EFFECTS OF SOIL TILLAGE ON SOIL PHYSICAL PROPERTIES AND THEIR RELATIONSHIP TO EARLY LOBLOLLY PINE GROWTH

By

BRUNO FERNANDINO FURTADO

(Under the Direction of Lawrence A. Morris)

ABSTRACT

Although basic relationships between loblolly pine growth and soil physical properties have been established, these have not been found useful for predicting pine growth response to soil tillage under field conditions. Data from 11 experiments, in the Piedmont, Upper Coastal Plain and Flatwoods of the Southeastern USA, were analyzed to investigate early loblolly growth response to operational tillage and its interaction with fertilizer application only, and fertilizer plus herbaceous weed control. The effect of these treatments on the growth response to tillage varied, but generally, the greatest response was to the combination of operational tillage and fertilization plus vegetation control. Overall, soil resistance to cone penetration varied linearly with volumetric water content, and the latter can be used to predict soil resistance based on a small number of penetrometer readings. A proposed Soil Tilth Index was tested and may be a useful tool for forest management decisions.

INDEX WORDS: Operational Site Preparation, *Pinus taeda*, Penetrometer, Volumetric Water Content, Fertilization, Herbaceous Weed Control, Soil Tilth Index

EFFECTS OF SOIL TILLAGE ON SOIL PHYSICAL PROPERTIES AND THEIR RELATIONSHIP TO EARLY LOBLOLLY PINE GROWTH

By

BRUNO FERNANDINO FURTADO

B.S., Universidade Federal de Viçosa, Brazil, 2004

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2007

EFFECTS OF SOIL TILLAGE ON SOIL PHYSICAL PROPERTIES AND THEIR RELATIONSHIP TO EARLY LOBLOLLY PINE GROWTH

By

BRUNO FERNANDINO FURTADO

Major Professor:	Lawrence A. Morris
Committee:	Daniel Markewitz David Radcliffe

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
University of Georgia
May 2007

DEDICATION

I dedicate this Thesis to my dad, Roberto Quintão Furtado Gomes, my mom, Consuelo Fernandino Furtado, and my brothers, Arthur Fernandino Furtado and Gabriel Fernandino Rutherford, for all their love and support. Always.

ACKNOWLEDGEMENTS

I would like to thank the University of Georgia and the Warnell School of Forestry and Natural Resources for providing the entire infrastructure necessary to develop my project, as well as MeadWestVaco, PlumCreek, and Rayonier, for providing areas for site establishment. Special thanks to Dr. Morris, for serving as my major advisor and for all his help and friendship throughout my time spent at UGA, and Dr. Markewitz and Dr. Radcliffe, for their assistance integrating my research committee. Many thanks to Lee Ogden, for all her help and for making my days better with her good morning smiles. Thanks to Anthony Myrick, for always giving me the best trucks available (with the best tires), making it possible to reach sites all over the State of Georgia and part of Alabama and Florida. I would also like to thank all my friends that in some way or another were part of this project: Ian Adams for all his support and help doing field work, Aaron Joslin, Marlos Vicenzi, Domingos Sárvio Magalhães Valente, Marco Gallant, Luke Pangle, Sammy Yatich, Josh Romeis, Doug Marshall, Adam Speir, Amanda Newman, Anna Mckee, Luke Worsham, Scott Devine, Nina Wurzburger, Tiago Moura, Daniel Moura, Fernando Simão, Mike Murphy, Jay Brown, Patrick Bussell, Thomaz, Kaykay, and everybody else not listed here. Many special thanks to Elizabeth Gaylor, for all her love, support, patience, and for bringing so much light to my life. Thanks to Kaan Tariman, Alex Cooper and Rich Suderman for all their friendship and support. And last, but not least, thanks to Blondie and Blackie for their therapeutic help.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The southeastern United States is the world's largest single industrial wood producer, with approximately 40 million acres of industrial pine timberland (Prestemon and Abt 2002, Haynes, 2002 and Smith et al., 2004). Since the 1950's, mechanical site preparation has been considered essential to southern pine plantation management (Martin and Shiver, 2002). Mechanical site preparation, such as shearing, piling and chopping, serves primarily to improve conditions for planting and enhance seedling survival. However, trafficking by heavy machinery can result in soil compaction, which is one possible reason for poor seedling growth (Froehlich et al., 1986 and Kozlowski, 1999).

Although basic relationships between loblolly pine growth and soil physical properties have been established, these have not been found useful for predicting pine growth response to soil tillage under field conditions. Some investigators have proposed that root growth is affected when soil resistance reaches a critical level of 2000-3000 kPa (Sands et al., 1979 and Da Silva et al. 1994). Thus, estimating soil resistance values throughout the growing season would be important to predict growth response to operational site preparation. Previous research has shown that, under field conditions, cone penetration resistance is linearly related to soil moisture content (Morris et al., 2006). Soil resistance is time-consuming to measure and few studies have effectively captured the variability in resistance occurring during the growing season. However, since it is related to field soil moisture, soil moisture can be used to estimate soil resistance.

This study was designed to isolate and quantify the effects of soil tillage on soil physical properties in their relationship to loblolly growth. This investigation did not evaluate the best tillage treatment for every site. Rather, we utilized operational tillage associated with further cultural treatments as an attempt to better explain site-specific growth response. It was proposed to evaluate the variation of soil resistance during the growing season by developing relationships between soil resistance and soil water content. A Soil Tilth Index is also proposed based on the effect of operational tillage on soil resistance and its relation to tree growth. In summary, the general questions related to this investigation were: (i) What are the changes in soil physical properties that affect loblolly pine growth? and (ii) Is it possible to incorporate soil physical changes into an index that ultimately could predict pine tree growth? To answer these questions, soil physical conditions and tree growth were measured during the first two growing seasons following operational soil tillage on 11 sites, in the Piedmont, Upper Coastal Plain and Flatwoods of the Southeastern USA.

CHAPTER I

LITERATURE REVIEW

Industrial Pine Plantations in the Southeastern US

The southeastern United States is the world's largest single industrial wood producer, with approximately 40 million acres of industrial pine timberland (Prestemon and Abt 2002, Haynes, 2002 and Smith et al., 2004). Although timber production competes with higher-valued urban development activities, aesthetic and recreational land uses (Wear and Newman, 2004 and Alig and Plantinga, 2004), projections reveal that wood demand is expected to continue to increase and the land base dedicated to silvicultural practices is expected to continue shifting from natural forests owned by non-industrial private landowners to pine plantations (Allen et al., 2005). Thus, the role of intensive forest management to maintain and increase wood production is increasing in significance (Fox, 2000, Borders and Bailey, 2001 and Martin and Shiver, 2002).

Trafficking and Soil Compaction

Since the 1950's, mechanical site preparation has been considered essential to southern pine plantation management (Martin and Shiver, 2002). Mechanical site preparation, such as shearing, piling and chopping, serves primarily to improve conditions for planting and improve seedling survival and tree growth. Water availability and nutrient resources can be improved by increasing the quantity and quality of soil volume available for rooting, or by controlling competing vegetation (Pehl, 1983 and Martin and Shiver, 2002).

Greater overall survival and increased early growth due to mechanical site preparation has been well documented (e.g. Shiver and Fortson, 1979, Wittwer et al., 1986, Tiarks and Haywood, 1996 and Rahman et al., 2006). However, other investigations designed to evaluate growth response beyond the first few years after plantation establishment have shown that early growth gains do not necessarily persist (Haywood, 1994 and Vitousek and Matson,1985). Critical factors for reduced growth response include soil erosion and compaction, and the inability to maintain site productivity.

Soil compaction is commonly observed as a consequence of heavy machinery traffic (Adams and Froehlich, 1981, Unger and Kaspar, 1994 Lacey and Ryan, 2000, and Defossez and Richard, 2002). The compressive disturbance affects soil mass and breaks down surface aggregates, decreasing macropore volume and increasing bulk density (Fisher and Binkley 2000). Many studies have shown that compacted soils often present characteristics that are unfavorable for plant development (e.g. McClurkin and Duffy, 1975, Froehlich et al., 1986 and Kozlowski, 1999). These characteristics, related to soil strength enhancement, include high bulk density and reduced total porosity, therefore decreasing water infiltration rate and affecting hydraulic conductivity. At matric potentials near field capacity, soil compaction reduces hydraulic conductivity by reducing macroporosity. At matric potentials near wilting point, increases in soil compaction usually enhance hydraulic conductivity by augmenting particle to particle contact (Greacen and Sands, 1980 and Taylor and Brar, 1991). In the absence of other limitations, root growth and extension generally declines linearly with increased mechanical impedance. Once a maximum resistance is reached, growth ceases and is confined to macropores. Restrictive resistances for root growth start at approximately 0.5 MPa, and stop beyond resistances in the range of 2.0 to 3.0 MPa (Morris, 2001).

The extensiveness of the effects resulting from heavy machinery traffic on rooting conditions is related to soil texture and moisture content during site traffic operations (Morris and Lowery, 1988 and Gomez et al., 2002). Soil mineralogy is strongly related to a number of soil physical properties, such as soil shrink/swell dynamics and macrostructure, which also affect root growth (Carlson et al., 2006). For example, soils with siliceous mineralogy tend to have massive structure, that could restrict root penetration (Fisher and Binkley, 2000), and soils with kaolinitic and mixed mineralogy are likely to provide better structure for root development (Van Rees and Comeford, 1986).

Although high soil mechanical impedance and/or poor aeration during wet periods are common restrictions for root growth on many sites in the South (Morris and Lowery, 1988), responses to site disturbance vary considerably. Eisenbies et al. (2005), conducting a study in the Coastal Plain of South Carolina, assessed the effects of wet- and dry-weather harvesting and mechanical site preparation on soil-site quality and subsequent growth response in a 5-yr-old loblolly pine (*Pinus taeda*) plantation. All soils included in the study were poorly to somewhat poorly drained, with surface drainage largely controlled by microtopography and subsurface drainage by thick argillic horizons, with the common presence of a perched water table. Trees on disturbed sites developed as well or better than trees on minimal disturbance sites and average levels of harvest residues. These authors concluded that moderate levels of disturbance could have influenced competition control and N mineralization rates, favoring tree growth. In another investigation, Gomez et al. (2002) assessed the effects of soil compaction on ponderosa pine (*Pinus ponderosa*) plantations on several California sites of contrasting textures (clayey, loamy and sandy loam). The age of the trees in the investigation varied from 3 to 8 years. The plots in this study had the organic soil horizon removed, and compacted and non-compacted treatments where compared. The researchers reported that, after compaction, stem volume measured in the clayey, loamy, and sandy loam site was lower, the same, and greater, respectively.

Tillage Practices and Tree Growth

Tillage treatments can be effective at ameliorating soil physical limitations (e.g., reducing soil mechanical impedance, increasing aeration and porosity) whether they occur naturally or resulting from soil compaction due to equipment trafficking (Wheeler et al., 2002, Allen et al., 2005 and Carlson et al., 2006). Soil tillage during site preparation, such as disking, bedding, combination plowing and subsoiling, can have major effects on the physical, chemical and biological properties and processes of the volume of soil available to each seedling (Morris and Lowery, 1988). In addition to the direct effects of better soil aeration on root growth, aeration can also improve nutrient availability by stimulating microbial activity, therefore benefiting mineralization rates. Each of the tillage treatments results in a different volume and configuration of tilled soil. Thus, understanding the restrictive conditions for root growth (aeration and/or soil resistance) is crucial to effectively use these treatments (Allen, 2001).

Rapid root system development during the first year in the field is critical for increasing the chance of good survival and early growth (Dougherty and Gresham, 1988 and Adegbidi et al., 2004). Surface tillage treatments, such as disking and bedding, can enhance root growth by decreasing soil mechanical impedance to root penetration, also improving aeration and water infiltration, with subsequent reduction of runoff. Other benefits are improved organic matter incorporation, improved nutrient incorporation, and competition control. Bedding has also the potential to lift seedlings in relation to the water table level (Morris and Lowery, 1988, Aust et al., 1998 and Wheeler et al., 2002). Subsoiling can enhance root growth by reducing subsoil bulk density, increasing macroporosity as well as rupturing subsurface hardpans. Furthermore, subsoiling can improve water infiltration, which can potentially reduce moisture stress during dry seasons (Morris and Lowery, 1988 and Wheeler et al., 2002). Soil tilth may also be improved by machine planting, which can affect the volume and depth of soil exploited by the roots during the first year of growth (Wheeler et al., 2002).

Several studies have shown the effects of tillage on tree growth and forest productivity. Investigations indicated that results vary according to site location, as a function of climatic and soil conditions. The benefits of tillage have been recently evaluated on Piedmont and Upper Coastal plains sites. Schilling et al. (2004) reported that root architecture was primarily influenced by subsoiling treatments regardless of surface tillage or machine planting. The results suggested that machine planting did not differ significantly from combination tillage in terms of young loblolly pine growth. Wheeler et al. (2002) investigated the effects of machine planting, disking, bedding and combination tillage on growth of loblolly pine on seven sites in the Piedmont and Upper Coastal Plain regions of Georgia. Results indicated that bedding resulted in the most consistent positive response, despite adding subsoiling tillage. Overall, growth responses to tillage practices were relatively small and site specific. Another recent study, conducted by Carlson et al. (2006), also examined the effect of surface and subsurface tillage on the survival and growth of loblolly pine on 15 sites in the Southeast. Responses to tillage on upland sites were assessed based on specific soil and site characteristics. Although subsoiling resulted in positive response in four Piedmont sites (in accordance to the investigation of Schilling et al., 2004), improving survival from 74 to 82 %, growth responses were unpredictable. Surface tillage resulted in the greatest short-term growth obtained in soils with siliceous mineralogy. Soils with kaolinitic or mixed mineralogy did not present the same growth response. After a 6-year period, growth response due to tillage treatment was lost. The investigators concluded that effects of tillage were relatively small when compared to fertilizer application and herbaceous woody control.

Growth Response Related to Fertilizer Application and Competing Vegetation Control

Nutrient limitations for pine growth are common in natural pine stands and plantations in the Southeast. Nitrogen (N) is one of the most limiting nutrients to plant development in forest soils (Vitousek and Matson, 1985 and Ludovici and Morris, 1996). Nitrogen restrictions typically occur beginning at crown closure on all but the most productive sites. Recognized phosphorus (P) deficiencies have been identified on well-drained, non-cultivated Coastal Plain sites. Although growth responses to Potassium (K) have been observed on soils with deep, sandy surfaces, K limitations do not appear to be widely distributed as N or P limitations (Allen et al., 1990).

Fertilizer application may result in either short or long term increases in nutrient availability and subsequent growth response depending on the nutrient, application rates, and site characteristics (Nilsson and Allen, 2003). Fertilizer application is commonly done in conjunction with vegetation control practices, since interespecific competition from herbaceous and woody plants can potentially promote a negative impact on the main factors related to loblolly pine growth such as moisture, nutrient and light availability, and rooting volume (Morris et al., 1993 and Martin and Shivers, 2002).

Several studies have reported significant increases in survival and positive growth responses to herbaceous woody control and fertilization. For example, Will et al. (2002) investigated the effects of annual nitrogen fertilization and complete competition control in different aged loblolly stands. Results indicated positive growth response for nutrition and competition control in both Piedmont and Coastal Plain sites. Another study presenting similar growth response was conducted by Borders et al. (2004). These researchers investigated the effect of complete competition control and annual N fertilization for a loblolly pine plantation in the lower Coastal Plain of Georgia. The authors reported that sites fertilized with N and treated with herbaceous weed control resulted in more than double the stem biomass production in comparison to the production of control sites.

Interactions among silvicultural treatments

The combined effects of two or more silvicultural treatments that affect resource availability and/or the allocation of resources in a similar manner may be less than the sum of each individual effect (combination is less then individual addition). For example, disking directly affects the rooting environment but indirectly also provides some hardwood competition control. The expectation would be that the combination of disking and chemical hardwood control would yield less than the two treatments applied individually. By contrast, the yield resulting from hardwood control in association with fertilizer application may be more than additive. Without vegetation control, hardwoods would also respond to fertilization, increasing competition for light, nutrients and water resources (Allen, 2001).

Although significant progress has been made in the South by incorporating research results into operational forest management prescriptions that include fertilization application and herbaceous woody control (Jokela et al., 2000), isolating the confounding influences on growth response resulting from tillage practices are crucial to provide forest managers with an understanding of the effects of improved soil physical properties on tree growth (Carlson et al., 2006). Obtaining optimum plantation production requires the use of integrated systems that couple interactions among different silvicultural treatments and genetics (Allen, 2001).

Soil Moisture and Growth

Water availability is one of the major physical factors influencing root growth (Hsiao et al., 1976 and Gholz et al., 1990 and Morris, 2001), and in the Southern US, soil moisture limitations for pine growth are assumed to be widespread (Allen et al., 1990). The effects of water stress in root distribution have been investigated in earlier studies (e.g. Kaufmann, 1968), and more recently researchers have been focusing on the interaction of soil water content and soil physical properties, and how tree growth is affected by these relationships (Siegel-Issem et al., 2005 and Morris et al., 2006).

Studies have shown that the establishment and growth of loblolly pine are influenced by extended water stress periods during growing seasons. Seedling growth response during drying cycles depends on soil conditions that affect root development and water transport (Kaufmann, 1968; Torreano and Morris, 1998). The latter researchers, conducting a rhizotron study investigating loblolly pine root growth and distribution under water stress, reported that relative root elongation rates were linearly related to soil water potential.

Soil water content controls mechanical impedance, water potential, and soil aeration, which are fundamental soil physical properties for tree seedling root growth (Morris et al., 2006). Therefore, soil moisture content represents a crucial factor for the elaboration of tree growth models based on soil physical properties.

Modeling Seedling Growth

As discussed previously, site preparation tillage, such as subsoiling, disking or bedding, can ameliorate the impacts of compaction resulting from mechanical site preparation, but the costs of these tillage treatments are high and growth response is site-specific. Currently there are no efficient methods to predict if the interaction of tillage, fertilizer application and herbaceous weed control will result in positive or negative responses in tree growth. Some researchers have suggested the incorporation of soil aeration, soil strength, and soil water potential measurements into a single index called least limiting water range (LLWR) to describe soil quality in terms of plant growth (Da Silva et al. 1994). The LLWR is defined as the range in which water availability is non-limiting to plants, and it is bounded by both wet and dry ends. Field capacity or air-filled porosity less than 10 % represents the wet limit to growth; and wilting point characterized by soil strength greater than 2.0 MPa or water potential less than -1.5 MPa, represents the dry limit. As soil bulk density increases, the LLWR becomes narrower, with mechanical resistance becoming limiting at the dry end and reduction of oxygen supply becoming limiting at the wet end (Siegel-Issem and Burger 2005 and Morris et al., 2006). Siegel-Issem and Burger (2005) examined greenhouse pine seedling growth and developed a response surface describing root growth as a function of soil bulk density and volumetric moisture content. A general model to describe growth potential was also suggested based on the response surface. The authors concluded that the LLWR had potential as a soil quality indicator, but seedling response was not consistently associated with the LLWR. Instead, root length density response surface models used in conjunction with soil water data showed potential for determining compaction-induced soil limitations for tree growth, but they concluded that further investigations that considered both soil and plant species would be necessary to calibrate the model under field conditions.

One major disadvantage of the LLWR approach to predict seedling growth response, as discussed by Morris et al. (2006), is the fact that this model does not account for differences between growth conditions within the suitable range. On upland sites, the wet limit to growth (poor aeration) is rarely reached and most of the tree growth response is likely to be influenced by soil conditions below the dry limit stipulated within the LLWR (Morris et al., 2006). In an attempt to overcome this limitation, these investigators developed a model that utilized root growth response to soil resistance, water potential and aeration. They tested their predicted growth in early loblolly pine plantations against growth measured in a field study of soil tillage treatments on an Upper Coastal Plain site. Seedling height predicted by the model differed from measured average height by –1 to +14 %, with absolute differences in height of 0.1 m or less. The same model predicted above-ground biomass between –12 to +41 % of the average measured biomass.

Although basic relationships between loblolly pine growth and soil physical properties have been established, these have not been found useful for predicting pine growth response to soil tillage under field conditions. Thus, an experiment designed to investigate these relationships could generate important information for forestry management decisions.

References

Adams, P.W., Froehlich,H.A.,1981. Compaction of forest soils. Oregon State Univ. Corvallis, Extension Service, PNW-217, 13 p.

Adegbidi, H.G., Comerford, N.B., Jokela, E.J., Barros, N.F., 2004. Root Development of Young Loblolly Pine in Spodosols in Southeast Georgia. Soil Sci. Am.J. 68, 596-604.

Alig, R.J., Plantinga, A.J., 2004. Future Forestland Land Area: Impacts from Population Growth and Other Factors that Affect Land Values. J. For. 102(8), 19-24.

Allen, H.L., Dougherty, P.M., Campbell, R.G., 1990. Manipulation of water and nutrients -- Practice and opportunity in Southern U.S. pine forests. Forest Ecology and Management 30, 437-453.

Allen, H.L.,2001. Silvicultural treatments to enhance productivity. Chapter 6 in the Forests Handbook. Vol II. Evans,J. (ed.). Blackwell Science Ltd., Oxford,UK, 382p.

Allen,H.L., Fox, T.R., Campbell, R.G., 2005. What is Ahead for Intensive Pine Plantation Silviculture in the South? South J. Appl. For. 29(2), 62-69.

Aust,W. M., G. A. Scheerer,M. D. Tippet, J.A. Burger and W.H.Mckee,Jr, 1998. Bedding and fertilization ameliorate effects of designated wet-weather skid trails after four years of loblolly pine (*Pinus taeda*) plantations. South.J. Appl. For. 22(4),222-226.

Borders, B.E., Bailey, R.L., 2001. Loblolly Pine: Pushing the Limits of Growth. South J. Appl. For. 25(2), 69-74.

Borders, B.E., Will, R.E., Markewitz, D., Clark, A., Hendrick, R., Teskey, R.O., Zhang, Y., 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. Forest Ecology and Management 192, 21-37.

Carlson, C.A., Fox, T.R., Colbert, S.R., Kelting, D.L., Allen, H.L., Albaugh, T.J., 2006. Growth and survival of Pinus taeda in response to surface and subsurface tillage in the southeastern United States. Forest Ecology and Management 234, 209-217.

Defossez, P., Richard, G., 2002. Models of soil compaction due to traffic and their evaluation. Soil and Tillage Research 67, 41-64.

Da Silva,A.P., Kay,B.D., Perfect E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58:1775–1781.

Dougherty,P.M., Gresham,C.A., 1988. Conceptual Analysis of Southern Pine Plantation Establishment and Early Growth. South. J. Appl. For. 12(3),160-166.

Eisenbies, M.H., Burger, J.A., Aust, W.M., Patterson, S.C., 2005. Soil Physical Disturbance and Logging Residue Effects on Changes in Soil Productivity in Five-Year-Old Pine Plantations. Soil Sci. Am.J. 69, 1833-1843.

Fisher,R.F., Binkley,D.,2000. Ecology and Management of Forest Soils (3rd ed.), Wiley Publishers 512 pp.

Fox, T.R., 2000. Sustained productivity in intensively managed forest plantations. Forest Ecology and Management 138, 187-202.

Froehlich, H.A., Miles, D.W.R., Robbins, R.W., 1986. Growth of young Pinus ponderosa and Pinus contorta on compacted soil in central Washington. Forest Ecology and Management 15, 285-294.

Gomez, G.A., R.F. Powers, M.J. Singer, and W.R. Horwath. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. 66:1334–1343.

Gholz, H.L., Ewel, K.C., Teskey, R.O., 1990. Water and forest productivity. Forest Ecology and Management 30, 1-18.

Greacen, E.L., Sands,R.,1980. Compaction of Forest Soils – A Review. Aust. J. Soil. Res. 18,163-189.

Haynes, R.W., 2002. Forest Management in the 21st Century: Changing Number, Changing Context. J. For. 100(2), 38-43.

Haywood, J.D., 1994. Early Growth Reductions in Short Rotation Loblolly and Slash Pine in Central Louisiana. South J. Appl. For. 18, 35-39.

Hsiao,T.C., Acevedo,E., Fereres,E.,Henderson,D.W.,1976. Water stress, growth, and osmotic adjustment. Philosophical Transactions of the Royal Society Series B 273**,** 479-500.

Jokella, E.J., Wilson, D.S., Allen, J.E., 2000. Early Growth Responses of Slash and Loblolly Pine Following Fertilization and Herbaceous Weed Control Treatments at Establishment. South J. Appl. For. 24,23-30.

Kaufmann, M.R., 1968. Water Relations of Pine Seedlings in Relation to Root and Shoot Growth. Plant Physiology 43, 281-288.

Kozlowski, T.T.,1999. Soil Compaction and Growth of Woody Plants. Scand. J. For. Res. 14, 596-619.

Lacey, S.T., Ryan, P.J., 2000. Cumulative management impacts on soil physical properties and early growth of Pinus radiata. Forest Ecology and Management 138, 321-333.

Ludovici, K.H., Morris, L.A.,1996 Responses of loblolly pine, sweetgum, and crab grass roots to localized increases in nitrogen in two watering regimes. Tree Physiol. 16, 933-939.

Martin, S.W., Shiver, B.D.,2002. Impacts of vegetation control, genetic improvement and their interaction on loblolly pine growth in the southern United States - age 12 results. South. J. Appl. For. 26(1),37-42.

McClurkin, D.C. and Duffy, P.D., 1975. Evaluating Impact of Forest Site Preparation on Soil and Water Quality in the U.S. Gulf Coastal Plain. In: Bernier, B. and Winget, C., H.

Forest Soils and Forest Land Management. Proceedings of the Fourth North American Forest Soils Conference 1973, Quebec, pp. 315-321.

Morris, L.A., Lowery,R.F.,1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South. J. Appl. For. 12(3), 170-178.

Morris, L.A., Moss,S.A., Garbett, W.S.,1993. Competitive interference between selected herbaceous and woody plants and *Pinus taeda* L. during two growing seasons following planting. For. Sci. 39, 166-187.

Morris,L.A.,2001. Sustainable Management of Soil and Site. Chapter 7 in the Forests Handbook. Vol II. Evans,J. (ed.). Blackwell Science Ltd., Oxford,UK, 382p.

Morris, L.A., Ludovici, K.H., Torreano, S.J., Carter, E.A., Lincoln, M.C., Will, R.E., 2006. An approach for using general soil physical condition-root growth relationships to predict seedling growth response to site preparation tillage in loblolly pine plantations. Forest Ecology and Management 227, 169-177.

Nilsson, U., Allen, H.L., 2003. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. Forest Ecology and Management 175, 367-377.

Pehl, C.E., 1983. Site Preparation Influences on Young Loblolly Pine Plantations in East Texas. South J. Appl. For. 7, 140-145.

Prestemon, J.P. and Abt, R.C., 2002. The Southern Timber Market to 2040. J. For. 100(7), 16-22.

Rahman, M.S., Messina, M.G., Fisher, R.F., 2006. Intensive Forest Management Affects Loblolly Pine (Pinus taeda L.) Growth and Survival on Poorly Drained Sites in Southern Arkansas. South J. Appl. For. 30, 79-85.

Schilling,E.B., Lockaky B.G., Rummer.R.,2004. Biomass partitioning and root architecture responses of loblolly pine seedlings to tillage in the Piedmont and Coastal plain soils. South.J. Appl. For. 28(2),76-82.

Siegel-Issem, C.M., Burger, J.A., Powers, R.F., Ponder, F., Patterson, S.C., 2005. Seedling Root Growth as a Function of Soil Density and Water Content. Soil Sci. Am.J. 69, 215-226.

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

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

Taylor,H.M., Brar, G.S., 1991. Effect of soil compaction on root development. Soil Tillage Res. 19,11-119.

Tiarks,A.E.,Haywood, J. D.,1996, Site preparation and fertilization effects on growth of slash pine for two rotations, Soil Sci. Soc. Amer. J. 60, 1654–1663.

Torreano, S.J., Morris, L.A., 1998. Loblolly pine root growth and distribution under water stress. Soil Sci. Am.J. 62, 818-827.

Unger, P.W., Kaspar, T.C.,1994. Soil Compaction and Root Growth: A Review. Agron. J. 86, 759-766.

Van Rees, K.C.J., Comerford,N.B.,1986.Vertical root distribution and strontium uptake of a slash pine stand on a florida spodosol. Soil Sci. Am.J. 50, 1042-1046.

Vitousek, P.M., Matson, P.A., 1985. Intensive Harvesting and Site Preparation Decrease Soil Nitrogen Availability in Young Plantations. South. J. Appl. For. 9, 120-125.

Wear, N.D., Newman,D.H., 2004. The speculative shadow over timberland values in the US South. J. Appl. For. 102(8), 25-31.

Wheeler,M.J., Jacobson,M.A., Shirley,A.M., Will,R.W., Markewitz,D.,2002. Early loblolly pine stand response to tillage on the Piedmont and Upper Coastal Plain of Georgia: mortality, stand uniformity, and second and third year growth. South. J. Appl. For. 26(4),181-189.

Will, R.E., Munger, G.T., Zhang, Y., and Borders, B.E. 2002. Effects of annual fertilization and complete competition control on current annual increment, foliar development, and growth efficiency of different aged Pinus taeda stands. Can. J. For. Res. 32,1728-1740.

Wittwer, R.F., Dougherty, P.M., Cosby, D., 1986. Effects of Ripping and Herbicide Site Preparation Treatments on Loblolly Pine Seedling Growth and Survival. South J. Appl. For. 10, 253-257.

CHAPTER II

RELATIONSHIP BETWEEN SITE PREPARATION AND EARLY LOBLOLLY PINE SEEDLING GROWTH[1]

[1] Furtado, B.F., Morris, L., Markewitz, D. and Radcliffe, D. 2007. To be submitted to *Soil and Tillage Research*.

Abstract

Compaction during harvest can decrease forest productivity by increasing soil physical impedance and by reducing oxygen supply to the roots due to reduction of macropore volume. Site preparation tillage, such as subsoiling, disking or bedding, can ameliorate these impacts but the costs of these tillage treatments are high and growth response is variable. The objective of this study was to isolate and quantify the effects of soil tillage on soil physical properties, and explain site-specific growth response. Data from 11 experiments, established on a range of sites using a common study design, were analyzed to investigate early loblolly growth response to tillage and its interaction with fertilizer application and fertilizer plus herbaceous weed control. Overall, tillage resulted in positive growth response. The greatest growth was associated with the Upper Coastal Plain site Troup, where the interaction of tillage and fertilizer plus herbaceous weed control resulted in an average SVI of 8932.0 cm^3 ± 784.8 SE. The lowest growth was observed in the Upper Coastal Plain site Faceville, where the non-tilled rows associated with operational site preparation resulted in an average SVI of 101.0 cm^3 ± 35.3 SE. Growth response was reasonably well correlated with measured differences in average resistance in tilled and non-tilled rows. Operational soil tillage reduced resistance by a maximum of 51 %, measured at the Piedmont site Rion, and by a minimum of 9 %, measured at the Upper Coastal Plain site Gritney. Generally, soil tillage also reduced volumetric water content, and the greatest water depletion was measured at the Piedmont site Lloyd. At this site, tilled rows were on average 15 % drier than non-tilled rows, in the 0.15-0.30 m interval, and 12 % drier in the 0.30-0.60 m interval. It is likely that water depletions in the deeper horizons could have been associated with growth loss to tillage. This study provides a large base of information on the probability and magnitude of loblolly pine early growth response to operational site preparation methods.

INDEX WORDS: Soil Tillage, Soil Resistance, Penetrometer, Volumetric Water Content, TDR, Fertilization, Herbaceous Weed Control, Loblolly Pine, *Pinus taeda*

Introduction

The southeastern United States is the world's largest single industrial wood producer, with approximately 40 million acres of industrial pine timberland (Prestemon and Abt 2002, Haynes, 2002 and Smith et al., 2004). Since the 1950's, mechanical site preparation has been considered essential to southern pine plantation management (Martin and Shiver, 2002). Mechanical site preparation, such as shearing, piling and chopping, serves primarily to improve conditions for planting and enhance seedling survival. Access to water and nutrient resources can be improved by increasing the quantity and quality of soil volume available for rooting or by controlling competing vegetation (Pehl, 1983 and Martin and Shiver, 2002).

Greater overall survival and increased early growth due to mechanical site preparation has been well documented (e.g. Shiver and Fortson, 1979, Wittwer et al., 1986, Tiarks and Haywood, 1996 and Rahman et al., 2006). However, some investigations designed to evaluate growth response beyond the first few years after plantation establishment have shown that early growth gains do not necessarily persist. In these cases, factors for reduced growth response include soil erosion and compaction due to trafficking, and consequently the inability to maintain site sustainability (Haywood, 1994 and Vitousek and Matson, 1985).

Soil compaction resulting from trafficking by heavy machinery during harvest is often observed (Adams and Froehlich, 1981, Unger and Kaspar, 1994 Lacey and Ryan, 2000, and Defossez and Richard, 2002) and is one possible reason for poor seedling growth on many planted sites. The compressive disturbance affects soil mass and breaks down surface aggregates, decreasing macropore volume and increasing bulk density (Fisher and Binkley, 2000). Many studies have shown that compacted soils often present characteristics that are unfavorable for plant development (e.g. McClurkin and Duffy, 1975, Froehlich et al., 1986 and Kozlowski, 1999). These characteristics include high bulk density, increased soil resistance to root penetration, lower microbiological activity, reduced total porosity and poor aeration (Greacen and Sands, 1980).

Tillage Practices and Tree Growth

Tillage treatments can be effective at ameliorating soil physical limitations (e.g., reducing soil mechanical impedance, increasing aeration and porosity) whether they occur naturally or resulting from soil compaction due to equipment trafficking (Wheeler et al., 2002, Allen et al., 2005 and Carlson et al., 2006). Soil tillage during site preparation, such as disking, bedding, combination plowing and subsoiling, can affect physical, chemical and biological properties and processes (Morris and Lowery, 1988). The direct effects of tillage on soil resistance and aeration are apparent (Sands et al., 1979). However, tillage can also improve nutrient availability by stimulating microbial activity, therefore benefiting mineralization rates (Eisenbies et al., 2005). Tillage treatments result in a different volume and configuration of tilled soil. Thus, understanding the restrictive conditions for root growth (aeration and/or soil resistance) is crucial to effectively use these treatments (Allen, 2001).

Growth Response Related to Fertilizer Application and Competing Vegetation Control

Nutrient limitations for pine growth are common in natural pine stands and plantations in the Southeast. Nitrogen (N) is one of the most limiting nutrients to plant development in forest soils (Vitousek and Matson, 1985 and Ludovici and Morris, 1996). Nitrogen restrictions typically occur beginning at crown closure on all but the most productive sites. Phosphorus (P) deficiencies have been identified on well-drained non-cultivated Coastal Plain sites, and on many poorly drained soils. Growth responses to Potassium (K) fertilization have been observed on soils with deep, sandy surfaces; however, K limitations do not appear to be as widely distributed as N or P limitations (Allen et al., 1990).

Fertilizer application may result in either short or long term increases in nutrient availability and subsequent growth response depending on the nutrient, application rates, and site characteristics (Nilsson and Allen, 2003). Fertilizer application is commonly done in conjunction with vegetation control practices, since interespecific competition from herbaceous and woody plants can potentially promote a negative impact on main factors related to loblolly pine growth such as moisture, nutrient and light availability, and rooting volume (Morris et al., 1993 and Martin and Shivers, 2002).

Interactions among silvicultural treatments

The combined effects of two or more silvicultural treatments that affect resource availability and/or the allocation of resources in a similar manner may be less than additive. For example, disking directly affects the rooting environment but indirectly provides some hardwood competition control. The expectation would be that the combination of disking and chemical hardwood control would yield less than the two treatments applied individually. In contrast, the yield resulting from hardwood control in association with fertilizer application may be more than additive. Without vegetation control, hardwoods would also respond to fertilization, increasing competition for light, nutrients and water resources (Allen, 2001).

Although significant progress has been made in the South by incorporating research results into operational forest management prescriptions that include fertilizer application and herbaceous and woody control (Jokela et al., 2000), the confounding influences on growth response resulting from isolated tillage practices are crucial to provide forest managers with an understanding of the effects of improved soil physical properties on tree growth (Carlson et al., 2006).

This study was predicated on the hypothesis that accurate measurement of soil properties on an individual tree basis would explain differences in growth response to tillage. Specifically, the objectives of this study were to (i) isolate and quantify the effects of soil tillage on soil physical properties and (ii) explain site-specific growth response.

Material and Methods

Site Locations

Eleven experimental sites, utilizing a common study design, were established over a two-year period from 2005 to 2006 in Georgia, Florida and Alabama, USA. Five sites were located in the Upper Coastal Plain (UCP) of Georgia, on tracts of land owned by MeadWeastvaco. Four of these sites were established near the city of Lumpkin, in Stewart County, GA, and one in the proximity of East of Omaha, in Russell County, AL. Three sites were located in the Piedmont region, on tracts of land owned by PlumCreek, two in the proximity of the city of White Plains, in Greene County, GA, and one near Watkinsville, in Oconee County, GA. Three sites were established in the Flatwoods region, on land owned by Rayonier, near the city of Hilliard, in Nassau County, FL (Fig.2.1). All sites were established on recently cut-over forested areas harvested approximately 1.5 years before the initial plot establishment, and were planted with three different loblolly (*Pinus taeda*) clone varieties (Table 2.1).

Study Design and Installation

The sites, characterized by main plots of approximately 280 m^2 (14 m x 20 m), were established using a strip-plot design in three replicate blocks. To control variability, each block consisted of a single clone, thus, clones were confounded with block effects. Strips consisted of three cultural treatments: no culture (O), fertilization alone (F) and fertilization plus weed control (F+V) intersecting with two tillage treatments: no tillage (NT) versus operational tillage (T). The cultural treatment strips were not completely randomized among blocks; consequently, cultural treatment randomization was applied on a site basis. The reason this violation was necessary was due to the small area of subplots, making it impractical to apply different cultural treatments on a subplot basis (Fig.2.2). Each subplot contained eight trees, four on the tilled line and four on the non-tilled (inter-row) line. For a total of 72 trees within the experiment, 36 were constantly monitored and utilized for measurements, and the remaining 36 worked as buffers (Fig.2.2).The varieties used in the experiment as replicate blocks were the following: LB-SE Q3802, LB-SE L3519 and LB-SE O3621. The pine tree seedlings were hand planted at 1.5 m spacing using dibble bars in February 14-16th, 2005 (Upper Coastal Plain and Piedmont sites) and in February 1st, 2006 (Flatwoods sites).

Annual fertilization treatments consisted of N, P and K at 56, 11 and 56 kg ha^{-1}, respectively. The total fertilizer application was 93 kg ha^{-1} of urea (46-0-0), 42 kg ha^{-1} of triple superphosphate - TSP (0-45-0), and 91 kg ha^{-1}of muriate of potash (0-0-60). Macro- and micronutrients were also applied in the form of Holly-Tone (Espoma Company, Millville, NJ) at 112 kg ha^{-1} (Appendix A).

Herbaceous weed control was done either by direct application of Roundup® (glyphosate) to foliage or by hand weeding throughout the 2-yr study period. The pesticide Sevin® (carbaryl) was applied to all seedlings in July and September of the first growing season (2005) to reduce tip-moth (*Rhyacionia frustrana*) infestation.

Height (Ht) and groundline diameter (GLD) were periodically measured for the same 36 pine seedlings per site throughout the 2-yr study. These measurements were used to calculate the stem volume index (SVI). The SVI was calculated using the following relationship (Wheeler et al. 2002):

$$SVI = Ht * GLD^2$$

Growth measurements were analyzed on a site basis for tillage, cultural treatments and tillagexcultural treatment for the appropriate strip-plot design using the SAS ANOVA procedures (SAS 2006). Tests of significance were made at 0.05 and 0.10 probability level.

Soil measurements

Moisture content was collected biweekly during the growing season, and it was measured by time domain reflectometry (TDR) using a Tecktronix cable tester (Tektronix, Inc. Beaverton, OR) (Topp et al. 1985). Pairs of steel rods (5 cm spacing) were inserted vertically into the soil at three depths: 15, 30 and 60 cm. Rods used to cover the 15 cm depth were 30 cm length rods installed at a 30^o angle to the soil surface, guaranteeing greater soil contact and avoiding rod misplacement. Moisture throughout the 30 and 60 cm depths was measured with rods of equivalent lengths to the respective depths. A total of 54 pairs of TDR rods were installed per site (Fig.2.2).

Soil mechanical impedance was measured with a Rimik cone penetrometer (Toowoomba, Australia). The shaft was mounted with a 30^o angle, 130 mm^2 cone (Standard ASAE S313.3 Feb 99). Measurements were taken for each one of the monitored pine tree seedlings, and 60 cm depth insertions were taken perpendicularly to the planting row. Each monitored tree received five insertions spaced by 15 cm, covering a 60 cm width. A total of 180 insertions were done per site. Penetrometer data was collected four times throughout the 2 yr period, and measurements were spaced 10 cm apart from the previous one (first data was collected at a 20 cm distance from the monitored tree).

Penetrometer data management

The data stored in the Rimik penetrometer unit consisted of soil resistance values collected at 2.5 cm depth increments, covering the 60 cm depth profile (24 resistance values per insertion). After experimental trials using the hand-held cone penetrometer utilized in this investigation, it was noticed that soil resistances greater than 4500 kPa were often times not recorded, since these pressure values exceed the load cell limit. For these specific cases, a Visual Basic (VBA, Microsoft® Excel, 2002) routine was developed to generate a matrix of missing resistance values at deeper horizons (Appendix B). When reaching the maximum load limit, this program would identify the last point of data recorded, averaging it with the previous value and completing the missing data with the resulted average, guaranteeing estimated resistance values throughout the 60 cm depth. The decision for developing this data management method was supported by analyzing previous investigations that utilized hand-held cone penetrometers, where data obtained for soils presenting great resistances resulted in missing data, or patterns of resistance vs. moisture content that were not realistic.

Results

Upper Coastal Plain and Piedmont sites

Pine Seedling Growth

Overall, tillage resulted in a positive pine growth response, as observed in the average values of Ht, GLD and SVI. Growth response to tillage was not significant at the Red Bay (UCP) and Lloyd (Piedmont) sites, although average growth was predominantly greater in the T treatment (Table 2.2 and Table2.3).

The greatest growth responses were related to the cultural treatment F+V (Fig.2.3). The greatest single growth response was associated with the UCP site Troup, where the interaction of T and F+V resulted in an average SVI of 8932.0 cm^3 ± 784.8 SE. The lowest growth was observed in the UCP site Faceville, where the NT treatment associated with O resulted in an average SVI of 101.0 cm^3 ± 35.3 SE. Overall, growth response to F treatment did not differ significantly from the O treatment (Table 2.2)

Soil Resistance

Soil resistance with tillage treatment was significantly different for all 2-yr sites at the 0.05 level of probability (Table 2.4). Soil resistance averages were overall greater in deeper horizons, significantly different for the sites Faceville, Gilead, Troup, Gritney, Cecil, Lloyd and Rion (P=0.0042, 0.0009, <0.0001, 0.0013, 0.0006, 0.0018 and 0.0001, respectively). Soil resistance did not differ significantly over different soil depths for the Red Bay site (P=0.1342). Greater resistance values were observed in NT 0.15-0.30 m in comparison to NT 0.30-0.60 m. The same pattern was observed at the Lloyd site (NT, F). Soil resistance values were significantly different for the F treatment at the Red Bay (P=0.0305) and CL/L (P=0.0595) sites, and for the O treatment at the Gritney (P=0.0461) and Cecil (P=0.0457) sites (Table 2.4).

Soil Moisture

Soil water content varied throughout the growing season with generally reduced moisture in summer due to lower precipitation and greater evapotranspiration. Overall, tillage resulted in lower volumetric moisture values, and the difference of moisture values between T and NT areas were less accentuated in deeper horizons (0.30-0.60 m) (Fig. 2.6). The greatest differences were measured at the Piedmont site Lloyd, where tilled rows were on average 15 % drier than non-tilled rows, in the 0.15-0.30 m interval, and 12 % drier in the 0.30-0.60 m interval.

Flatwoods sites

One year growth data did not generate any consistent growth response pattern related to tillage and cultural treatments (Fig. 2.9). Although glyphosate was applied to control competing vegetation, considerable vegetation developed on F+V subplots. Statistical analysis did not suggest any significant growth difference between treatments. Collected data indicates that the response dynamics to tillage and cultural treatments associated with the Flatwoods region after the first growing season differs from Piedmont and Upper Coastal Plain regions.

Discussion

Tillage treatments can be effective at ameliorating soil physical limitations to growth whether they occur naturally or resulting from soil compaction due to equipment trafficking. In this investigation, there was a positive correlation between tillage and pine growth. This positive correlation was most likely due to improved soil physical conditions that enabled pine tree seedlings to better capture and exploit soil resources (Wheeler et al.,2002, Allen et al., 2005 and Carlson et al., 2006). Positive response to tillage was mainly associated with reducing soil resistance. Tillage treatments at sites with greater soil mechanical impedance resulted in consistent positive early growth responses. For example, subsoiling treatment at the Rion site reduced soil resistance considerably (Fig. 2.4), directly affecting seedling development. However, tillage did not result in a significant growth response at the Red Bay (LS/SCL) and

Lloyd (10" L/CL) sites. Although there was an indication of a possible tillage pan present at the Red Bay site (Table 2.4 and Fig. 2.5), NT soil resistance values for this particular location did not seem to be limiting growth. This was despite the fact that during dry periods soil resistance values were in the 2,000 - 3,500 kPa range (Fig. 2.5), above the restrictive 2,000 kPa limit suggested by some investigators (Dasilva, Kay et al. 1994). Overall, T areas were drier than NT, as depicted in the soil volumetric moisture data for this site (Fig. 2.6). The insignificant difference in terms of pine tree development at T and NT areas is likely to be correlated to seedlings' high root growth potential in this site (Dougherty and Gresham 1988), as soil resistance did not appear to limit roots to exploit soil resources.

The deep topsoil present in the Lloyd (10"L/CL) site naturally provided an environment more conducive to root development (Fig.2.3) (Haines and Davey, 1979), and this was supported by the growth data (Fig.2.7). The moisture data for this particular location indicated significant water depletion as a result of the subsoiling treatment. Unlike other sites included in this investigation, at the Lloyd site, tillage significantly affected moisture at the 0.30 - 0.60 m depth (Fig.2.8), suggesting that subsoiling negatively influenced growth by generating water stress in the rooting zone. Previous studies have reported the effects of tillage practices on saturated soil hydraulic conductivity on loamy texture soils. Pikul and Aase (2003), investigating the effect of subsoiling and subsoiling/disking on water infiltration and storage, showed that the Williams loam soil considered in that study could hold only ≈ 450 mm of water in the top 1.83 m (0.25 m m^{-3}), and water infiltration and drainage data provided evidence that runoff and deep percolation occurred rapidly. Their study showed that subsoiling initially improved infiltration, but no additional water storage was discernable after 15 days. Water loss due to soil loosening has also been investigated in laboratory studies. Foil and Raston (1967) compared growth of loblolly pine seedlings after simulating traffic and tillage treatments. Trafficking was simulated by compacting (using a bearing-ratio test machine) and tillage by loosening (using a trowel) soils presenting loamy sand, loam and clay textures. By the end of the first growing season, in the loamy sand soil, loosening reduced height growth in comparison to undisturbed soil, while compaction treatments resulted in uniformly retarded seedling height growth. The growth decline associated with loosening the loamy sand soil was attributed to reduced water availability and nutrients resulting from limited lateral root proliferation into zones of air filled porosity, although considerable vertical growth was noticed.

Comparing subsoiling and subsoiling/disking treatments, Pikul and Aase (2003) concluded that the first improved water infiltration, but the latter disrupted the vertical continuity of macropore channels, reducing water infiltration rates. Similar results were obtained by Reynolds et al. (1995), investigating the effect of subsoiling and combination subsoiling/disking on water movement in sandy clay loam, sandy, and sandy loam soils.

Although the overall effect of soil tillage on tree size may decrease with stand age, the benefits of accelerated early growth may persist throughout stand development. Morris and Lowery (1988) suggested that short-term response to tillage is related to increased nutrient availability due to greater decomposition and mineralization rates, and longer term tillage responses to increased macroporosity on fine textured soils. Considering that most sites in this study in the Piedmont and Upper Coastal Plain regions are relatively fine textured, it is likely that tillage may have a longer positive impact on these uplands sites than on sandy Flatwoods sites.

Overall, growth response at subplots that were tilled, but did not receive any further cultural treatment besides operational site preparation, was lower compared to subplots that were not tilled but received fertilizer application and herbaceous weed control. This is consistent with the findings of Carlson et al. (2006). The response loss to isolated F application is likely to be related to increased interespecific competition from herbaceous and woody plants promoting a negative impact on moisture, nutrient, light availability, and rooting volume (Morris et al., 1993 and Martin and Shivers, 2002).

Quantifying the magnitudes and mechanisms of southern pine growth responses to intensive site preparation has important implications for meeting future silviculture demands in the South. This study did not evaluate the best tillage treatment for every site. Rather, we utilized operational tillage associated with further cultural treatments as an attempt to better explain site-specific growth response. Overall, tillage resulted in positive growth response. The greatest growth was associated with the Upper Coastal Plain site Troup, where the interaction of tillage and fertilizer plus herbaceous weed control resulted in an average SVI of 8932.0 $cm^3 \pm 784.8$ SE. The lowest growth was observed in the Upper Coastal Plain site Faceville, where the non-tilled rows associated with operational site preparation resulted in an average SVI of 101.0 $cm^3 \pm 35.3$ SE. Growth response was reasonably well correlated with measured differences in average resistance in tilled and non-tilled rows. Operational soil tillage reduced resistance by a maximum of 51 %, measured at the Piedmont site Rion, and by a minimum of 9 %, measured at the Upper Coastal Plain site Gritney. Generally, soil tillage also reduced volumetric water content, and the greatest water depletion was measured at the Piedmont site Lloyd, where tilled rows were on average 15 % drier than non-tilled rows, in the 0.15-0.30 m interval, and 12 % drier in the 0.30-0.60 m interval.

Table2.1. Characteristics of eleven sites used in field experiments of growth response to operational tillage vs. non-tilled conditions.

Location	Texture[£]	Drainage[§]	Soil Series	Operational site prep.	Planted[1]
Piedmont					
Watkinsville, GA	2” SL/CL	W	Cecil	08/03/2003- clearcut null 05/11/2004- chemical aerial 10/07/2004- mechanical round pile and mechanical subsoiling	2/14/2005
Watkinsville, GA	10” L/CL	W	Lloyd	09/25/2003- clearcut null 05/17/2004- chemical aerial 10/19/2004- mechanical round pile and mechanical subsoiling	2/14/2005
White Plains, GA	2” SL/SCL	W	Rion	09/25/2003- clearcut null 05/17/2004- chemical aerial 10/19/2004- mechanical round pile and mechanical subsoiling	2/14/2005
Upper Coastal Plain					
Lumpkin, GA	2” LS/SCL	W	Red Bay	03/16/2004- mechanical subsoiling/disking 09/28/2004- chemical aerial	2/15/2005
Lumpkin, GA	2” CL/SC	MW	Faceville	03/11/2004- mechanical subsoiling/disking 09/17/2004- chemical aerial	2/15/2005
Lumpkin, GA	3” LS/SC	SP	Gilead	03/11/2004- mechanical subsoiling/disking 09/17/2004- chemical aerial	2/15/2005
Lumpkin, GA	8” LS/SL	W	Troup	03/11/2004- mechanical subsoiling/disking 09/19/2004- chemical aerial	2/15/2005
East of Omaha, AL	16” LS/C	SP	Gritney	10/23/2004- chemical aerial 11/15/2004- mechanical round pile 12/15/2004- mechanical disking	2/16/2005
Flatwoods					
Hilliard, FL	30” S/SL	SP	Olustee	11/2005- mechanical disking	2/1/2006
Hilliard, FL	60” LS/SL	SP	Chipley	11/2005- mechanical disking	2/1/2006
Hilliard, FL	50” S/LS	P	Osier	11/2005- mechanical disking	2/1/2006

1 Planted with varieties: LB-SE Q3802, LB-SE L3519 and LB-SE O3621 (Cellfor Corp. Atlanta,GA);
£ Textures related to surface and subsurface. Numbers indicate depth of surface horizon;
§ Drainage Class: W-Well, MW-Moderately Well, SP-Somewhat Poorly, P-Poorly drained.

Table 2.2. Loblolly pine planted on tilled and non-tilled rows, receiving three cultural treatments. Average height (Ht), ground line diameter (GLD) and stem volume index (SVI) after two growing seasons – Upper Coastal Plain and Piedmont sites.

Site		Ht (cm)		GLD (mm)		SVI[*] (cm^3)	
		T	NT	T	NT	T	NT
				UCP			
Red Bay							
	O	[§¶]178^{a,c}	142^{a,c}	43.1^{a,c}	32.9^{a,c}	3307^{a,c}	1537^{a,c}
	F	140^{a,c}	157^{a,c}	33.1^{a,c}	34.8^{a,c}	1534^{a,c}	1901^{a,c}
	F+V	222^{a,d}	199^{a,d}	46.5^{a,d}	44.2^{a,d}	4800^{a,d}	3888^{a,d}
Faceville							
	O	120^{a,c}	70^{b,c}	25.7^{a,c}	12.0^{b,c}	793^{a,c}	101^{b,c}
	F	150^{a,c}	93^{b,c}	35.2^{a,d}	19.4$^{b.d}$	1859^{a,d}	350^{b,d}
	F+V	175^{a,d}	136^{b,d}	40.0^{a,d}	27.3^{b,d}	2800^{a,d}	1014^{b,d}
Gilead							
	O	144^{a,c}	110^{b,c}	29.6^{a,c}	20.6^{b,c}	1262^{a,c}	467^{b,c}
	F	125^{a,c}	77^{b,c}	26.3^{a,c}	14.4^{b,c}	865^{a,c}	160^{b,c}
	F+V	227^{a,d}	147^{b,d}	49.0^{a,d}	32.7^{b,d}	5450^{a,d}	1572^{b,d}
Troup							
	O	235^{a,C}	221^{B,C}	53.0^{a,c}	43.9^{B,c}	6601^{a,c}	4259^{B,c}
	F	226^{a,C}	187^{B,C}	50.6^{a,c}	36.4^{B,c}	5786^{a,c}	2478^{B,c}
	F+V	261^{a,C}	245^{B,C}	58.5^{a,d}	49.3^{B,d}	8932^{a,d}	5955^{B,d}
Gritney							
	O	164^{a,c}	156^{b,c}	31.9^{a,c}	27.6^{b,c}	1669^{a,c}	1188^{B,c}
	F	198^{a,c}	177^{b,c}	40.4^{a,c}	30.2^{b,c}	3232^{a,c}	1614^{B,c}
	F+V	231^{a,d}	182^{b,d}	46.9$^{a.d}$	38.2^{b,d}	5081$^{a.d}$	2656^{B,d}
				Piedmont			
Cecil							
	O	153^{a,c}	113^{b,c}	31.3^{a,c}	19.9^{B,c}	1499^{a,c}	447^{B,c}
	F	162^{a,d}	127^{b,d}	32.0^{a,c}	21.5^{B,c}	1659^{a,c}	587^{B,c}
	F+V	167^{a,d}	164^{b,d}	36.3^{a,d}	33.3^{B,d}	2201^{a,d}	1819^{B,d}
Lloyd							
	O	120^{a,c}	127^{a,c}	23.3^{a,c}	22.2^{a,c}	651^{a,c}	626^{a,c}
	F	148^{a,d}	181^{a,d}	32.8^{a,d}	30.5^{a,d}	1592^{a,c}	1684^{a,c}
	F+V	173^{a,d}	200^{a,d}	36.6^{a,e}	41.7^{a,e}	2317^{a,d}	3478^{a,d}
Rion							
	O	168^{a,c}	138^{b,c}	32.8^{a,c}	27.5^{b,c}	1807^{a,c}	1044^{b,c}
	F	171^{a,c}	118^{b,c}	32.9^{a,c}	25.8^{b,c}	1851^{a,c}	785^{b,c}
	F+V	175^{a,c}	150^{b,c}	39.5^{a,c}	29.1^{b,c}	2730^{a,c}	1270^{b,c}

* SVI = Hgt(cm)x ground line diameter^2 (cm^2).
§ Means with dissimilar first letters are significantly different for tillage treatment at the 0.05 (lower case) and 0.10 (upper case) level using Tukey's significance difference test.
¶ Means with dissimilar second letters are significantly different for cultural treatments at the 0.05 (lower case) and 0.10 (upper case) level using Tukey's significance difference test.

Table 2.3. Summary of statistical significance (P<F) for tree growth responses to tillage, clone, cultural treatment and interaction between tillage and cultural treatment after two growing seasons in the UCP and Piedmont regions.

Source		DF	Ht	GLD	SVI
			Upper Coastal Plain		
Orangeburg					
	till £	1	0.4227	0.2933	0.3357
	clone	2	0.9431	0.5631	0.9012
	cult §	2	0.0046	0.0094	0.0021
	till x cult	2	0.1887	0.1514	0.2201
Faceville					
	till	1	0.0321	0.0207	0.039
	clone	2	0.2227	0.5473	0.7451
	cult	2	0.0028	0.0011	0.0213
	till x cult	2	0.7679	0.8199	0.4513
Gilead					
	till	1	0.0152	0.0136	0.0545
	clone	2	0.0532	0.2064	0.5314
	cult	2	0.0002	<0.0001	<0.0001
	till x cult	2	0.0836	0.1858	0.0049
Troup					
	till	1	0.1155	0.1155	0.1045
	clone	2	0.1475	0.8794	0.7628
	cult	2	0.1022	0.0035	0.0072
	till x cult	2	0.757	0.4072	0.7663
Gritney					
	till	1	0.0513	0.054	0.1166
	clone	2	0.0556	0.1716	0.3055
	cult	2	0.0614	0.002	0.0042
	till x cult	2	0.5573	0.8258	0.5645
			Piedmont		
Cecil					
	till	1	0.0519	0.0639	0.0691
	clone	2	0.2572	0.6719	0.7646
	cult	2	0.0315	0.0082	0.0154
	till x cult	2	0.1669	0.1969	0.7627
Lloyd					
	till	1	0.3599	0.9797	0.7429
	clone	2	0.2425	0.5863	0.4347
	cult	2	0.0113	0.0009	0.0024
	till x cult	2	0.6705	0.5013	0.6712
Rion					
	till	1	0.0324	0.022	0.0148
	clone	2	0.1178	0.6477	0.2774
	cult	2	0.6631	0.4655	0.4386
	till x cult	2	0.7436	0.8234	0.9207

£ T and NT treatment
§ Cultural treatments: fert., herb. + fert. and operational site prep.

Table 2.4. Average soil resistance values of four penetrometer measurements by tillage and cultural treatments over three different depth increments.

	depth (m)					
	0-0.15		0.15-0.30		0.30-0.60	
Site	T*	NT*	T	NT	T	NT
	kPa					
			UPC			
Red Bay						
O[b]	1493	3015	2046	3061	2559	2942
F[a]	1629	3387	2522	3575	3039	3488
F+V[b]	1336	2632	1707	2574	2275	2567
Faceville						
O[b]	1198	2512	1792	2761	2100	2742
F[a]	1123	2604	1891	3175	2518	3218
F+V[b]	998	2293	1474	2511	2143	2813
Gilead						
O[a]	745	1896	1479	2502	2237	2742
F[a]	821	1789	1502	2661	2075	2825
F+V[a]	927	2360	1281	2665	2086	2749
Troup						
O[a]	1021	1682	1997	2967	3434	4246
F[a]	689	1826	1598	2952	2953	3612
F+V[a]	715	1952	1437	3255	2518	3357
Gritney						
O[a]	1021	1618	1243	1605	1619	1770
F[b]	832	1396	1189	1653	1502	1755
F+V[b]	870	1184	1014	1487	1473	1733
			Piedmont			
Cecil						
O[a]	1885	2776	2390	3611	3366	4072
F[b]	1675	2361	1798	2959	3334	4108
F+V[b]	1886	2505	2373	3521	2924	3798
Lloyd						
O[a]	946	2225	1410	2928	2501	3191
F[a]	1046	2344	1615	3390	2695	3307
F+V[a]	961	1710	1113	2215	2023	2645
Rion						
O[a]	1498	2329	2165	3838	3188	4231
F[a]	1489	2970	2113	4328	2637	4361
F+V[a]	2161	3066	2869	4158	4033	4683

1 Averages with the same letters do not differ significantly using Tukey's significance difference test (α=0.05)
* All soil resistance values are statistically different for T and NT treatment comparison (α=0.05)

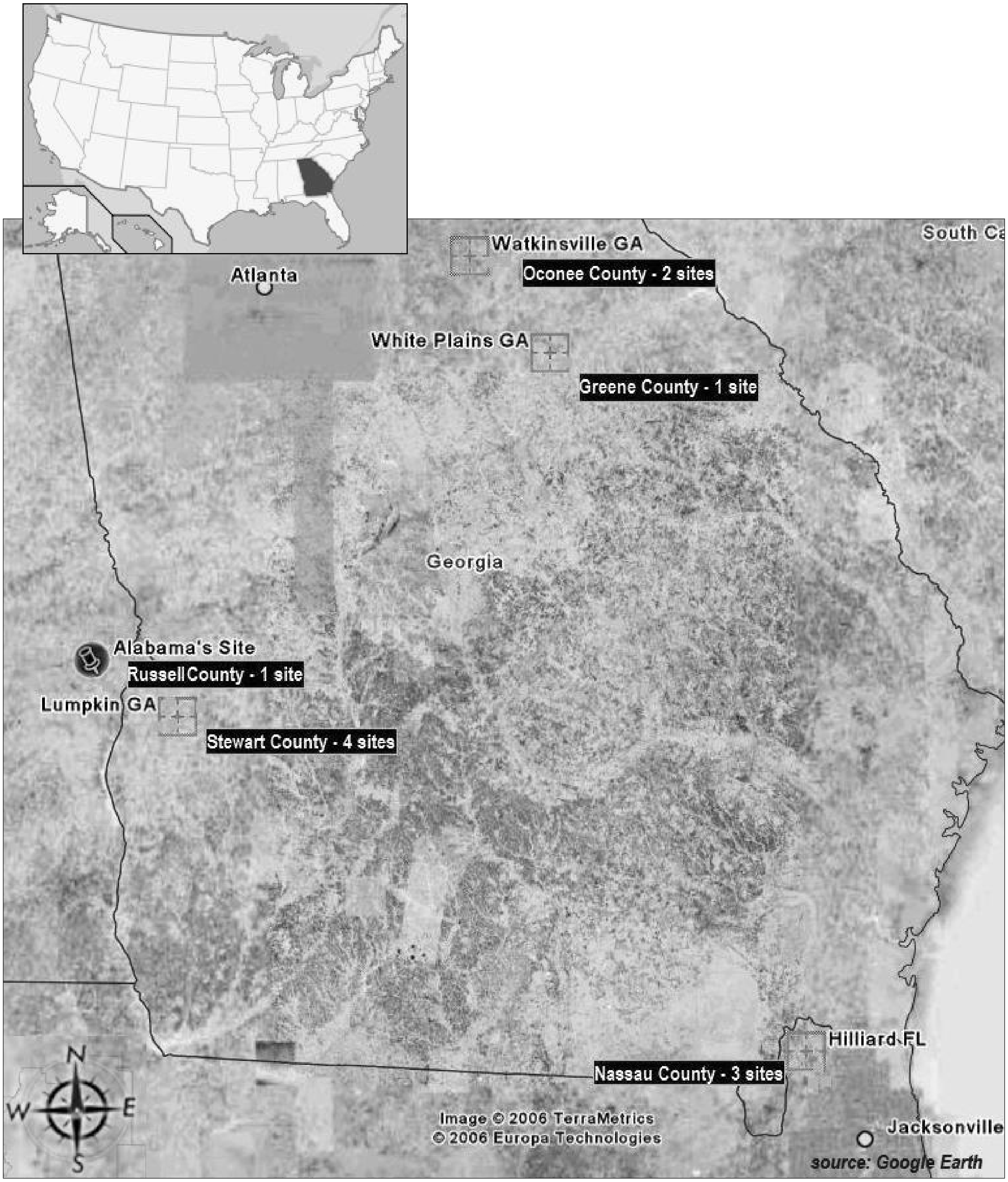


Fig.2.1. Site location map.

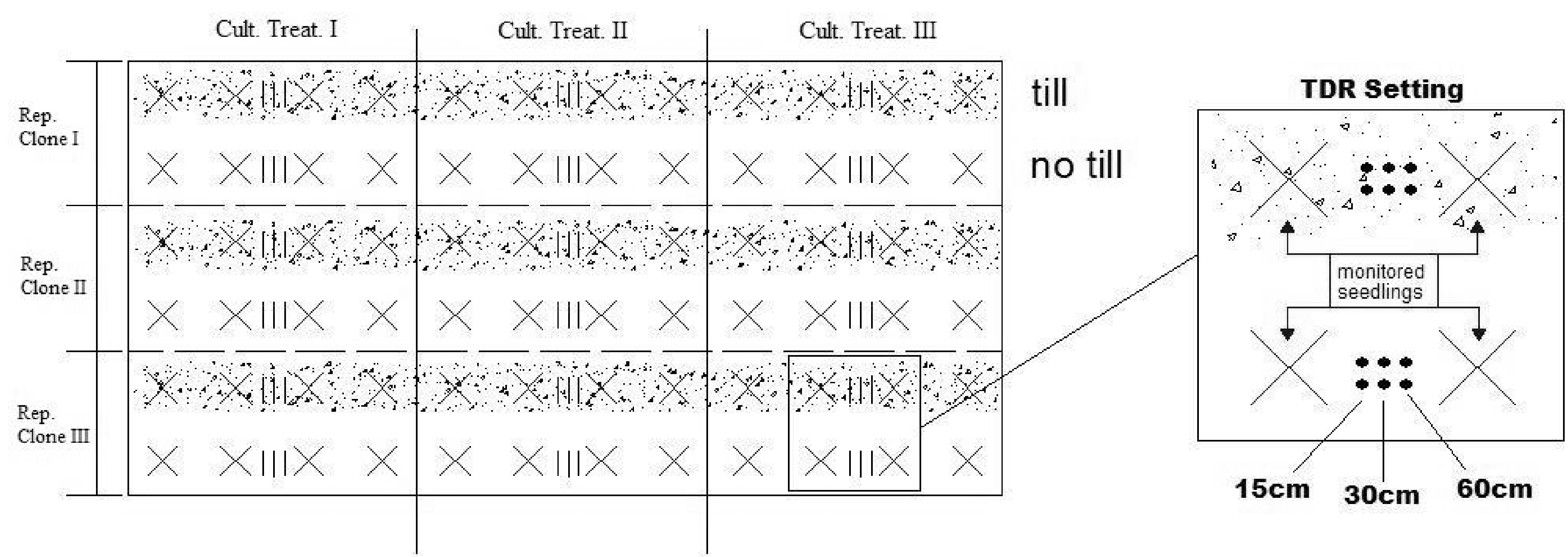
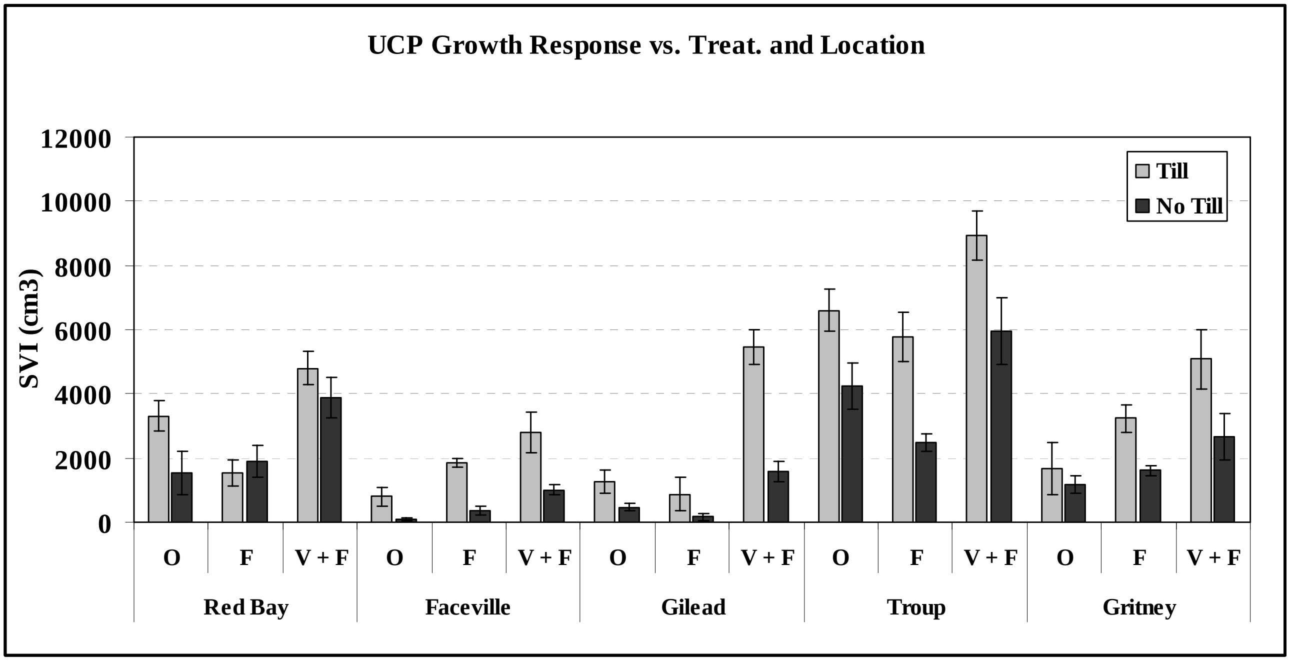


Fig. 2.2. Site schematics showing tillage (T, NT) and cultural (O, F, F+V) treatments; three different clone replicates: LB-SE Q3802, LB-SE L3519 and LB-SE O3621, and TDR rod settings.



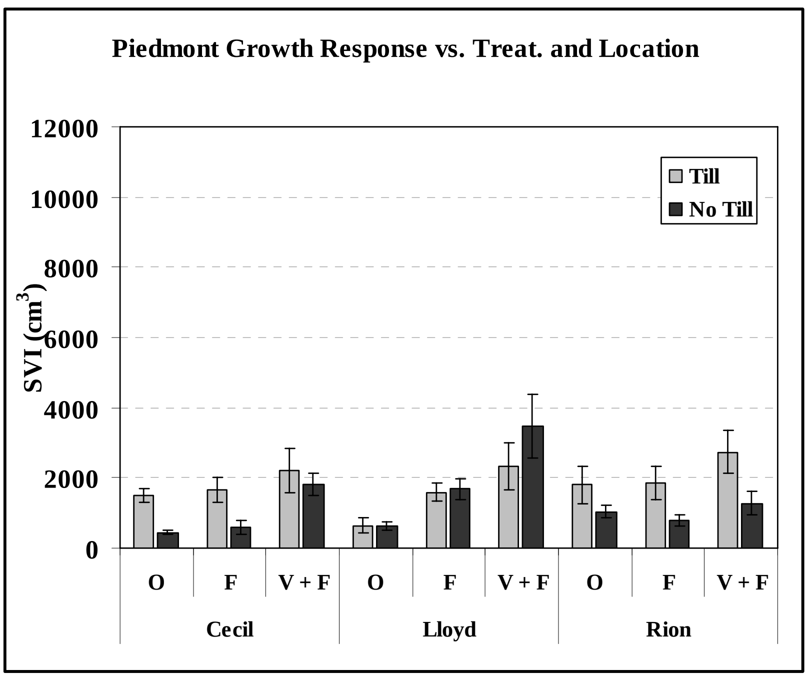
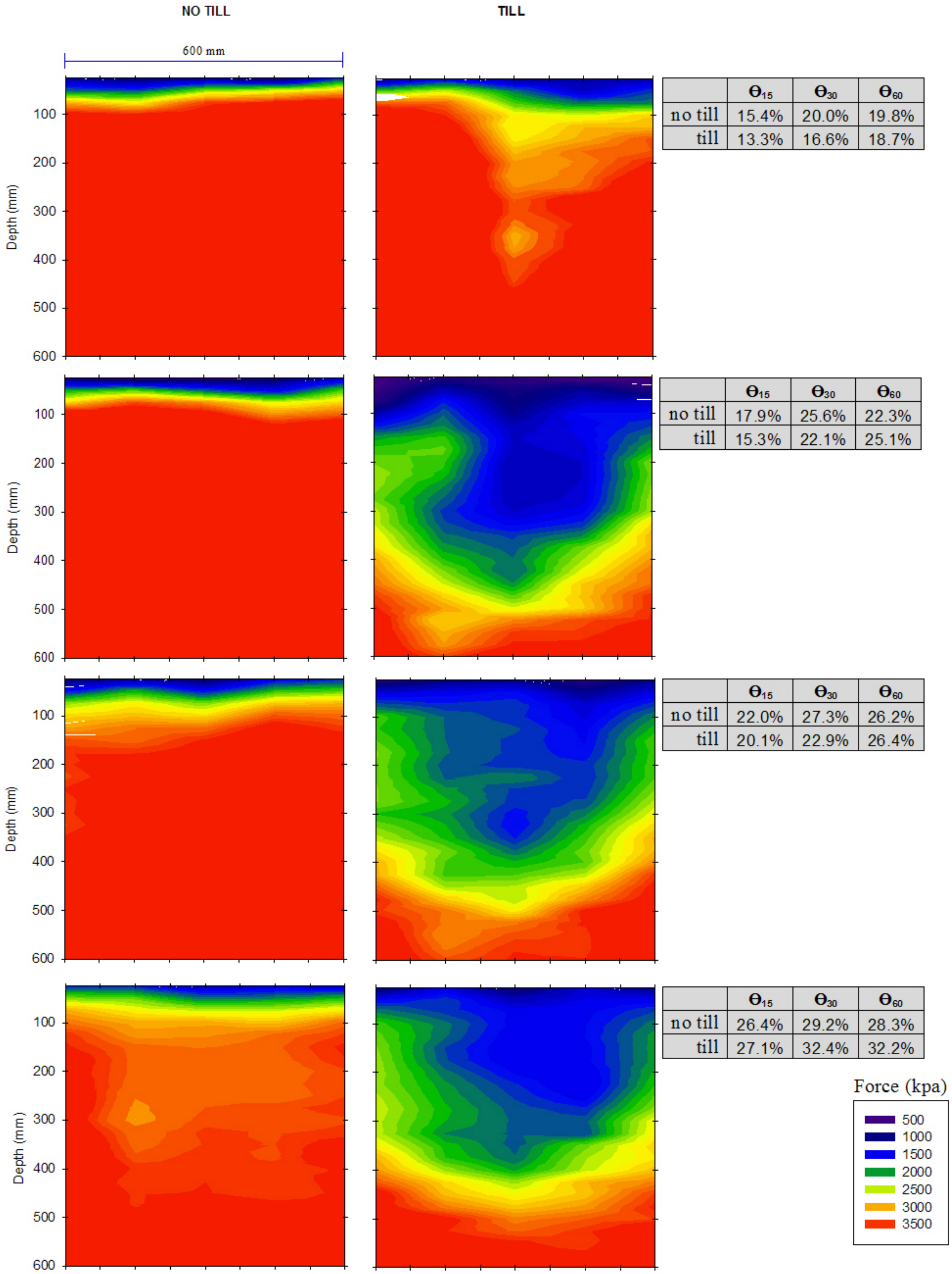


Fig. 2.3. Second year growth response and s.e. for tillage and cultural treatments. UCP and Piedmont regions. Each value corresponds to the average of six trees (two per clone replicate).



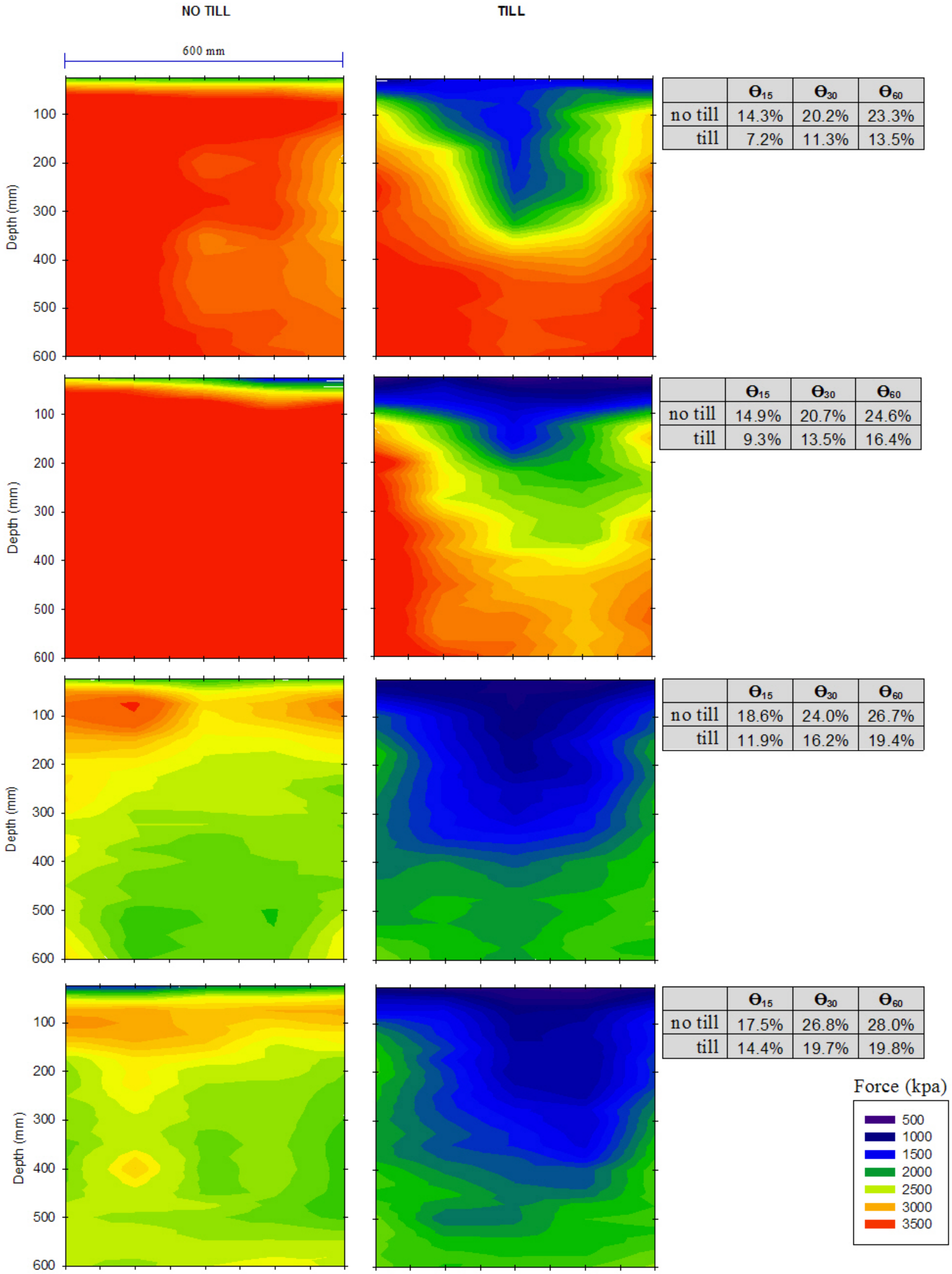
	Θ_{15}	Θ_{30}	Θ_{60}
no till	15.4%	20.0%	19.8%
till	13.3%	16.6%	18.7%

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

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

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

Fig 2.4. Rion site (Piedmont). Average soil resistance for T (subsoiling) and NT treatments. Measurements taken over four different moisture conditions.



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

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

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

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

Fig 2.5. Red Bay site (UCP). Average soil resistance for T (subsoiling/disking) and NT treatments. Measurements taken over four different moisture conditions.

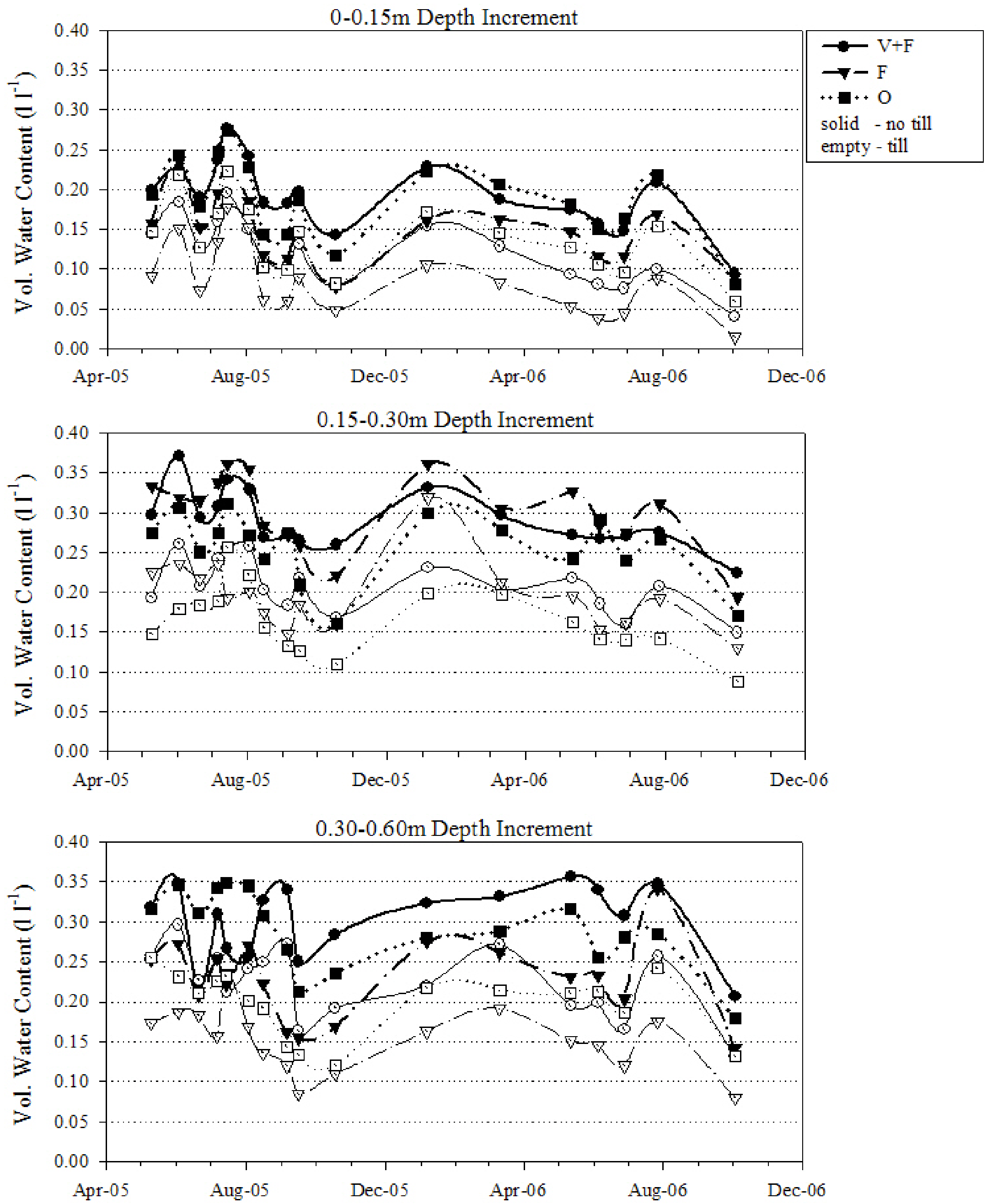
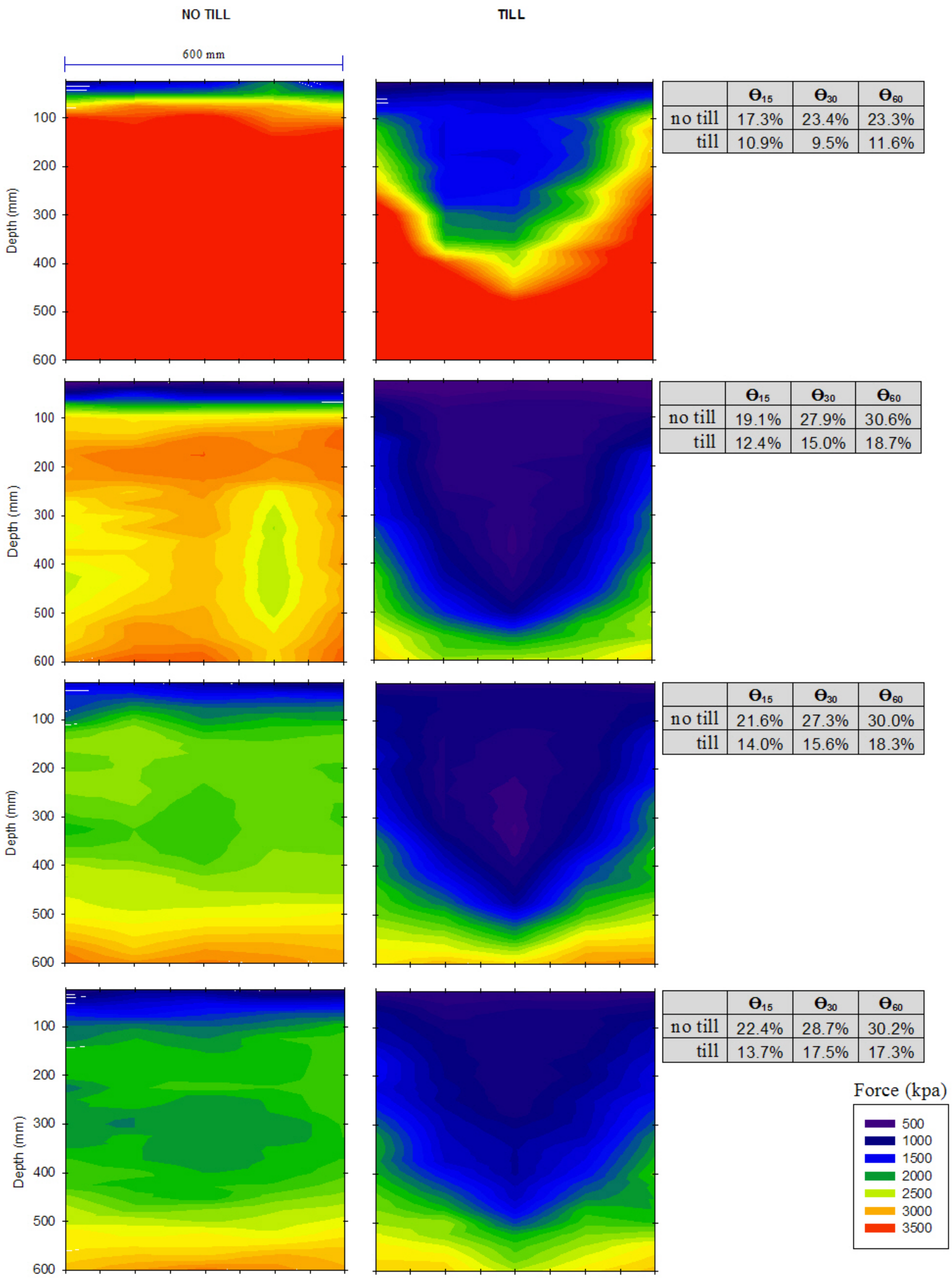


Fig. 2.6. Volumetric water content by tillage and cultural treatment during two growing seasons. Red Bay site - UCP region.



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

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

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

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

Fig 2.7. Lloyd (10"L/CL) site (Piedmont). Average soil resistance for T (subsoiling) and NT treatments. Measurements taken over four different moisture conditions.

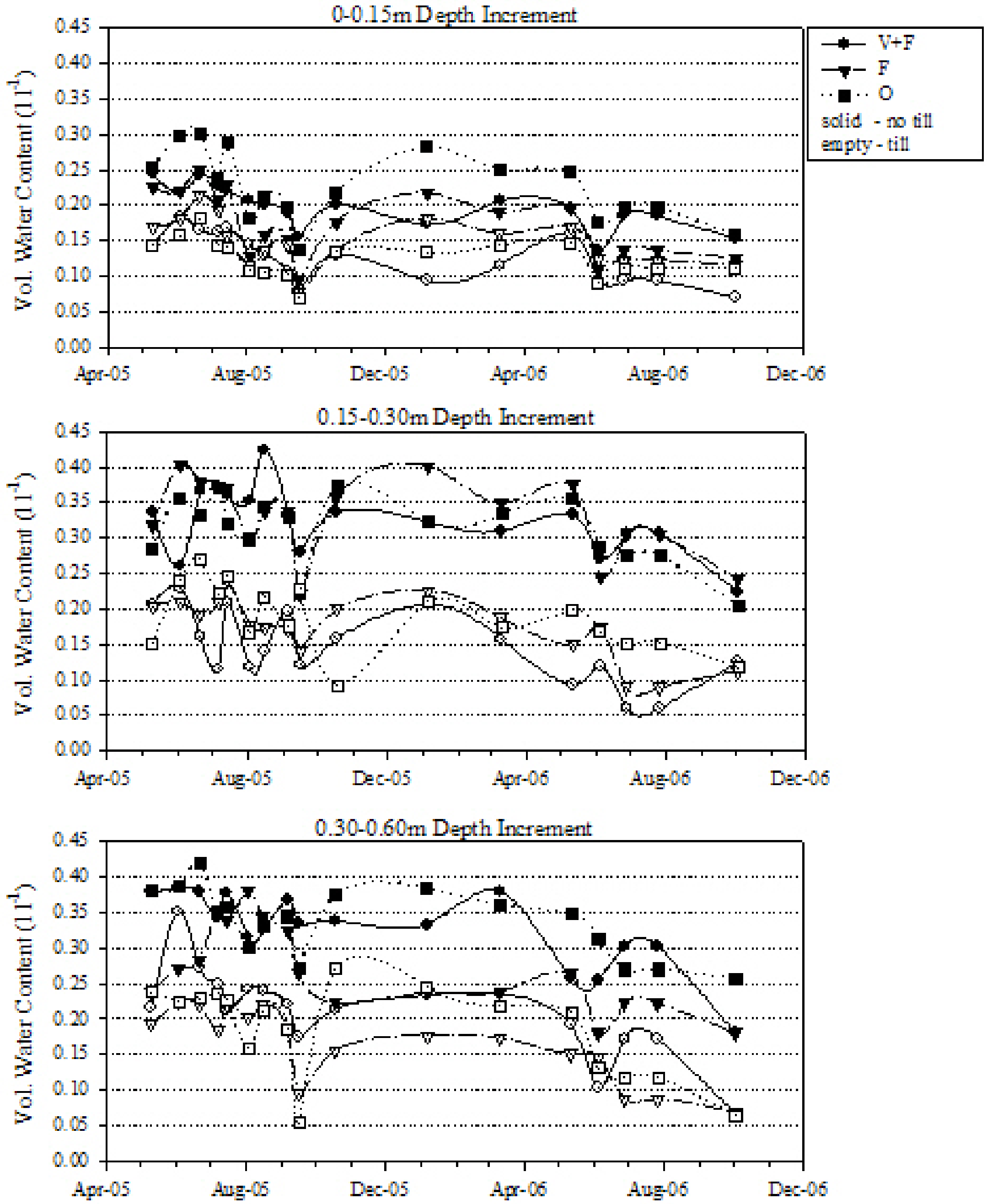


Fig. 2.8. Volumetric water content by tillage and cultural treatment during two growing seasons. Lloyd (10”L/CL) site - Piedmont region.

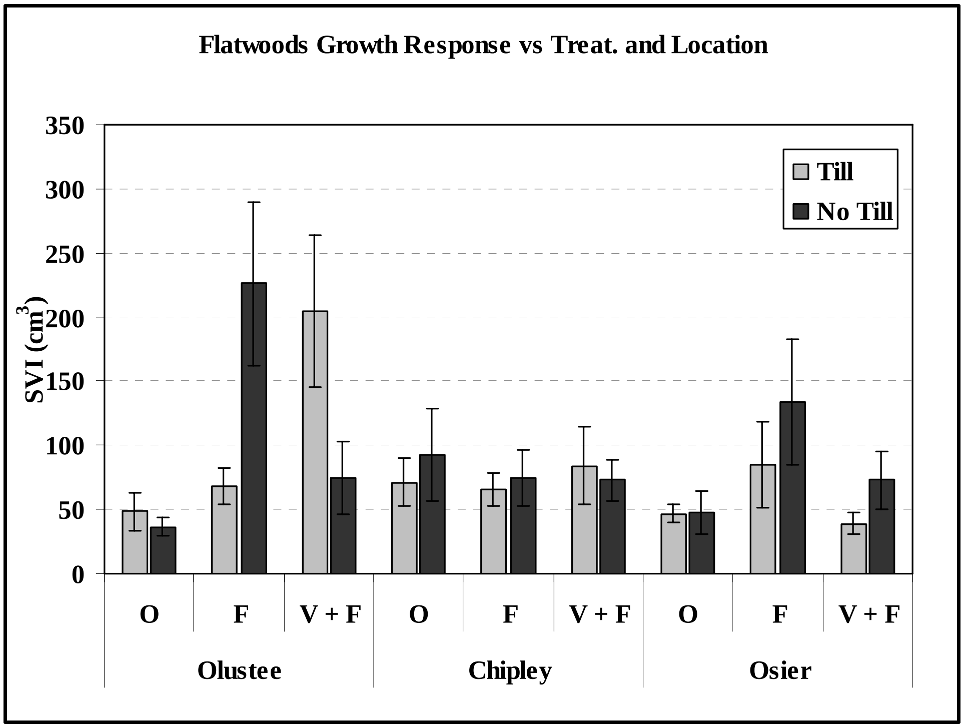


Fig. 2.9. First year average growth response and s.e. for tillage and cultural treatments. Flatwoods region. Each value corresponds to the average of six trees (two per clone replicate).

References

Adams, P.W., Froehlich,H.A.,1981. Compaction of forest soils. Oregon State Univ. Corvallis, Extension Service, PNW-217, 13 p.

Allen, H.L., Dougherty, P.M., Campbell, R.G., 1990. Manipulation of water and nutrients -- Practice and opportunity in Southern U.S. pine forests. Forest Ecology and Management 30, 437-453.

Allen, H.L.,2001. Silvicultural treatments to enhance productivity. Chapter 6 in the Forests Handbook. Vol II. Evans,J. (ed.). Blackwell Science Ltd., Oxford,UK, 382p.

Allen,H.L., Fox, T.R., Campbell, R.G., 2005. What is Ahead for Intensive Pine Plantation Silviculture in the South? South J. Appl. For. 29(2), 62-69.

Carlson, C.A., Fox, T.R., Colbert, S.R., Kelting, D.L., Allen, H.L., Albaugh, T.J., 2006. Growth and survival of Pinus taeda in response to surface and subsurface tillage in the southeastern United States. Forest Ecology and Management 234, 209-217.

Da Silva,A.P., Kay,B.D., Perfect E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58:1775–1781.

Defossez, P., Richard, G., 2002. Models of soil compaction due to traffic and their evaluation. Soil and Tillage Research 67, 41-64.

Dougherty,P.M., Gresham,C.A., 1988. Conceptual Analysis of Southern Pine Plantation Establishment and Early Growth. South. J. Appl. For. 12(3),160-166.

Eisenbies, M.H., Burger, J.A., Aust, W.M., Patterson, S.C., 2005. Soil Physical Disturbance and Logging Residue Effects on Changes in Soil Productivity in Five-Year-Old Pine Plantations. Soil Sci. Am.J. 69, 1833-1843.

Fisher,R.F., Binkley,D.,2000. Ecology and Management of Forest Soils (3rd ed.), Wiley Publishers 512 pp.

Foil,R.R., Ralston,C.W.,1967. The establishment and growth of loblolly pine seedlings on compacted soils. Soil Sci. Am.J. 31, 565-568.

Froehlich, H.A., Miles, D.W.R., Robbins, R.W., 1986. Growth of young Pinus ponderosa and Pinus contorta on compacted soil in central Washington. Forest Ecology and Management 15, 285-294.

Greacen, E.L., Sands,R.,1980. Compaction of Forest Soils – A Review. Aust. J. Soil. Res. 18,163-189.

Haines,S.G., Davey,C.B., 1979. Biomass response of loblolly pine to selected cultural treatments. Soil Sci. Am.J. 43, 1034-1038.

Haynes, R.W., 2002. Forest Management in the 21st Century: Changing Number, Changing Context. J. For. 100(2), 38-43.

Haywood, J.D., 1994. Early Growth Reductions in Short Rotation Loblolly and Slash Pine in Central Louisiana. South J. Appl. For. 18, 35-39.

Jokella, E.J., Wilson, D.S., Allen, J.E., 2000. Early Growth Responses of Slash and Loblolly Pine Following Fertilization and Herbaceous Weed Control Treatments at Establishment. South J. Appl. For. 24,23-30.

Kozlowski, T.T.,1999. Soil Compaction and Growth of Woody Plants. Scand. J. For. Res. 14, 596-619.

Lacey, S.T., Ryan, P.J., 2000. Cumulative management impacts on soil physical properties and early growth of Pinus radiata. Forest Ecology and Management 138, 321-333.

Ludovici, K.H., Morris, L.A.,1996 Responses of loblolly pine, sweetgum, and crab grass roots to localized increases in nitrogen in two watering regimes. Tree Physiol. 16, 933-939.

Martin, S.W., Shiver, B.D., 2002. Impacts of vegetation control, genetic improvement and their interaction on loblolly pine growth in the southern United States - age 12 results. South. J. Appl. For. 26(1),37-42.

McClurkin, D.C. and Duffy, P.D., 1975. Evaluating Impact of Forest Site Preparation on Soil and Water Quality in the U.S. Gulf Coastal Plain. In: Bernier, B. and Winget, C., H.

Forest Soils and Forest Land Management. Proceedings of the Fourth North American Forest Soils Conference 1973, Quebec, pp. 315-321.

Morris, L.A., Lowery,R.F.,1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South. J. Appl. For. 12(3), 170-178.

Morris, L.A., Moss,S.A., Garbett, W.S.,1993. Competitive interference between selected herbaceous and woody plants and *Pinus taeda* L. during two growing seasons following planting. For. Sci. 39, 166-187.

Morris, L.A., Ludovici, K.H., Torreano, S.J., Carter, E.A., Lincoln, M.C., Will, R.E., 2006. An approach for using general soil physical condition-root growth relationships to predict seedling growth response to site preparation tillage in loblolly pine plantations. Forest Ecology and Management 227, 169-177.

Nilsson, U., Allen, H.L., 2003. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. Forest Ecology and Management 175, 367-377.

Page-Dumroese, Deborah S.; Jurgensen, Martin F.; Tiarks, Allen E.; Ponder, Felix; Sanchez, Felipe G., Jr.; Fleming, Robert L.; Kranabetter, J. Marty; Powers, Robert F.; Stone, Douglas M.; Elioff, John D.; Scott, D. Andrew 2006. Soil physical property changes at the North American long-term soil productivity study sites: 1 and 5 years after compaction. Canadian Journal of Forest Research. 36(3): 551-564.

Pehl, C.E., 1983. Site Preparation Influences on Young Loblolly Pine Plantations in East Texas. South J. Appl. For. 7, 140-145.

Pikul, J. L., Aase Jr.J. K.,2003.Water Infiltration and Storage affected by Subsoiling and Subsequent Tillage. Soil Sci. Am.J.. 67(3): 859-866.

Prestemon, J.P. and Abt, R.C., 2002. The Southern Timber Market to 2040. J. For. 100(7), 16-22.

Rahman, M.S., Messina, M.G., Fisher, R.F., 2006. Intensive Forest Management Affects Loblolly Pine (Pinus taeda L.) Growth and Survival on Poorly Drained Sites in Southern Arkansas. South J. Appl. For. 30, 79-85.

Reynolds, W. D.,Gregorich,E.G., Curnoe,W.E.,1995.Characterisation of water transmission properties in tilled and untilled soils using tension infiltrometers. Soil and Tillage Research 33,117-131.

Sands, R., Graecen, E.L., Gerard, C.J., 1979. Compaction of sandy soils in Radiata pine forests. I. A penetrometer study. Aust. J. Soil Res. 17, 101–113.

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

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

Tiarks,A.E.,Haywood, J. D.,1996 Site preparation and fertilization effects on growth of slash pine for two rotations, Soil Sci. Soc. Amer. J. 60, 1654–1663.

Topp,G.C; Davis,J.L.,1985. Measurement of Soil Water Content Using Time-Domain Reflectrometry (TDR): A Field Evaluation. Soil Sci. Soc. Amer. J. 49, 19–24.

Unger, P.W., Kaspar, T.C.,1994. Soil Compaction and Root Growth: A Review. Agron. J. 86, 759-766.

Vitousek, P.M., Matson, P.A., 1985. Intensive Harvesting and Site Preparation Decrease Soil Nitrogen Availability in Young Plantations. South. J. For. 9, 120-125.

Wheeler,M.J., Jacobson,M.A., Shirley,A.M., Will,R.W., Markewitz,D.,2002. Early loblolly pine stand response to tillage on the Piedmont and Upper Coastal Plain of Georgia: mortality, stand uniformity, and second and third year growth. South. J. Appl. For. 26(4),181-189.

Wittwer, R.F., Dougherty, P.M., Cosby, D., 1986. Effects of Ripping and Herbicide Site Preparation Treatments on Loblolly Pine Seedling Growth and Survival. South J. Appl. For. 10, 253-257.

CHAPTER III

EFFECTS OF SOIL TILLAGE ON SOIL PHYSICAL PROPERTIES AND THEIR RELATIONSHIP TO EARLY LOBLOLLY PINE GROWTH[2]

[2] Furtado, B.F., Morris, L., Markewitz, D. and Radcliffe, D. 2007. To be submitted to *Soil and Tillage Research*.

Abstract

Compaction during harvest can decrease forest productivity by increasing soil physical impedance and by reducing oxygen supply to the roots due to reduction of macropore volume. Site preparation tillage, such as subsoiling, disking or bedding, can ameliorate these impacts but the costs of these tillage treatments are high and growth response is variable. Although basic relationships between loblolly pine growth and soil physical properties have been established, these have not been found useful for predicting pine growth response to soil tillage under field conditions. Soil physical properties and tree growth were measured during the first two growing seasons following operational soil tillage on 8 sites, in the Piedmont and Upper Coastal Plain of the Southeastern USA. The objectives of this investigation were to evaluate the growing season long response of soil resistance to operational tillage, and to test the use of a Soil Tilth Index based on the effect of operational tillage on soil resistance and relate that to tree growth. Our results indicate that soil resistance and volumetric water content overall could be described with a linear relationship, and soil resistance values throughout the growing season could be estimated using soil water content data. The proposed Soil Tilth Index worked as an efficient indicator to assess the likelihood of growth response to operational tillage. Overall, a positive response to tillage focusing on benefiting growth by soil resistance reduction could be expected at sites with $STI_g < 0.20$.

INDEX WORDS: Soil Resistance, Penetrometer, Volumetric Water Content, TDR, Fertilization, Herbaceous Weed Control, Loblolly Pine, *Pinus taeda*

Introduction

The southeastern United States is the world's largest single industrial wood producer, with approximately 40 million acres of industrial pine timberland (Prestemon and Abt 2002, Haynes, 2002 and Smith et al., 2004). Since the 1950's, mechanical site preparation has been considered essential to southern pine plantation management (Martin and Shiver, 2002). Mechanical site preparation, such as shearing, piling and chopping, can improve conditions for planting and enhance seedling survival. This is particularly true for compacted sites that have decreased macroporosity, poor structure and greater resistance to root penetration (Shiver and Fortson, 1979, Wittwer et al., 1986, Tiarks and Haywood, 1996 and Rahman et al., 2006). Water availability and nutrient resources can be improved by increasing the quantity and quality of soil volume available for rooting or by controlling competition vegetation (Pehl, 1983 and Martin and Shiver, 2002).

Tillage treatments can be effective at ameliorating soil physical limitations (e.g., reducing soil mechanical impedance, increasing aeration and porosity) whether they occur naturally or resulting from soil compaction due to equipment trafficking (Wheeler et al., 2002, Allen et al., 2005 and Carlson et al., 2006). Soil tillage during site preparation, such as disking, bedding, combination plowing or subsoiling, can affect physical, chemical and biological properties and processes (Morris and Lowery, 1988). The direct effects of tillage on soil resistance and aeration are apparent (Sands et al., 1979). However, tillage can also alter water holding capacity and water relations of the soil and improve nutrient availability by stimulating microbial activity and mineralization rates (Eisenbies et al., 2005). Different tillage treatments result in a different volume and configuration of tilled soil. Thus, understanding the restrictive conditions for root growth (aeration and/or soil resistance) is crucial to effectively use these treatments (Allen, 2001).

Previous studies have shown that the growth response to site preparation tillage is site specific (Wheeler et al., 2002 and Carlson et al., 2006). Currently there are no efficient methods to predict the benefits of tillage on an individual site, or how tillage will interact with fertilizer application and herbaceous weed control. Some researchers have suggested the incorporation of soil aeration, soil strength, and soil water potential measurements into a single index called the least limiting water range (LLWR), which describes soil quality in terms of plant growth (Da Silva et al. 1994). The LLWR is defined as the range in which water availability is non-limiting to plants, and it is bounded by both wet and dry ends. Field capacity or air-filled porosity less than 10 % represents the wet limit to growth; and wilting point characterized by soil strength greater than 2.0 MPa or water potential less than -1.5 MPa, represents the dry limit. As soil bulk density increases, the LLWR becomes narrower, with mechanical resistance becoming limiting at the dry end and reduction of oxygen supply becoming limiting at the wet end (Siegel-Issem and Burger 2005 and Morris et al., 2006). Siegel-Issem and Burger (2005) examined greenhouse pine seedling growth and developed a response surface describing root growth as a function of soil bulk density and volumetric moisture content. A general model to describe growth potential was also suggested based on the response surface. The authors concluded that the LLWR had potential as a soil quality indicator, but seedling response was not consistently associated with the LLWR. Instead, root length density response surface models used in conjunction with soil water content showed potential for determining compaction-induced soil limitations for tree growth, but they concluded that further investigations that considered both soil and plant species would be necessary to calibrate the model under field conditions.

One major disadvantage of the LLWR approach to predict seedling growth response, as discussed by Morris et al. (2006), is the fact that this model does not account for differences between growth conditions within the suitable range. On upland sites, the wet limit to growth (poor aeration) is rarely reached and most of the tree growth response is likely to be influenced by soil conditions below the dry limit stipulated within the LLWR (Morris et al., 2006). In an attempt to overcome this limitation, these investigators developed a model that utilized root growth response to soil resistance, water potential, and aeration. They tested their predicted growth against growth measured in a field study of soil tillage treatments on an Upper Coastal Plain site. Seedling height predicted by the model differed from measured average height by –1 to +14 %, with absolute differences in height of 0.1 m or less. The same model predicted above-ground biomass between –12 to +41 % of the average measured biomass.

Since growth response to tillage is likely to be affected both by inherent soil physical properties and the change in those properties that result from tillage (Carlson et al., 2006), the objectives of this investigation were to: (i) evaluate the growing season long response of soil resistance to operational tillage by developing relationships between soil resistance and soil water content; and (ii) test the use of a Soil Tilth Index based on the effect of operational tillage on soil resistance and relate that to tree growth.

Material and Methods

Site Locations

Eight experimental sites, with a common study design, were established in 2005 in Georgia and Alabama. Five sites were located in the Upper Coastal Plain (UCP) of Georgia and Alabama, on tracts of land owned by MeadWeastvaco. Four of these sites were established near the city of Lumpkin, in Stewart County, GA, and one in the proximity of East of Omaha, in Russell County, AL. Three sites were located in the Piedmont region, on tracts of land owned by PlumCreek, two in the proximity of the city of White Plains, in Greene County, GA, and one near Watkinsville, in Oconee County, GA. All sites were established on recently cut-over forested areas harvested approximately 1.5 years before the initial plot establishment, and were planted with three different loblolly (*Pinus taeda*) clone varieties.

Study Design and Installation

The sites were established using a strip-plot design in three replicate blocks. To control variability, each block consisted of a single clone, thus, clones were confounded with block effects. Strips consisted of three cultural treatments: no culture (O), fertilization alone (F), and fertilization plus weed control (F+V), intersecting with two tillage treatments: no tillage (NT) versus operational tillage (T). The cultural treatment strips were not completely randomized among blocks; consequently, cultural treatment randomization was applied on a site basis. The reason this violation was necessary was due to the small area of subplots, making it impractical to apply different cultural treatments on a subplot basis (Fig.2.2, Chapter II). Each subplot contained eight trees, four on the tilled line and four on the non-tilled (inter-row) line. For a total of 72 trees within the experiment, 36 were constantly monitored and utilized for measurements, and the remaining 36 worked as buffers (Fig.2.2, Chapter II). Measurements of growth consisted of height (Ht) and groundline diameter (GLD), which were used to calculate the stem volume index: $SVI=Ht*GLD^2$. Moisture content was collected biweekly during the growing season and measured by time domain reflectometry, using a Tecktronix cable tester (Tecktronix, Inc. Beaverton, OR). Soil resistance was measured with a Rimik cone penetrometer (Toowoomba, Australia). The detailed design, including soil measurements and penetrometer data management were previously described in Chapter II of this volume.

Soil resistance and soil volumetric moisture interaction

Previous research has shown that, under field conditions, cone penetration resistance is linearly related to soil moisture content (Morris et al., 2006). Soil resistance is time-consuming to measure and few studies effectively captured the variability in resistance occurring during the growing season. However, since it is related to field soil moisture, soil moisture can be used to estimate soil resistance. This investigation included four campaigns to measure soil resistance and the respective soil water data. To assess the correlation of soil resistance and soil volumetric moisture, linear equations were obtained for each one of the 36 monitored trees at each location, with 18 equations representing the no till (NT) treatment and 18 representing the till (T) treatment. The number 18 is the result of three clone replicates containing six trees divided in pairs that received operational site preparation (O), fertilizer application (F), and fertilizer application with herbaceous weed control (F+V) [(2+2+2) x 3]. Refer to Fig.2.2 on Chapter II for site design schematics.

The calculated equations were based on the average resistance value for each insertion throughout the 60 cm profile and the associated soil volumetric moisture from 0-60cm ($\Theta_{0\text{-}60}$). The variation of soil resistance throughout the growing season was estimated using biweekly measurements of volumetric moisture and the obtained linear equation.

Area affected by tillage

A square grid of 3600 cm^2 (60cm x 60cm) was used to estimate the effect of tillage on soil resistance (Fig.3.1). Each penetrometer insertion collected soil resistance data in a 2.5 cm depth increment up to 60 cm, totaling 24 resistance values per insertion. The five insertions were horizontally spaced 15 cm apart, covering a 60 cm width. To estimate the area affected by tillage, the two insertions at the extremity were assumed to have a 7.5 cm width and the three middle insertions a 15 cm width (Fig.3.1 detail). Each soil resistance value was associated with one respective area cell in the proposed grid. A counter (Microsoft Excel, 2002) was develop to identify cells with soil resistance values <2000 kPa and count the number of area cells containing this value, allowing an estimation of the area <2000 kPa throughout the 3600 cm^2 sampling grid. The 2000 kPa limit was chosen based on previous studies that attempted to model root development (Da Silva and Kay, 1996, Wu et al., 2003 and Leao et al., 2006).

Soil Tilth Index (STI)

A Soil Tilth Index (STI) was developed by determining the fraction of the cross-sectional area < 2000 kPa:

$$STI = \frac{\text{area} < 2000\ \text{kPa}}{\text{total cross - section area}}$$

The STI was obtained for each penetrometer sampling campaign. In order to correlate the STIs collected over four different soil moisture contents and the final growth response, a general STI was calculated:

$$STI_g = average(STI_1, STI_2, STI_3, STI_4)$$

where the identification numbers (1,2,3 and 4) represent each penetrometer sampling campaign with the respective soil volumetric moisture. In this investigation, the STI concept was applied on a site average basis. The values used to obtain this index were the same used to describe the general site tillage effect on soil resistance (e.g. Chapter II Figs.2.5 and 2.7), which considered the average resistance values for each one of the five 60 cm insertions in T and NT areas.

Results

Soil resistance and soil volumetric moisture relationship

Although results varied according to site location, overall, soil resistance exhibited a linear relationship with soil volumetric moisture, with greater water content resulting in lower soil resistance. Generally, non-tilled rows resulted in better relationships for soil resistance vs. soil water content (Fig. 3.2a, b and c) than tilled rows. The greatest R^2 values were related to the UCP site Gilead (R^2 >90=38.9 % for non-tilled rows, and R^2 >90=88.9 % for tilled rows). The lowest were related to the UCP site Gritney (R^2<50=77.8 % for non-tilled rows and R^2 <50=72.2 % for tilled rows) (Table3.1). Linear equations and R^2 values for individual sites are presented in Appendix C. As an attempt to assess the accuracy of the soil resistance calculated using these linear equations, the estimated values were plotted against measured values (Fig.3.3a ,b and c). The least accurate estimations were both from the Piedmont site Rion, resulting differences between calculated and measured by -39.8 % for NT and -31.1 % for T rows. The most accurate calculated values were for the UCP sites Troup and Gilead, with differences of 12.9 % (NT) and 8.7 % (T), respectively. To obtain an estimation of soil resistance throughout the growing season, soil water data collected biweekly was substituted in the respective linear equations calculated for each particular location (Fig.3.4).

Relationships between growth and soil resistance were site specific (Fig3.5a,b,c). Although across all sites tillage generally resulted in a positive growth response, the relationship between growth and reduction of soil resistance within the tillage treatment was not evident. However, in sites that showed greater average resistance (>2500 kPa) throughout the growing season, tree growth was linearly related to soil resistance (Fig.3.5c) for both tilled and non-tilled rows.

Soil Tilth Index (STI)

Considering a site average soil resistance value for NT and T areas, tillage treatment resulted in consistently greater STI values ($P<0.0001$) (Table 3.2). Soil water content affected STI values, showing a tendency of greater STI values with increased moisture. Results obtained for STI_g followed the same pattern observed in STI (Table 3.3). There was not a strong correlation between absolute change in STI_g and absolute change in SVI, and some of this may be the result of natural variation in productivity among different sites. However, when sites were analyzed individually, growth response was related to the calculated STI_g and, overall, a greater STI_g resulted in greater growth (Fig.3.6). The greatest growth response to tillage was observed at the Gilead site, where a 0.54 absolute difference in STI_g resulted in 3878 cm^3 extra growth. The lowest response was observed at the Lloyd site, where a 0.52 STI_g difference resulted in an average growth reduction of -1056 cm^3.

Discussion

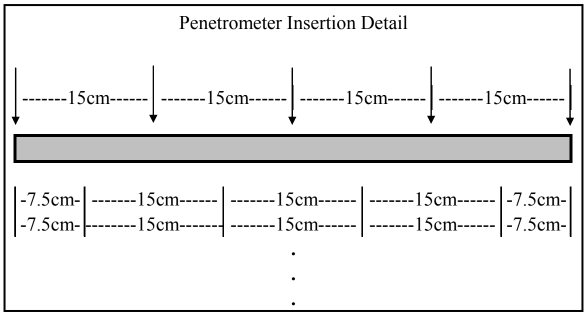
Our results support the findings of Morris et al. (2006), who showed that soil water content could be used to predict soil resistance based on a small number of penetrometer readings. Most of the poor relationships between soil resistance and soil water content were from sites that had average soil resistance <2000 kPa. In the case of the Faceville site (Fig.3.2a), operational tillage reduced soil resistance bellow this threshold limit, and the loss of linearity between soil resistance and soil moisture is likely to be related to the change in size and geometry of the voids due to tillage (Greacen and Sands, 1980). Poor relationships were also observed in locations where variation in soil resistance was low, particularly at the Gritney site. At this location, the soil volumetric water content (Fig.3.7) did not vary as much as at most sites during the growing season (e.g. Fig.2.6 and Fig.2.8, Chapter II). Thus, lower variation for soil resistance would also be expected. Since the Gritney site showed overall lower soil resistance for both tilled and non-tilled rows (Table 2.4, Chapter II), the estimated values for soil resistance were also low. The Gritney site also had the lowest R^2 values. However, differences between measured and calculated values were not great. Rather, the greatest differences were related to the Piedmont site Rion, which overall had the greatest soil resistance values among all sites considered in this investigation.

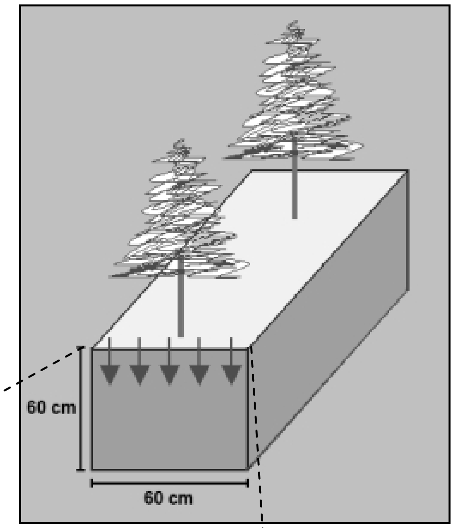
Although a significant growth response to tillage was observed on a site basis, the relationship between growth and soil resistance within the tillage treatments on a tree basis did not show any clear relationship for most of the sites (Fig.3.2a,b,c). However, poor tree growth was observed at sites where the critical soil strength level of 3000 kPa, as proposed by Sands et al. (1979), was reached (Fig.3.5c). This was most evident at the Piedmont upland sites. Poor growth response associated with average greater soil strength was probably related to the inability of trees to better capture and exploit soil resources (Allen et al., 2005).

The proposed Soil Tilth Index applied on a site basis worked as a useful indicator for tree growth and, overall, high STI values were correlated to greater growth (Fig. 3.6). The observed growth decline with increased STI_g at the Lloyd site was consistent with the growth results to tillage treatments, as presented in Chapter II of this volume. At this specific location, it is likely that tillage resulted in water depletion in the rooting zone, which probably negatively affected tree growth.

Some operational tillage practices, such as bedding on saturated soils, are mostly done to improve aeration for the roots by lifting the seedling above the water table (Aust et al., 1998), rather than focusing on the reduction of soil resistance. For these particular locations, high values for STI_g would be expected, which was the case of the Upper Coastal Plain Gritney. The high STIg values for this location reflected the low natural soil resistance variation even prior to tillage. In locations where operational tillage focused on the reduction of soil resistance to benefit growth, our results indicated that sites that have a $STI_g < 0.20$ are likely to respond positively to tillage (Table 3.3). The advantage of using an index instead of direct soil resistance values is the applicability of this measure when comparing different sites and soil types.

We conclude that soil resistance and volumetric water content overall described a linear relationship, and soil resistance values throughout the growing season can be estimated using soil water content data. Thus, it is possible to develop a tool with potential application for forest management since it gives a close estimation of the soil resistance throughout the growing season. The proposed Soil Tilth Index worked as an efficient indicator to assess the likelihood of growth response to operational tillage. Overall, positive response to tillage focusing on benefiting growth by soil resistance reduction could be expected at sites presenting $STI_g < 0.20$.





Penetrometer Insertions

------60cm------

Depth increment -----cm-----	7.5	15	15	15	7.5
0-2.5	18.75	37.5	37.5	37.5	18.75
2.5-5.0	18.75	37.5	37.5	37.5	18.75
5.0-7.5	18.75	37.5	37.5	37.5	18.75
7.5-10.0	18.75	37.5	37.5	37.5	18.75
10.0-12.5	18.75	37.5	37.5	37.5	18.75
12.5-15.0	18.75	37.5	37.5	37.5	18.75
15.0-17.5	18.75	37.5	37.5	37.5	18.75
17.5-20.0	18.75	37.5	37.5	37.5	18.75
20.0-22.5	18.75	37.5	37.5	37.5	18.75
22.5-25.0	18.75	37.5	37.5	37.5	18.75
25.0-27.5	18.75	37.5	37.5	37.5	18.75
27.5-30.0	18.75	37.5	37.5	37.5	18.75
30.0-32.5	18.75	37.5	37.5	37.5	18.75
32.5-35.0	18.75	37.5	37.5	37.5	18.75
35.0-37.5	18.75	37.5	37.5	37.5	18.75
37.5-40.0	18.75	37.5	37.5	37.5	18.75
40.0-42.5	18.75	37.5	37.5	37.5	18.75
42.5-45.0	18.75	37.5	37.5	37.5	18.75
45.0-47.5	18.75	37.5	37.5	37.5	18.75
47.5-50.0	18.75	37.5	37.5	37.5	18.75
50.0-52.5	18.75	37.5	37.5	37.5	18.75
52.5-55.0	18.75	37.5	37.5	37.5	18.75
55.0-57.5	18.75	37.5	37.5	37.5	18.75
57.5-60.0	18.75	37.5	37.5	37.5	18.75
Total area (cm2):	450	900	900	900	450
					3600

$7.5cm \times 2.5cm = 18.75cm^2$

Fig.3.1. Designed grid for soil resistance area calculation. Each arrow represents one penetrometer insertion.

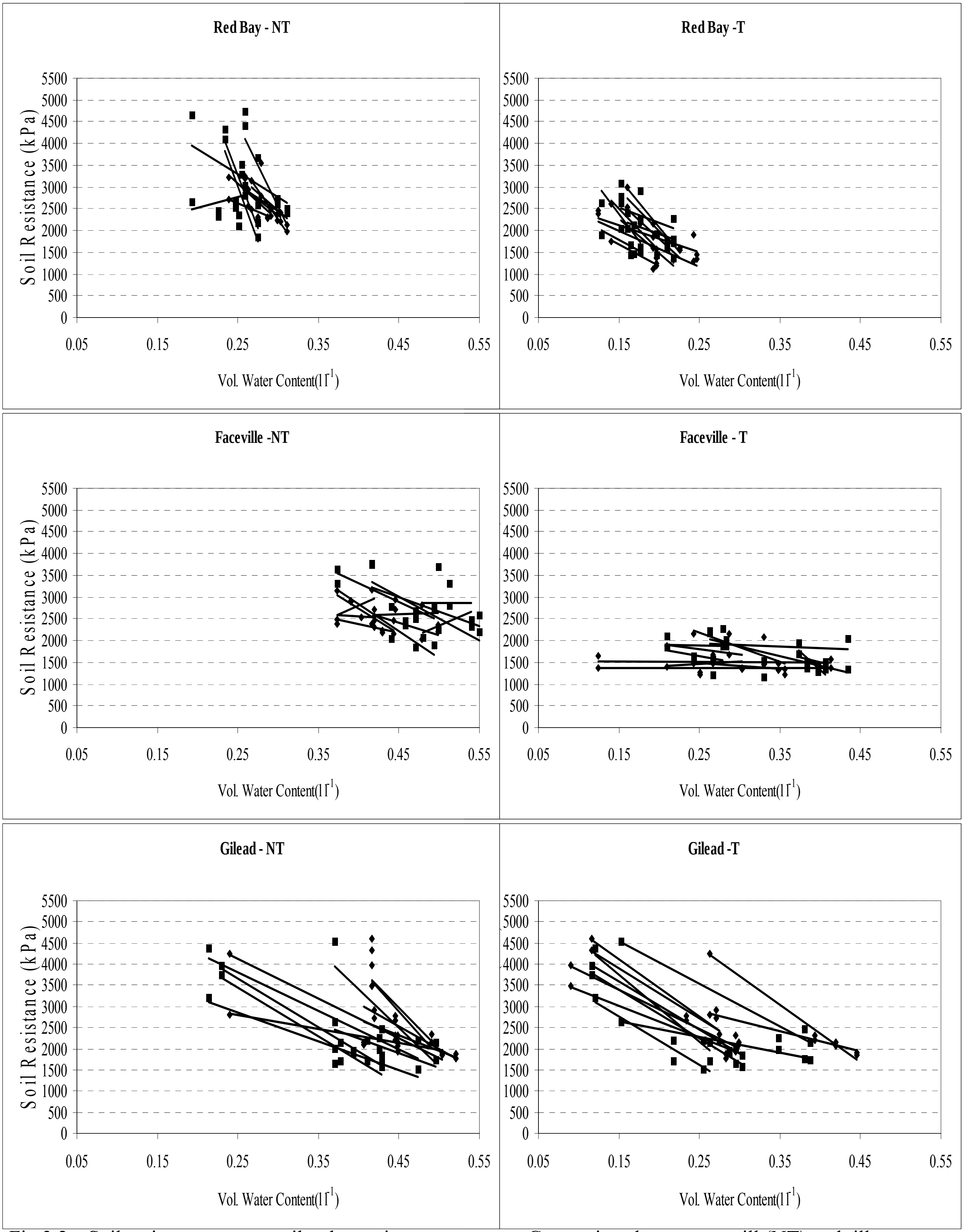


Fig.3.2a. Soil resistance versus soil volumetric water content. Comparison between no till (NT) and till (T) areas. Graphs show values for operational site preparation (■) and fertilizer application with herbaceous weed control (♦). Red Bay, Faceville and Gilead – Upper Coastal Plain sites.

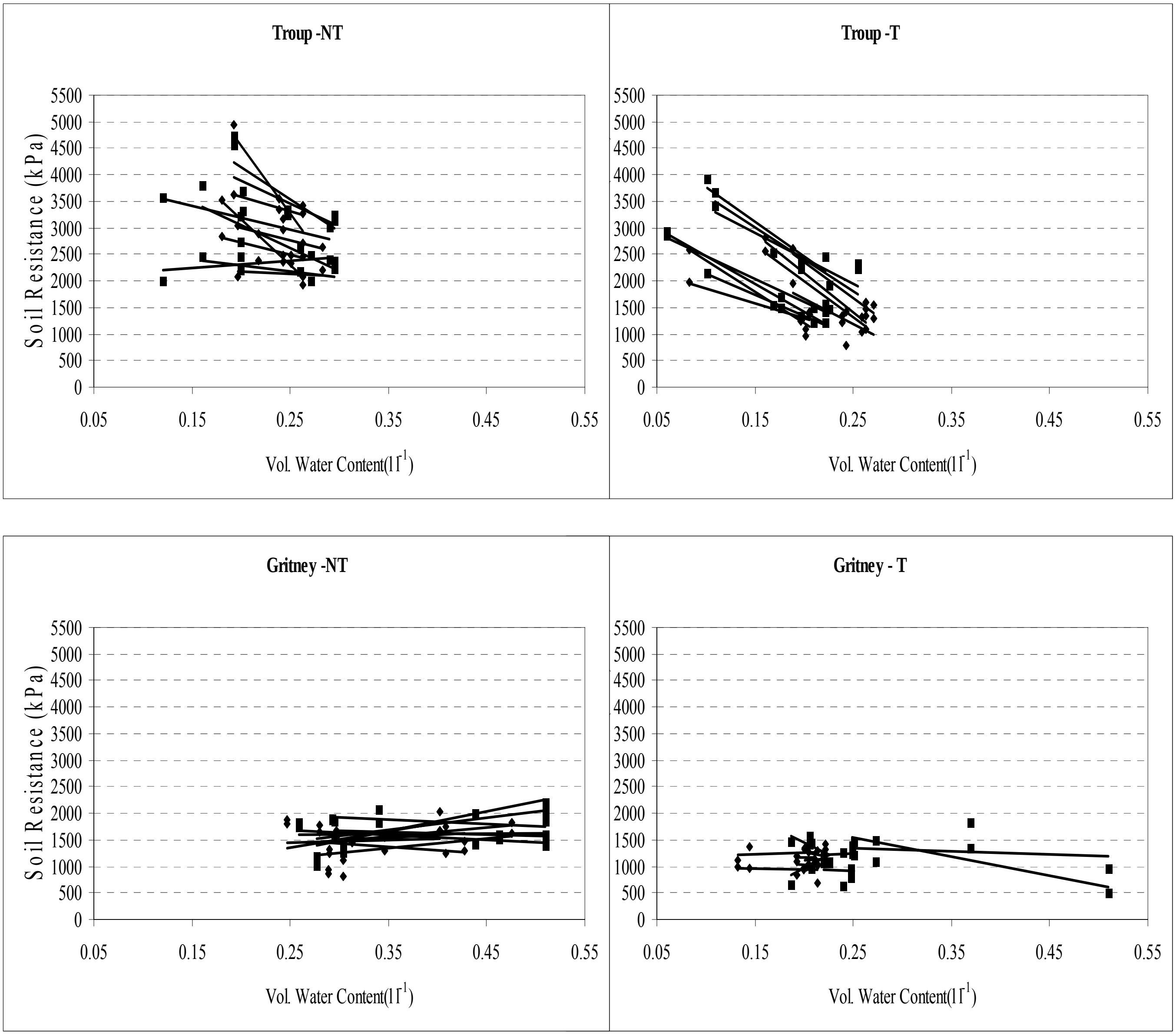


Fig.3.2b. Soil resistance versus soil volumetric water content. Comparison between no till (NT) and till (T) areas. Graphs show values for operational site preparation (■) and fertilizer application with herbaceous weed control (♦). Troup and Gritney – Upper Coastal Plain sites.

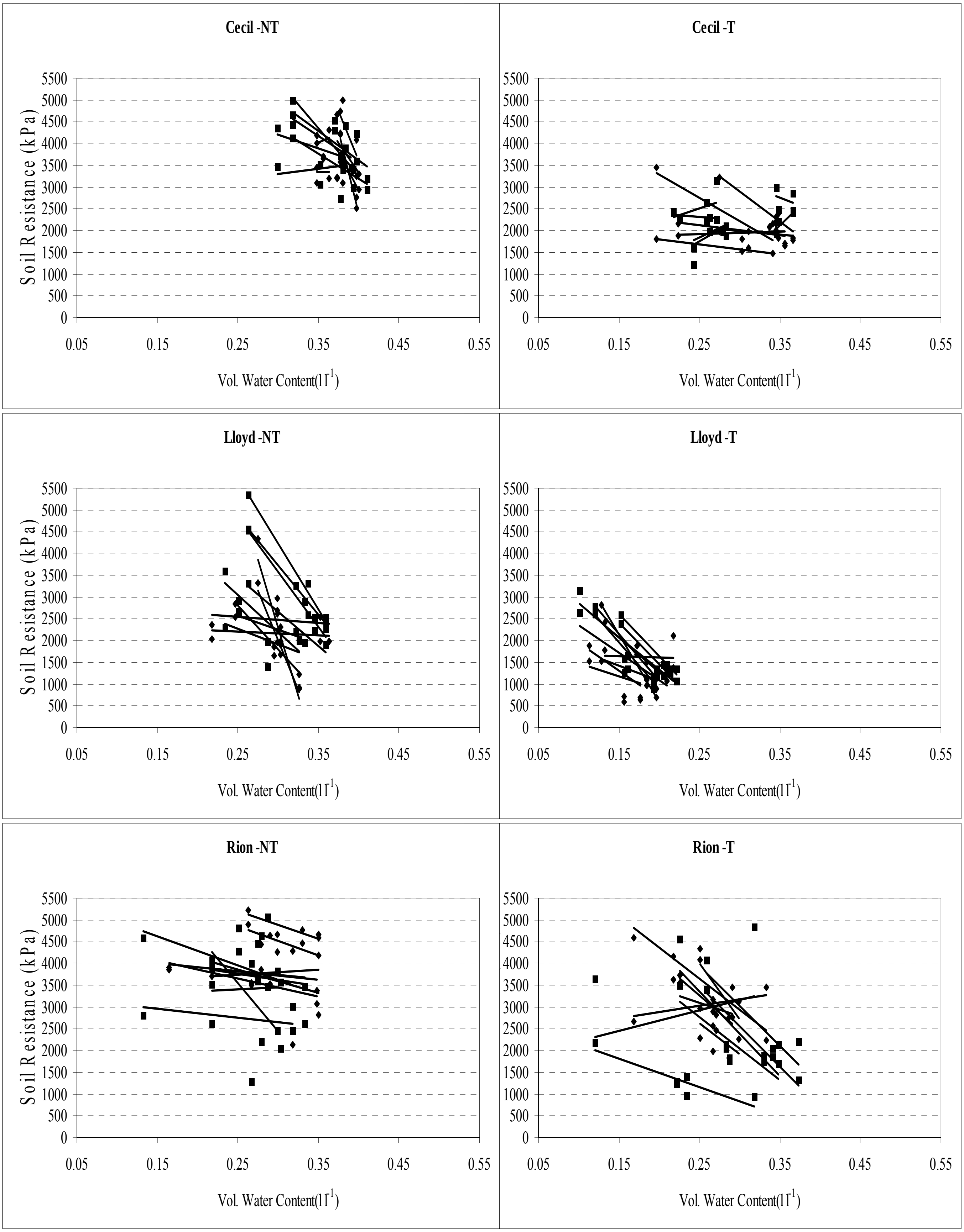
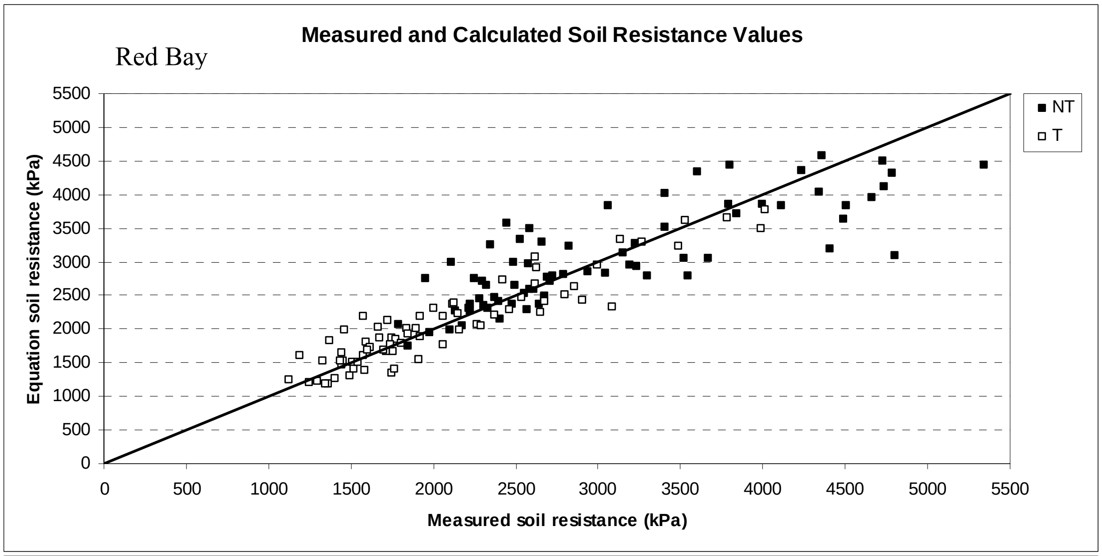
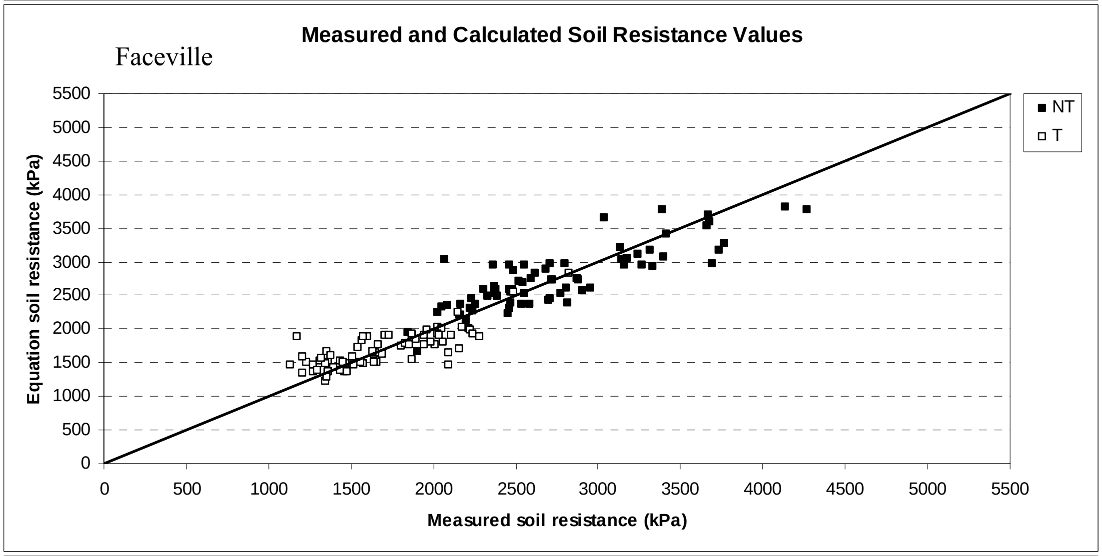


Fig.3.2c. Soil resistance versus soil volumetric water content. Comparison between no till (NT) and till (T) areas. Graphs show values for operational site preparation (■) and fertilizer application with herbaceous weed control (♦). Cecil, Lloyd and Rion – Piedmont sites.





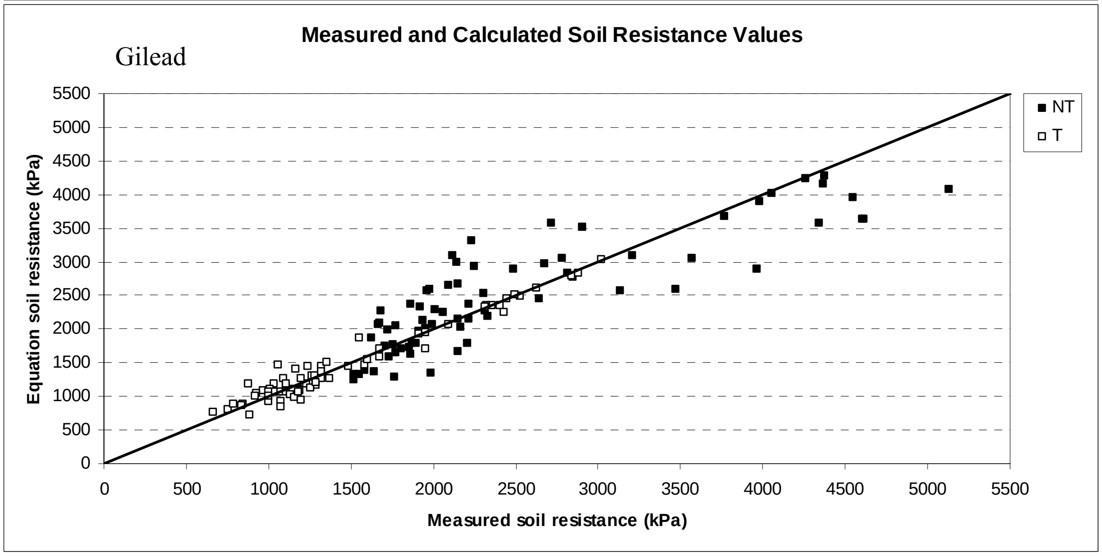
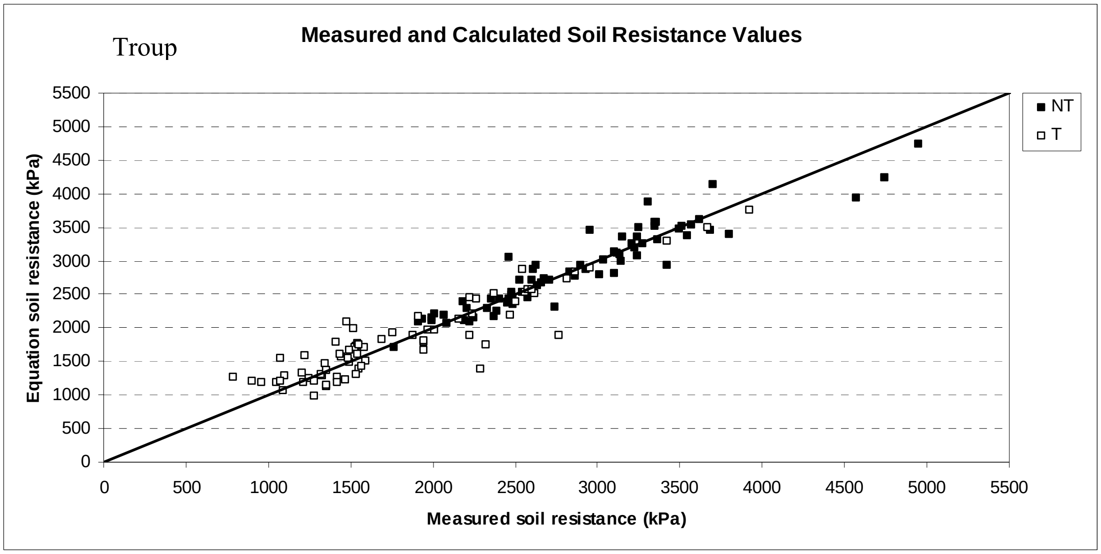


Fig.3.3a. Calculated and measured values for soil resistance. Predicted values were determined using the specific linear equation for each tree measured per site. Soil resistance values are averages for the 60cm depth. Red Bay, Faceville and Gilead -Upper Coastal Plain sites.



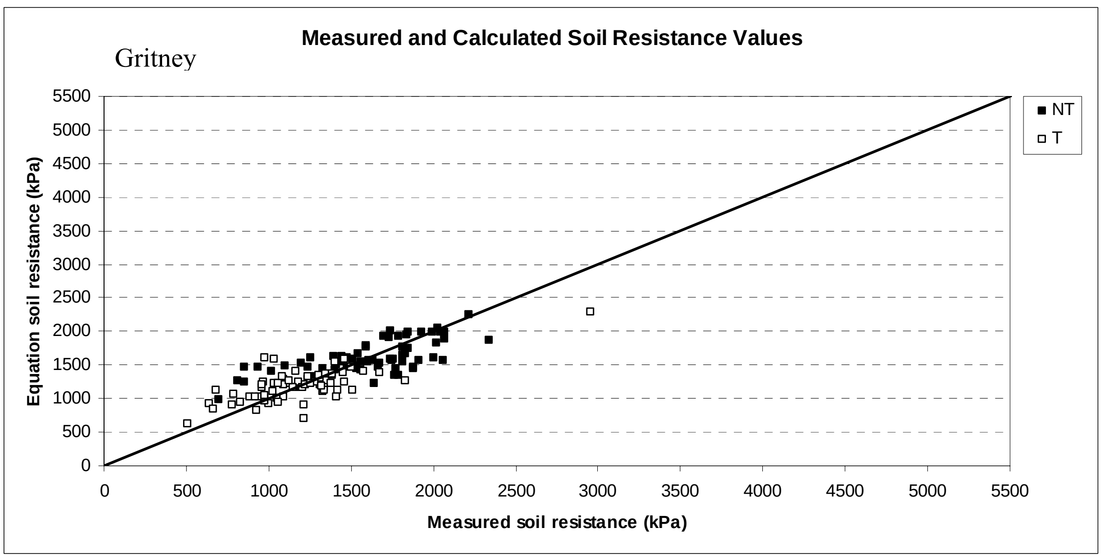


Fig.3.3b. Calculated and measured values for soil resistance. Predicted values were determined using the specific linear equation for each tree measured per site. Soil resistance values are averages for the 60cm depth. Troup and Gritney- Upper Coastal Plain sites.

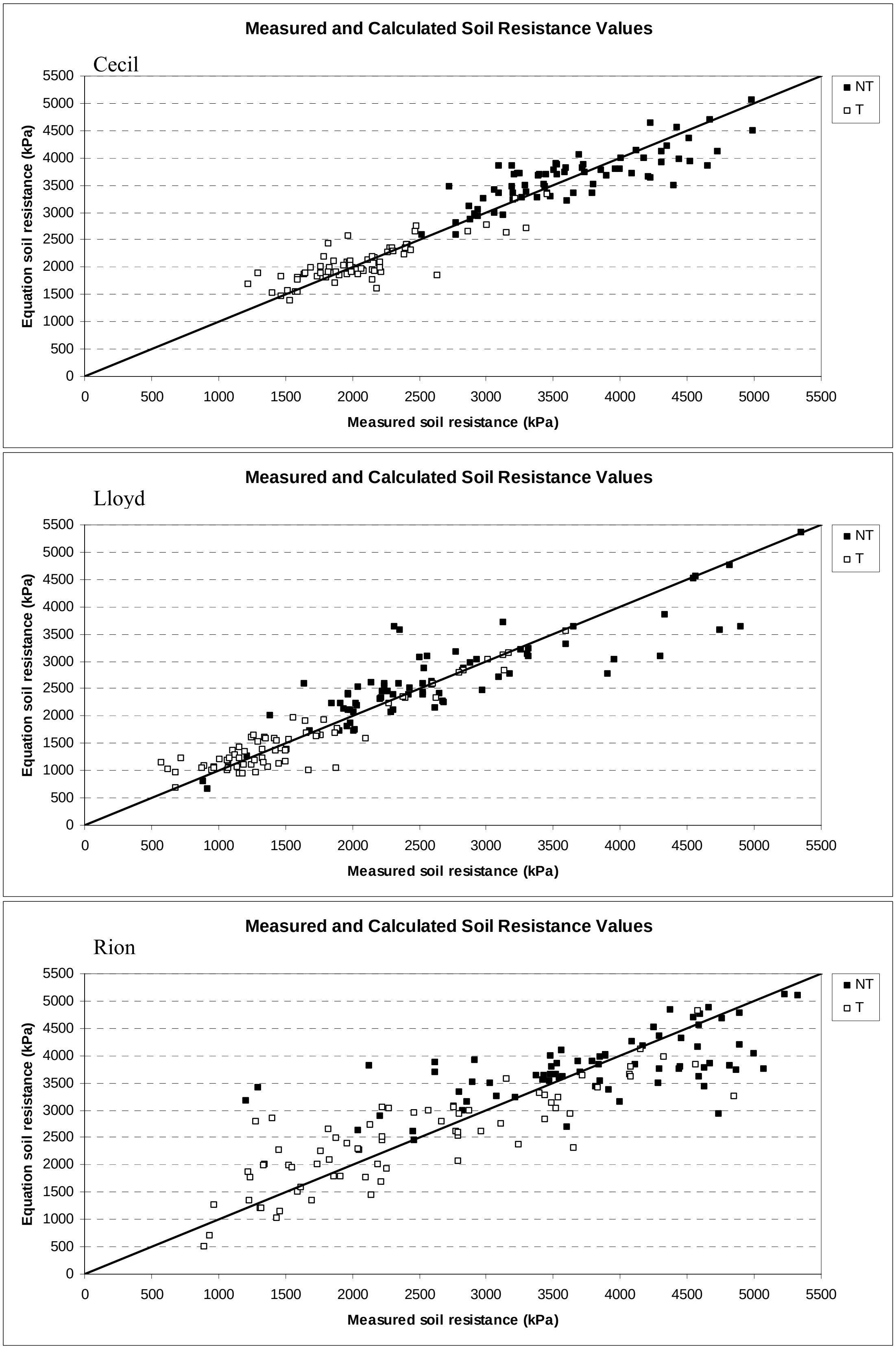
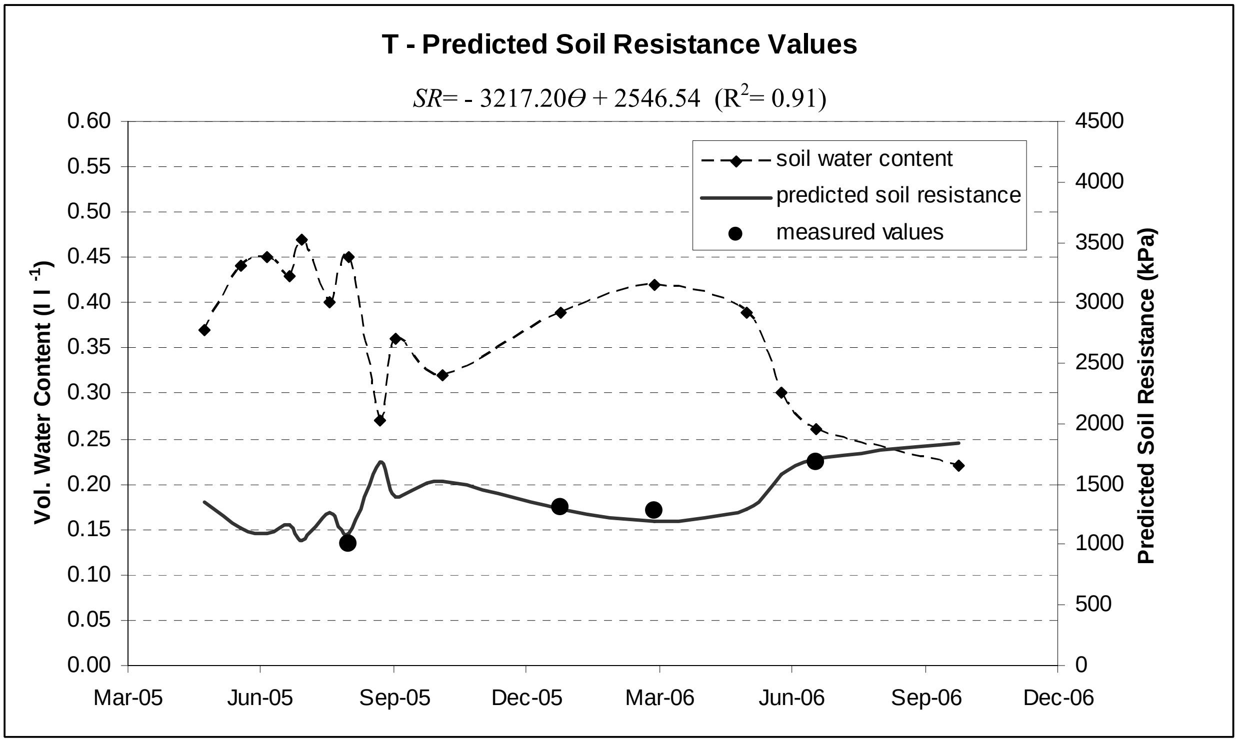


Fig.3.3c. Calculated and measured values for soil resistance. Predicted values were determined using the specific linear equation for each tree measured per site. Soil resistance values are averages for the 60 cm depth. Cecil, Lloyd and Rion - Piedmont sites.



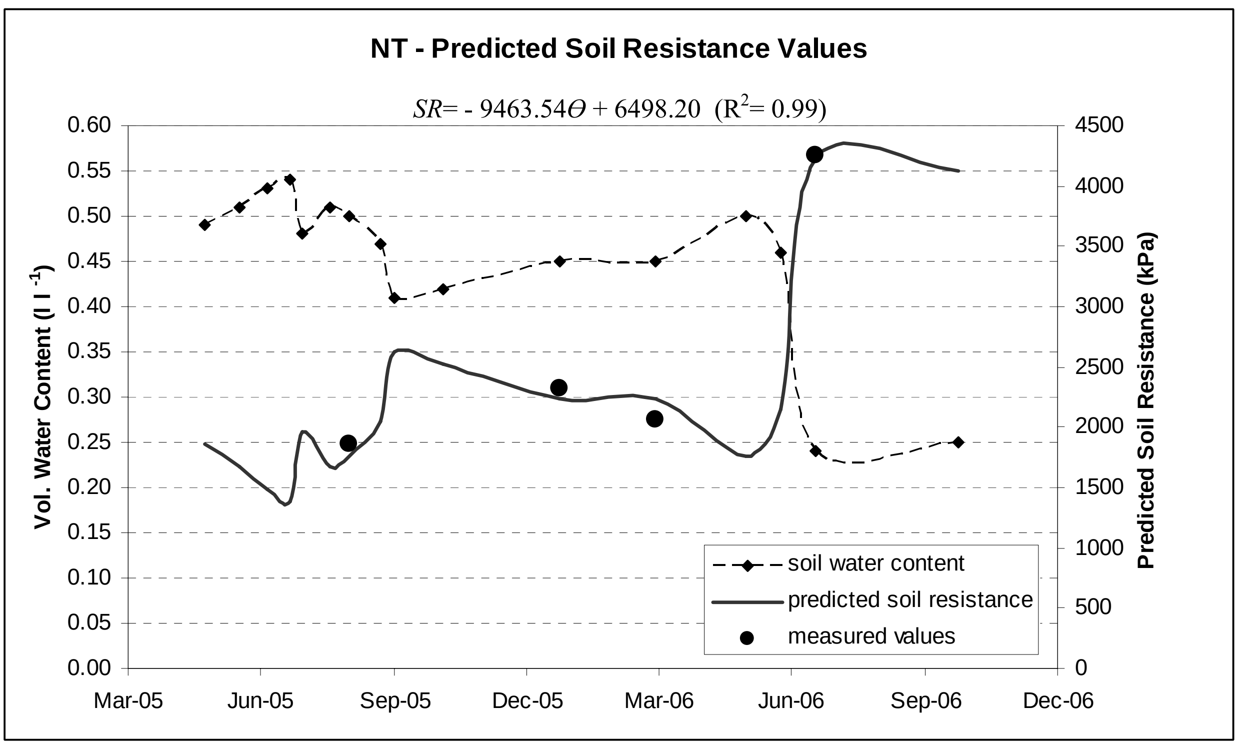
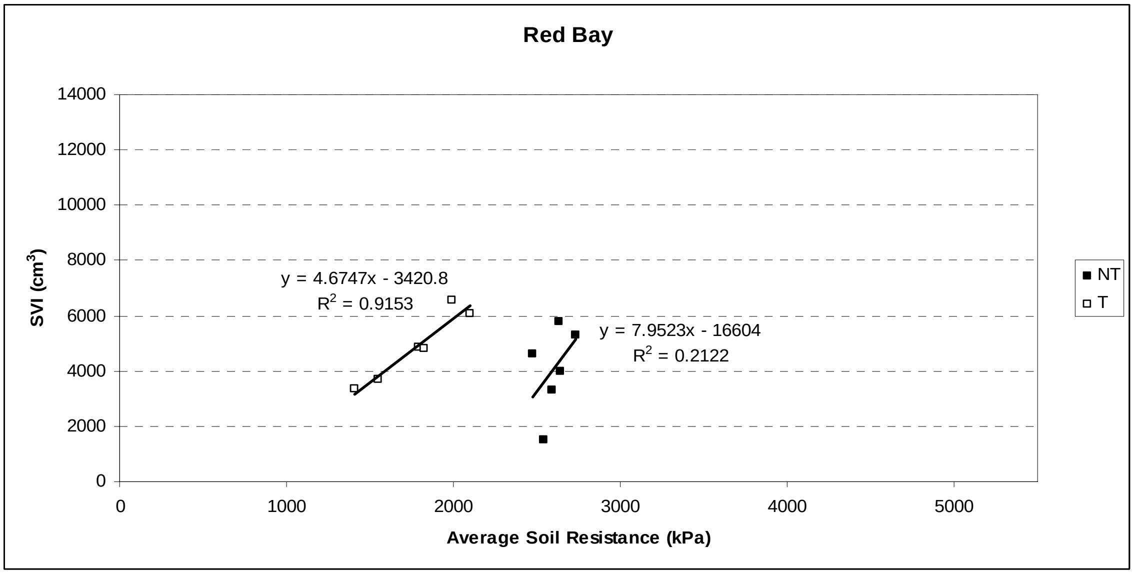
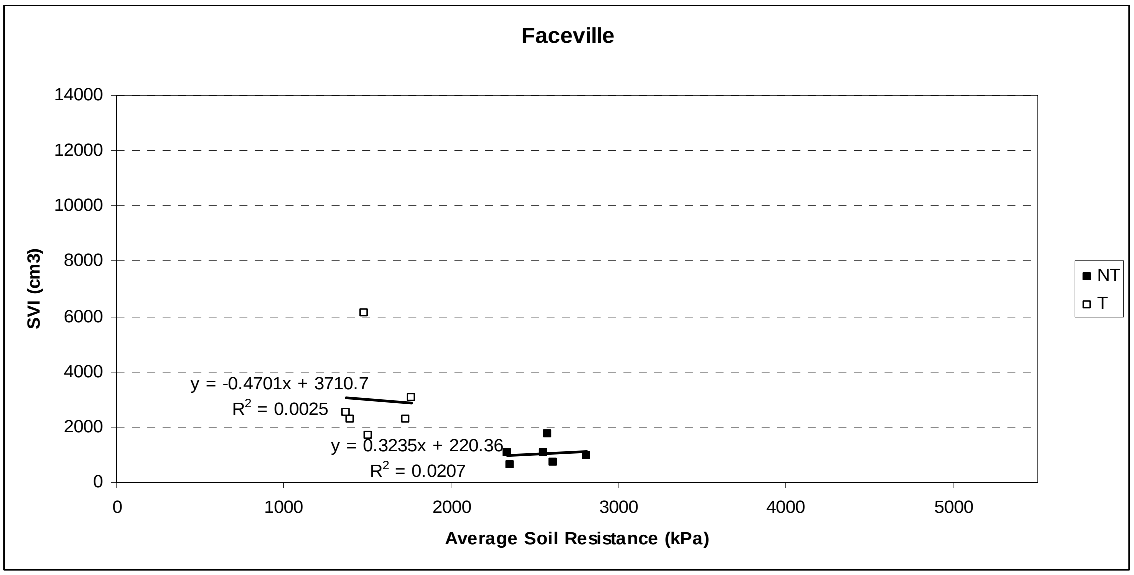


Fig.3.4.Predicted soil resistance (SR) values. Data related to Upper Coastal Plain site Gilead, T and NT, fertilizer and herbaceous weed control treatments. Replicate clone 3621.

Table3.1. R^2 values for NT and T. Each value is the percent of 18 linear regression equations resulting from four penetrometer measurements and respective moisture contents (0-60 cm depth) collected during the same campaign.

Site	No Till				Till			
	R^2>90	R^2 70-90	R^2 50-70	R^2<50	R^2>90	R^2 70-90	R^2 50-70	R^2<50
	%				%			
Red Bay	27.8	0.0	22.2	50.0	27.8	33.3	22.2	16.7
Faceville	5.6	22.2	16.7	55.6	5.6	16.7	16.7	61.1
Gilead	38.9	11.1	33.3	16.7	88.9	5.6	0.0	5.6
Troup	27.8	16.7	27.8	27.8	33.3	38.9	11.1	16.7
Gritney	5.6	0.0	16.7	77.8	0.0	5.6	11.1	72.2
Cecil	5.6	16.7	27.8	50.0	16.7	11.1	5.6	66.7
Lloyd	38.9	11.1	5.6	44.4	61.1	16.7	0.0	22.2
Rion	0.0	11.1	33.3	55.6	16.7	27.8	22.2	33.3





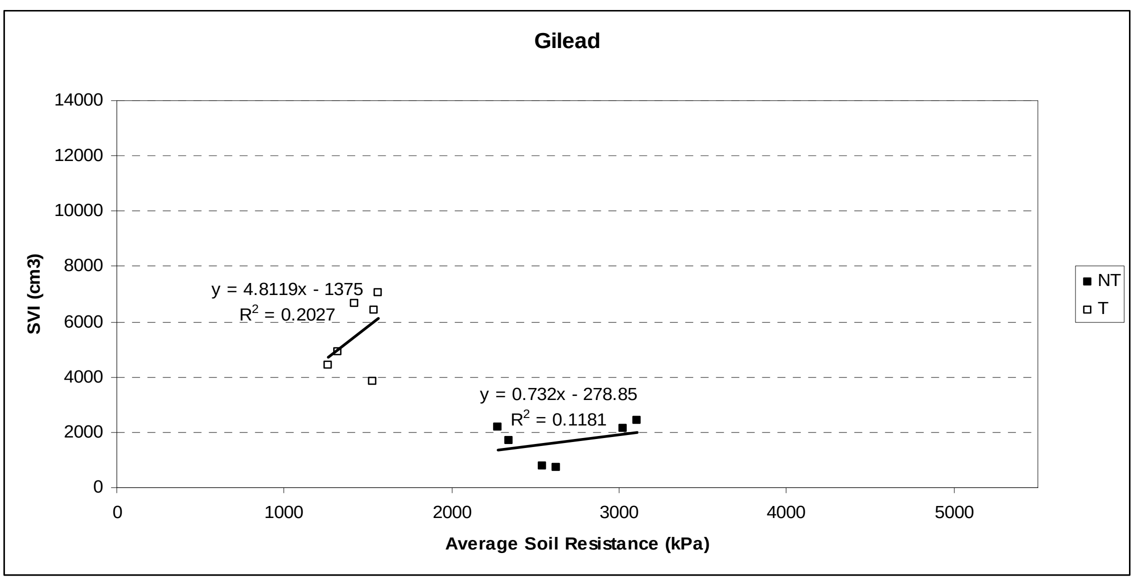
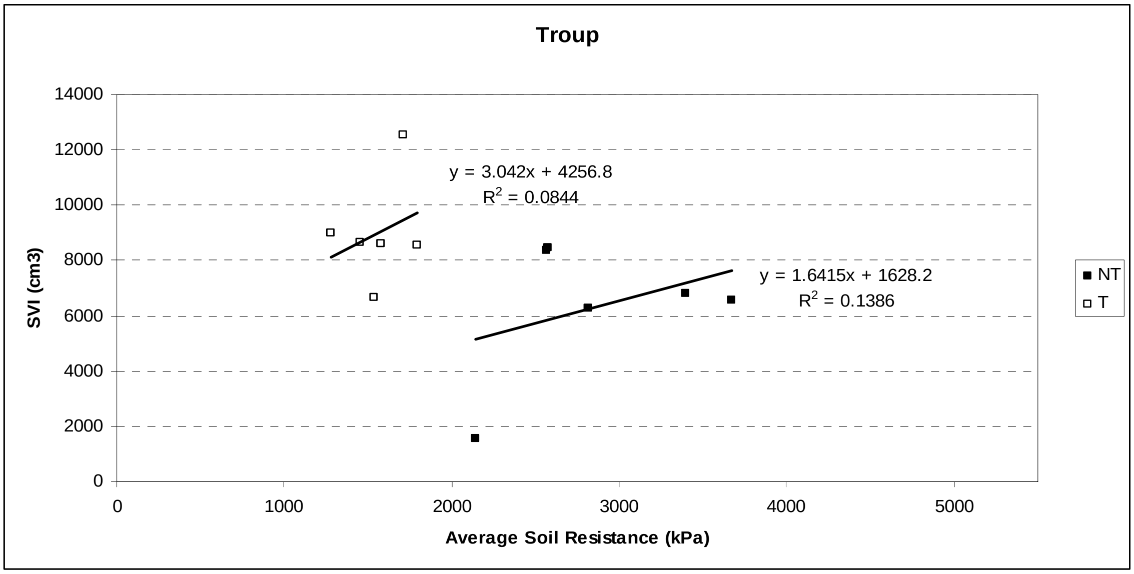


Fig.3.5a. Final Stem Volume Index and average soil resistance from four penetrometer campaigns. Each point represents a tree treated with fertilizer and herbaceous weed control, and the respective soil resistance average. Upper Coastal Plain sites.



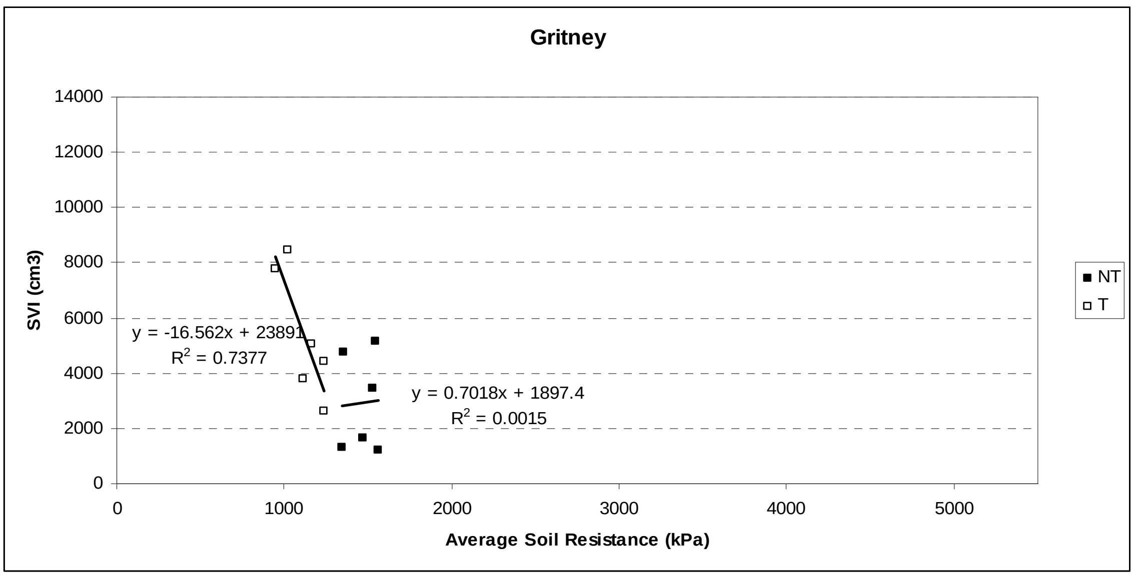
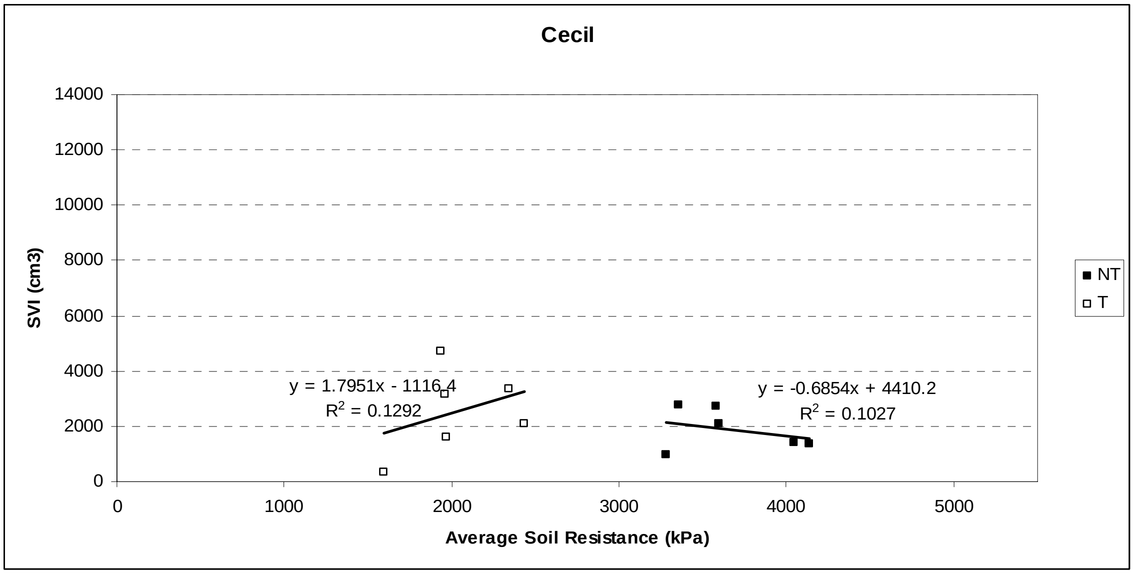
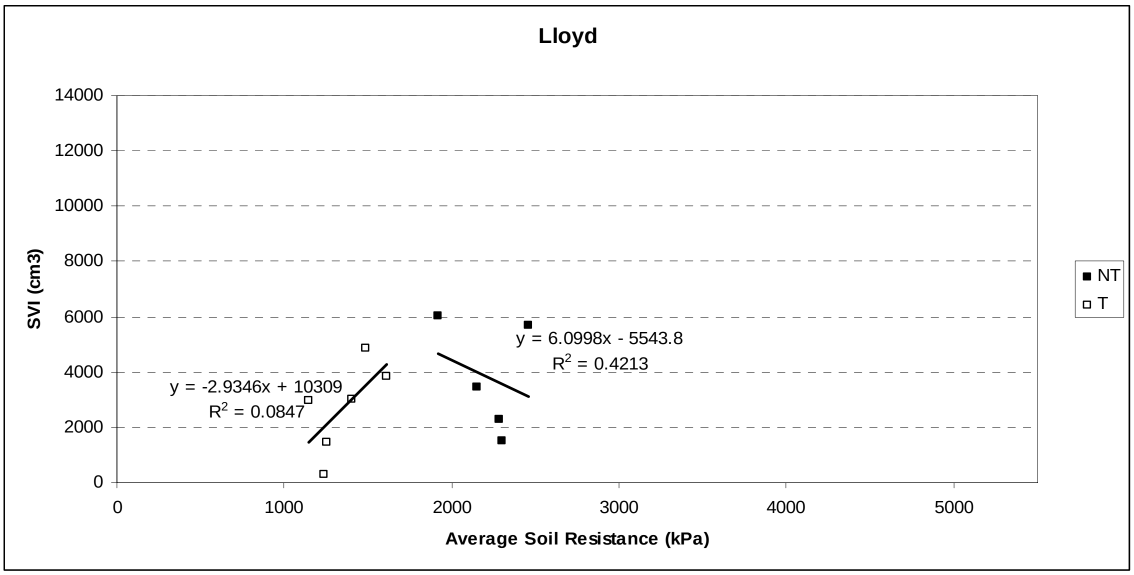


Fig.3.5b. Final Stem Volume Index and average soil resistance from four penetrometer campaigns. Each point represents a tree treated with fertilizer and herbaceous weed control, and the respective soil resistance average. Upper Coastal Plain sites.





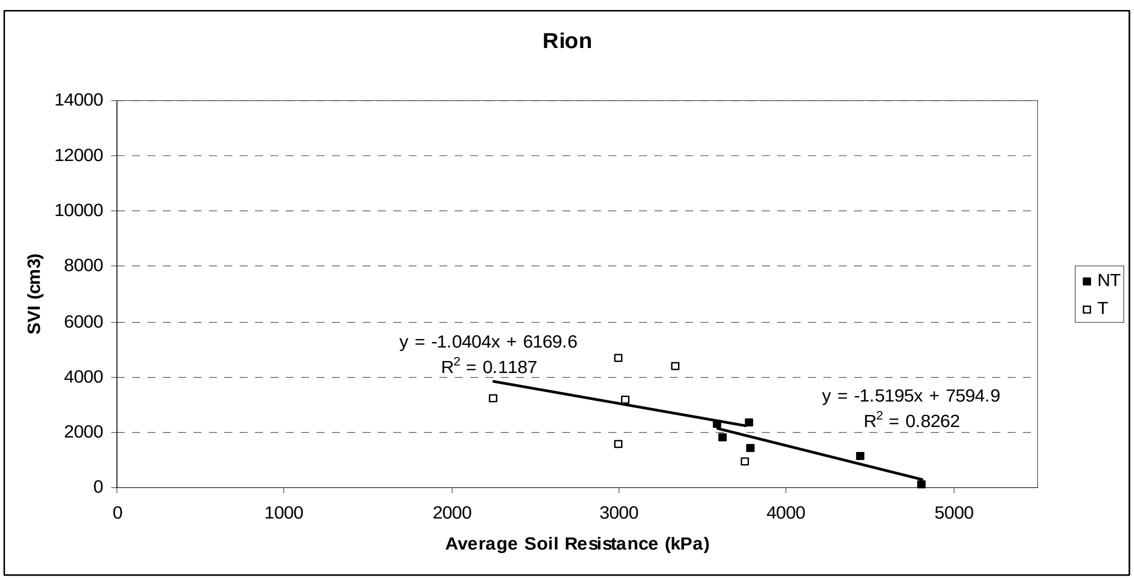


Fig.3.5c. Final Stem Volume Index and average soil resistance from four penetrometer campaigns. Each point represents a tree treated with fertilizer and herbaceous weed control, and the respective soil resistance average. Piedmont sites.

Table3.2. STIs and vol. water content for NT and T. Site average penetrometer measurements, collected over four different moisture conditions.

Site	STI[a] NT[b]	STI[a] T	$\Theta_{(0\text{-}60cm)}$ % NT	$\Theta_{(0\text{-}60cm)}$ % T
		Upper Coastal Plain		
Red Bay	0.00	0.25	23.3	13.5
	0.02	0.22	24.6	16.4
	0.00	0.78	26.7	19.4
	0.04	0.73	28.0	19.8
Faceville	0.11	0.77	36.1	30.3
	0.03	0.49	38.7	21.0
	0.01	0.53	43.3	29.3
	0.07	0.73	47.7	34.0
Gilead	0.00	0.32	30.3	15.7
	0.20	0.79	39.0	29.6
	0.21	0.86	43.5	32.1
	0.30	0.92	49.5	31.1
Troup	0.08	0.30	18.7	10.2
	0.14	0.63	21.6	19.3
	0.17	0.67	24.9	21.1
	0.14	0.59	27.0	21.9
Gritney	0.82	1.00	30.8	21.6
	1.00	1.00	34.0	24.0
	0.99	1.00	36.9	26.2
	0.96	0.96	44.1	24.8
		Piedmont		
Cecil	0.06	0.34	33.7	28.3
	0.04	0.52	36.6	28.2
	0.07	1.04	36.8	30.2
	0.04	0.54	38.3	30.9
Lloyd	0.07	0.41	23.3	11.6
	0.15	0.76	30.0	18.3
	0.33	0.74	30.2	17.3
	0.08	0.81	30.6	18.7
Rion	0.06	0.08	19.8	18.7
	0.07	0.51	22.3	25.1
	0.06	0.43	26.2	26.4
	0.06	0.47	28.3	32.2

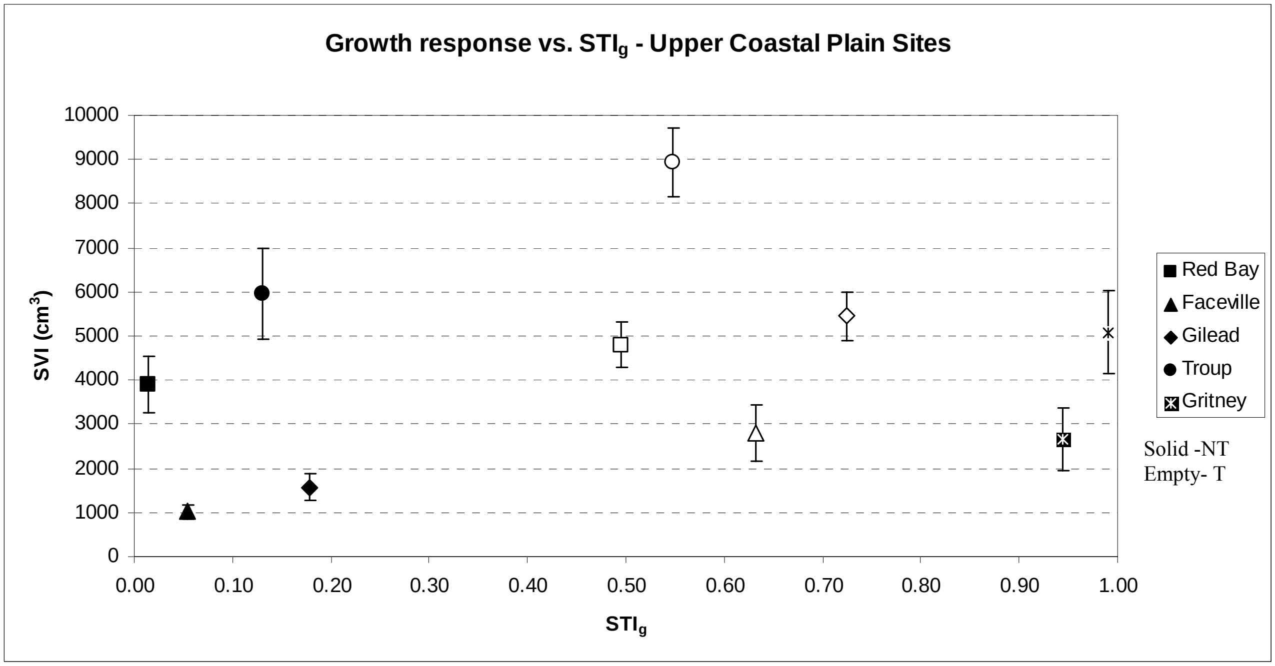
[a] STI= (area<2000 kPa)/(3600 cm^2)

[b] All STI values are statistically different for T and NT treatment (α=0.05)

Table3.3. Average values for Soil Tilth Index (STIg), Stem Volumetric Index (SVI) and soil water content. The STIg was calculated as an average for the entire site, using the STI calculated at each penetrometer campaign, with respective average moisture. The SVI value shows the average of six trees (two per rep. clone) at the subplot treated with fertilizer and herbaceous weed control.

	STIg		SVI(cm^3)		$\Theta_{(0\text{-}60cm)}$ %	
Site	NT	T	NT	T	NT	T
Red Bay	0.01±0.01*	0.50±0.15	3888±635	4800±518	25.7±1.1	17.3±1.5
Faceville	0.06±0.02	0.63±0.07	1014±163	2800±650	41.5±2.6	28.7±2.8
Gilead	0.18±0.06	0.72±0.14	1572±301	5450±543	40.6±4.1	27.1±3.9
Troup	0.13±0.02	0.55±0.08	5955±1029	8932±785	23.1±1.9	18.1±2.7
Gritney	0.94±0.04	0.99±0.01	2656±722	5081±934	36.5±2.9	24.2±1.0
Cecil	0.05±0.01	0.61±0.15	1819±310	2201±626	36.4±1.0	29.4±0.7
Lloyd	0.16±0.06	0.68±0.09	3478±902	2317±669	28.5±1.8	16.5±1.7
Rion	0.06±0.00	0.37±0.10	1270±341	2730±610	24.2±1.9	25.6±2.8

* *Standard Error*



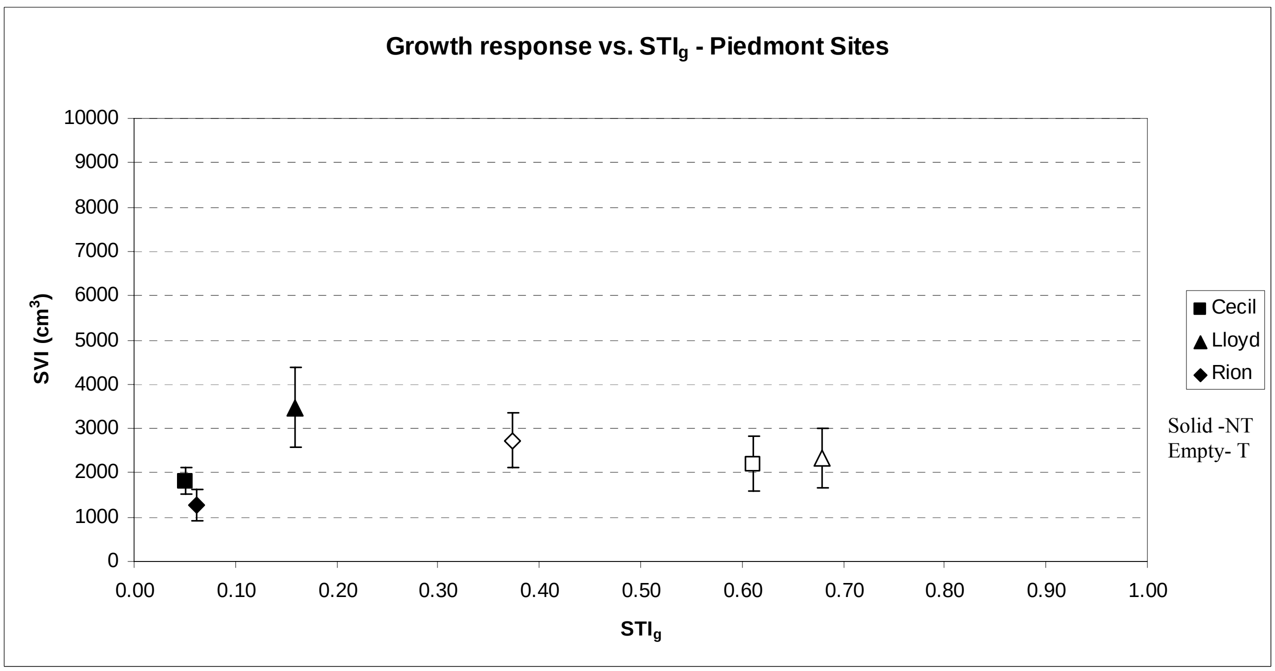


Fig. 3.6. Stem Volume Index vs. Soil Tilth Index for UCP and Piedmont sites. The SVI was calculated using the average of six trees (two per rep. clone) at the subplot treated with fertilizer and herbaceous weed control. The STI_g was obtained by averaging the STI calculated for each penetrometer campaign. Solid – **No Till**, Empty – **Till**. Bars indicate standard errors.

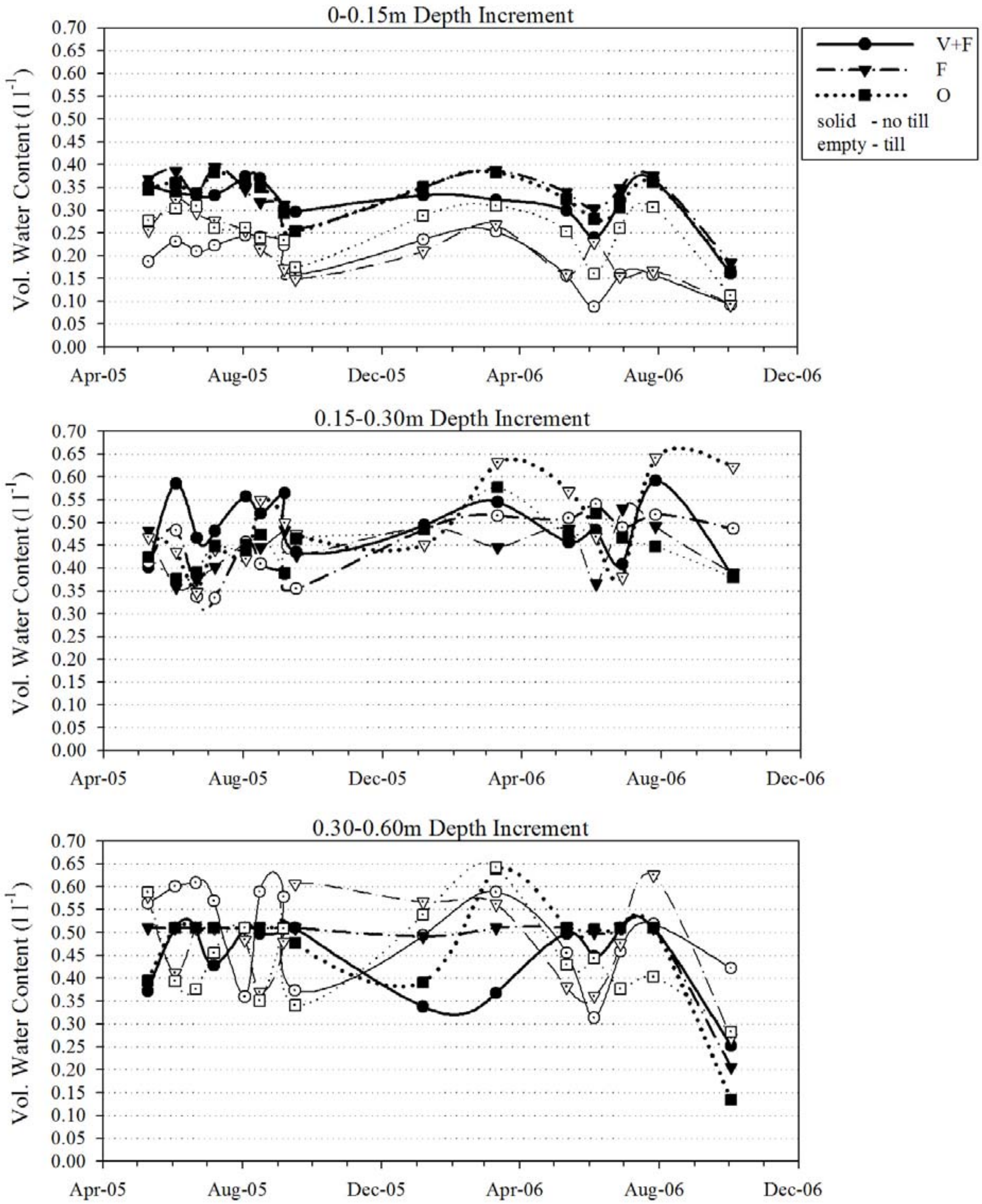


Fig. 3.7. Volumetric water content by tillage and cultural treatment during two growing seasons. Gritney site – Upper Coastal Plain Region.

References

Allen, H.L., 2001. Silvicultural treatments to enhance productivity. Chapter 6 in the Forests Handbook. Vol II. Evans,J. (ed.). Blackwell Science Ltd., Oxford,UK, 382p.

Allen,H.L., Fox, T.R., Campbell, R.G., 2005. What is Ahead for Intensive Pine Plantation Silviculture in the South? South J. Appl. For. 29(2), 62-69.

Aust,W. M., G. A. Scheerer,M. D. Tippet, J.A. Burger and W.H.Mckee,Jr, 1998. Bedding and fertilization ameliorate effects of designated wet-weather skid trails after four years of loblolly pine (*Pinus taeda*) plantations. South.J. Appl. For. 22(4),222-226.

Carlson, C.A., Fox, T.R., Colbert, S.R., Kelting, D.L., Allen, H.L., Albaugh, T.J., 2006. Growth and survival of Pinus taeda in response to surface and subsurface tillage in the southeastern United States. Forest Ecology and Management 234, 209-217.

Da Silva,A.P., Kay,B.D., Perfect E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58:1775–1781.

Da Silva,A.P., Kay,B.D., 1996. The sensitivity of shoot growth of corn to the least limiting water range of soils. Plant and Soil 184, 323-329.

Eisenbies, M.H., Burger, J.A., Aust, W.M., Patterson, S.C., 2005. Soil Physical Disturbance and Logging Residue Effects on Changes in Soil Productivity in Five-Year-Old Pine Plantations. Soil Sci. Am.J. 69, 1833-1843.

Greacen, E.L., Sands,R.,1980. Compaction of Forest Soils – A Review. Aust. J. Soil. Res. 18,163-189.

Haynes, R.W., 2002. Forest Management in the 21st Century: Changing Number, Changing Context. J. For. 100(2), 38-43.

Leao, T.P., da Silva, A.P., Macedo, M.C.M., Imhoff, S., Euclides, V.P.B., 2006. Least limiting water range: A potential indicator of changes in near-surface soil physical quality after the conversion of Brazilian Savanna into pasture. Soil and Tillage Research 88, 279-285.

Morris, L.A., Ludovici, K.H., Torreano, S.J., Carter, E.A., Lincoln, M.C., Will, R.E., 2006. An approach for using general soil physical condition-root growth relationships to predict seedling growth response to site preparation tillage in loblolly pine plantations. Forest Ecology and Management 227, 169-177.

Morris, L.A., Lowery,R.F.,1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. South. J. Appl. For. 12(3), 170-178.

Pehl, C.E., 1983. Site Preparation Influences on Young Loblolly Pine Plantations in East Texas. South J. Appl. For. 7, 140-145.

Prestemon, J.P. and Abt, R.C., 2002. The Southern Timber Market to 2040. J. For. 100(7), 16-22.

Rahman, M.S., Messina, M.G., Fisher, R.F., 2006. Intensive Forest Management Affects Loblolly Pine (Pinus taeda L.) Growth and Survival on Poorly Drained Sites in Southern Arkansas. South J. Appl. For. 30, 79-85.

Sands, R., Graecen, E.L., Gerard, C.J., 1979. Compaction of sandy soils in Radiata pine forests. I. A penetrometer study. Aust. J. Soil Res. 17, 101–113.

Siegel-Issem, C.M., Burger, J.A., Powers, R.F., Ponder, F., Patterson, S.C., 2005. Seedling Root Growth as a Function of Soil Density and Water Content. Soil Science Society of America Journal 69, 215-226.

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

Shiver, B.D., Martin, S.W., 2002. Impacts of vegetation control, genetic improvement and their interaction on loblolly pine growth in the southern United States - age 12 results. South. J. Appl. For. 26(1),37-42.

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

Tiarks,A.E.,Haywood, J. D.,1996, Site preparation and fertilization effects on growth of slash pine for two rotations, Soil Sci. Soc. Amer. J. 60, 1654–1663.

Wheeler,M.J., Jacobson,M.A., Shirley,A.M., Will,R.W., Markewitz,D.,2002. Early loblolly pine stand response to tillage on the Piedmont and Upper Coastal Plain of Georgia: mortality, stand uniformity, and second and third year growth. South. J. Appl. For. 26(4),181-189.

Wittwer, R.F., Dougherty, P.M., Cosby, D., 1986. Effects of Ripping and Herbicide Site Preparation Treatments on Loblolly Pine Seedling Growth and Survival. South J. Appl. For. 10, 253-257.

Wu, L., Feng, G., Letey, J., Ferguson, L., Mitchell, J., McCullough-Sanden, B., Markegard, G., 2003. Soil management effects on the non limiting water range. Geoderma 114, 401-414.

CONCLUSIONS

This study was designed to isolate and quantify the effects of soil tillage on soil physical properties in their relationship to loblolly pine growth. It was proposed to evaluate the variation of soil resistance during the growing season by developing relationships between soil resistance and soil water content. A Soil Tilth Index based on the effect of operational tillage on soil resistance and its relation to tree growth was also suggested. In summary, the general questions related to this investigation were: what are the changes in soil physical properties that substantially affect loblolly pine growth? Is it possible to incorporate soil physical changes into an index that ultimately could predict pine tree growth? To answer these questions, soil physical conditions and tree growth were measured during the first two growing seasons following operational soil tillage on 11 sites, in the Piedmont, Upper Coastal Plain and Flatwoods of the Southeastern USA.

Our results showed that, in the Piedmont and Upper Coastal Plain sites, tillage resulted in positive growth response. One year results in the Flatwoods were inconclusive. Although responses were site-specific, average growth was reasonably well correlated with measured differences in average resistance in tilled and non-tilled rows. A negative growth response to tillage was observed in only one location, where a site with a considerable amount of loamy topsoil (10”) over clay loam received subsoiling treatment. The negative response was probably related to water depletion in the rooting zone due to the tillage treatment. Our findings also showed that soil resistance and volumetric water content overall described a linear relationship, and soil resistance values throughout the growing season can be estimated using soil water content data. The proposed Soil Tilth Index worked as an efficient indicator to assess the likelihood of growth response to operational tillage. Overall, positive response to tillage focusing on benefiting growth by soil resistance reduction could be expected at sites with STI_g <0.20.

This study provides a large base of information on the probability and magnitude of loblolly pine early growth response to operational site preparation methods. These findings could be an important tool for forestry management decisions, especially when overlapping information related to costs and financial returns associated with these common silvicultural treatments.

APPENDICES

Appendix A: Macro and micro-nutrient percentages in Holly Tone fertilizer:

Produced by: The Espoma Company • 6 Espoma Road, Millville, NJ 08332 •

Telephone: 1-888-ESPOMA (1-888-377-6621) • Fax: 856-825-1385 • www.espoma.com

Analysis:

Total Nitrogen (N) .... 4.0 %

1.90 % Ammoniacal Nitrogen

0.55 % Other Water Soluble Nitrogen

1.55 % Water Insoluble Nitrogen

Available Phosphate (P2O5) .... 6.0 %

Soluble Potash (K2O)...4.0 %

Calcium (Ca) ....3.0 %

Total Magnesium (Mg)... 0.5 %

0.3 % Water Soluble Magnesium (Mg)

Sulfur (S) .... 5.0 %

5.0 % Combined Sulfur (S)

Boron (B).. 0.02 %

Chlorine (Cl) .... 0.1 %

Cobalt (Co) .... 0.0005 %

Total Copper (Cu)..0.05 %

Total Iron (Fe) .... 1.0 %

Total Manganese (Mn)... 0.05 %

0.01 % Water Soluble Manganese (Mn)

Molybdenum (Mo)... 0.0005 %

Sodium (Na)... 0.1 %

Total Zinc (Zn) .... 0.05 %

Derived from: Dehydrated Manure, Feather Meal, Crab Meal, Cocoa Meal, Corn Gluten, Cottonseed Meal, Dried blood, Sunflower Meal, Kelp Meal, Alfalfa Meal, GreenSand, Rock Phosphate, Sulfate of Potash, Humates, Ammonium Sulfate,and Triple Super Phosphate.

Appendix B: Visual Basic code developed for penetrometer data analysis.

```
Private Sub CommandButton1_Click()
For i = 2 To 1419
        Set curCell = Worksheets("Sheet1").Cells(i, 28)
        If curCell.Value <= 4500 Then
            Worksheets("sheet1").Range(Cells(i, 1), Cells(i, 27)).Copy
            Worksheets("sheet1").Cells(i, 29).PasteSpecial
        End If
    Next i
End Sub

Private Sub CommandButton2_Click()
For i = 2 To 1419
    For j = 4 To 27
    Set curCell = Worksheets("sheet1").Cells(i, j)
    If Cells(i, 4) = "" Then
    Worksheets("Sheet1").Range(Cells(i, 4), Cells(i, j)).FillLeft
    Range(Cells(i, 4), Cells(i, j)).Interior.ColorIndex = 39
    End If
    If Cells(i, 6) = "" Then
    Worksheets("sheet1").Cells(i, 6) = Cells(i, 5)
    Cells(i, 6).Interior.ColorIndex = 39
    End If
    If Cells(i, 5) = "" Then
    Worksheets("sheet1").Cells(i, 5) = Cells(i, 4)
    Cells(i, 5).Interior.ColorIndex = 39
    End If
    Next j
Next i
End Sub

Private Sub CommandButton3_Click()
For i = 2 To 1419
    For j = 4 To 27
        Set curCell = Worksheets("sheet1").Cells(i, j)
        If curCell.Value = "" Then
            Worksheets("sheet1").Cells(i, j).FormulaR1C1 = "=Average(RC[-1],RC[-2])"
            curCell.Interior.ColorIndex = 15
            For k = j + 1 To 27
                Set curCell = Worksheets("sheet1").Cells(i, k)
                If curCell = "" Then
                    Worksheets("sheet1").Cells(i, k) = curCell.Offset(columnoffset:=-1)
                    curCell.Interior.ColorIndex = 39
                Else
                    Exit For
                End If
```

Appendix B: continued

```
            Next k
        End If
    Next j
Next i
End Sub
Private Sub CommandButton4_Click()
For i = 2 To 1419
        Set curCell = Worksheets("Sheet1").Cells(i, 28)
        If curCell.Value > 4500 Then
             Worksheets("sheet1").Range(Cells(i, 1), Cells(i, 27)).Copy
             Worksheets("sheet1").Cells(i, 29).PasteSpecial
        End If
    Next i
End Sub
```

Appendix C: Soil Resistance vs. Soil Water Content. Linear regression equations and respective R^2 values obtained on a tree basis for the Upper Coastal Plain and Piedmont sites.

Site	Clone Rep.	Cultural Treat.	Tillage Treat.	R^2	y=ax + b a	b	Clone Rep.	Cultural Treat.	Tillage Treat.	R^2	y=ax + b a	b
						Upper Coastal Plain						
Red Bay	3519	F	NT	0.97	-23486.14	8534.48	3519	F	T	0.96	-30888.40	7340.79
	3519	F	NT	0.01	-1833.77	4822.16	3519	F	T	0.96	-41947.44	8701.68
	3802	F	NT	0.64	-28736.52	10249.79	3802	F	T	0.86	-25381.20	6454.67
	3802	F	NT	0.33	-27904.56	9521.22	3802	F	T	0.78	-21700.83	5775.50
	3621	F	NT	0.00	217.22	3792.80	3621	F	T	0.95	-24527.12	5906.28
	3621	F	NT	0.92	-33486.71	10952.81	3621	F	T	0.71	-8903.14	3337.89
	3519	O	NT	0.08	-11579.74	6186.08	3519	O	T	0.67	-18632.43	5715.63
	3519	O	NT	0.24	5052.39	1516.63	3519	O	T	0.65	-6816.11	3278.06
	3802	O	NT	0.64	-48714.84	15453.08	3802	O	T	0.31	-7189.22	3607.05
	3802	O	NT	0.66	-51103.13	15803.92	3802	O	T	0.58	-16054.78	4681.76
	3621	O	NT	0.65	-38031.51	13955.79	3621	O	T	0.48	-10039.15	3287.16
	3621	O	NT	0.27	-11355.00	6174.60	3621	O	T	0.49	-24761.63	6097.63
	3519	F+V	NT	1.00	-27106.96	10369.41	3519	F+V	T	0.95	-18824.01	5314.32
	3519	F+V	NT	0.27	-16585.07	7427.20	3519	F+V	T	0.87	-9922.94	3159.79
	3802	F+V	NT	0.33	-11950.97	6031.56	3802	F+V	T	0.50	-6278.49	3067.83
	3802	F+V	NT	0.46	-14429.98	6684.56	3802	F+V	T	0.75	-8445.84	3263.57
	3621	F+V	NT	0.92	-16872.38	7286.55	3621	F+V	T	0.99	-22076.18	6494.33
	3621	F+V	NT	0.98	-7747.85	4564.68	3621	F+V	T	0.89	-16654.41	5142.62
Faceville	3802	F+V	NT	0.47	-5825.91	5032.19	3802	F+V	T	0.10	-2590.24	2454.43
	3802	F+V	NT	0.00	484.52	2386.09	3802	F+V	T	0.07	881.54	1244.39
	3519	F+V	NT	0.01	-1135.69	3006.66	3519	F+V	T	0.58	-6683.41	3858.35
	3519	F+V	NT	0.40	8175.92	-462.20	3519	F+V	T	0.28	-1277.99	1801.14
	3621	F+V	NT	0.50	-3836.10	3916.85	3621	F+V	T	0.00	-107.46	1528.82
	3621	F+V	NT	0.74	-11520.09	7332.17	3621	F+V	T	0.00	17.82	1363.03
	3802	F	NT	0.29	8512.12	208.20	3802	F	T	0.85	-8457.43	4609.40
	3802	F	NT	0.11	3035.58	2547.64	3802	F	T	0.99	-3721.93	2807.44
	3519	F	NT	0.72	-12654.49	8400.67	3519	F	T	0.83	-5795.24	3245.56
	3519	F	NT	0.96	14519.62	-3740.93	3519	F	T	0.01	-461.63	1590.41
	3621	F	NT	0.37	-12912.50	8554.32	3621	F	T	0.24	-1502.43	2222.10
	3621	F	NT	0.62	-19440.28	11510.79	3621	F	T	0.06	426.33	1796.50
	3802	O	NT	0.80	-8512.64	6721.58	3802	O	T	0.52	-5010.43	3498.97
	3802	O	NT	0.88	-12535.13	7850.80	3802	O	T	0.63	-16537.19	7947.34
	3519	O	NT	0.31	-5166.44	5319.50	3519	O	T	0.01	-717.09	2113.68
	3519	O	NT	0.60	-8091.05	6642.94	3519	O	T	0.83	-4316.09	3152.07
	3621	O	NT	0.10	-3119.00	4531.32	3621	O	T	0.11	-3288.48	2461.97
	3621	O	NT	0.09	1159.30	1784.05	3621	O	T	0.00	-188.03	1938.71

Appendix C: Continued

	3802	F+V	NT	0.43	-19287.90	11658.46		3802	F+V	T	0.98	-9006.98	3547.84
	3802	F+V	NT	0.59	-20834.33	12255.35		3802	F+V	T	0.95	-7430.73	2928.87
	3519	F+V	NT	0.26	-7510.15	5706.37		3519	F+V	T	0.97	-6938.40	3237.23
	3519	F+V	NT	0.32	-10723.71	7348.98		3519	F+V	T	0.99	-6141.70	2909.19
	3621	F+V	NT	0.98	-3265.94	3610.44		3621	F+V	T	0.97	-6911.31	4168.93
	3621	F+V	NT	0.99	-9463.54	6498.20		3621	F+V	T	0.91	-3217.20	2546.54
	3802	O	NT	0.86	-9113.47	6095.55		3802	O	T	0.95	-9198.16	3448.73
	3802	O	NT	0.94	-6853.55	4564.30		3802	O	T	0.96	-6209.62	2668.90
	3519	O	NT	0.93	-11467.65	6304.91		3519	O	T	0.98	-7807.60	3368.03
	3519	O	NT	0.95	-11464.35	6530.12		3519	O	T	1.00	-8173.45	3273.63
Gilead	3621	O	NT	0.68	-18168.17	10670.79	Gilead	3621	O	T	1.00	-7343.99	4149.64
	3621	O	NT	0.74	-6974.53	5036.73		3621	O	T	0.98	-5302.22	3322.70
	3802	F	NT	0.67	-18547.34	10476.49		3802	F	T	0.95	-15357.93	6362.44
	3802	F	NT	0.57	-30071.20	16113.83		3802	F	T	0.97	-14484.02	6179.09
	3519	F	NT	0.95	-35708.46	18224.21		3519	F	T	0.96	-9456.86	2973.19
	3519	F	NT	0.98	-28694.94	15215.14		3519	F	T	0.94	-14700.18	4441.77
	3621	F	NT	0.56	-9005.20	6461.94		3621	F	T	0.48	-3876.37	2535.65
	3621	F	NT	0.57	-16024.82	10545.93		3621	F	T	0.81	-6256.37	3585.91
	3802	F+V	NT	0.96	-4831.59	3695.56		3802	F+V	T	0.53	-9638.55	3602.54
	3802	F+V	NT	0.99	-17418.82	6649.67		3802	F+V	T	0.80	-13515.21	5053.14
	3519	F+V	NT	0.99	-4597.17	3923.44		3519	F+V	T	0.94	-13604.95	4708.35
	3519	F+V	NT	0.04	-954.90	2372.16		3519	F+V	T	0.88	-14631.30	5073.91
	3621	F+V	NT	0.75	-25680.31	9683.02		3621	F+V	T	0.86	-5756.45	2439.45
	3621	F+V	NT	0.52	-5391.18	4660.91		3621	F+V	T	0.94	-11695.62	3544.42
	3802	F	NT	0.14	2514.47	2661.78		3802	F	T	0.32	-3652.87	2545.22
	3802	F	NT	0.83	-6568.76	4918.28		3802	F	T	0.89	-9392.28	4043.59
	3519	F	NT	0.96	-15810.87	6682.68		3519	F	T	0.96	-7356.97	3144.22
	3519	F	NT	0.88	-9756.07	5512.76		3519	F	T	0.84	-8109.42	3433.61
Troup	3621	F	NT	0.95	-11535.30	5611.21	Troup	3621	F	T	0.07	2344.18	1035.93
	3621	F	NT	0.31	-3658.80	3847.28		3621	F	T	0.03	1566.46	1644.68
	3802	O	NT	0.66	-12246.93	6596.78		3802	O	T	0.69	-12003.75	4796.10
	3802	O	NT	0.37	-8496.55	5582.16		3802	O	T	0.82	-9600.49	4334.68
	3519	O	NT	0.10	1376.76	2035.26		3519	O	T	0.99	-7950.12	2938.39
	3519	O	NT	0.70	-4425.55	4073.25		3519	O	T	0.85	-13054.60	5074.77
	3621	O	NT	0.50	-2148.06	2719.86		3621	O	T	0.95	-10522.09	3525.21
	3621	O	NT	0.61	-8519.81	4755.61		3621	O	T	0.97	-8626.57	3342.55

Appendix C: Continued

Gritney	3621	F+V	NT	0.14	1144.32	1125.45	Gritney	3621	F+V	T	0.05	-460.33	1024.05
	3621	F+V	NT	0.45	-1302.41	1818.64		3621	F+V	T	0.03	530.74	1150.81
	3802	F+V	NT	0.19	3146.54	560.14		3802	F+V	T	0.05	-3207.04	1907.97
	3802	F+V	NT	0.00	476.08	1324.73		3802	F+V	T	0.00	1238.10	854.93
	3519	F+V	NT	0.15	1742.88	730.14		3519	F+V	T	0.03	-1440.14	1307.70
	3519	F+V	NT	0.20	1678.58	973.59		3519	F+V	T	0.00	699.62	1021.66
	3621	F	NT	0.00	94.87	1958.36		3621	F	T	0.00	848.97	1026.09
	3621	F	NT	0.08	-1529.20	2392.42		3621	F	T	0.01	-1384.52	1253.85
	3802	F	NT	0.61	5266.93	-763.49		3802	F	T	0.52	-9372.57	3331.07
	3802	F	NT	0.36	6311.63	-1199.72		3802	F	T	0.26	9679.73	-970.75
	3519	F	NT	0.60	-3553.32	3156.50		3519	F	T	0.02	-516.05	1461.54
	3519	F	NT	0.99	-1599.12	1973.39		3519	F	T	0.87	-3590.10	2446.41
	3621	O	NT	0.23	-925.24	2211.00		3621	O	T	0.52	5416.95	-503.54
	3621	O	NT	0.09	-402.63	1779.63		3621	O	T	0.47	23491.77	-5030.72
	3802	O	NT	0.30	-894.84	1894.13		3802	O	T	0.17	-3365.79	2132.70
	3802	O	NT	0.00	108.44	1563.92		3802	O	T	0.01	642.43	1196.82
							Piedmont						
Cecil	3621	F	NT	0.94	-3498.85	4110.06	Cecil	3621	F	T	0.93	-7238.81	3855.84
	3621	F	NT	0.65	-7622.69	5786.29		3621	F	T	0.15	-2827.81	2609.13
	3802	F	NT	0.54	42858.67	-12757.10		3802	F	T	0.61	35849.01	-9044.03
	3802	F	NT	0.01	-1810.35	4486.05		3802	F	T	0.35	69845.86	-18724.25
	3519	F	NT	0.74	-3480.28	4655.76		3519	F	T	0.07	2284.16	1385.99
	3519	F	NT	0.66	-5821.03	5833.87		3519	F	T	0.00	-371.93	1968.41
	3621	O	NT	0.74	-11693.73	7855.40		3621	O	T	0.38	8963.98	-410.33
	3621	O	NT	0.65	-13545.45	9017.85		3621	O	T	0.12	10349.56	-825.17
	3802	O	NT	0.49	-12156.93	8433.59		3802	O	T	0.07	-6113.33	4883.99
	3802	O	NT	0.86	-21951.23	12041.18		3802	O	T	0.86	17925.64	-4152.18
	3519	O	NT	0.02	2370.46	2583.53		3519	O	T	0.40	-1437.25	2664.73
	3519	O	NT	0.48	-6333.44	6112.84		3519	O	T	0.11	6158.05	959.82
	3621	F+V	NT	0.11	-12488.13	8370.16		3621	F+V	T	0.93	-2267.32	2247.23
	3621	F+V	NT	0.36	-34696.54	16816.41		3621	F+V	T	0.81	-10833.10	5465.24
	3802	F+V	NT	0.49	-46147.32	22041.67		3802	F+V	T	0.95	-13956.30	7093.13
	3802	F+V	NT	0.67	-75391.20	32526.47		3802	F+V	T	0.13	-1603.88	2471.71
	3519	F+V	NT	0.00	-13.09	3357.23		3519	F+V	T	0.42	-2317.48	2701.88
	3519	F+V	NT	0.05	8489.36	1041.32		3519	F+V	T	0.02	544.45	1789.87

Appendix C: Continued

Lloyd	3802	F+V	NT	0.03	-757.58	2383.67	Lloyd	3802	F+V	T	0.99	-31297.04	6840.85
	3802	F+V	NT	0.05	-1391.35	2883.94		3802	F+V	T	0.48	-7039.76	2473.98
	3621	F+V	NT	0.32	-6356.43	4148.90		3621	F+V	T	0.00	-660.22	1737.28
	3621	F+V	NT	0.98	-19986.31	7789.24		3621	F+V	T	0.85	-14740.76	4271.91
	3519	F+V	NT	0.94	-45579.64	15667.88		3519	F+V	T	0.06	-5710.91	2029.80
	3519	F+V	NT	0.81	-62428.32	21012.82		3519	F+V	T	0.34	-12704.80	3204.12
	3802	F	NT	0.61	-13218.75	7588.11		3802	F	T	0.98	-21658.82	5189.87
	3802	F	NT	0.92	-9409.07	5651.85		3802	F	T	0.98	-21577.38	5473.71
	3621	F	NT	0.23	-14122.78	6828.66		3621	F	T	0.98	-14519.64	4898.10
	3621	F	NT	0.21	-14448.08	6967.06		3621	F	T	0.94	-15829.23	4946.00
	3519	F	NT	0.15	10234.73	522.26		3519	F	T	0.92	-13073.79	3042.14
	3519	F	NT	0.38	20436.39	-1412.41		3519	F	T	0.98	-25953.20	5167.04
	3802	O	NT	0.97	-30345.12	13329.93		3802	O	T	0.97	-18970.96	5242.82
	3802	O	NT	0.97	-25189.12	11128.92		3802	O	T	0.98	-19360.43	5512.02
	3621	O	NT	1.00	-22511.84	10474.72		3621	O	T	0.71	-12580.48	3606.08
	3621	O	NT	0.94	-15698.06	7358.79		3621	O	T	0.77	-15765.27	4426.34
	3519	O	NT	0.80	-17131.71	7330.47		3519	O	T	0.97	-21528.15	5381.43
	3519	O	NT	0.29	-7136.34	4053.49		3519	O	T	0.96	-21391.86	5169.09
Rion	3519	F+V	NT	0.09	-1868.79	4283.90	Rion	3519	F+V	T	0.64	-25591.22	10397.09
	3519	F+V	NT	0.66	-4020.97	4657.03		3519	F+V	T	0.38	-14484.63	6249.23
	3802	F+V	NT	0.65	-6818.74	6560.19		3802	F+V	T	0.90	-15790.17	7207.02
	3802	F+V	NT	0.72	-6443.26	6809.04		3802	F+V	T	0.09	-6051.42	4598.88
	3621	F+V	NT	0.22	-5211.25	5156.32		3621	F+V	T	0.11	2991.54	2276.74
	3621	F+V	NT	0.00	1222.53	3422.60		3621	F+V	T	0.91	-14360.19	7242.66
	3519	O	NT	0.00	-1559.82	4205.40		3519	O	T	0.75	-18354.14	8536.89
	3519	O	NT	0.12	-2775.90	4449.55		3519	O	T	0.96	-18461.42	8092.82
	3802	O	NT	0.59	-6707.08	5637.20		3802	O	T	0.74	-14466.30	6390.56
	3802	O	NT	0.07	-2051.89	3257.05		3802	O	T	0.58	-19464.90	8235.04
	3621	O	NT	0.60	-22148.67	9073.23		3621	O	T	0.82	-6572.94	2803.55
	3621	O	NT	0.00	852.02	3187.46		3621	O	T	0.05	4811.17	1720.84
	3519	F	NT	0.58	-6281.11	5404.11		3519	F	T	0.77	-7005.13	3402.97
	3519	F	NT	0.75	3462.55	3159.67		3519	F	T	0.67	-9915.25	4269.94
	3802	F	NT	0.57	-10955.63	6422.23		3802	F	T	0.87	-19844.60	6748.17
	3802	F	NT	0.06	2955.39	3090.45		3802	F	T	0.65	-12485.26	5708.81
	3621	F	NT	0.39	-6165.18	5630.21		3621	F	T	0.36	-6979.94	3348.17
	3621	F	NT	0.11	-5099.44	4589.64		3621	F	T	0.04	-1527.34	2282.22