seasons with mandarin fruit, Guthrie and Walsh (2002) recommend adding data of *ca* 15 fruit to update the calibration across growing seasons.

During the first growing season (2004) of this study, very strong calibrations were achieved (Figure 4-2). Across the two growing seasons, however, the foliar N predictions were not as useful and it was not possible to update the calibration with 2005 samples to improve prediction. Unfortunately, foliar samples were collected slightly differently in 2004 and 2005. In 2004, individual needles from a tree were analyzed while in 2005 a composite of needles from a tree from each plot were analyzed. It might be the case that composited samples increased spectral variance such that they were not as useful for predictions. There is little doubt about the quality of the dry combustion analysis. In general, the mechanism that separated the two analyses could not be explained; in the literature, others have addressed similar questions regarding the robust nature of NIRS calibrations (Guthrie and Walsh 2002).

Extractable Soil Nitrogen

Extractable nitrogen comes in two forms, NH_4 and NO_3. Microorganisms and plants can take up and use both NH_4 and NO_3 but often prefer NH_4 if it is more readily available. Ammonium, the product of ammonification, is held in the soil through cation exchange processes while NO_3, the product of nitrification, is typically more mobile and can permanently be lost from the soil by leaching. Nitrogen mineralization and nitrification affect the quantity and the form of inorganic N available for tree growth and N availability is a driver for pine plantation productivity (Federer 1983).

In the current study, NIRS calibration with extractable NH_4 and NO_3 were possible but only at higher NH_4 and NO_3 concentrations. Bremer and Keeny (1966) notes that methods for extraction of exchangeable ammonium, nitrate and nitrite from soils must meet the following requirements: (i) extraction of the form(s) of N under analysis must be practically quantitative; (ii) no change may occur in the amount of this N as a result of biological or non-biological reactions; (iii) the extract must be compatible with the method(s) of analysis to be employed and must not contain any substance that would interfere with the analysis; and (iv) the extract must be stable so that it can safely be stored for later analysis. While all of these conditions were met using the extraction technique outlined by Mulvaney (1996), the extract concentrations were extremely low and close to the possible limit of detection of the Alpkem analytical machine. Calibration with NIRS is clearly dependent on the accuracy of the constituent; similarly NIR spectral signals are dependent on constituent concentration.

This lack of variation was amply demonstrated in the unfertilized Lumpkin data whereas the unfertilized Cuthbert data had slightly higher concentrations, although in neither case were calibrations strong. Generally, the pooling of points from both sites increased the variance along the axis of extractable N

Total Soil Nitrogen

The present data are consistent with this ealier work in demonstrating relatively good relationships between NIRS and total soil N. Clearly, the best results were achieved when both sites were pooled as only 10 samples were analyzed from the Cuthbert location. The RPD values for the pooled calibration were 1.98 for the calibration, and 2.28 for the prediction.

Conclusions

It was hypothesized that NIRS could be used to predict foliar and soil N across years and the two research sites, respectively. For foliar samples, very good calibrations were achieved with the 2004 data. Unfortunately, the 2004 calibration was not particularly successful for prediction of foliar samples collected in 2005. Furthermore, updates of the calibration through inclusion of some portion of the 2005 samples did not resolve the problem. The robust nature of NIRS calibrations has been raised with other analysis and clearly was a concern here for foliar tissues. For soil extractable N, NIRS demonstrate predictive ability but only when the range of values exceeded ~ 2 μg/g. For total soil N, the NIR spectroscopy calibrations were very good. NIRS clearly demonstrates promise for foliar and soil N analysis in pine plantations but additional work on the robust nature of calibrations is necessary.

Table 4-1. Soil data predicted March 2005. In each case, 60-75 % of data was used to predict the remaining 40-25 % of data. Data was chosen randomly, and for each experiment, no two data was used for both the classification and the prediction. PCs=principal components, SECV=standard error of cross validation, and SEP=standard error of prediction. RPD=ratio of predicted deviation, for RPD_{class}=SDEV/SECV, for RPD_{pre}=SDEV/SEP; n_c=number of data used in the calibration, and n_p=number of data predicted.

Descriptor	Cuthbert	Lumpkin	Pooled Prediction
PCs:	2	7	5
SECV:	0.04	0.01	0.02
SEP:	0.02	0.01	0.01
$RPD_{class:}$	0.97	1.32	1.98
$RPD_{pre:}$	2.97	3.22	2.28
$n_{c:}$	4	22	30
$n_{p:}$	6	8	10

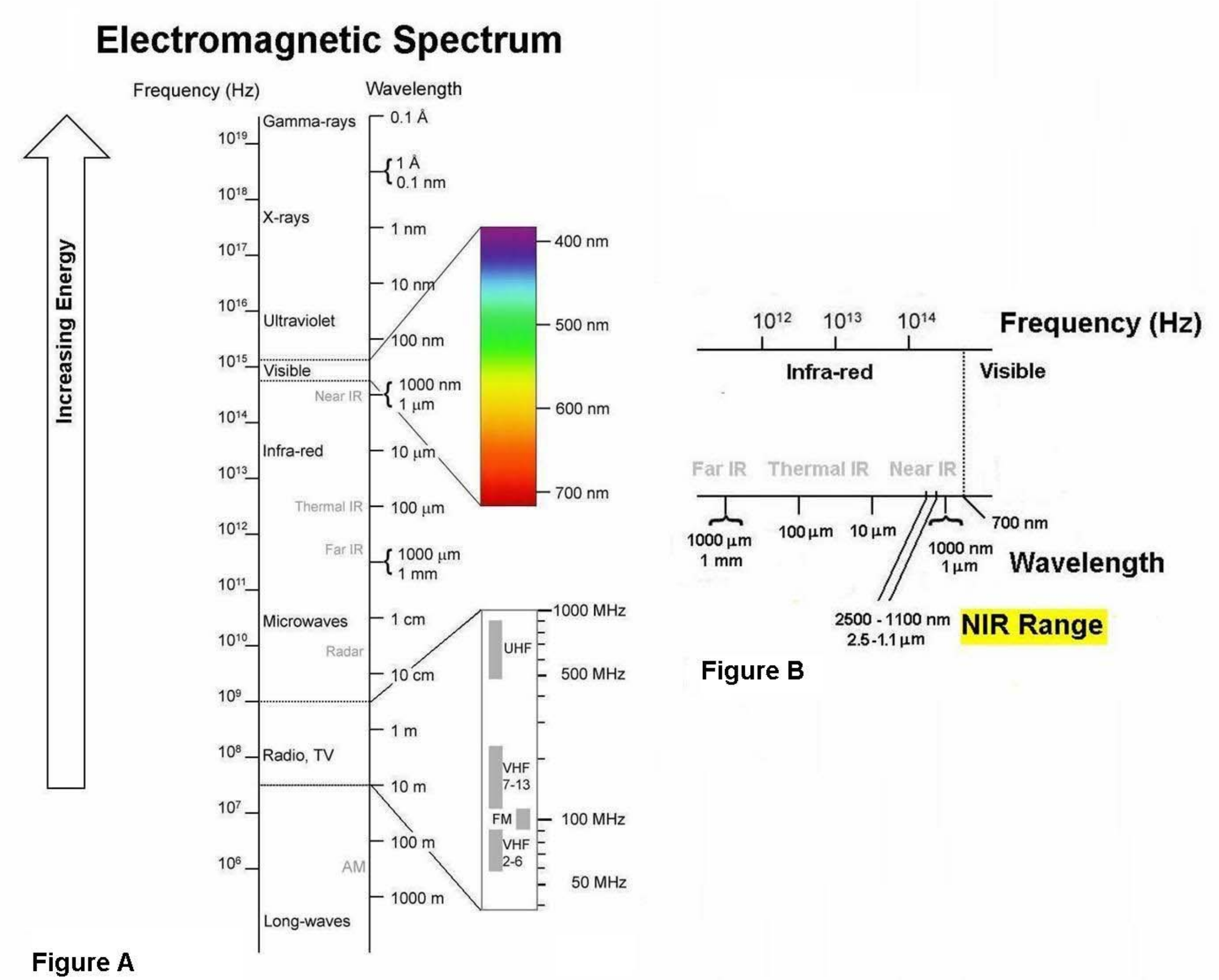

Figure 4-1. Electromagnetic spectrum and near infrared wavelength range. Figure A shows the entire electromagnetic spectrum, and figure B shows the infrared range, 1100-2500 nanometers (nm), of light energy in which samples were subjected to in order to measure absorbance.

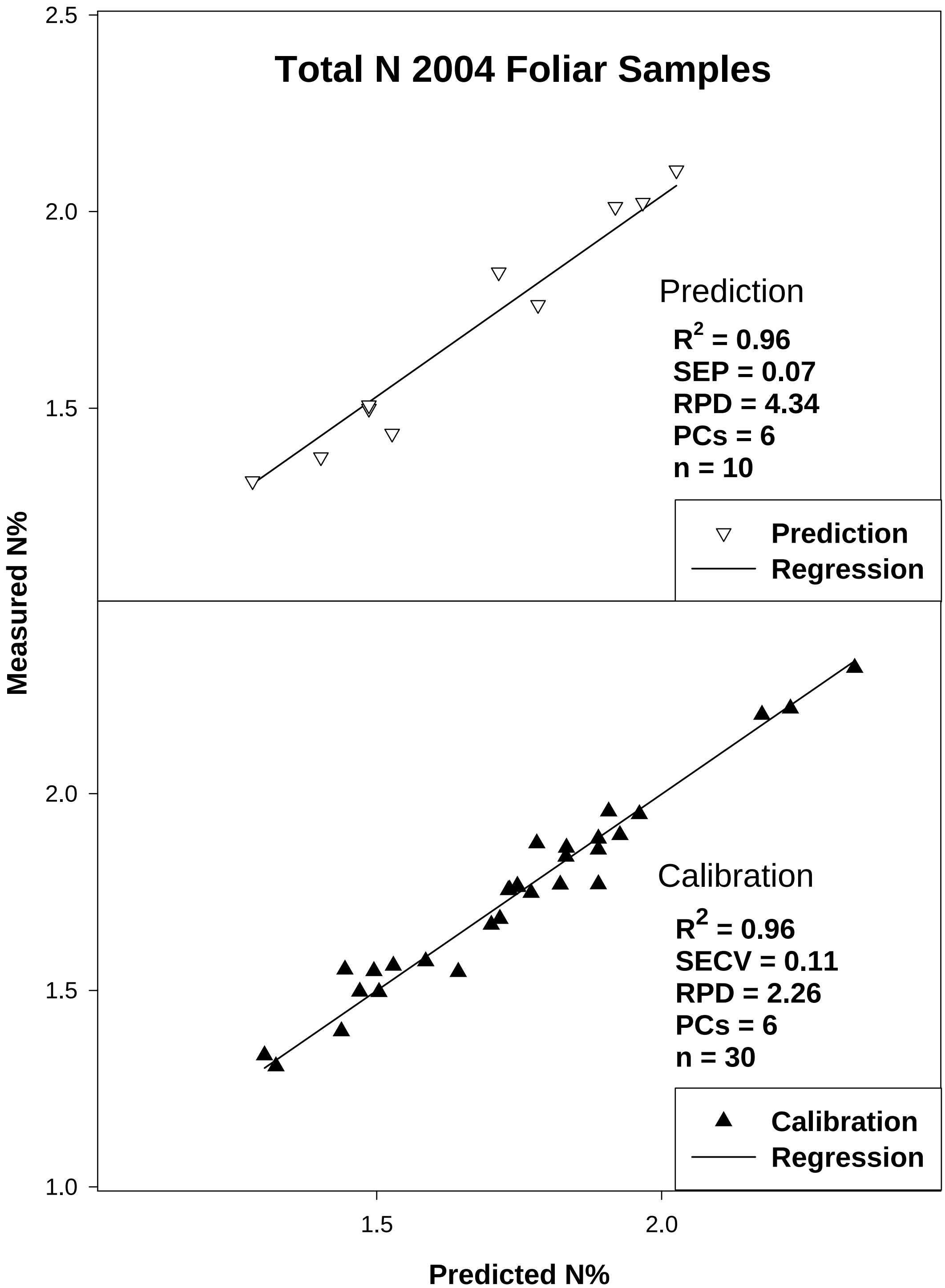

Figure 4-2. Foliar N predicted with Near Infrared Reflectance Spectroscopy vs. foliar N measured via dry combustion analysis. Loblolly pine (*Pinus taeda* L.) foliage were collected in pine plantations in Cuthbert and Lumpkin, GA at the end of the first growing season in December of 2004. Each data point represents foliar tissue from one tree.

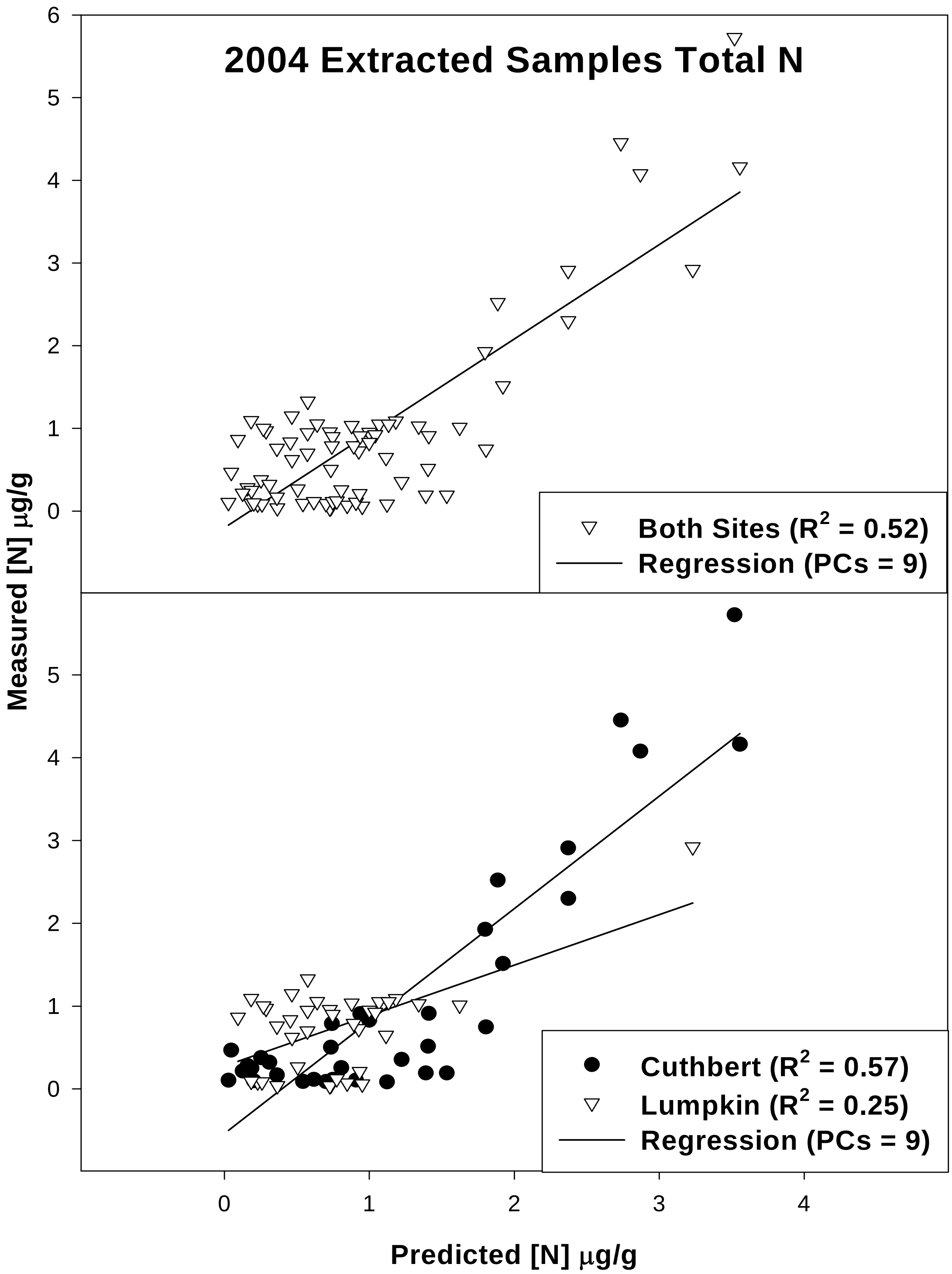

Figure 4-3. Total extractable N (i.e., the sum of extractable NH_4-N and NO_3-N) predicted with Near Infrared Reflectance spectroscopy vs. the sum of extractable N measured after 2M KCl extraction. Samples from 0-15 cm were collected from pine plantation in Cuthbert and Lumpkin, GA at the end of the first growing season in December 2004.

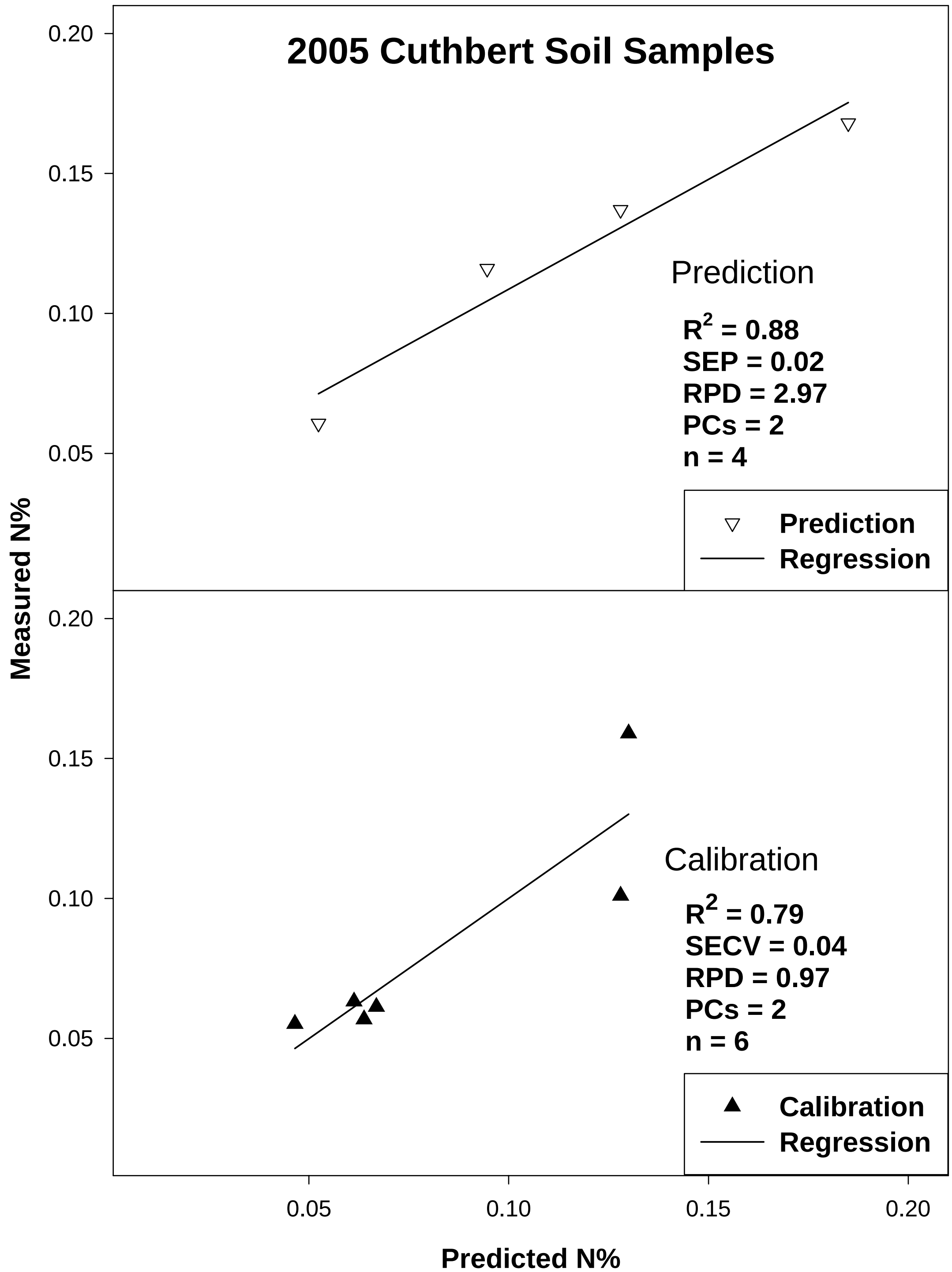

Figure 4-4. Calibration (bottom) and prediction (top) for total N predicted with Near Infrared Reflectance spectroscopy vs. total N measured by dry combustion analysis. Samples from 0-15 cm were collected in Greenville series soil under a 2-year-old loblolly pine plantation in Cuthbert, GA early during the second growing season in March 2004.

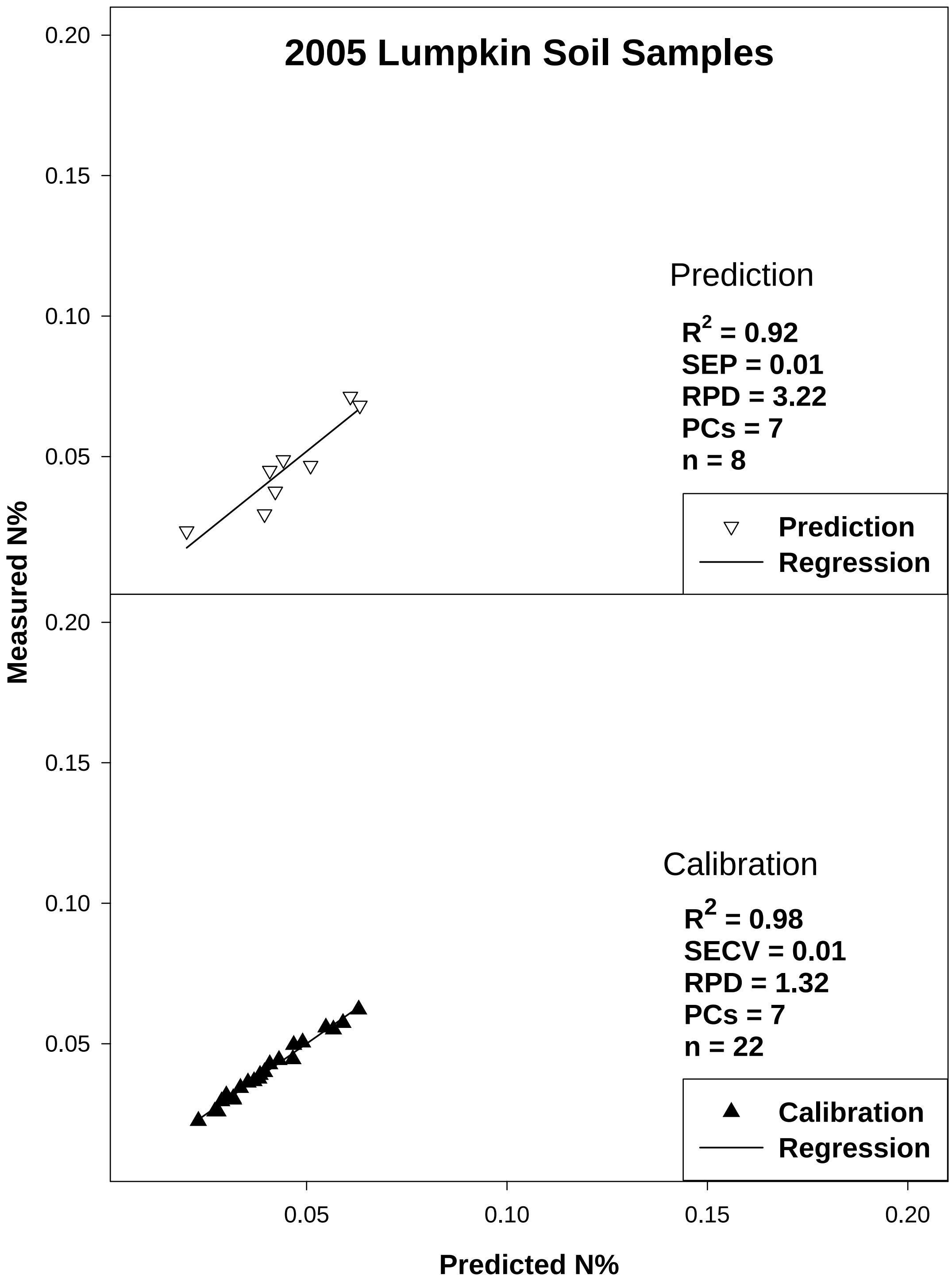

Figure 4-5. Calibration (bottom) and prediction (top) for total N predicted with Near Infrared Reflectance spectroscopy vs. total N measured by dry combustion analysis. Samples from 0-15 cm were collected in Orangeburg series soil under a 2-year-old loblolly pine plantation in Lumpkin, GA early during the second growing season in March 2004.

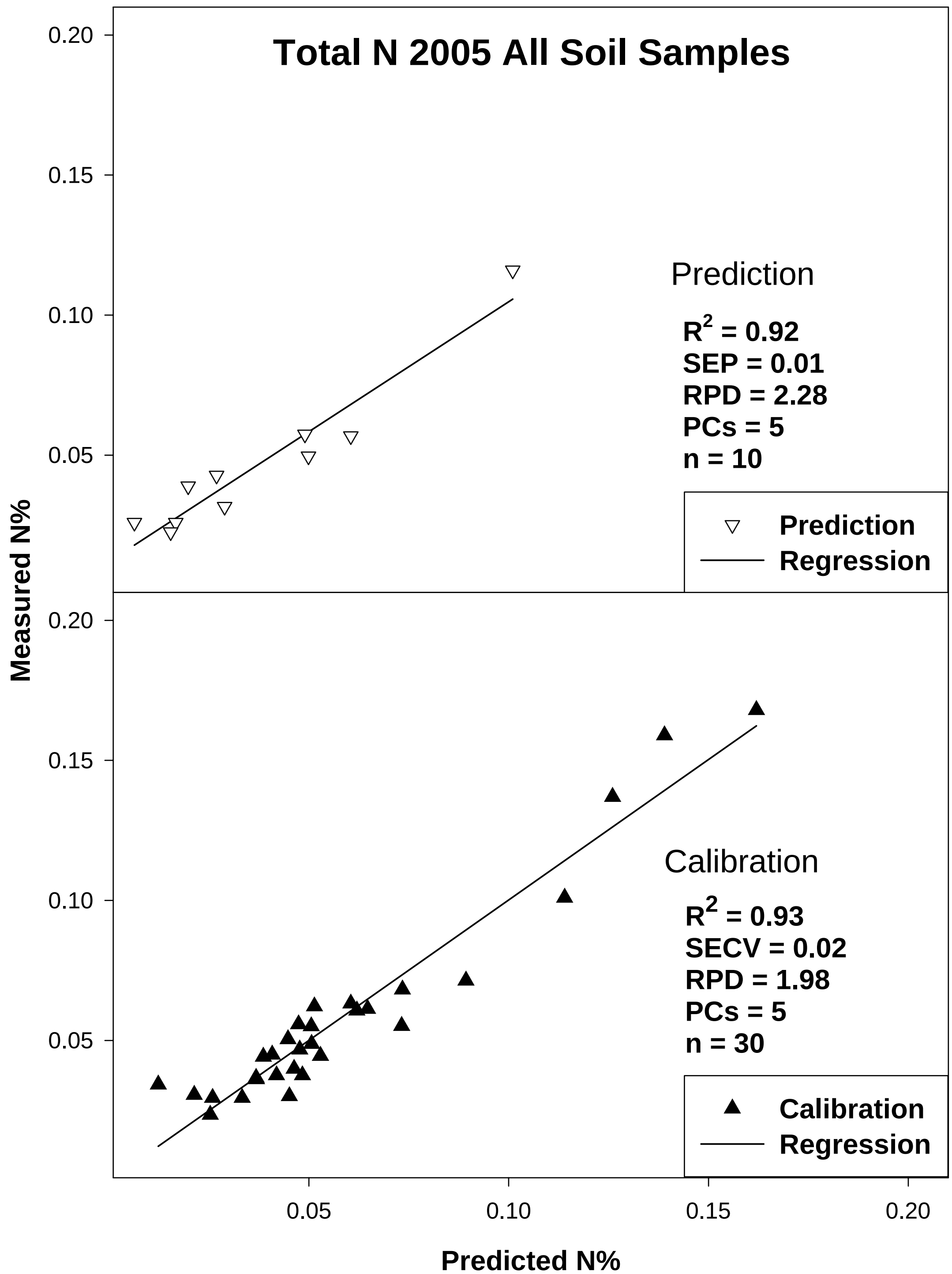

Figure 4-6. Calibration (bottom) and prediction (top) for total N predicted with Near Infrared Reflectance spectroscopy vs. total N measured by dry combustion analysis. Samples from 0-15 cm were collected under a 2-year-old loblolly pine plantations in Cuthbert and Lumpkin, GA early during the second growing season in March 2004.

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CHAPTER V

CONCLUSIONS

In the tillage study, the two sites responded differently. At Cuthbert, volume index at age three under any tillage treatment exceeded the control. The coulter only treatment had the greatest growth although tillage treatments did not differ statistically. At Lumpkin, CB≥CBS=NT>CS=C for volume index at age three. At this site C preformed worse than the NT control. Results did not support increasing tillage intensity in upland Coastal Plain locations—especially on a well-drained site.

In the resistivity surveys, there was a linear relationship between decreasing soil electrical resistivity and increasing soil moisture; this was expected and it has been previously demonstrated. However, what has not been previously demonstrated is how changes in bulk density affect the relationship between soil electrical resistivity and volumetric water content. In the CBS plot soil disturbance and decreasing bulk density decreased the strength of the resistivity-VWC relationship (i.e., decreasing R^2). Even though that the VWC on the beds are lower and the resistivity values on the beds are higher (inverse relationship), it seems to be unclear how the relationship between soil electrical resistivity and moisture content changes with soil disturbance. In this study, I was not able to infer changes in soil moisture utilization with tillage using resistivity.

NIR methodology for foliar N did not seem to produce strong predictions with composited foliar samples—when compared to individual tree samples; the robustness of predictions using individual samples were much higher than the samples that were composited. NIR methodology for soil N seemed to predict N, obtained via extraction, better over a larger range of data; the potential capability of NIR technology to predict a constituent is dictated by the ability of the method to obtain constituent data accurately.