## ABSTRACT

O'BERRY, SERENIA MARIE LARRISON Soil Compaction in Loblolly Pine Seed Orchards and the Impacts on Tree Health. (Under the direction of Steven E. McKeand and Fikret Isik).

To understand the impact of heavy equipment on soil compaction in seed orchards of loblolly pine (*Pinus taeda* L.), soil strength (surrogate for soil compaction) was measured using a penetrometer for five sample positions per tree for 303 trees across five loblolly pine seed orchards in coastal Georgia and South Carolina. Soil compaction was significantly increased in the traffic rows around all trees in each orchard. The percentage of "usable soil" (defined as the volume of soil having a soil strength < 2750 kPa) ranged from an average of only 7% to 18% in the traffic rows for the five orchards sampled but was 18% to 45% in the sample positions near the tree where traffic was minimal. For each tree in the study, cone yield per tree and crown density using UrbanCrowns software were measured to determine the impacts of soil compaction on tree health. Mixed models were used to determine significant parameters in explaining variation in cone yields and crown density. When assessing crown density, orchard and crown volume were significant, but no soil compaction variables had a significant impact on crown density. Orchard, clone, crown volume, and a soil compaction variable were all significant parameters in understanding variation in cone yields. This means soil compaction, after accounting for orchard, clone and crown volume, is having a negative impact on cone yields. Therefore, while there are high genetic gains from control crosses, producing them on a mass scale may have detrimental effects on cone production.

Based on these results, heavy equipment use is causing major soil compaction in loblolly pine seed orchards, and compaction is impacting cone yields. Due to the high

economic value of controlled cross seeds, a practice requiring heavy aerial lift use, soil compaction is a problem that orchard managers will continue to face. It is important to manage equipment use to minimize soil compaction while optimizing the economic potential of orchards.

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Soil Compaction in Loblolly Pine Seed Orchards and the Impacts on Tree Health and Cone Yields.

by
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## DEDICATION

For my husband, Brian, you have always been my biggest supporter. You have offered me the encouragement to succeed in anything I put my mind to. You are my rock, and without you this would not have been possible.

For my parents, Chrissy and Mike, you have supported every dream I've ever had, and for that I will be forever grateful.

## BIOGRAPHY

Serenia grew up on the coast of Georgia in White Oak, a small town with few people. As a child, she loved the outdoors and spent much of her time outside. In high school, she joined FFA which had a major impact in her life. It allowed her to discover her love for forestry and environmental sciences.

She completed an associate’s degree in applied sciences from Abraham Baldwin Agricultural College in Tifton Ga. She then moved to Athens, Ga to complete a bachelor’s degree in forestry from the University of Georgia. While attending the UGA she did several internships, which allowed her to discover her love from tree improvement.

## ACKNOWLEDGMENTS

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## TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# Introduction

## Pine Importance in the Southern US

Millions of products are made from wood every year, and they are used in everyday life by many people. Products vary from simple structural components such as dimensional lumber and plywood to chemical components used to make LCD screens in many electronics such as cellphones and TVs (Canada 2017). With so many products produced from wood and large industry opportunities, the Southern United States has become one of the most important regions in the world for the commercial production of wood (Boby et al. 2013). Findings from Southern Forest Resource Assessment report include: in 1997 timber harvest led to 700,000 jobs as well as $118 billion in industry output in the Southeast. With an estimated 214 million acres of forested land in 2002, the Southeast has demonstrated the massive potential for the forestry industry. In 1998, 1.6 billion seedlings were planted in the US, and 78% of those seedlings were planted in the Southeast. By 2040 the production of wood in the region is predicted to increased beyond current production by nearly a third. In 2010, timber management organizations managed 20 million acres of forested lands, valued at 35 billion dollars in the Southeast (Zhang et al. 2011). With the addition of publicly traded real estate investment trusts as well as private landowners, forest production and economic potential in the Southeast is enormous. The production of wood in the region has increased substantially over the years, and the trend is predicted to continue well into the future. The global trend for wood demand has been increasing by approximately 1.5-2 percent every year, and with increased demand greater importance is placed on growing more wood on fewer hectares (Wear and Greis 2002). The deployment of genetically improved loblolly pine (*Pinus taeda*) seedlings helps to give landowners the ability to meet that wood production on fewer acres, due to increased volume growth, disease resistance and better form.

## Tree Improvement

There are nearly 1.1 billion loblolly pine seedlings being grown in the US, and approximately 80% of those seedlings are grown in the southeastern US (Starkey et al. 2015). Most seedlings are genetically improved material, and the estimated productivity increase over unimproved seedlings ranges from 10-30% (McKeand et al. 2003). There are several levels of genetically improved seedlings, and each has different economic impacts. The varying levels of improvement involve different deployment populations that allow for more control over what genetics are planted in specific stands. Four deployment strategies can be used: (1) Bulk mixes of seed collected from seed orchards. This strategy of deployment has the least genetic gain but the most diversity. Given low level of genetic gain, this strategy has the least economic impact and is not commonly used today. (2) Single well-tested open-pollinated (OP) families collected from a wind pollinated seed orchard provide more genetic gain over bulk mixes. Deployment of OP families is by far the most common practice. (3) Single full-sibling (FS) families are created through controlled crosses of well tested parents propagated from seed or through vegetative propagation. FS family deployment uses very intensive, large-scale controlled crossing, but because of the significant genetic gains, the benefits of these practices often outweigh the costs. (4) Single well-tested clones deployed through vegetative propagation strategy provides the most genetic gain potential. Clonal deployment is still small compared to other strategies, accounting for about 2% of all loblolly pine being planted (McKeand 2015).

Genetic gains from full-sibling crosses of superior parents can produce volume gains of 50% (Jannson 2004). The volume gains from genetically improved seedlings have substantial financial gains over non-improved seedlings (McKeand et al. 2006). Due to the yield, economic gains seen from using the full-sibling deployment strategy (mass production of controlled crosses or MPCC), and use of this strategy has increased over the last 15 years. In a non-published survey of cooperators in the North Carolina State University Cooperative Tree Improvement Program for loblolly pine, there were an estimated 116.3 million seedlings produced from MPCC in 2017 (McKeand 2017). The mass production of controlled crosses is an intensive strategy that involves large scale application of pollen on physically isolated female reproductive strobili (Bramlett 1997). Female reproductive strobili are physically isolated using a bag placed over the female strobili (commonly referred to as flowers) once development begins. The strobili are closely monitored as development continues throughout the spring. Once the female strobili are receptive to pollination, previously collected and processed pollen is used to complete the cross. This strategy of breeding allows for the control of both maternal and paternal parents, therefore, there is more genetic gain from selecting the two outstanding parents (Grattapaglia et al. 2014).

## Seed Orchards

Seed orchards are the production vectors between tree improvement programs and seedling deployment or reforestation efforts (Chaloupková et al. 2016). Parents are selected from a breeding population; scion material is collected from the parent clone and is grafted onto rootstock in a seed orchard in a grid pattern with rows and columns of trees at a specified spacing. Each grafted tree of a specific clone is referred to as a ramet of that clone.

Trees in seed orchards are managed intensely. Close attention is paid to fertilization, to not only sustain healthy trees but also to induce flower and pollen production. Tree spacing, ground cover management and insect control are also extremely important factors in managing a seed orchard.  The extra attention and resources provided to a seed orchard are a direct result of financial decisions. The high cost associated with the establishment and maintenance of a seed orchard calls for careful attention to managing each orchard sustainably while considering cost versus benefits of all deployment strategies.

Although there are substantial genetic and financial gains from an intensive breeding and deployment strategy such as MPCC, the mechanics can have negative impacts on the seed orchards.  Due to the anatomy of loblolly pine, crossing is performed on terminal branches in the top of the crown. Often orchard trees grow to substantial heights (20m to 35m) that prevent the performance of these practices without the assistance of heavy equipment such as aerial lifts. This heavy equipment coupled with the frequently moist soils of early spring can result in significant soil damage and increased soil compaction. Other industries have found alternatives to the use of heavy equipment such as dwarfing rootstock, which limits the height growth allowing flexibility in harvesting and pollination practices, and pruning to control crown shape and overall height. The apple industry, for example uses a Malling 9 dwarfing rootstock to shorten the juvenile period, reduce vegetative growth, and increase flowering (Foster et al. 2013). This allows harvesting with the use of ladders rather than heavy equipment. There have been no significant strides made in finding a dwarfing rootstock for loblolly pine (Jayawickrama et al. 1991), nor have there been techniques developed to control height without having overwhelming negative impacts on female flower production (Gerwig 1987).

As the number of seedlings produced from controlled crosses has increased from effectively 0 in the year 2000 to over 116 million in 2017(McKeand 2017), the use of aerial lifts in orchards has also drastically increased. When using open pollinated families to produce seedlings, orchard trees are pollinated naturally with the majority of the pollen coming from other trees within the orchard. This method of seed production requires minimal traffic inside an orchard. Lifts would be used to estimate cone crops, monitor cone development, and collect cones from desired ramets in the fall when cones ripen. In contrast, when performing MPCC, lifts are used for multiple tasks including:

flower monitoring, done daily or every other day as flowers begin to progress,
bagging branches with pollination bags to prevent outside pollen contamination,
two or three pollinations each separated by one to two days,
bag removal ten days to two weeks following pollination,
pollen monitoring done daily or every other day as pollen strobili begin to mature and produce pollen,
pollen collection,
cone crop estimations,
cone monitoring,

and cone collection 18 months later.

Not only has the use of aerial lifts increased considerably, the conditions during which lift use occurs are often not ideal. The time-sensitive nature of flower and pollen development of loblolly pine can often require aerial lift use in an orchard during unfavorable conditions such as after a heavy rainfall when the soil moisture content is very high. The continued increase of lift use often in unfavorable soil moisture conditions can cause extensive soil compaction in orchards.

Orchard design and clone layout varies based on the ultimate objective of the orchard, but the design can have a substantial impact on traffic patterns.  Often genetic improvement intensity, such as open pollinated versus controlled pollinated seed is a major contribution to decision making for layout design (Chaloupková et al. 2016). While clonal blocks (placing multiple ramets of the same clone in groups) can be more efficient when doing controlled pollination, it decreases the flexibility of the orchard. Often when ramets of the same clone are grouped together, as in a clonal block design, selfing or inbreeding may occur if controlled pollination is not practiced. Inbreeding will result in inbreeding depression, and therefore can be harmful to the deployment population (Chaloupková et al. 2016). Randomized orchards or systematically randomized orchards are designed to decrease the possibility of selfing or inbreeding in open-pollinated seed, while having the flexibility to also be used for control pollination practices. However, this can be inefficient as it requires more travel through an orchard with heavy aerial lifts.  Clones can have specific phenological development with some female strobili developing earlier than strobili on other clones (Bramlett 1997). Female strobili will mature at different stages, and when clones are scattered throughout an orchard, more time and resources are required to pollinate all ramets. In clonal blocks, ramets of each clone are grouped together requiring less travel to perform operations on all ramets of a specific clone.

The number of clones grafted into an orchard, as well as the number of ramets per clone, also varies among orchards based on the objectives of the orchard. The number of clones can be directly related to equipment traffic in an orchard just as layout of those clones. With each clone having a different phenology, the number of trips through an orchard increases, and the travel pattern to move from one ramet to the next is repeated many times.

Studies have been conducted in agricultural crops as well as in forest logging sites to evaluate the impact of heavy equipment on soil compaction. A study evaluating the impacts of tractor use on soil compaction in an almond (*Prunus amigdalus*) orchard found between one to three passes over a designated path caused significant soil compaction. However, the addition of three to eight passes had no significant impacts on soil compaction in the topsoil, but with more than eight passes, there was significant compaction in the subsoil (Becerra et al. 2010). This suggests that if equipment is used in designated paths, soil compaction will be extreme in those areas, but surrounding areas will not be damaged.

Studies of this nature have led to the agricultural industry designing equipment with specific axle and tire widths to perfectly match designated traffic passes. Similar practices have not been adopted in loblolly pine seed orchards.  Aerial lifts are often driven in random patterns throughout the orchard without any designated traffic paths. The random spatial design of many orchards can result in a need to travel to trees positioned far from one another.  Lifts also move fairly slowly, therefore when needing to travel to other trees, the shortest possible path between the trees is often used. While most lift traffic occurs between columns (traffic rows), some traffic still occurs between trees within the tree rows, because it is frequently the shortest path. The increased use of aerial lifts and the use of lifts during periods of unfavorable soil moisture conditions and seemingly random travel patterns may be contributing to a major soil compaction problem in orchards.

This study is designed to evaluate the degree of soil compaction in seed orchards and the impacts that compaction may have on the health and vigor and the cone production of seed orchards trees. In this study, soil samples were taken to measure soil compaction in five seed orchards in the southeastern US. Within each orchard, specific trees were selected as sampling units. Foliage and crown densities, cone yields, and tree vigor were measured for each tree to determine the relationships between soil compaction and the various tree health responses.

### *Study Objectives*

There are two main objectives: 1) Characterize and understand soil compaction in five loblolly pine seed orchards in the Southeastern United States and 2) Find possible associations between soil compaction and tree health and cone yields.

Becerra, A.T., Botta, G.F., Bravo, X.L., Tourn, M., Melcon, F.B., Vazquez, J. *et al.* 2010 Soil compaction distribution under tractor traffic in almond (*Prunus amigdalus L.*) orchard in Almería España. *Soil and Tillage Research*, **107** (1), 49-56.

Boby, L., Henderson, J. and Hubbard, W. 2013 The Economic Importance of Forestry in the South. Southern Regional Extension Forestry.

Bramlett, D.L. 1997 Southeastern Conifers: Genetic Gain from Mass Controlled Pollination and Topworking. *Journal of Forestry*, **95** (3), 15-19.

Canada, N.R. 2017 Wood products: everywhere for everyone. http://www.nrcan.gc.ca/node/13313#screens.

Chaloupková, K., Stejskal, J., El-Kassaby, Y.A. and Lstibůrek, M. 2016 Optimum neighborhood seed orchard design. *Tree Genetics & Genomes*, **12** (6), 105.

Foster, T.M., Watson, A.E., Hooijdonk, B.M. and Schaffer, R.J. 2013 Key flowering genes including FT-like genes are upregulated in the vasculature of apple dwarfing rootstocks. *Tree Genetics & Genomes*, **10** (1), 189-202.

Gerwig, D.M. Annual top pruning as crown management technique in a young loblolly pine seed orchard to reduce height and still produce flowers.

Grattapaglia, D., Amaral Diener, P.S. and Santos, G.A. 2014 Performance of microsatellites for parentage assignment following mass controlled pollination in a clonal seed orchard of loblolly pine (*Pinus taeda L.*). *Tree Genetics & Genomes*, **10** (6), 1631-1643.

Jannson, G., annd B. Li. 2004 Genetic gains of full-sib families from disconnected diallels in loblolly pine *Silvae Genet*, **53**, 60-64.

Jayawickrama, K.J.S., Jett, J.B. and McKeand, S.E. 1991 Rootstock effects in grafted conifers: A review. *New Forests*, **5** (2), 157-173.

McKeand, S. 2015 In *Annual Report*, North Carolina State University Cooperative Tree Improvment Program

McKeand, S. 2017 Mass production of controll crosses in TIP cooperative 2016. S. Larrison (ed.).

McKeand, S., Mullin, T., Byram, T. and White, T. 2003 Deployment of genetically improved loblolly and slash pines in the south. *Journal of Forestry*, **101** (3), 32-43.

McKeand, S.E., Abt, R.C., Allen, H.L., Li, B. and Catts, G.P. 2006 What are the best loblolly pine genotypes worth to landowners? *Journal of Forestry*, **104** (7), 352-358.

Starkey, T.E., Enebak, S.A. and Smith, D.B. 2015 Forest seedling nursery practices in the Southern United States: bareroot nurseries. In *Tree Planters Notes*.

Wear, D.N. and Greis, J.G. 2002 Southern Forest Resource Assessment: Summary of findings. *Journal of Forestry*, **100** (7), 6-14.

Zhang, M., Mei, B., Harris, T.G., Siry, J.P., Clutter, M.L. and Baldwin, S.S. 2011 Can timber hedge against inflation? An analysis of timber prices in the US south. *Forest Products Journal*, **61** (4), 276-282.

# CHAPTER 1:

## Characterizing Soil Compaction in Loblolly Pine Seed Orchards

## Abstract

Heavy equipment use in loblolly pine (*Pinus taeda* L) seed orchards has increased with the increase of mass production of controlled crosses. Soil strength (a surrogate for soil compaction) was measured at five sample positions for 303 trees in five seed orchards. Three sample positions were taken within traffic rows where most heavy equipment use occurs, and two samples were taken between trees within tree rows. Overall mean soil strength in all orchards was higher than 2750 kPa, a value determined to be detrimental to root growth and nutrient based on various literature. Traffic use had a significant impact, as soil strength in traffic rows was significantly higher than that found closer to the tree. The percentage of "usable soil" (defined as the volume of soil having a soil strength < 2750 kPa) ranged from an average of only 7% to 18% in the traffic rows for the five orchards sampled but was 18% to 45% in the sample positions near the tree where traffic was minimal. Soil profiles illustrating soil strength by depth also showed a general increase in soil strength as depth increased in all orchards that were not subsoiled. In the subsoiled orchard, soil strength increased to a peak then decreased, showing the residual effects subsoiling had on the orchard.

Overall, the study showed that soil strength in loblolly pine seed orchards used in this study is high, and the soil should be considered compacted. Seed orchards are high capital investments, and orchard managers should consider management regimes and designs to better deal with the negative impacts that heavy equipment use has on orchard soils.

## Introduction

The high genetic and economic value of genetically improved full-sibling loblolly pine (*Pinus taeda*) seedlings has increased the incentive for seed orchard managers to produce large quantities of control-cross seed. Mass production of controlled crosses (MPCC) requires heavy aerial lift use in seed orchards, and this increased lift traffic may be having negative impacts on soil compaction which in turn could have negative impacts on tree health and cone yields.

Soil compaction can be defined as the reduction of pore volume or the increase of solid mass per unit volume of soil (Becerra et al. 2010). When soil is compacted, the bulk density, pore size, and moisture content is altered (Cambi et al. 2015). Soil compaction, often a result of equipment use, changes the distribution of pore sizes in the impacted soils. Macro pore space decreases substantially leaving only micro pores spaces (Lipiec and Hatano 2003), and this redistribution of pore size can have serious impacts on roots' ability to grow. While roots can displace soil if soil strength is sufficiently low enough, soil penetrability is often determined based on pore size. This is because a root is only able to penetrate a pore that is larger in diameter than the root when displacing soil is not possible due to high soil strength (Wiersum 1957). These impacts can have detrimental effects on plant health, root function, and disease resistance.

Many studies have shown the impacts of compaction on agricultural plants. In several cereal grain plants, compaction can decrease root elongation and thickness by 50-70%, varying by species, when compared to root growth in "uncompacted" soils (Lipiec et al. 2012). The distance between root systems was examined in compacted and none compacted areas. In the compacted areas, distance between root systems of maize plants was a maximum of 63.7mm, while distance between root systems is non-compacted area was less than 5.3mm (Lipiec and Hatano 2003). Biomass yields for barley were examined based on treatment groups with varying number of passes with equipment (Arvidsson 1999). Soils compaction was examined in each treatment group, and biomass was harvested several times. In each harvest, the amount of biomass was significantly less in the more compacted areas (Arvidsson 1999).

Compaction can also have serious impacts on the health of many tree species. Short-term effects of soil compaction were assessed on lodgepole pine seedlings (*Pinus contorta)* (Conlin and Driessche 1996). Nutrient uptake was less as soil compaction increased based on a foliage analysis. Three soil compaction levels had a significant impact on various tree health measurements, including shoot and root growth.

Bulk density is a direct measure of the ratio of solid soil particles to a specified volume of soil and is an excellent measurement of soil compaction (Cambi et al. 2015). However, bulk density is a very labor intensive measurement to collect and analyze. Soil cores of a known volume must be carefully extracted, weighed, dried, and weighed again.

A soil penetrometer measures soil strength and can be used as an indirect measurement of soil compaction (Duiker 2002). Basic machines are equipped with a cone tip, that can be changed, and vary by size, a driving shaft, and a pressure gage. Penetrometers are designed to mimic the resistance a root will experience as it grows through the soil profile (Duiker 2002). There are some disadvantages of a penetrometer when used to understand the impacts that soil strength are having on roots. First, the diameter of the shaft is much larger than the diameter of a root. This will cause the resistance measured by the penetrometer to be slightly higher than the resistance experienced by roots. The shaft is also straight and moves through one path of the soil, preventing the machine from traveling through all possible paths available to a root. Roots however, move through the soil through the path of least resistance. They will also move in many directions in an attempt to grow. This will also cause the resistance seen by the penetrometer to be slightly higher than the actual resistance experienced by roots.

Penetrometer readings are also heavily impacted by soil moisture content. As moisture content decreases, soil strength increases (Cambi et al. 2015). This relationship places high importance on knowledge of moisture content at the time of sampling, as root growth may be limited while the moisture content is low but will increase when moisture content increases. In a study assessing the impacts of soil drying on penetrometer readings, it was concluded that as soil dries, soil strength increases (Gao et al. 2012). The preferred time to take penetrometer samples is when the entire profile being measured is at field capacity (Duiker 2002).

Soil strength is known to have negative impacts on plant growth. It is widely accepted that a soil strength value of 2500 kPa (360 PSI) has serious restrictions on agricultural plant root elongation and nutrient uptake (Groenevelt et al. 2001).

In this study, a penetrometer was used to measure the soil strength surrounding 303 sample trees in five loblolly pine seed orchards in the coastal plain of Georgia and South Carolina. The resulting measurements were used to characterize soil compaction in each orchard in the study.

***The objectives*** of the study described in this chapter are 1) Measure and characterize soil compaction based on measured soil strength in loblolly pine seed orchards and 2) Compare measured soil strength in loblolly pine seed orchards to known detrimental soil strength values.

## Materials and Methods

### *Orchards*

This study consists of five loblolly pine seed orchards located in the Coastal Plain of Georgia and South Carolina in the Southeastern United States. Each orchard varies with soil type, age, climate, and management style (Table 1. 1) and is owned and managed by members of the North Carolina State University Cooperative Tree Improvement Program. At each orchard, cooperators identified the sample trees to be used in the study. Only clones that were operationally harvested were considered, and the number of sample trees varied among orchards. In October 2015, cooperators counted the number of bushels of cones collected from each sample tree. The number of cones per tree was estimated by counting the number of cones in one bushel then multiplying by the number of bushels harvested per tree.

Crown density was estimated for every tree in the initial sample using UrbanCrowns, a software created by the U.S. Forest Service (Winn et al. 2011). To determine a smaller sample, trees were grouped, first by orchard then by clone. After grouping, ramets of the same clone were sorted based on estimated crown density. Ramets were then selected across the range of crown density variation, with some having a high crown density, some in the middle, and some with low crown density. The final number of trees in each orchard ranged from 50 to 70 trees.

Each orchard is arranged in a row and column position with varying spacing at each orchard (Table 1. 2). Spacing is often a shorter distance between trees within rows than between rows. The space between rows of trees is more likely to be used for travel of heavy equipment such as tractors and aerial lifts due to easier accessibility. The space between rows of trees was designated "within traffic" rows, and the spacing between trees within the rows was designated as "within tree" rows.

Traffic management was different among orchards. None of the orchards except Orchard C has any kind of management rules about where equipment was allowed to travel. In Orchard C, the orchard manger regularly discussed with workers about traveling only within traffic rows and not within tree rows. These rules were established due to concern for soil compaction and rutting in the orchard. No orchard except E has had any soil remediation in recent years. Orchard E was subsoiled to a depth of 60 cm with on pass down the center of the within traffic row in summer 2014.

The sampling area of Orchards A and B was a Tifton Loamy Sand. The Tifton soil series have deep well drained soils that developed from loamy marine sediments. Orchard C had two major soil types, each comprising of about half the sampling area: a Lynchburg Loamy Sand, which is a somewhat poorly drained sandy soil from marine deposits, and a Plummer Sand, a poorly drained sandy soil also developed from marine deposits. The sampling area in Orchard D was a Chipley Loamy Fine Sand. Chipley soil series are somewhat poorly drained formed from sandy marine deposits. The soil type in Orchard E was a Greenville Sandy Loam; these soils are well drained and formed from clayey marine sediments (Appendix A).

### ***Preliminary Sampling***

A preliminary sampling was performed on a single orchard (Orchard A) in the study to help guide decisions on the best protocol for the soil strength sampling. For the preliminary sampling, 21 trees from Orchard A were selected from the initial set of sample trees. Each tree was randomly assigned a quadrant between one and four (Figure 1.1). This quadrant dictated which tree row and which traffic row would be sampled. Penetrometer samples to measure soil strength along the tree and traffic row were taken every 50cm beginning 1.5m from the base of the tree using a Field Scout SC 900 Soil Compaction Meter. The penetrometer was pushed into the soil to a maximum depth of 30.5 cm. The model penetrometer used in this study was incapable of measuring strength above 6900 kPa, therefore once the resistance reached 6900 kPa, or it penetrated 30.5 cm in depth, the measurement was complete. The penetrometer provided a soil strength measurement (kPa) every 2.5cm depth increment when a sample was taken. If a tree was randomly assigned to quadrant I, then samples would be taken along that axis within that tree row and along the adjacent traffic row. Each tree had a total of 16 penetrometer samples taken during the preliminary sampling scheme.

There was a steady increase in average soil strength values within the traffic row moving further away from the base of the tree (Figure 1.2B). The small standard errors associated with the traffic row measurements also indicated low variances between trees. Soil strength within the tree rows had less consistency between samples as sample points moved away from the tree. There seemed to be two groups within the tree row. One group, from 1.5m to 3.0m indicated lower compaction while the second group 3.5m to 5m indicated a greater compaction (Figure 1.2A). When comparing the sample means within the tree row or within the traffic row at the 2-meter position, there was little difference between the two. Therefore, regardless of row type, within tree rows or within traffic rows, the 2-meter positions were similar for each tree. This suggest the 2 meter position is relatively non-disturbed and provides a comparison for the soil disturbed by the equipment.

***Soil Strength Samples***

Based on the preliminary sampling, five soil strength sample positions per tree were determined. There were three sample positions within the traffic row, taken on one side of the tree. A random number generator was used to determine which side of the tree the within traffic row samples were taken. Samples within the traffic row were taken at 2 m, 3.5 m and 5 m from the tree. Two more sample positions were determined within the tree row. On each side of the tree within the tree row, a sample was taken at 3.5 meters (Figure 1. 3).

A soil penetrometer (Field Scout SC 900 Soil Compaction Meter[1]) was used to measure soil strength at each sample position. The penetrometer was equipped with a 12mm cone tip with a 30° angle. At each sample position, a metal plate with a hole in the center was placed on the ground. The cone tip of the penetrometer was placed in the center hole, and the

[1] http://www.specmeters.com/soil-and-water/soil-compaction/fieldscout-sc-900-meter/sc900/ referenced April 30, 2017

probe was pushed slowly and at a consistent rate of approximately 2.5cm per second into the soil profile (Figure 1. 4). The meter uses an ultrasonic depth sensor to record a soil strength measurement every 2.5 cm as the probe moved through the profile. The metal plate used at each sample position ensured a smooth level surface for proper function of the ultrasonic depth sensor. At every 2.5cm, a soil strength reading in kPa was recorded. The recordings were then uploaded as a column separated value (CSV) file (Technologies 2009).  This soil penetrometer model had an equipment restriction that only allowed the machine to measure a maximum of 6900 kPa. Due to limitations of the penetrometer, samples were taken to a maximum depth of 30.5 cm when possible. However, if soil strength reached 6900 kPa before 30.5 cm in depth, sampling stopped. This left a range of depths across the sampling points with a minimum of 5 cm to a maximum of 30.5 cm.

Penetrometer sampling began in October 2016 and concluded in January 2017. All samples were taken at each orchard over the course of 48 hours to ensure consistent soil conditions, including moisture content, between samples. This allowed samples within an orchard to be compared to other samples within the same orchard.  Samples taken within the tree row were taken by the same person, while samples taken within the traffic row were taken by a different person. Two penetrometers of the same model were used to collect the samples, and were designated as either the within tree row machine or the within traffic row machine. This was done to reduce any bias in the machine or its user.

### *Bulk Density and Moisture Content Sampling*

Soil strength is a surrogate measurement for soil compaction, therefore a small number of bulk densities (a direct measure of soil compaction) were taken to understand the relationship between soil strength and soil compaction. Penetrometer readings are heavily impacted by soil moisture content, because soil strength increases as moisture content decreases (Gao et al. 2012). These relationships are important factors in understanding soil strength and how it relates to soil compaction.

Soil bulk density and moisture content were determined from ten soil core samples taken in each orchard. Samples were taken using a hammer driven core sampler with a ring inside a sampling head (7.62 cm in height and inside diameter). It was placed on level ground and was gently hammered into the soil at the desired depth, depending on the soil strength. The larger cylinder was carefully extracted, making sure not to lose any contents during extraction. The smaller cylinder contained the soil core and was separated from the larger cylinder. Once the smaller cylinder was removed from the larger, any excess soil outside of the cylinder was shaved with a knife to ensure an exact volume of soil. The contents were placed into a sealed bag and brought back to the lab for processing (Figure 1. 5).

To understand the relationship between soil strength and bulk density, it is important to have bulk density samples that are representative across the full range of possible soil strength values. Flags were placed at soil strength sample positions where desired soil strength values occurred. Once all soil strength measurements were taken, core sample positions were selected based on the range of soil strength values represented and the location in the orchard.  Core samples were taken across a range of soil strength values between 0 kPa and 6900 kPa. Since desired ranges of soil strength occurred at different depths within the soil profile, core samples were taken at varying depths from the soil surface. Samples were also taken from multiple positions in the orchard. The spread of samples was to ensure a representation of the entire orchard.

Core samples were processed in the lab to determine bulk density and moisture content. Each core was broken apart and placed into a labeled aluminum container that had been previously weighed. The soil and the container where weighed together, and the container weight was subtracted to determine the wet weight of soil. Samples were placed in a drying oven set to 105℃ for 24 hours (Figure 1. 6). After drying, samples and containers were weighed again and container weight was subtracted to determine dry weight of soil. Bulk density was calculated as

$$BD = M_D/V_S \qquad \text{(Eq. 1)}$$

Where $M_D$ is mass of dry soil

$V_S$=volume of soil calculated by the volume of the cylinder used to extract the soil core.

Moisture content was calculated as

$$MC = \left(\frac{M_W - M_D}{M_D}\right) * BD * 100 \qquad \text{(Eq. 2)}$$

where

$M_w$ is the wet weight of soil, $M_d$ is the weight of dry soil.

### ***Statistical Analysis***

The overall mean soil strength and standard error for each orchard was calculated for each orchard. Mean soil strength and standard error for each sample position were also calculated by orchard to assess where traffic patterns were located and how much compaction existed at each of the sample positions. Soil strength in the profile was also examined to understand how soil strength changed with depth. Soil strength was plotted by depth for a visual assessment. Mean bulk density and moisture content were calculated from each orchard.

A linear model with soil strength and moisture content as predictors was developed to assess the relationship with bulk density.

$$y_i = \beta_0 + \beta_1 S + \beta_2 M + \varepsilon_i \qquad \text{(Eq. 3)}$$

Where

$y_i$ is the response of bulk density for the i-th sample,

$\beta_0$ is the intercept,

$\beta_1$ and $\beta_2$ are coefficients for soil strength and moisture content,

S is the effect soil strength,

M is the effect of the moisture content, and

$\varepsilon_i$ is the residual error for the i-th sample with expectations ~NID (0, $\sigma_\varepsilon^2$)

The model was run using the REG procedure of SAS software (SAS Institute Inc. 2013).

To understand traffic patterns and which sample positions were most impacted, a one-way analysis of variance (ANOVA) was conducted on the response of soil strength by sample position grouped by orchard. Sample positions were assessed by each orchard separately, due to the differences in management styles.

$$y_{ij} = \mu + P_i + \varepsilon_{ij} \qquad \text{(Eq. 4)}$$

Where

$y_{ij}$ is the response of soil strength at the i-th sample position for the j-th tree,

μ is the overall mean,

$P_i$ the effects of sample position *i* on response soil strength (i=1,2,3,4,5) and

$\varepsilon_{ij}$ the residual error for the i-th sample position on the j-th tree with expectations ~NID(0, $\sigma_\varepsilon^2$).

The Tukey-Kramer multiple comparison test was also performed on all pairwise contrasts within an orchard to determine which sample positions were statistically different at α=0.05 level. The model was run using the GLM procedure of SAS software (SAS Institute Inc. 2013).

*Soil strength threshold and useable soil volume*

It is widely accepted that a soil strength value of 2500 kPa or more has serious restrictions on agricultural plant root elongation and nutrient uptake (Groenevelt et al. 2001). A soil strength value of 3000 kPa has also been associated with root restrictions on trees (Coder 2007). Based on these studies, a value of 2750 kPa was used to determine a restrictive threshold used in the study. A mean depth to restrictive soil condition (the depth in the profile when soil strength exceeded 2750 kPa) was found for each sample position in each orchard. This is considered the mean maximum depth.

The “total possible soil” volume that was usable for root function was determined for each sample tree and soil sample position based on the volume of a cylinder around each tree: $V=\pi r^2 d$ where r is the radius of the cylinder (r = 2, 3.5, or 5m depending on the sample position), and d is the depth of the cylinder (d = 0.305m, the maximum depth in meters of any sample taken).

$$TV_{2m} = (\pi 2^2 0.305)/4 \quad \text{(Eq. 5)}$$

$$TV_{3.5m} = [(\pi 3.5^2 0.305) - (\pi 2^2 0.305)]/4 \quad \text{(Eq. 6)}$$

$$TV_{5m} = [(\pi 5^2 0.305) - (\pi 3.5^2 0.305)]/4 \quad \text{(Eq. 7)}$$

This 0.305m depth was used to calculate the volume of possible soil, because it the highest volume of soil that could have possibly been measured. Note that for the $V_{3.5m}$ and the $V_{5m}$ values, the value from the inner cylinder was subtracted. Each total volume was divided by four to represent each quadrant of the soil that was sampled.

The volume of “usable soil” at each sample position was also determined for each sample tree in the study. As above, usable soil volume for a tree was based on the volume of a cylinder: $V=\pi r^2 d$, where r is the radius of the cylinder, and d is the depth of the cylinder, but for “usable soil”, d is the depth in the profile when soil strength exceeded 2750 kPa.

$$UV_{2m} = (\pi 2^2 d)/4 \quad \text{(Eq. 8)}$$

$$UV_{3.5m} = [(\pi 3.5^2 d) - (\pi 2^2 d)]/4 \quad \text{(Eq. 9)}$$

$$UV_{5m} = [(\pi 5^2 d) - (\pi 3.5^2 d)]/4 \quad \text{(Eq. 10)}$$

The same method was also used for the within tree row sample positions. The inner 2 m cylinder was subtracted. This was done to assess the tree row positions similarly to the traffic row positions. If the inner 2 meter cylinder were not removed, there would have been added volume within the tree row when compared to the within traffic row.

## Results

### ***Soil Strength***

Overall orchard means for soil strength value for all sample positions for all trees in each orchard ranged from a high of 4123 kPa (Orchard A) to a low of 2773 kPa (Orchard E) (Figure 1. 7). All the orchards however, had a mean soil strength above the 2750 threshold used to determine usable soil (Table 1. 6). The mean soil strength per position for the orchards was also assessed to understand how compaction patterns were distributed throughout the orchards. Within the traffic row, there was an increasing mean soil strength moving away from the tree, with the lowest mean soil strength (least compaction) observed at the within traffic row 2-meter position and the highest mean soil strength at the within traffic row 5-meter position (Figure 1.8).

Within the tree row for all the orchards not subsoiled, there was little difference seen between the two different sides of the tree; soil strength values varied less than 140 kPa between the two within tree row sample positions when assessed on an orchard basis (Table 1.6). Orchard E which was subsoiled, showed similar patterns to the other orchards.  Within traffic row 2-meter position had the lowest soil strength, while within traffic row 5-meter position had the highest soil strength.

Soil profiles for each orchard were examined for soil strength patterns. Soil strength was plotted by depth and visual assessments of the patterns were made. In the orchards that were not subsoiled, the general trend was for soil strength to increase as depth increased such as in Orchard C. In Orchard A, both the 2 meter within traffic row position and the 5 meter within traffic row position showed an increase in soil strength with depth, but then a slight decrease in soil strength with depth. The pattern seen in the subsoiled Orchard E was slightly different; the soil strength increased to a peak, and then began to decrease (Figure 1. 9).

***Bulk Density and Moisture Content***

A mean bulk density and standard deviation were estimated for each orchard based on 10 soil cores collected. The means ranged from 1.26 $g/cm^3$ in Orchard B to 1.57 $g/cm^3$ in Orchard E. The standard deviations suggest considerable variation within an orchard, ranging from 0.12 to 0.23 (Table 1. 3).

Moisture content was also examined for means and standard deviation for each orchard. In Orchard B, the mean moisture content for the 10 soil cores was 9%. This is on the low side of moisture content for even a sandy soil. In Orchard E, however the moisture content was much higher at 41% (Table 1.3)

Linear regression of soil strength and moisture content to predict bulk density are summarized in Table 1. 4  Soil strength (t-value Pr=0.0318) and moisture content (t-value

Pr<0.001) were both significant predictors in determining bulk density. The model explained 56% of the variance in bulk density ($R^2 = 0.56$).

### *Differences Among Sample Positions for Soil Strength*

An Analysis of Variance (ANOVA) was performed to understand the differences among positions for soil strengths (Table 1. 5). For each orchard, the overall F test was significant ($P<0.0001$). A multiple range test was also done to determine which sample positions were different (Table 1. 6). Orchards C and D had the same traffic patterns. In both orchards, there was no statistically significant differences between the within traffic row 2-meter position and within tree row positions. In the same orchards, there was no difference between the within traffic row 3.5-meter position and the within traffic row 5-meter position. Orchards A, B and E all had unique patterns. In Orchard A, the within traffic row 2 meter position was the only position significantly different from the other positions. The within traffic row 2-meter position in Orchard B was significantly different than the within traffic row 5-meter position, but unlike the other orchards that were not subsoiled, it is not different from the within traffic 3.5-meter position or either within tree row positions. Once again, the within traffic row 3.5-meter position and the within traffic row 5-meter position were not significantly different from one another. Both 3.5-meter within tree row positions were also not significantly different from one another.

The multiple range tests for Orchard E also shows unique compaction patterns when compared to the other orchards (Table 1. 6). The 2-meter traffic position in Orchard E is significantly different from two other positions. Similar, to the other orchards, the within traffic row 3.5-meter position and the within traffic row 5-meter position were not significantly different from each other.  In the other orchards, aside from Orchard A, the 2 meter within traffic row position was not significantly different from either of the within tree row positions.

### *Soil Strength Threshold and Useable Soil Volume*

The mean maximum depth before a soil strength threshold of 2750 kPa was reached differed for each position in each orchard (Figure 1. 9). The within traffic positions for all orchards that were not subsoiled have the same patterns. Closest to the tree at the 2-meter position, the max depth was the highest (more non-compacted soil), while it was the lowest at the 5-meter position. Orchard C had the highest mean depths at all within traffic row samples, but the highest depth was at the 2-meter position, and was less than 15 cm. The two within tree row positions in all orchards not subsoiled were very similar, less than 2 cm different.

In all orchards, the amount and percentage of usable soil volume at all sampling positions was low (Table 1. 7). Orchard C had the highest percentage of usable soil volume at 32%, and Orchard A had the lowest at 9%.

In many of the orchards, there were large differences between the percentage of usable soil at the within traffic row 2-meter position and the within traffic row 5 meter positions (Table 1. 7). Orchard A shows a large difference between these two positions with the 5-meter position having about one-third less usable soil on a percentage basis than at the 2 meter position. This was a similar trend observed in the other orchards as well. Both sample positions within the tree row are similar in percentage of usable soil when compared to the within traffic row 2 meter position in most orchard. In Orchard A, the percentage of within tree row usable soil at 3.5 m was only approximately half of the within traffic row 2 meter position (Table 1. 7).

## Discussion

### Differences Among Sample Positions for Soil Strength

Based on the ANOVA and multiple range tests for soil strength means per sample positions, most equipment use in orchards occurred in the middle of the traffic row. Compaction significantly decreased closer to the tree, as in the 2-meter position (Figure 1. 8). It was also much lower within the tree row than in the middle of the traffic row. Based on this and the knowledge of where equipment usually travels in orchard, the 2-meter within traffic row position can be thought of as relatively undisturbed soil.

Each orchard has slightly different traffic patterns, most likely resulting from management styles. In Orchard B, the within traffic 2-meter position was not significantly different from the within traffic row 3.5 meter position. This differs from the other three orchards that were not subsoiled, in which the two positions were significantly different. An explanation for this could be in the management and age (34 years) of Orchard B. While the width of traffic rows in Orchard B is now 9.15m, it was only 4.6m at establishment of the orchard. As the orchard aged, every other row of trees was removed leaving a current spacing of 9.15m. The tree removal left large stumps in the middle of the row, and these positions were most likely avoided by lift operators. It is presumed that the location of stumps often forced a lift operator to travel closer to the 2-meter position to avoid the stumps.

In Orchard A, the only significantly different sample position was the within traffic row 2 meter position. This also may be a result of traffic management. In this orchard, there were no rules outlined to workers about where lifts were and were not allowed to travel. As a result, lift operators often crossed within tree rows wherever it was most convenient. This may have caused traffic within the tree rows to be just as high as traffic within the traffic rows.

Orchard E was the subsoiled orchard and also expressed different traffic patterns than the other orchards. The within traffic row 2-meter position was significantly different from both within traffic row sample positions, unlike the orchards that were not subsoiled (Table 1. 6). This may also be a result of management practices and thinning. This orchard did not have lift management rules and has been thinned. The thinning allows operators to travel within tree rows, and without management rules they are much more likely to do so. This would mean the within tree row is impacted more.

Many important feeder roots of trees exist in the top 30.5 cm of the soil (Day 2009). These roots are required for nutrient and water uptake for the tree. This places an increased importance on the soil conditions of the top 30.5cm of the profile. In all the orchards studied, relatively little of the top 30.5 cm of the soil was usable based on soil strength (Table 1. 7). This means the amount of soil in which roots can grow and function properly was very limited, impacting root function and subsequently the tree health.

### *Soil Strength, Bulk Density, and Moisture Content*

The overall higher compaction in Orchards A and D and a lower compaction in Orchard E, may be a result of traffic. However, other factors need to be taken into consideration. Comparing orchards can be deceptive due to the differences in soil type at the orchards as well as the difference in moisture content. Moisture content is known as a major contributing factor that can impact the readings seen from penetrometers (Gao et al. 2012). These factors necessitate caution when assessing data across orchards.

Bulk density samples suggest soil compaction in these orchards is not as drastic as shown from the soil strength samples. Ideal bulk densities for root growth for sandy soils, the soil type of most orchards in the study, is less than 1.6 g/cm$^3$ (Service). The mean bulk density for each orchard is less than this. However, it is important to understand the limitations of these samples. Only ten bulk density samples were taken from each orchard, therefore a small sample size was used to indicate bulk density for a very large area. Samples were also purposefully taken across as range of penetrometer samples to be used in an analysis to understand the relationship between bulk density and soil strength. Therefore, these bulk densities are not the most valid representation of soil compaction for the orchards in this study.

Penetrometer and moisture content explained about 56% of the variation in soil bulk density and was significant (model F-test Pr<0.0001). Taking into account the small sample size, there seems to be a good relationship between the two measurements. Bulk density is the best measure to determine actual soil compaction, because there are no restrictions or inflation due to moisture content. However, bulk density is a very labor intensive method for detecting soil compaction. Soil strength, while not the most ideal method of characterizing soil compaction could be a valid alternative when labor is considered. There is less labor and resources required to sample an entire orchard using soil strength vs bulk density. A soil penetrometer also provides a simple tool that will allow orchard managers to monitor compaction in their orchards.

***Soil Profiles***

Soil strength by depth was visually examined. In orchards that were not subsoiled, there was an increase in soil strength as the depth increased for all sample positions. In some orchards at the within traffic row 5 meter position there seemed to be a peak then decrease as seen in Orchard A (Figure 1. 9.) This is not likely the actual overall trend seen. Due to the limitation on the equipment that only allows the machine to measure to 6900 kPa, a false pattern likely appeared. In most orchards at the 5 meter sample position the penetrometer maxed out before the desired depth of 30.5 cm was reached. There were few instances when the desired depth was actually reached, and in those instances, that sample position was most likely less compacted compared to the rest. This is indicated by the large variation seen around the line (Figure 1. 9).

The most interesting difference observed between the orchards that were not subsoiled and the orchard that was subsoiled was seen in the soil profile (Figure 1. 9). In Orchard E, a very distinct pattern was observed at all sample positions within the traffic row. Soil strength increased down to approximately 7cm at the 5 meter position, and then it sharply decreased (Figure 1. 9). This appears to be the result of the subsoiling. Subsoiling took place in 2014 and the impacts of subsoiling seem to be still present. The sublayer of the soil was less compacted than the top layer. The impacts of equipment after subsoiling can be seen in the top 7 cm of the soil, however those impacts have yet to reach the subsoil layers.

### ***Conclusion***

The ideal way to assess soil compaction in these orchards would have been to take numerous bulk density samples. This was logistically not possible, so an attempt to understand soil compaction was based on the soil strength measurements using the soil penetrometer. The assumption that the within traffic row 2-meter position is relatively non-disturbed is based on where aerial lifts travel and the differences observed between this point's mean soil strength the others, especially the other within traffic row positions. This assumption allows for a comparison to be made between all other sample positions and the 2-meter position. In all orchards, the percentage of usable soil for the within traffic row 3.5 and 5-meter positions were only about 1/3 to 1/2 that percentage seen in the within traffic row 2-meter position (Table 1. 7). If the within traffic row 2-meter positions is assumed to be relatively non-disturbed, this would indicate the 3.5 and 5-meter within traffic row positions were highly compacted in comparison. The soil strength observed in these five orchards indicated that there was a serious problem with soil compaction, and this compaction may ultimately create serious problems in tree health, cone yields, and disease occurrence.

Arvidsson, J. 1999 Nutrient uptake and growth of barley as affected by soil compaction. *Plant and Soil*, **208** (1), 9-19.

Becerra, A.T., Botta, G.F., Bravo, X.L., Tourn, M., Melcon, F.B., Vazquez, J. *et al.* 2010 Soil compaction distribution under tractor traffic in almond (*Prunus amigdalus L.*) orchard in Almería España. *Soil and Tillage Research*, **107** (1), 49-56.

Cambi, M., Certini, G., Neri, F. and Marchi, E. 2015 The impact of heavy traffic on forest soils: A review. *Forest Ecology and Management*, **338**, 124-138.

Coder, K. 2007 Soil Compaction Stress & Trees: Symptoms, Measures, and Treatments.

Conlin, T.S.S. and Driessche, R.v.d. 1996 Short-term effects of soil compaction on growth of Pinuscontorta seedlings. *Canadian Journal of Forest Research*, **26** (5), 727-739.

Day, S.D. 2009 At the Root of It

Duiker, S.W. 2002 Diagnosing Soil Compaction Using a Penetrometer (Soil Compaction Tester). PennState Extension.

Gao, W., Watts, C.W., Ren, T. and Whalley, W.R. 2012 The effects of compaction and soil drying on penetrometer resistance. *Soil and Tillage Research*, **125**, 14-22.

Groenevelt, P.H., Grant, C.D. and Semetsa, S. 2001 A new procedure to determine soil water availability. *Soil Research*, **39** (3), 577-598.

Lipiec, J. and Hatano, R. 2003 Quantification of compaction effects on soil physical properties and crop growth. *Geoderma*, **116** (1–2), 107-136.

Lipiec, J., Horn, R., Pietrusiewicz, J. and Siczek, A. 2012 Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil and Tillage Research*, **121**, 74-81.

Service, N.R.C. Bulk Density: Guide for Educators.

Technologies, S. 2009 Field Scout SC 900 Compaction Meter Product Manual. Spectrum Technologies, Inc.

Wiersum, L.K. 1957 The relationship of the size and structural rigidity of pores to their penetration by roots. *Plant and Soil*, **9** (1), 75-85.

Winn, M.F., Araman, P.A. and Lee, S.-M. 2011 UrbanCrowns: an assessment and monitoring tool for urban trees, p. 1-10.

**Table 1. 1.** Orchard descriptions including location, soil type, slope, drainage class, water table depth, and age. Note: Orchard C has two major soil types in the measurement area, and the percentage of each soil type is illustrated.

| **Orchard** | **County/state** | **Soil Type** | **Drainage Class** | **Depth to Water Table (cm)** | **Age** |
|---|---|---|---|---|---|
| A | Toombs, GA | Tifton Loamy Sand | Well Drained | 100-140 | 14 |
| B | Tattnall, GA | Tifton Loamy Sand | Well Drained | 100-140 | 34 |
| C | Wayne, GA | Lynchburg Loamy Sand (60% of area) | Somewhat Poorly Drained | 45-76 | 15 |
| C | Wayne, GA | Plummer Sand (40% of area) | Poorly Drained | 0-30 | 15 |
| D | Dorchester, GA | Chipley Loamy Fine Sand | Moderately Well Drained | 45-91 | 31 |
| E | Pulaski, GA | Greenville Sandy Loam | Well Drained | >200 | 29 |

*More details describing soil series are in appendix A.

**Table 1. 2.** Number of final sample trees, clones per orchard, initial tree row spacing, and initial traffic row spacing and the management rule (regulating where lifts could and could not travel in each seed orchard). Orchard E was the only orchard that was subsoiled.

| Orchard | Sample Trees | Number of Clones | Tree Row Spacing (m) | Traffic Row Spacing (m) | Management rule |
|---|---|---|---|---|---|
| A | 68 | 11 | 9.15 | 9.15 | No |
| B | 63 | 7 | 4.57 | 9.15 | No |
| C | 54 | 9 | 7.62 | 9.15 | Yes |
| D | 63 | 5 | 4.57 | 9.15 | No |
| E | 56 | 6 | 4.57 | 9.15 | No |

**Table 1. 3.** Mean and standard errors of means (SE) of 10 bulk density samples and moisture content in each orchard.

| Orchard | Bulk Density ($g/cm^3$) | SE | Moisture Content (%) | SE |
|---|---|---|---|---|
| A | 1.56 | 0.06 | 15.1 | 1.04 |
| B | 1.26 | 0.05 | 9.9 | 0.93 |
| C | 1.34 | 0.07 | 18.0 | 2.20 |
| D | 1.32 | 0.04 | 18.3 | 1.17 |
| E | 1.57 | 0.05 | 41.3 | 2.15 |

**Table 1. 4.** Parameter estimates and probability of significance of parameter estimates in a regression model where bulk density was the response variable, and soil strength and moisture content were used as predictors. The $R^2$ for the model was 0.56

| **Variable** | **Parameter Estimate** | **t value** | **Probability** |
|---|---|---|---|
| Intercept | 0.96 | 14.77 | <0.0001 |
| Soil Strength (kPa) | 0.00011 | 7.43 | <0.0001 |
| Moisture Content | 0.00631 | 2.21 | 0.0318 |

**Table 1. 5.** Analysis of Variance test to determine if mean soil strength is significantly different among sample positions in each orchard.

| **Orchard** | **DF** | **Mean Square** | **F Value** | **Prob** |
|---|---|---|---|---|
| **A** | 4 | 1103234 | 15.2 | <0.0001 |
| **B** | 4 | 869479 | 8.2 | <0.0001 |
| **C** | 4 | 1961773 | 25.2 | <0.0001 |
| **D** | 4 | 1795087 | 27.6 | <0.0001 |
| **E** | 4 | 2932900 | 109.3 | <0.0001 |

**Table 1. 6.** Mean soil strengths (kPa) for each orchard at each sample position and multiple range tests for the positions within each orchard (letter grading). Within a specific orchard, if two means within a column share a letter, those sample positions were not significantly different at $\alpha = 0.05$ in that orchard.

| | | Orchard | | | | |
|---|---|---|---|---|---|---|
| **Sample** | **Position** | **A** | **B** | **C** | **D** | **E** |
| **Within Traffic Row** | **2-Meter** | 3636 **b** | 3501 **bc** | 2860 **b** | 3849 **b** | 2589 **b** |
| | **3.5-Meter** | 4324 **a** | 3868 **ab** | 3609 **a** | 4411 **a** | 3306 **a** |
| | **5-Meter** | 4547 **a** | 3978 **a** | 3661 **a** | 4452 **a** | 3281 **a** |
| | | **A** | **B** | **C** | **D** | **E** |
| **Within Tree Row** | **3.5-Meter** | 4203 **a** | 3255 **c** | 2837 **b** | 3683 **b** | 2373 **c** |
| | **3.5-Meter** | 4235 **a** | 3352 **c** | 2814 **b** | 3657 **b** | 2388 **c** |

**Table 1. 7.** Total possible volume of soil in a quadrant around each sample tree in the five orchards studied. The actual volume (and percentage) of usable soil is defined as the depth of the soil sample before soil strength value of 2750 kPa was reached. The 2750 kPa value was used as the threshold where root growth was substantially restricted.

| **Within Traffic Row Sample Position** | **Total Possible Volume ($m^3$)** | **Actual Volume ($m^3$) and (%) of Usable Soil in Each Orchard** | | | | |
|---|---|---|---|---|---|---|
| | | **A** | **B** | **C** | **D** | **E** |
| 2-Meter ($m^3$) | 0.96 | 0.18 (18%) | 0.23 (24%) | 0.43 (45%) | 0.23 (24%) | 0.25 (26%) |
| 3.5-Meter ($m^3$) | 1.98 | 0.23 (11%) | 0.39 (20%) | 0.48 (24%) | 0.25 (13%) | 0.21 (11%) |
| 5-Meter ($m^3$) | 4.01 | 0.27 (7%) | 0.52 (13%) | 0.72 (18%) | 0.35 (9%) | 0.30 (7%) |
| **Within Tree Row Sample Position** | | | | | | |
| Sample 1 | 1.98 | 0.20 (10%) | 0.44 (22%) | 0.96 (49%) | 0.51 (26%) | 0.65 (33%) |
| Sample 2 | 1.98 | 0.19 (10%) | 0.44 (22%) | 0.91 (46%) | 0.56 (28%) | 0.80 (40%) |
| **Total** | **10.9** | **1.10** | **2.02** | **3.50** | **1.91** | **2.20** |
| **Total %** | | **10%** | **19%** | **32%** | **18%** | **20%** |

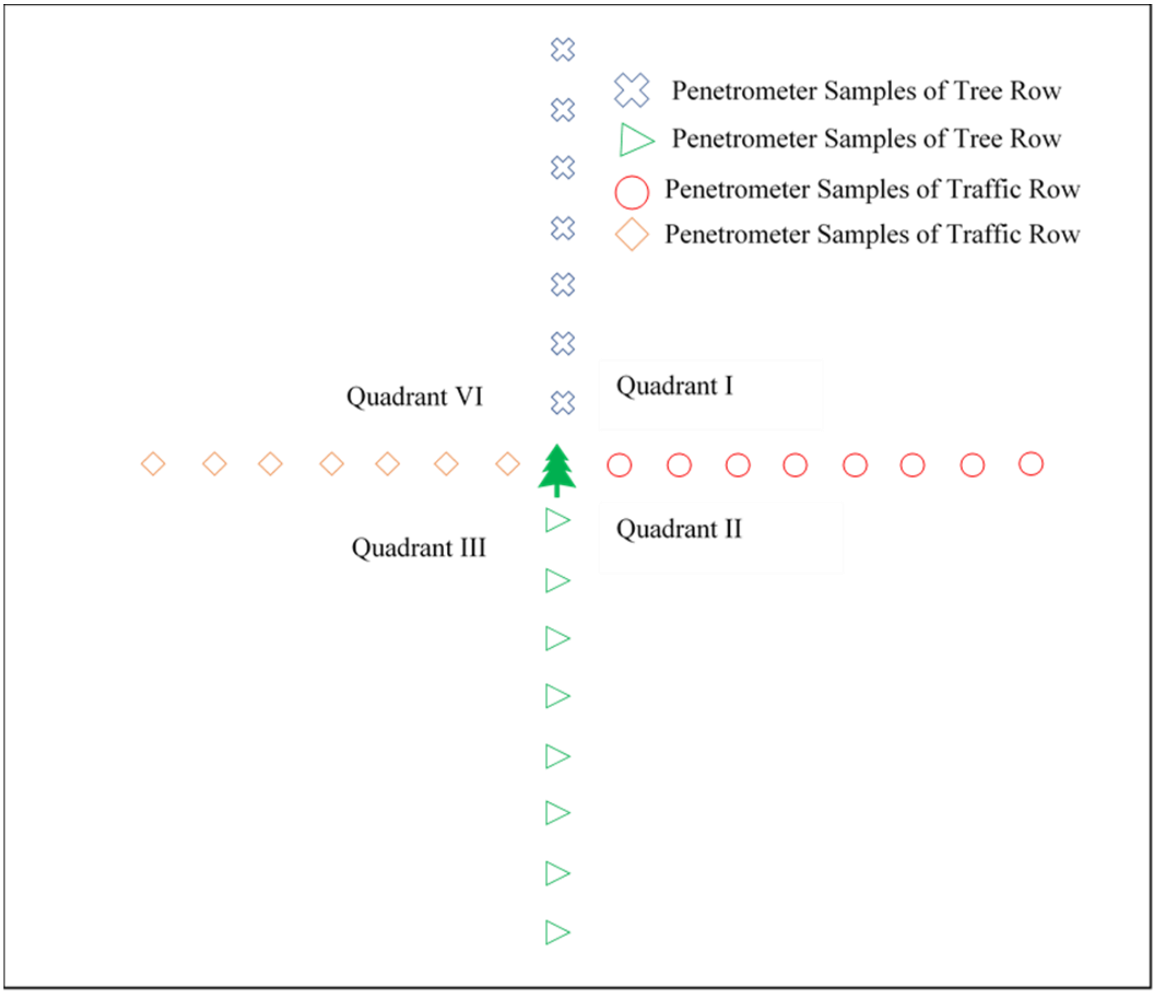



**Figure 1. 1.** Locations of preliminary sample points. Sample positions within the two traffic rows are red circles and orange diamonds. Sample positions in the two within tree rows are blue Xs and green triangles. Each sample point is 50 cm from the first sample point beginning at 1.5m from tree base.

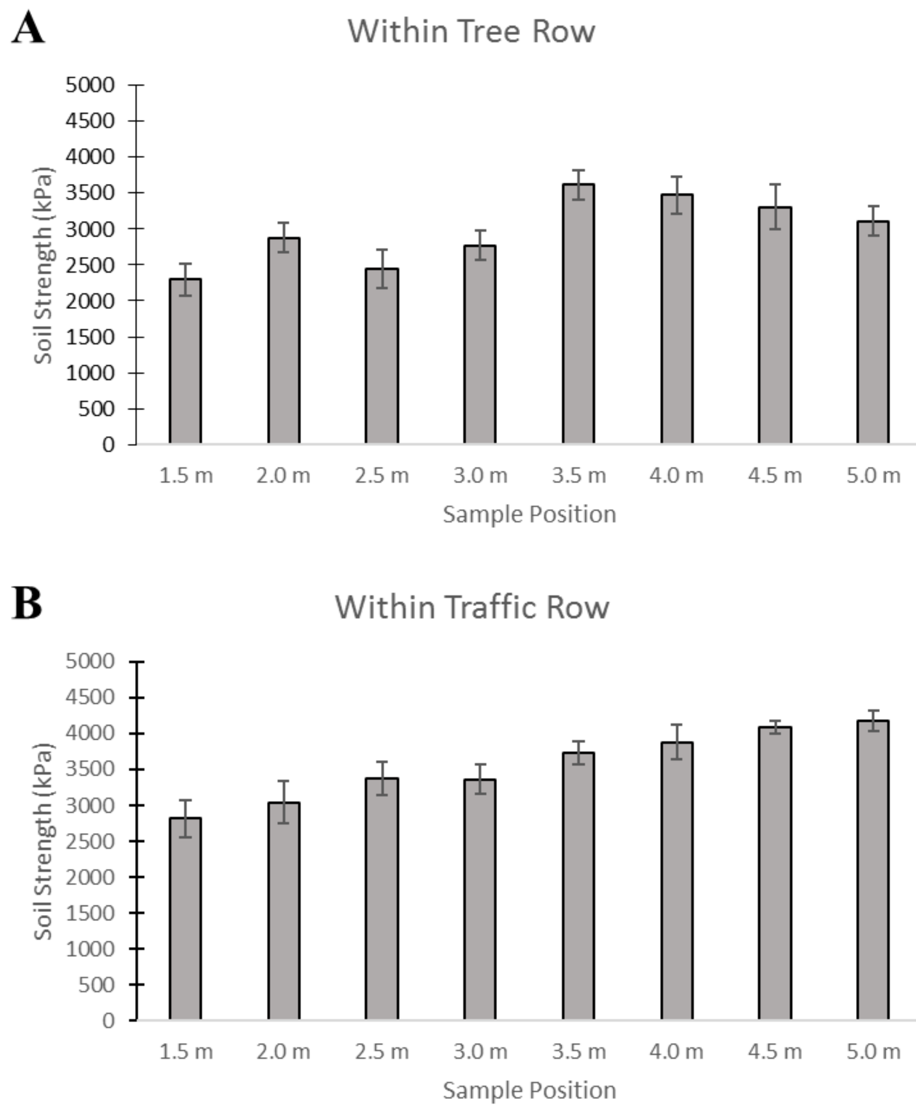



**Figure 1. 2.** Means and standard error bars of penetrometer samples taken from within the tree row (A) and within the traffic row (B) for preliminary sampling of 21 trees at Orchard A.

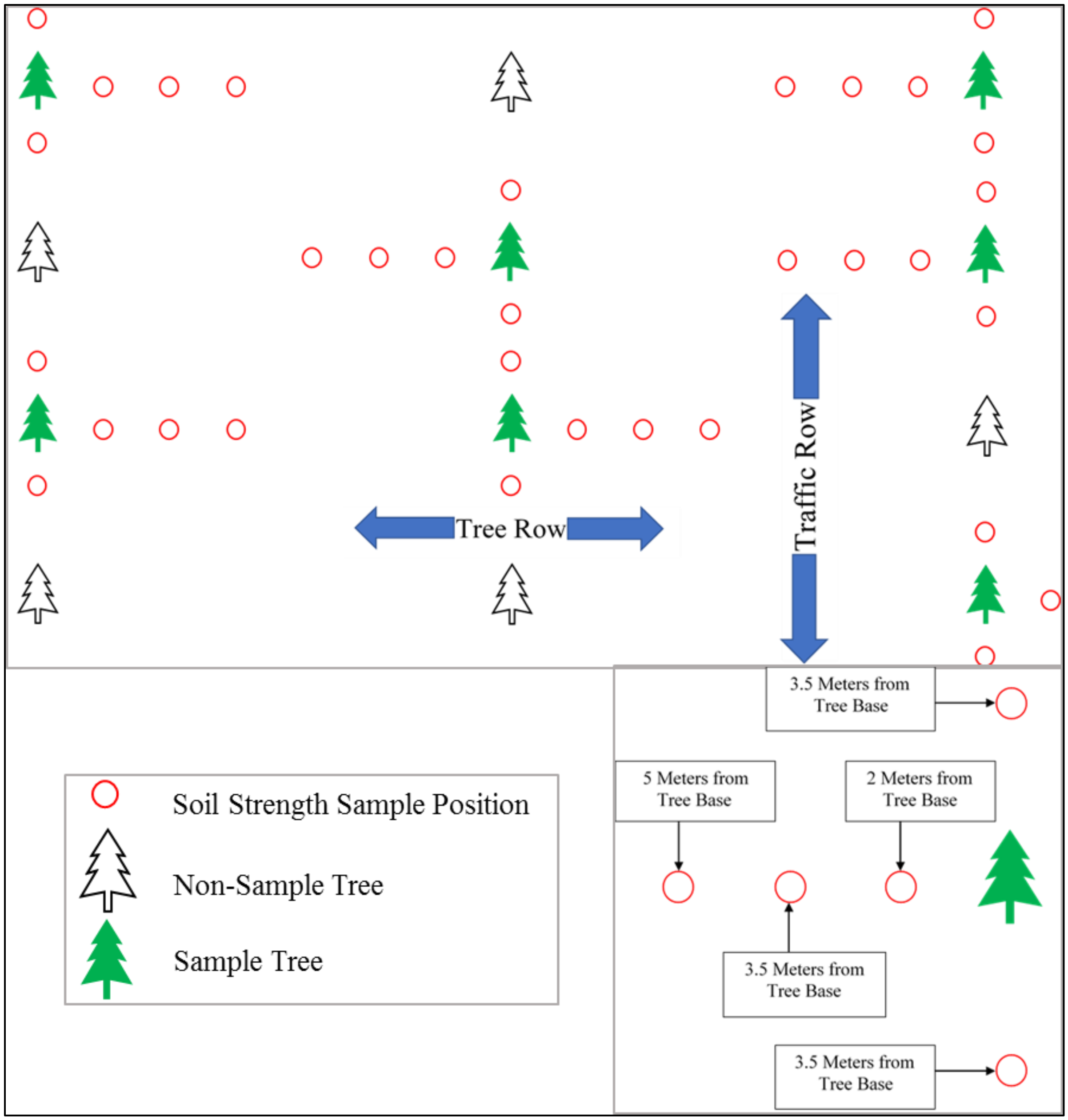



**Figure 1. 3.** Example of sampling in part of an orchard illustrating the location of tree and traffic rows and where the sampling points were taken at each tree. The inset in the lower right corner indicates dimensions of sample locations around one tree.

**Figure 1. 4.** Examples of proper penetrometer use (A & B); constant and consistent pressure was applied to the penetrometer. Data were recorded for each sample position (C). PVC pipe was marked to determine proper distance for each sample position from tree base (D).


**Figure 1. 5.** Soil core sampling for bulk density and soil moisture: (A) Using a drop hammer to push the core into the ground (B) Extracting the core once hammered into the ground C) Separating the larger cylinder from the smaller. (D) Shaving excess soil to ensure an exact volume.


**Figure 1. 6.** Soil core samples in the lab during processing. (A) Samples in water tight bags for processing. (B) Weighting samples. (C & D) Drying samples in the oven.

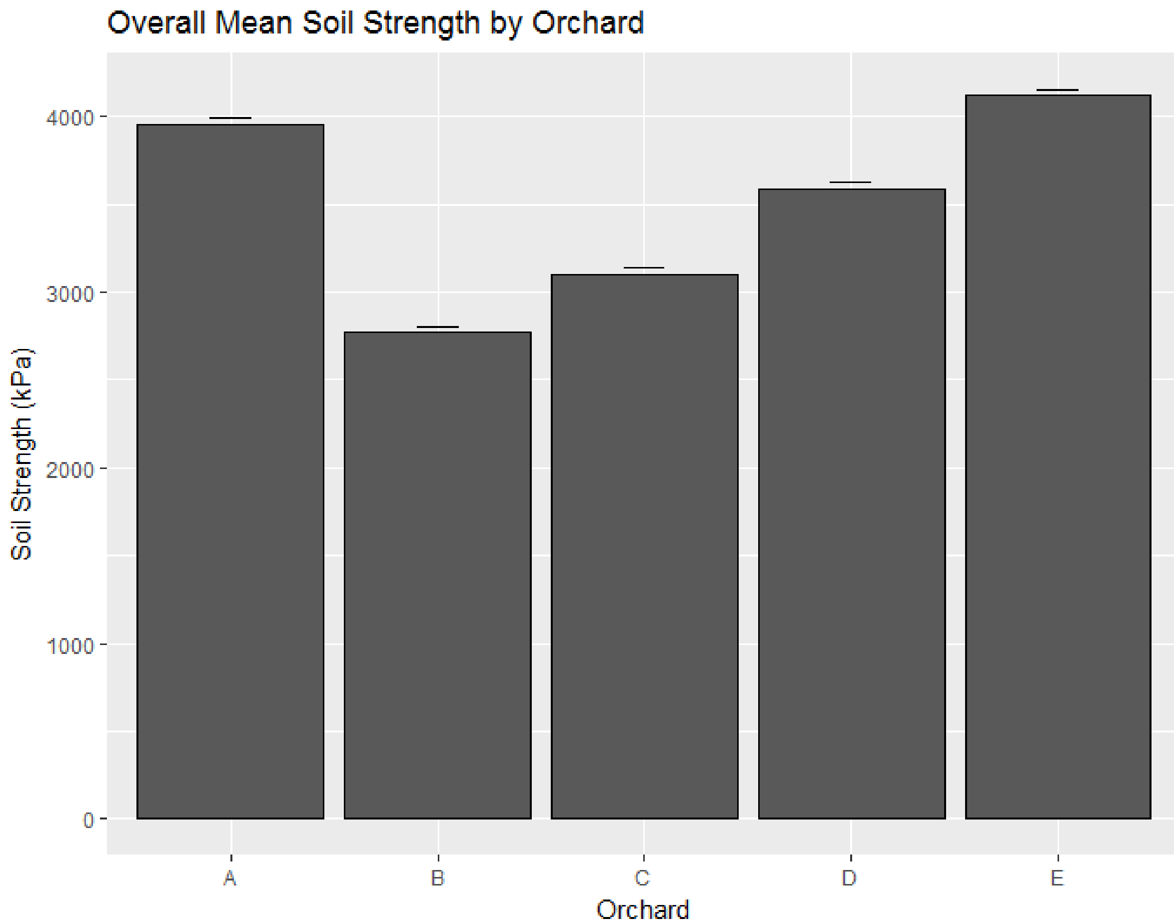


**Figure 1. 7.** Overall mean soil strength for all sample positions in each orchard.

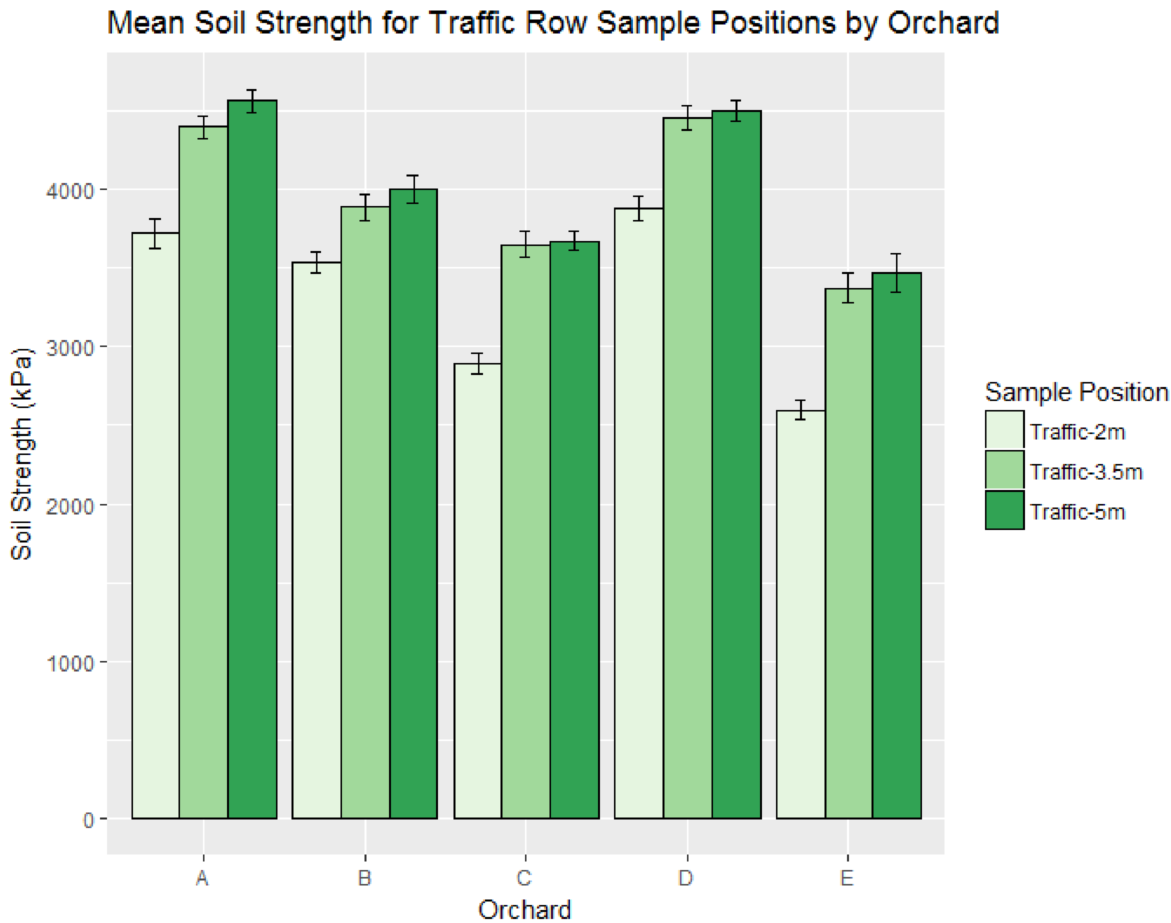



**Figure 1. 8.** Means with standard error bars for soil strength (surrogate for soil compaction) for soil profiles to 30.5 cm depth within the traffic row positions of 2, 3.5, and 5 meters away from the tree.

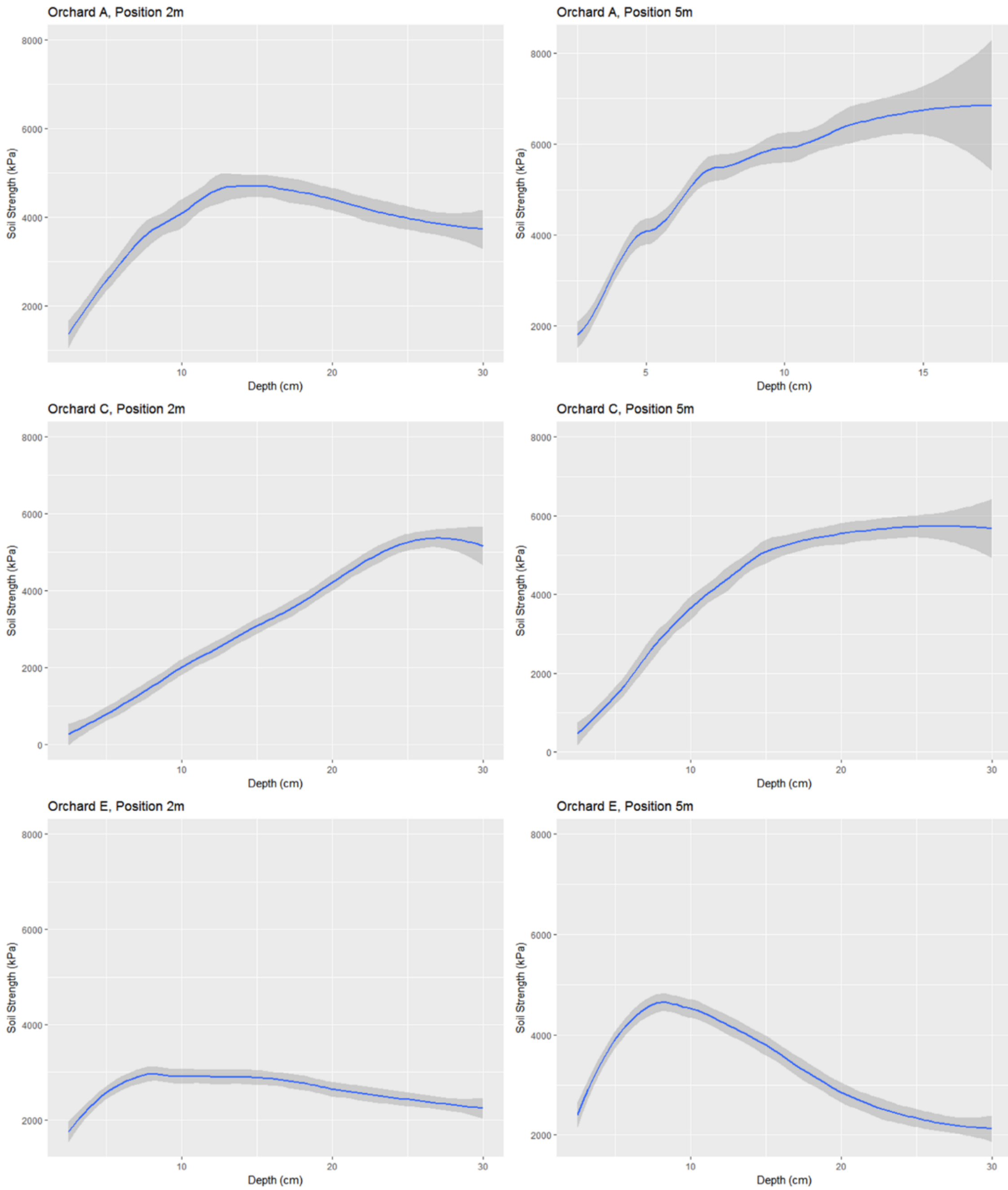



**Figure 1. 9.** Soil strength profiles illustrating depth by soil strength for Orchards A, C, and E for within traffic row sample positions 2 and 5 meters. The gray area indicates 95% confidence interval. A soil strength reading (kPa) was taken every 2.5 cm. All profiles for each orchard and each position are found in appendix C.

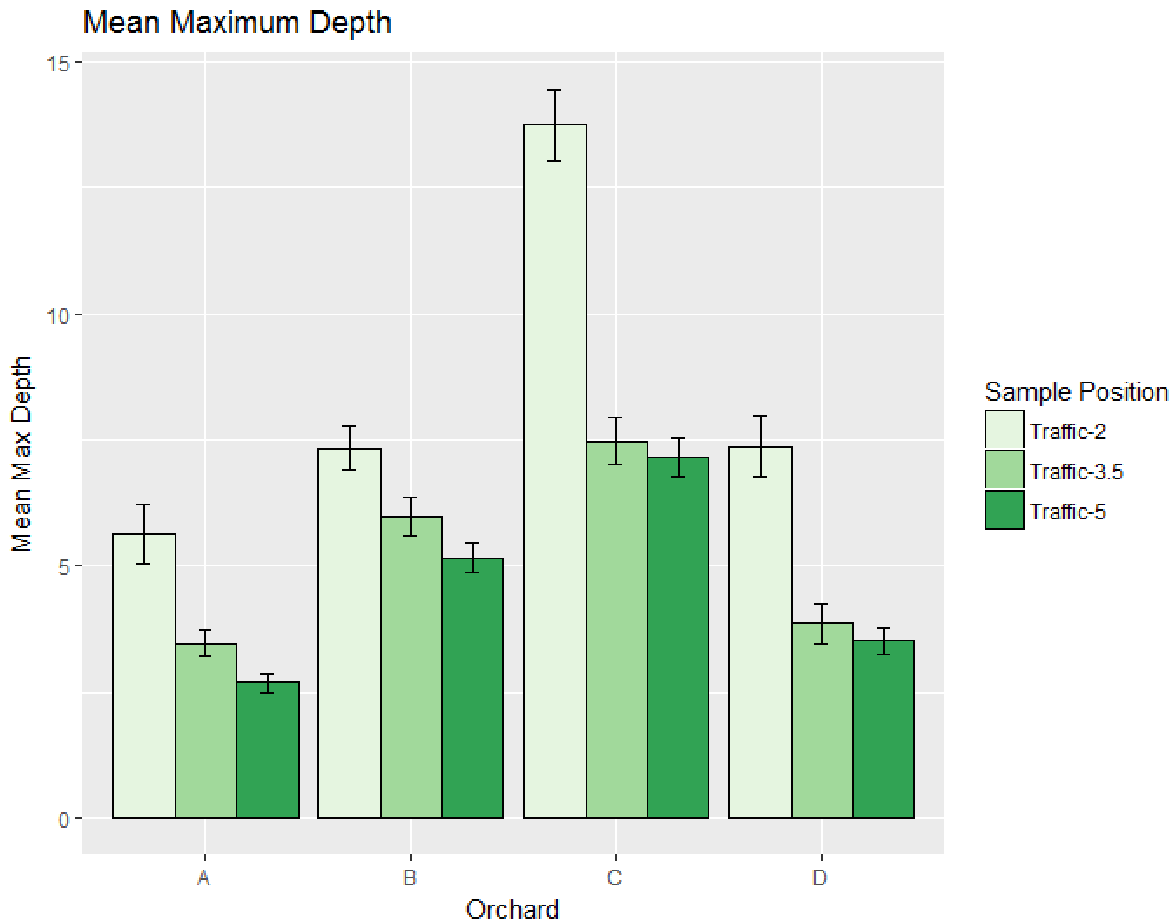



**Figure 1. 10.** Means with standard error bars for maximum penetrometer depth to reach the restrictive soil condition (the depth in the profile when soil strength exceeded 2750 kPa) for each soil sample position (2, 3.5, and 5 meters from the tree) within the traffic row for the four orchards that were not subsoiled

# CHAPTER 2:

## Impacts of Soil Compaction on Tree Health and Cone Production in Seed Orchards of Loblolly Pine

## Abstract

To understand the impacts soil compaction from heavy equipment on tree health and cone yields in loblolly pine (*Pinus taeda* L) seed orchards, soil strength was measured at five sample positions per tree for 303 trees in five seed orchards. Three samples were taken within the traffic row where heavy equipment use most often occurs, and two samples were taken between trees within tree rows. Soil compaction was characterized into eight soil measurements per tree, four measurements relating to a usable volume of soil calculated using a threshold of 2750 kPa, and four measurements relating to the mean soil strength of usable soil volume. For each tree in the study, cone yield per tree and crown density using UrbanCrowns software were measured to determine the impacts of soil compaction on tree health. Mixed models were used to determine significant soil compaction parameters in explaining variation in cone yields and crown density. When assessing crown density, orchard and crown volume were significant, but no soil compaction variables had a significant impact on crown density. Orchard, clone, crown volume, and a soil compaction variable were all significant parameters in understanding variation in cone yields. While soil compaction was not found to be significant in explaining variation in crown volume, it was significant in explaining cone yields. Based on the results of this study, soil compaction is a problem in loblolly pine seed orchards, and it has negative impacts on cone production. The high value of full-sib seeds places an importance on the practice of mass production of controlled crosses. However, the problems with soil compaction places new pressures on orchard managers to find more efficient orchard designs and new ways of managing equipment traffic.

## Introduction

Mass production of controlled crosses of loblolly pine (*Pinus taeda* L.) has become a significant component of planting programs in the southern US. Seedlings produced from the process have more desirable phenotypes such as faster height and diameter growth than seedlings grown from open-pollinated seed. Genetically improved seedlings can have 50% more volume growth over non-improved seedlings (Jannson 2004). Due to the volume gains, there is a substantial financial advantage from using genetically improved seedlings over non-improved (McKeand et al. 2006). The process of producing controlled crosses is very intense, requiring the use of heavy equipment such as aerial lifts to reach the reproductive organs in the tops of tree crowns. The use of aerial lifts has become a major concern in many loblolly pine seed orchards, because of the impacts on soil structure.

Soil compaction in these seed orchards may be substantial, and this compaction may be having negative impacts on tree health and cone yields. The negative impacts of soil compaction on plant species has been documented in agricultural studies as well as in forestry studies. High soil compaction has been shown to contribute to reduced water consumption by roots, decreased nutrient uptake including nitrogen, potassium, and phosphorous, and an imbalance in hormonal growth regulators (Kozlowski 1999). Many studies have shown the impacts of compaction on agricultural plants. In several cereal plants, compaction can decrease root elongation and thickness by 50-70% varying by species when compared to root growth in “uncompacted” soils (Lipiec et al. 2012). There was a large decrease in the size of maize root systems due to soil compaction created from equipment passes. The distance between root systems was examined in compacted and non compacted areas. In the compacted areas, distance between root systems of maze plants was a maximum of 63.7mm, while distance between root systems in non-compacted area was less than 5.3mm (Lipiec and Hatano 2003). Biomass yields for Barley were examined based on treatment groups with varying number of passes with equipment. Soil compaction was examined in each treatment group, and biomass was harvested several times. In each harvest, the amount of biomass was significantly less in the more compacted areas (Arvidsson 1999).

Compaction can also have serious impacts on the health of many tree species. Short-term effects of soil compaction were assessed on lodgepole pine (*Pinus contorta)* seedlings. Based on foliage analysis, nutrient uptake was less as soil compaction increased (Conlin and Driessche 1996). Three soil compaction levels had a significant impact on various tree health measurements, including shoot and root growth on lodgepole pine.

The best measurement of soil compaction is bulk density. However, it is a very intensive measurement to take; it is very laborious and unrealistic to collect on a large scale with limited resources and time. Collection requires a core of a known volume to hammered into the ground and the soil carefully extracted. The soil then needs to be processed in the lab which requires drying and weighing (Service).

As an alternative to collecting bulk density samples, soil strength can be found using a soil penetrometer (Duiker 2002). A soil penetrometer is used to mimic the resistance a root would experience as it growths through a soil. The penetrometer is designed to measures the pressure a root would require pushing through layers of soil. This is a good alterative because it is less labor intensive, and more samples can be taken with less resources when compared to bulk density.

### *Study Objectives*

1. Understand the impacts of soil compaction on tree health using crown density as a surrogate assessed by UrbanCrowns software
2. Understand the impacts of soil compaction on cone yields in loblolly pine seed orchards

## Materials and Methods

### *Soil compaction assessment*

Soil strength, a surrogate for soil compaction, was measured using a soil penetrometer in five orchards, owned and managed by members of the North Carolina State University Cooperative Tree Improvement Program. Orchards varied by soil type, age, climate, and management style. Orchards A, B, C, and D were not subsoiled. Orchard E was subsoiled one year prior to sampling. A varying number of clones and their ramets were sampled in each orchard. The total number of trees sampled ranged from 68 to 56 in each orchard. In total, there were 251 trees included in the study.

Orchard E was ultimately removed from the data for modeling the tree health and cone yields due to the subsoiling that was completed a year prior to sampling. The decline in tree health observed in this orchard may be unrelated to soil compaction. It is also possible a decline in tree health is related to previous soil compaction that is no longer detectable due to the subsoiling. Therefore, the orchard was not used in the analysis.

Five soil strength measurements per tree were obtained. Three soil strength measurements within the traffic row (the area most used by heavy equipment) were obtained at 2m, 3.5m and 5m from the base of the tree. Within traffic row measurements were only obtained on one side of the tree, chosen at random. One soil strength sample was taken on each side of the tree within the tree row (areas in between the trees and less likely to be trafficked) at 3.5m from the base of the tree.

Based on agricultural and forestry studies, a soil strength greater than 2750 kPa was selected as the threshold value detrimental to root growth and function. This value was used to calculate a "usable volume" of soil for each sample. Usable soil volume for a sample position was based on the volume of a cylinder: $V = \pi r^2 d$, where *r* is the radius of the cylinder, and *d* is the depth of the cylinder. However, for "usable soil", *d* is the depth in the profile when soil strength exceeded 2750 kPa. Note that for the $V_{3.5m}$ and the $V_{5m}$ values, the value from the inner cylinder was subtracted. Each total volume was divided by four to represent each quadrant of the soil that was sampled.

$$V_{2m} = (\pi 2^2 d)/4 \qquad \text{(Eq. 1)}$$

$$V_{3.5m} = [(\pi 3.5^2 d) - (\pi 2^2 d)]/4 \qquad \text{(Eq. 2)}$$

$$V_{5m} = [(\pi 5^2 d) - (\pi 3.5^2 d)]/4 \qquad \text{(Eq. 3)}$$

The same method was also used for the within tree row sample positions. The inner 2 m cylinder was subtracted. This was done to assess the tree row positions similarly to the traffic row positions. If the inner 2-meter cylinder were not removed, there would have been added volume within the tree row when compared to the within traffic row.

The soil strength measurements and the calculated usable volume of soil were used to determine eight soil strength variables that would be used to model the response variables of crown density and cone yields. There were two variables associated with the within tree row samples. The first one is the mean usable volume of soil ($m^3$) for both within tree row samples combined (TreeVolume3.5). The second one is the mean soil strength of usable volume (WithinTreeMean) at within tree row sample position. This was found by determining the mean soil strength for both sample positions within the tree row for depths before 2750 kPa was reached. For example, if soil strength reached 2750 kPa at a depth of 7cm, only soil strength values for the depths of 1-7 cm were used to find the mean. A mean for the two within tree row variables was chosen over using the two within tree row samples separately because in previous analysis, these values were not significantly different. Combining both sample positions into one within tree variable allowed for simplification of the within tree row impact.

There are six variables associated with the within traffic row sample positions. Three variables were the mean volume of usable soil ($m^3$) at each sample position of 2m (TrafficVolume2), 3.5m (TrafficVolume3.5), and 5m (TrafficVolume5), calculated using the procedure described in the previous chapter. The other three variables are the mean soil strength of that usable volume at each sample position of 2m (TrafficMean2), 3.5m (TrafficMean3.5), and 5m (TrafficMean5), similar to WithinTreeMean.

Overall means of soil strength per tree was considered, as was the mean for the three within traffic row sample positions. However, these values were considered too vague, and details were lost when assessing travel patterns.

Other soil strength thresholds for the “usable soil” variable were also considered, after visualization of the data and consideration of other studies, 2750 kPa was decided as the final threshold. This was based on studies showing 2500 kPa to be restrictive for agricultural plants and 3000 kPa to be restrictive for some tree species. Overall the soil compaction predictors used to model the response variables biologically represent how much space a root has to grow, and how compacted that space is for each sample point in the study.

***Cone Yields***

Cone yields in 2015 were determined by each Cooperator that participated in the study. For each tree, the number of bushels (35.2 liters) of harvested cones were provided. The number of cones per tree was estimated by counting the number of cones in one bushel then multiplying by the number of bushels harvested per tree.

***UrbanCrowns Density***

UrbanCrowns is a software developed by the U.S. Forest Service Southern Research Station to assess and monitor the crown and health characteristics of urban trees (Winn et al. 2011). UrbanCrowns density, defined as the amount of skylight blocked by the crown, was expressed as a percentage of the total 2-dimensional tree crown area structure and was determined by the UrbanCrowns software. A picture of each initial sample tree was taken using a digital camera. Each photograph was taken with specific requirements such as: horizontally and vertically centering the sample tree in the photo, ensuring at least a portion of the crown had a background of open sky, and avoiding taking a photo directly into the sunlight (Figure 2. 1A). These specifications were requirements given by the software program. Horizontal distance from the tree and the angles to the top and base of the tree from the position where the photo was taken was found using a Nikon Forestry 550 Hypsometer. These measurements are required input for the software to calculate UrbanCrowns density.

Photos for each tree were uploaded into the software along with the measurements taken. Once uploaded, the full stem is digitized by using a simple line that follows the stem from base to top. Next, the entire crown is digitized, being careful not to include foliage from the sample tree that overlapped with foliage from another tree. The software is unable to distinguish foliage between trees. Lastly, the portion of the crown exposed to a skyline background is digitized (Figure 2. 1B). This does not have to be as exact as the crown digitization, as the program is able to distinguish foliage from skyline background. The assessment for each tree includes tree height, tree length, crown height, crown diameter, crown ratio, crown transparency, crown volume, and crown density. Once the assessment is made, each tree and the corresponding information is saved into a spreadsheet. In this study, only UrbanCrowns density was used as a measure of tree health, while tree height and crown volume were used as covariates in some statistical models.

***Crown Density Score***

A visual crown density score from one to five was also assigned to each tree. The crown density score was assigned based on the density of foliage on branches. Spacing of branches and spread of crown was not considered. Trees with the densest foliage were scored a one while trees with the least dense foliage were scored a five. All visual scores were determined by a single person to eliminate inconsistency in scoring. The visual crown density score was developed as a check to understand how the visual look of a tree related to the software generated UrbanCrowns density.

When assessing the overall health of trees in these orchards, the sample was likely biased. Often when trees begin to visually decline in health, they are removed from the orchard to prevent pest and disease outbreaks. Thus, few visually unhealthy trees are available in the study. Therefore, a true range of health was not assessed, leaving a biased sample.

## Statistical Analyses

A visual assessment of the data was performed using scatter plots. Histograms and summaries were also produced to understand the distribution of the data. Relationship between all tree health measures were investigated by producing product-moment correlations.

There was significant variation among orchards for cone yield, most likely due to age differences between orchards. Data were standardized to remove scale effect using the overall mean and standard deviation of cone yield. The Proc Standard procedure of SAS/STAT Software was used to standardize cone yield (SAS Institute Inc. 2013).

The GLMSelect, a general linear model procedure of SAS/STAT Software was used for model selection for the two response variables, UrbanCrowns density and cone yields (SAS Institute Inc. 2013). All eight soil compaction variables and up to three-level interactions were considered in the model. In addition, clone and orchard effects were included as classification variables. Crown volume and tree height were included as covariates. The Stepwise selection option was used to select potential models among the large number of possible models. Significance level was set to $\alpha=0.1$ for predictor variables that were allowed into the model, while a significance level of $\alpha=0.15$ was required for predictors to remain in the model as other predictors were added and removed. The model selected for UrbanCrowns was

$$Y_{ijk} = \mu + \beta_1 V + O_i + C_j + \varepsilon_{ijk} \tag{Eq. 4}$$

Where

$Y_{ijk}$ is the UrbanCrowns density for the k-th tree of the j-th clone in the i-th orchard

$\mu$ is the overall mean

$\beta_1$ is the coefficient for crown volume

V is the effect of crown volume

$O_i$ is the random i-th orchard effect with the expectations ~ NID$(0, \sigma_\varepsilon^2)$, (i=1,2,3,4)

$C_j$ is the random effect of the j-th clone (j=1,2,3,…,11) with the expectations ~ NID$(0, \sigma_C^2)$

$\varepsilon_{ijk}$ is the residual error term of k-th tree with assumptions of ~NID$(0, \sigma_\varepsilon^2)$

The model selected for cone yield was

$$Y_{ijk} = \mu + \beta_1 V + \beta_2 K + O_i + C_j + \varepsilon_{ijk} \tag{Eq. 5}$$

Where

$Y_{ijk}$ is the cone yield for the k-th tree of the j-th clone in the i-th orchard

$\mu$ is the overall cone yield mean

$\beta_1$ is the coefficient for crown volume

V is the effect of crown volume

$\beta_2$ is the coefficient for soil volume at TrafficVolume3.5 position

K is the effect of soil volume at TrafficVolume3.5 position

$O_i$ is the random effect of the i-th orchard (i=1,2,3,4) with the expectations ~ NID$(0, \sigma_O^2)$

$C_j$ is the random effect of the j-th clone (j=1,2,3,…,11) with the expectations ~ NID$(0, \sigma_C^2)$

$\varepsilon_{ijk}$ is the residual error of k-th tree with assumptions of ~NID$(0, \sigma_\varepsilon^2)$

The selected models were run using the Mixed procedure of SAS/STAT software version 9.4 (SAS Institute Inc. 2013). Model assumptions for residuals and for all random effects were checked. Least squares means and probability of differences of pairs of means of fixed effects were produced. When variance components for seed orchard effect were examined, the ratio of the estimate over its standard error (SAS/STAT Mixed procedure names the ratio as Z values) were between 1 and 2. In order to test if the orchard effect was significant, Residual Log Likelihood Ratio Test was run (LRT) by running a subset model without the orchard effect and comparing its -2LogL value with the full model, in which orchard effect is included.

$$LRT = -2(LogL_{full} - LogL_{reduced}) \qquad \text{(Eq. 6)}$$

The LRT value has a chi-square distribution with 1 degrees of freedom. A one-tail chi-squared test was performed with a probability of 0.025 to compare the full and the reduced models (for the extra random term), which is orchard effect (Isik et al. 2017).

## Results

*Exploratory data analysis results*

The mean crown density score based on the 1 to 5 scale was fairly similar in all orchards, with a range of 1.8 to 2.0 (Table 2.1). The standard errors of means had a similar narrow range, 0.6-0.8. For the UrbanCrowns density (percentage of skylight blocked by the crown), the orchards were more variable. UrbanCrowns density means ranged from about 76 to 84%. Total cone yield per tree (count) was quite different among orchards with a range of 657 to 3707, most likely due to age and size of sample trees. Orchard B had almost six times greater cone yield compared to orchard A. Orchard B is older than Orchard A, and therefore the trees in Orchard B are larger. Old trees with large crowns are expected to produce more cones than younger trees with smaller crowns.

The correlations with probability of significance, scatter plots and histograms of UrbanCrowns density, crown density score, and cone yield are presented in Figure 2. 2. The correlation between UrbanCrowns density and the crown score was high (-0.68). The direction of the scatter plot and the sign of the correlation indicated that the higher crown density score (1 was good and 5 was bad), the lower the density percentage from UrbanCrowns. This shows UrbanCrowns was correctly identifying trees that looked unhealthy in the field by producing a lower density percentage. UrbanCrowns density and cone yields had a correlation of -0.28. Although this is a weak correlation, it shows that a higher UrbanCrowns density is correlated to a lower cone yield across all trees in all orchards. Crown density score and cone yields had a correlation of 0.03, which indicates no relationship between the variables.

*Variance components explained by the clone and orchard effects*

Significance tests for fixed covariate effects, crown volume and soil volume at TrafficVolume3.5, are presented in Table 2. 2. Crown volume (Pr = 0.0008) and soil volume at TrafficVolume3.5 (Pr = 0.0136) were both significant covariates affecting cone yield, when the orchard and clone effects were absorbed. The parameter estimates for TrafficVolume3.5 was 77.4 suggesting that with one unit ($m^3$) increase in soil volume at 3.5 meters from the tree within the traffic row, cone yield per tree would increase by 77.4 cones. Crown volume was highly significant, but had little impact on cone yields with a parameter estimate of 1.93E-04. This means that for every one unit ($m^3$) increase in crown volume the increase in cone yield would only be 0.000193. For the UrbanCrowns density response variable, crown volume was the only covariate significant when random effects of clone and orchard effects were absorbed. The parameter estimate for crown volume was 0.027, and with every increase in one unit of crown volume, UrbanCrowns density percentage would increase by 0.027%. Showing once again that while crown volume was highly significant, the impact on UrbanCrowns density is minimal.

For cone yield, the random clone effect was significant and explained a considerable amount of variation (Z =2.94, Pr=0.0016). Orchard effect was not significant with a Z value of 1.02 and Pr = 0.1537 (Table 2. 3). For UrbanCrowns density, clone effect was marginally significant (Z =1.59, Pr=0.0562) whereas orchard effect was marginally significant (Z=1.12, Pr = 0.0562). The parameter estimates, the amount of variation explained by each parameter, for clone and orchard when compared to the total variation for cone yields showed clone explains approximately 48% of the variation, and orchard explains about 17%. For UrbanCrowns density, clone effect explained 7.5% of the variation in crown density and orchard effect explained 22.8%.

The Z values reported by the Mixed procedure of SAS software are the ratios of the estimates and their standard errors (SAS Institute Inc. 2013). The probability values of Z values test the null hypothesis H0: Estimate = 0. The test statistics for variance components from SAS Mixed procedure can be misleading when the degrees of freedom for random effect is not large, and when the Z value is between 1-2 as in this study. In such cases, Residual Log Likelihood ratio tests should be performed to test the null hypothesis (Isik et al. 2017). Orchard effect was highly significant for UrbanCrowns density (chi-square value 19.3 with Pr < 0.0001) and for cone yield (chi-square value 11.5 with Pr = 0.0003) (Table 2. 4). Model AIC fit statistic also showed significant improvement when orchard effect is included in the models for both traits.

## Discussion

The high correlation observed between the two measures of crown density (UrbanCrown and Crown Score) indicated that both measures are similar in ranking the health of the tree. The goal of using the categorical visual score Crown Score was to serve as a check for the software measure of crown density. Trees that looked unhealthy in the field were scored 5 while healthy trees were scored 1. It was important to know if the software was generating concurrent information to what was observed in the field. Since the correlation between the two variables is fairly high, it is reasonable to state that the UrbanCrowns software was a fair measurement of tree health. The sign of the correlation shows that trees that looked unhealthy had lower percentage of density (the amount of light blocked by the canopy of the trees), and the trees that looked healthy had highest density scores.

UrbanCrowns density and cone yields had a correlation of -0.28. This suggests that trees with a dense crown that seem to be the healthy produced fewer cones than trees that have less dense crowns and are assumed to be less healthy. However, this may be a result of age effect not accounted for in the correlation. Older trees produce more cones, but can have less dense foliage. Also, trees under the stress and thus with less crown density may produce more cones.

Since there was almost no correlation between either crown density measures and cone yields, it may indicate that cone yield is not the most useful measure for tree health. However, cone yield as a response variable is important due to the economic value of producing as many cones per tree as possible. Correlations are exploratory variables and they do not necessarily pinpoint causative factors and they should be interpreted cautiously.

UrbanCrowns density was used to assess the effects of soil compaction on tree health. Crown volume was chosen as the only covariate. The final model did not include any significant soil compaction predictors (Table 2. 2). It did however include random clone and orchard effects, and these predictors make sense biologically. Genetic variation among clones plays an important role in many traits, particularly crown form and cone yield, as seen in Korean pine (*Pinus korazenszs S et. Z*) (Kang and Lindgren 1999). Therefore, it is not surprising to see a significant crown volume effect on crown density. Orchard would also play an important role due to size, age, and climate of each orchard. Trees in different orchards would be expected to differ for many reason such as the amount of water available based on climate. Crown volume is closely related to crown density, as crown density is calculated based on the light allowed through the canopy as a function of crown area. Crown volume is also a function of crown area.

While cone yield may not be the best indicator of tree health, it is an important economic factor in loblolly pine seed orchards. The best fit model included clone, orchard and crown volume, as well as a significant soil compaction variable, TrafficVolume3.5 (Table 2. 2). Once again, these predictors make biological sense. Genetics are known to have an impact on reproduction (Kang and Lindgren 1999), therefore it is understandable that clone has a significant effect on the number of cones produced. Age is also a major factor for cone production, therefore orchards that are older generally produce more cones. Crown volume can impact cone production, because a larger crown has more potential to produce more cones than a small crown. The compaction variable found to be significant was the volume of usable soil at 3.5 meters (TrafficVolume3.5) away from the tree within the traffic row when a threshold of 2750 kPa is used to calculate volume. This also makes sense biologically. Many important feeder roots can be found at that distance from the tree. Trees with less usable soil volume whose roots have less space to grow have a reduced amount of access to water and nutrients than a tree with more usable volume would have.

Soil volume at 3.5 meters from the tree within the traffic row being a significant variable places importance on understanding and managing equipment use in orchards. Use of aerial lifts in orchards is necessary to reap the increased financial gains from controlled cross seeds, but that heavy equipment use can compact the soil resulting in less “usable soil” which might negatively affect the cones yield.

It is also important to understand and consider the bias in cone yield for the sample trees. Since trees are typically removed from orchards when they begin to visually decline in health. This study was unable to include many unhealthy trees. The removal of unhealthy trees prevented sampling from a wider range of crown density and made it difficult to detect some variation in tree decline because of soil compaction.

This study was also a survey study rather than a controlled experiment. Survey studies would have less control on factors affecting tree health in seed orchards and mask the differences between various soil compaction levels. These factors create noise in the data making it difficult to detect the impacts of soil compaction.

## Conclusion

Soil compaction is most likely having negative impacts in loblolly pine seed orchards in the southeastern US where aerial lift use is common for pollination and cone harvest. No significant soil compaction on crown density does not mean soil compaction is not impacting tree health. Crown density may not have been the best measure of tree health. More studies should be conducted to better understand the impact of soil compaction on tree health. Foliage nutrient analysis should be considered as a measure of tree health, because many studies have shown that compaction impacts roots nutrient uptake ability (Miransari et al. 2009).

This study showed how much soil compaction can exist in seed orchards and developed a method of diagnosing when compaction is becoming a problem. Seed orchard managers can now use a penetrometer to regularly sample their orchards. When soil strength begins to approach 2750 kPa, when soil is at field capacity, an orchard manager should consider soil remediation methods such as subsoiling.

Orchard managers may also consider designing future orchards to account for increased aerial lift traffic and protect the largest portion of the tree's root zone as possible. Creating designated places where lifts are only allowed to travel may help protect more of a tree's root zone.

Arvidsson, J. 1999 Nutrient uptake and growth of barley as affected by soil compaction. *Plant and Soil*, **208** (1), 9-19.

Conlin, T.S.S. and Driessche, R.v.d. 1996 Short-term effects of soil compaction on growth of Pinuscontorta seedlings. *Canadian Journal of Forest Research*, **26** (5), 727-739.

Duiker, S.W. 2002 Diagnosing Soil Compaction Using a Penetrometer (Soil Compaction Tester). PennState Extension.

Jannson, G., annd B. Li. 2004 Genetic gains of full-sib families from disconnected diallels in loblolly pine *Silvae Genet*, **53**, 60-64.

Kang, K.-S. and Lindgren, D. 1999 Fertility variation among clones of Korean pine (Pinus koraiensis S. et Z.) and its implications on seed orchard management. *For. Genet*, **6** (3), 191-200.

Kozlowski, T.T. 1999 Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research*, **14** (6), 596-619.

Lipiec, J. and Hatano, R. 2003 Quantification of compaction effects on soil physical properties and crop growth. *Geoderma*, **116** (1–2), 107-136.

Lipiec, J., Horn, R., Pietrusiewicz, J. and Siczek, A. 2012 Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil and Tillage Research*, **121**, 74-81.

McKeand, S.E., Abt, R.C., Allen, H.L., Li, B. and Catts, G.P. 2006 What are the best loblolly pine genotypes worth to landowners? *Journal of Forestry*, **104** (7), 352-358.

Miransari, M., Bahrami, H.A., Rejali, F. and Malakouti, M.J. 2009 Effects of soil compaction and arbuscular mycorrhiza on corn (Zea mays L.) nutrient uptake. *Soil and Tillage Research*, **103** (2), 282-290.

Service, N.R.C. Bulk Density: Guide for Educators.

Winn, M.F., Araman, P.A. and Lee, S.-M. 2011 UrbanCrowns: an assessment and monitoring tool for urban trees, p. 1-10.

**Table 2.1.** Summary statistics (mean and standard error of mean, SE) of crown density score (1-5 score), and crown density calculated using UrbanCrowns (a software developed by the US Forest Service) and cone yield (count).

| | | Crown Density Score | | UrbanCrowns | | Cone yield | |
|---|---|---|---|---|---|---|---|
| **Orchard** | **N** | **Mean** | **SE** | **Mean** | **SE** | **Mean** | **SE** |
| A | 68 | 1.9 | 0.08 | 82.2 | 0.77 | 657 | 55 |
| B | 63 | 2.0 | 0.08 | 79.4 | 1.03 | 2600 | 111 |
| C | 56 | 1.8 | 0.11 | 84.0 | 0.93 | 1059 | 56 |
| D | 64 | 2.0 | 0.10 | 76.3 | 1.24 | 3707 | 244 |

**Table 2. 2.** Significant tests of fixed covariate effects (crown volume and TreeVolume3.5) on the response variables cone yield and UrbanCrowns density from mixed models. The estimates and their standard errors (SE within parenthesis) are also reported. An increase of one unit ($m^3$) of usable soil volume (TreeVolume3.5) will result in 77.4 more cones per tree. The increase in crown volume was highly significant for cone yield and UrbanCrowns (crown density), but the effect was small.

| Trait | Covariate | Estimate (SE) | DF | Pr > \|t\| |
|---|---|---|---|---|
| **Cone yeild** | TrafficVolume3.5 | 77.4 (2.34) | 220 | 0.0136 |
| | CrownVolume | 1.93E-04 (5.0E-05) | 220 | 0.0008 |
| **UrbanCrowns** | CrownVolume | 0.027 (0.0079) | 221 | 0.0001 |

**Table 2. 3.** Parameter estimates, Z value and Pr >Z for random effects of clone and orchard for two response variables, UrbanCrowns density and cone yield. For cone yields, clone explained a significant amount of variation while orchard was marginal in explaining variation. For UrbanCrowns, clone was once again significant in explaining variation while orchard was marginally significant. The estimate indicates the amount of variation explained by each source when compared to the total variation in each response.

| | Cone Yield | | | UrbanCrowns density | | |
|---|---|---|---|---|---|---|
| **Source** | **Estimate** | **Z Value** | **Pr > Z** | **Estimate** | **Z Value** | **Pr > Z** |
| Clone | 1761139 | 2.94 | 0.0016 | 5.8 | 1.59 | 0.0562 |
| Orchard | 653459 | 1.02 | 0.1537 | 17.5 | 1.12 | 0.1322 |
| Residual | 1240850 | 10.29 | <.0001 | 53.4 | 10.56 | <.0001 |

**Table 2. 4.** Log likelihood ratio test for the random orchard effect for two response variables, Cone yield and UrbanCrowns density. Orchard effect was highly significant for both response variables. Model AIC fit statistic also shows significant improvement when orchard effect is included in the models for both traits.

| Response | Model | AIC | -2 Res Log Likelihood | Chi-square | Pr |
|---|---|---|---|---|---|
| UrbanCrowns | Full | 1757 | 1751 | 19.3 | < 0.001 |
| | Reduced | 1774 | 1770 | | |
| Cone Yield | Full | 4319 | 4314 | 11.5 | 0.0003 |
| | Reduced | 4329 | 4325 | | |

**Figure 2. 1.** A) Correct photo to be taken and used in the UrbanCrowns Software. B) Photo indicating digitizing of the stem in yellow, digitization of the crown in blue, and reference for of sky and foliage background to calculate crown density in pink.

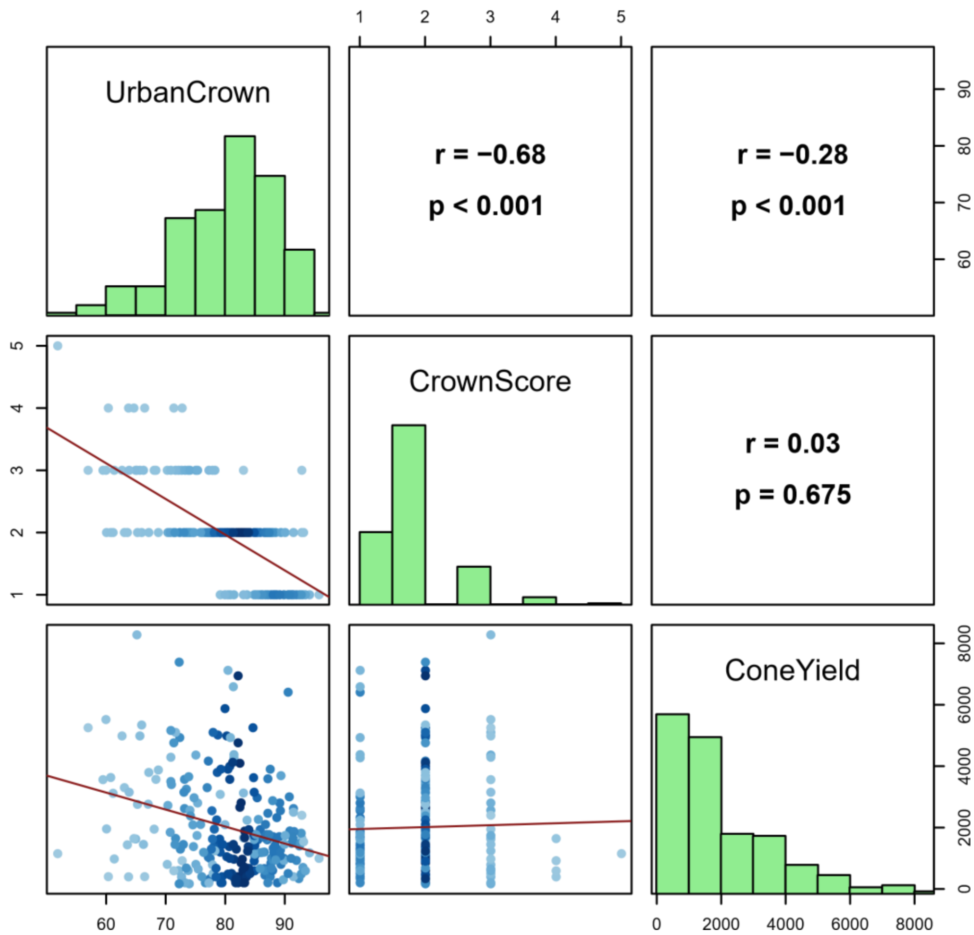



**Figure 2. 2.** Histograms (in the diagonal) showing the frequency distributions for UrbanCrowns density (percent skylight blocked by the crown), crown score (1 = low, 5=high) and cone yield (count). Scatter plots between three variables: center left indicating crown density score on the y axis and UrbanCrowns percentage on the x axis, lower left illustrating UrbanCrowns percentage on the x axis and cone counts on the y axis, and lower middle illustrating crown density score on the y axis and cone counts on the x axis. Correlations coefficients with probability of significance are presented for all three variables: UrbanCrowns and crown density score (upper middle), UrbanCrowns and cone yields (upper right), crown density score and cone yields (center right).

## References


Arvidsson, J. 1999 Nutrient uptake and growth of barley as affected by soil compaction. *Plant and Soil*, **208** (1), 9-19.

Becerra, A.T., Botta, G.F., Bravo, X.L., Tourn, M., Melcon, F.B., Vazquez, J. *et al.* 2010 Soil compaction distribution under tractor traffic in almond (*Prunus amigdalus L.*) orchard in Almería España. *Soil and Tillage Research*, **107** (1), 49-56.

Boby, L., Henderson, J. and Hubbard, W. 2013 The Economic Importance of Forestry in the South. Southern Regional Extension Forestry.

Bramlett, D.L. 1997 Southeastern Conifers: Genetic Gain from Mass Controlled Pollination and Topworking. *Journal of Forestry*, **95** (3), 15-19.

Cambi, M., Certini, G., Neri, F. and Marchi, E. 2015 The impact of heavy traffic on forest soils: A review. *Forest Ecology and Management*, **338**, 124-138.

Canada, N.R. 2017 Wood products: everywhere for everyone. http://www.nrcan.gc.ca/node/13313#screens.

Chaloupková, K., Stejskal, J., El-Kassaby, Y.A. and Lstibůrek, M. 2016 Optimum neighborhood seed orchard design. *Tree Genetics & Genomes*, **12** (6), 105.

Coder, K. 2007 Soil Compaction Stress & Trees: Symptoms, Measures, and Treatments.

Conlin, T.S.S. and Driessche, R.v.d. 1996 Short-term effects of soil compaction on growth of Pinuscontorta seedlings. *Canadian Journal of Forest Research*, **26** (5), 727-739.

Day, S.D. 2009 At the Root of It

Duiker, S.W. 2002 Diagnosing Soil Compaction Using a Penetrometer (Soil Compaction Tester). PennState Extension.

Foster, T.M., Watson, A.E., Hooijdonk, B.M. and Schaffer, R.J. 2013 Key flowering genes including FT-like genes are upregulated in the vasculature of apple dwarfing rootstocks. *Tree Genetics & Genomes*, **10** (1), 189-202.

Gao, W., Watts, C.W., Ren, T. and Whalley, W.R. 2012 The effects of compaction and soil drying on penetrometer resistance. *Soil and Tillage Research*, **125**, 14-22.

Gerwig, D.M. Annual top pruning as crown management technique in a young loblolly pine seed orchard to reduce height and still produce flowers.

Grattapaglia, D., Amaral Diener, P.S. and Santos, G.A. 2014 Performance of microsatellites for parentage assignment following mass controlled pollination in a clonal seed orchard of loblolly pine (*Pinus taeda L.*). *Tree Genetics & Genomes*, **10** (6), 1631-1643.

Groenevelt, P.H., Grant, C.D. and Semetsa, S. 2001 A new procedure to determine soil water availability. *Soil Research*, **39** (3), 577-598.

Isik, F., Holland, J., Maltecca, C. (2017). In press: Genetic Data Analysis for Plant and Animal Breeding. Springer International Publishing, 204p, DOI: 10.1007/978-3-319-55177-7.

Jannson, G., annd B. Li. 2004 Genetic gains of full-sib families from disconnected diallels in loblolly pine *Silvae Genet*, **53**, 60-64.

Jayawickrama, K.J.S., Jett, J.B. and McKeand, S.E. 1991 Rootstock effects in grafted conifers: A review. *New Forests*, **5** (2), 157-173.

Kang, K.-S. and Lindgren, D. 1999 Fertility variation among clones of Korean pine (Pinus koraiensis S. et Z.) and its implications on seed orchard management. *For. Genet*, **6** (3), 191-200.

Kozlowski, T.T. 1999 Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research*, **14** (6), 596-619.

Lipiec, J. and Hatano, R. 2003 Quantification of compaction effects on soil physical properties and crop growth. *Geoderma*, **116** (1–2), 107-136.

Lipiec, J., Horn, R., Pietrusiewicz, J. and Siczek, A. 2012 Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil and Tillage Research*, **121**, 74-81.

McKeand, S. 2015 In *Annual Report*, North Carolina State University Cooperative Tree Improvment Program

McKeand, S. 2017 Mass production of controll crosses in TIP cooperative 2016. S. Larrison (ed.).

McKeand, S., Mullin, T., Byram, T. and White, T. 2003 Deployment of genetically improved loblolly and slash pines in the south. *Journal of Forestry*, **101** (3), 32-43.

McKeand, S.E., Abt, R.C., Allen, H.L., Li, B. and Catts, G.P. 2006 What are the best loblolly pine genotypes worth to landowners? *Journal of Forestry*, **104** (7), 352-358.

Miransari, M., Bahrami, H.A., Rejali, F. and Malakouti, M.J. 2009 Effects of soil compaction and arbuscular mycorrhiza on corn (Zea mays L.) nutrient uptake. *Soil and Tillage Research*, **103** (2), 282-290.

Service, N.R.C. Bulk Density: Guide for Educators.

Starkey, T.E., Enebak, S.A. and Smith, D.B. 2015 Forest seedling nursery practices in the Southern United States: bareroot nurseries. In *Tree Planters Notes*.

Technologies, S. 2009 Field Scout SC 900 Compaction Meter Product Manual. Spectrum Technologies, Inc.

Wear, D.N. and Greis, J.G. 2002 Southern Forest Resource Assessment: Summary of findings. *Journal of Forestry*, **100** (7), 6-14.

Wiersum, L.K. 1957 The relationship of the size and structural rigidity of pores to their penetration by roots. *Plant and Soil*, **9** (1), 75-85.

Winn, M.F., Araman, P.A. and Lee, S.-M. 2011 UrbanCrowns: an assessment and monitoring tool for urban trees, p. 1-10.

Zhang, M., Mei, B., Harris, T.G., Siry, J.P., Clutter, M.L. and Baldwin, S.S. 2011 Can timber hedge against inflation? An analysis of timber prices in the US south. *Forest Products Journal*, **61** (4), 276-282.

# APPENDICES

# Appendix A

Typical soil profile for each soil type in the orchards sampled.

| Tifton Loamy Sand | | | Lynchburg Loamy Sand | | | Plummer Sand | | | Chipley Loamy Fine Sand | | | Greenville Sandy Loam | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hor.** | **Depth** | **Texture** | **Hor.** | **Depth** | **Texture** | **Hor.** | **Depth** | **Texture** | **Hor.** | **Depth** | **Texture** | **Hor.** | **Depth** | **Texture** |
| Apc | 0-11 | loamy sand | H1 | 0-23 | loamy sand | H1 | 0-50 | sand | Ap | 0-6 | loamy fine sand | H1 | 0-5 | sandy loam |
| Btc1 | 11-22 | fine sandy loam | H2 | 23-33 | sandy loam | H2 | 50-72 | sandy clay loam | C1 | 6-40 | loamy fine sand | H2 | 5-12 | sandy clay loam |
| Btc2 | 22-40 | sandy clay loam | H3 | 33-75 | sandy clay loam | | | | C2 | 40-50 | sand | H3 | 12-62 | sandy clay |
| Btv1 | 40-50 | sandy clay loam | | | | | | | | | | | | |
| Btv2 | 50-56 | paragravelly sandy clay loam | | | | | | | | | | | | |
| BC | 56-65 | sandy clay | | | | | | | | | | | | |
| C | 65-80 | sandy clay loam | | | | | | | | | | | | |

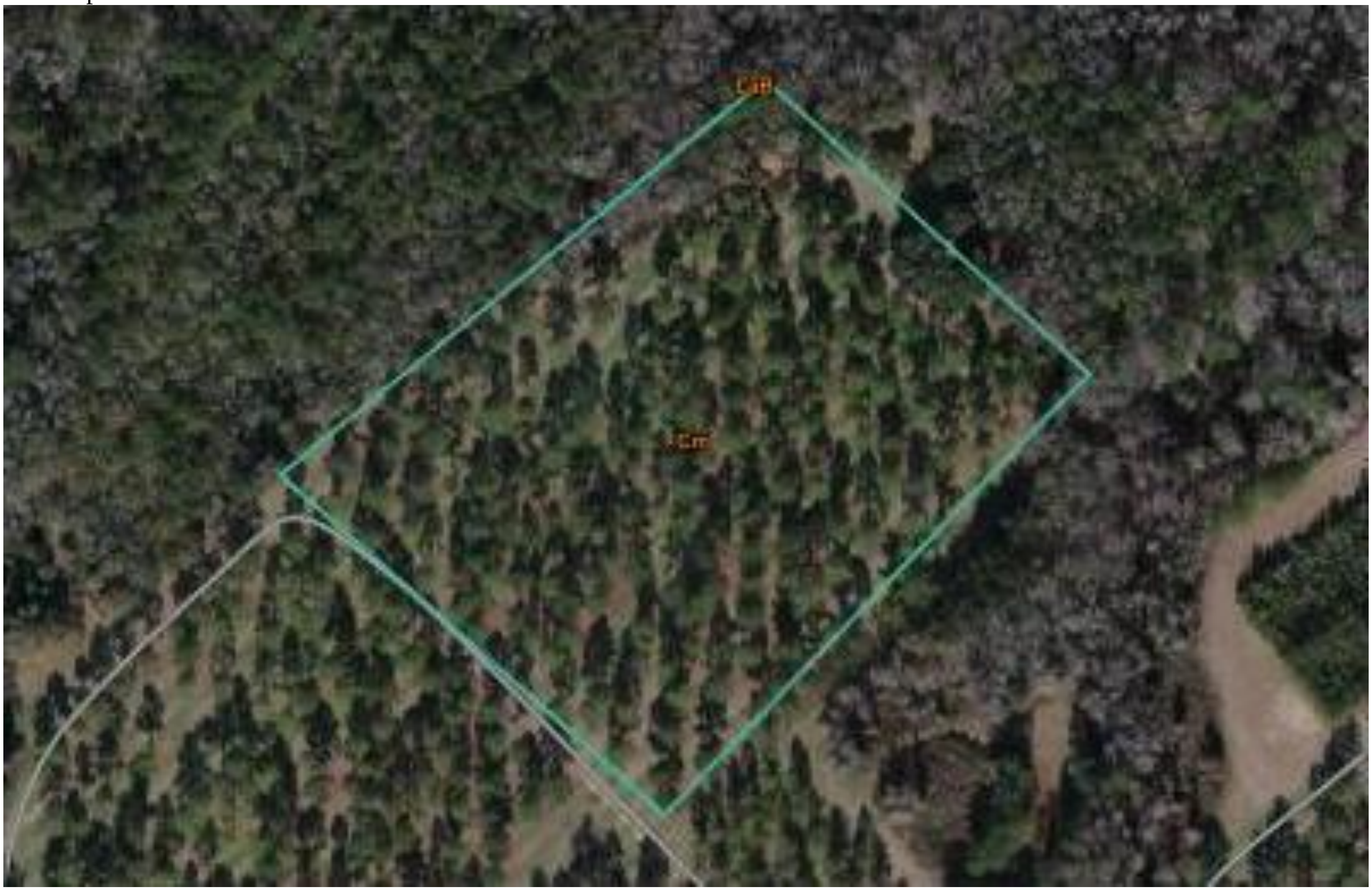
# Appendix B

Soil map of Orchard A. Only trees in the Tifton soil type (TqB) were sampled.

Soil map of Orchard B

Soil map of Orchard C , Only trees in the PeA and LzA soil types were sampled.

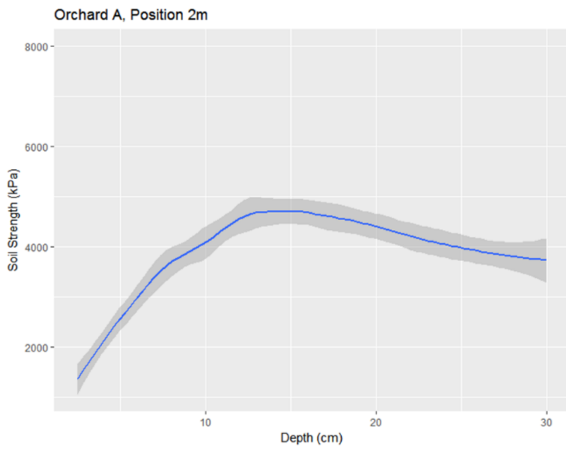
Soil map Orchard D

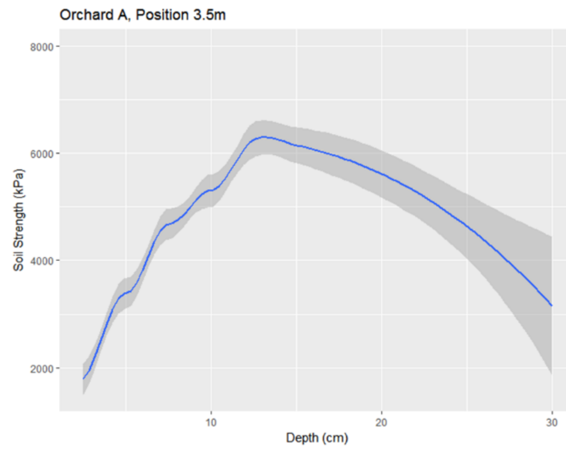


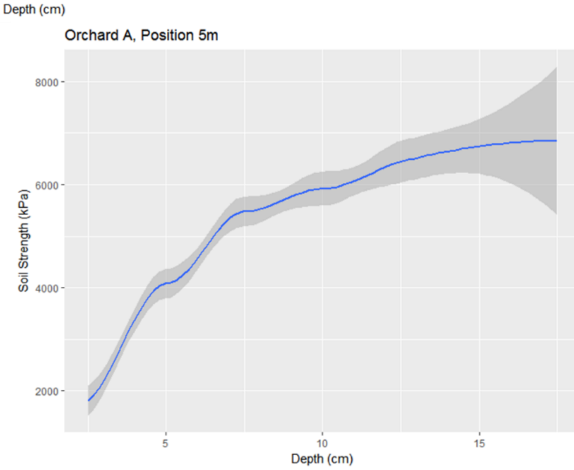
Soil map of Orchard E

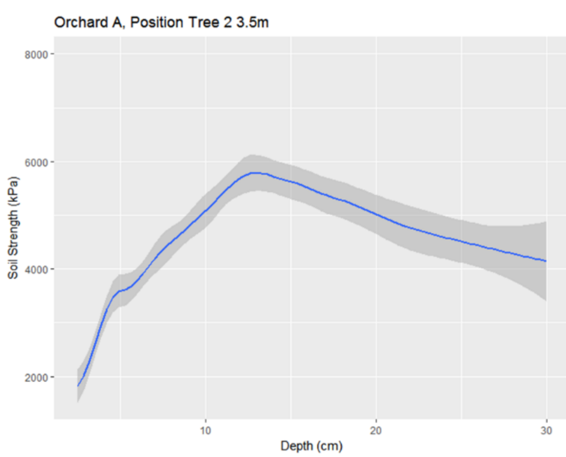
# Appendix C

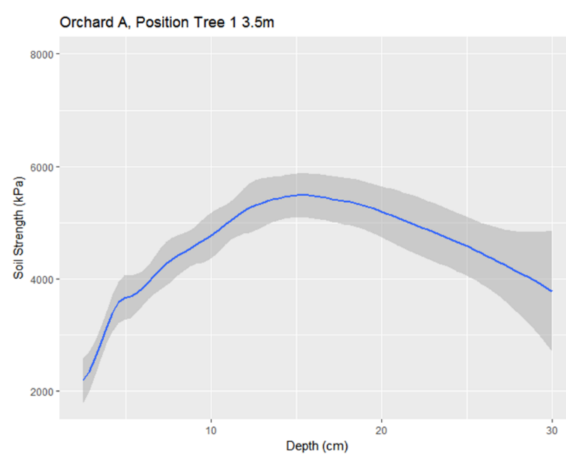
Soil strength by depth profiles for all sample positions in orchad A



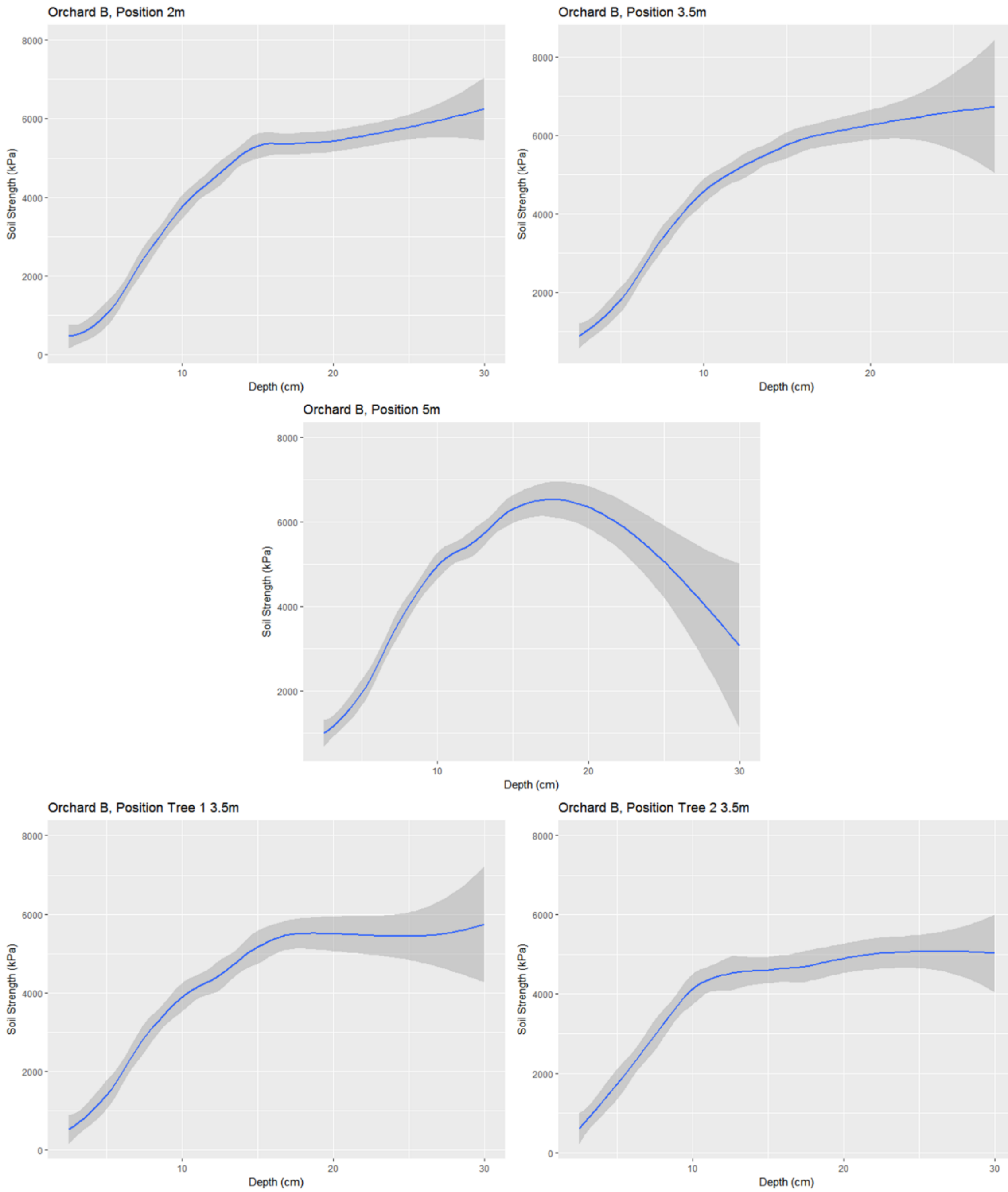



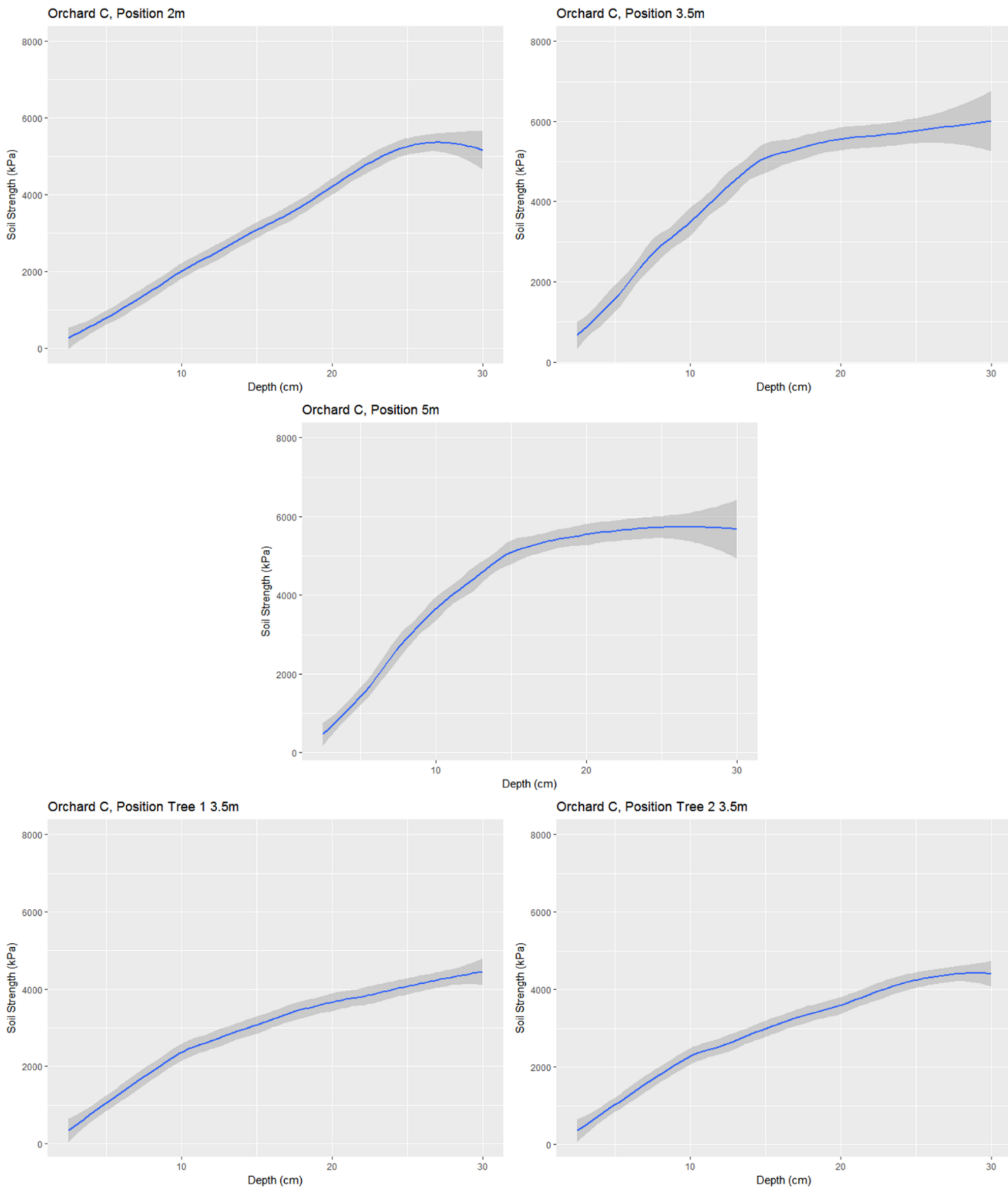



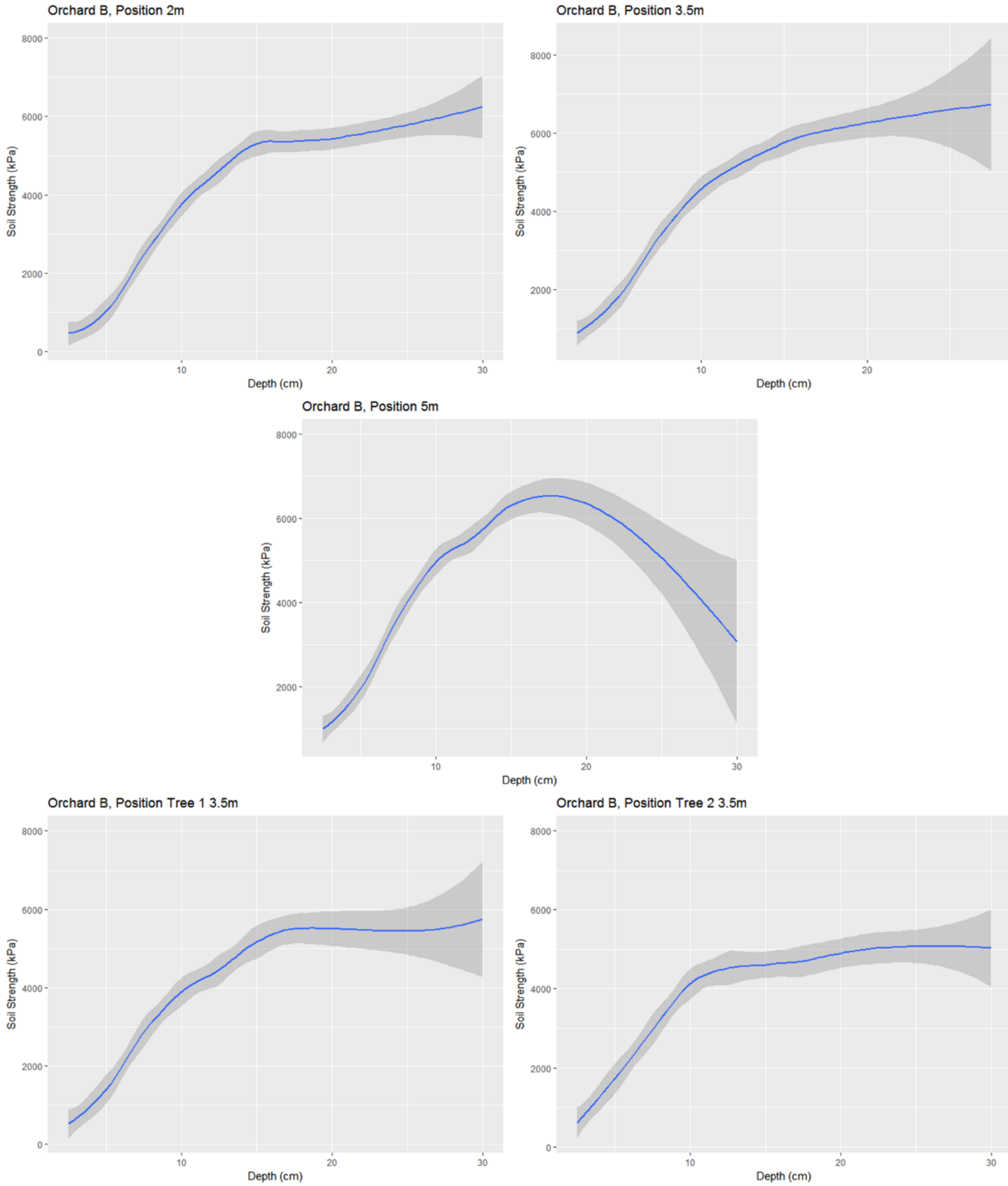
Soil strength by depth profiles for all sample positions in orchad B



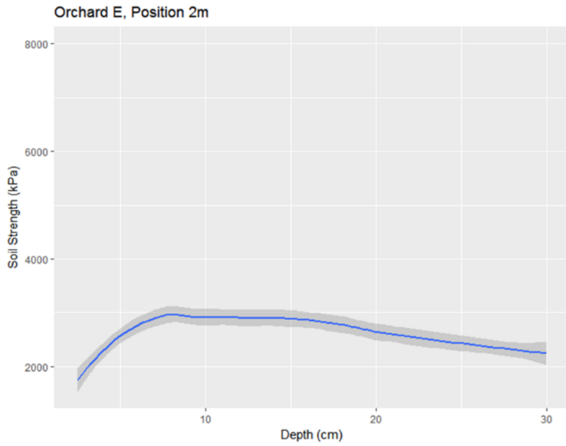
Soil strength by depth profiles for all sample positions in orchad C

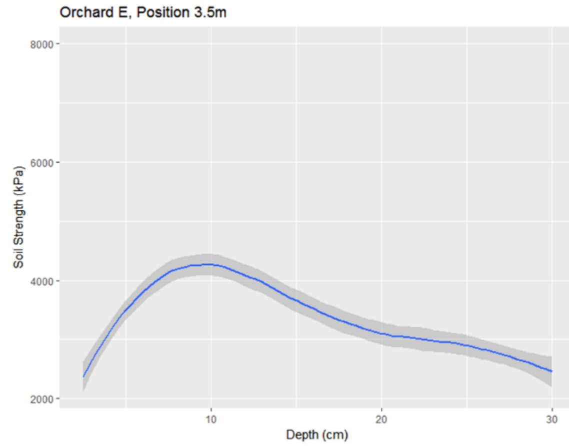


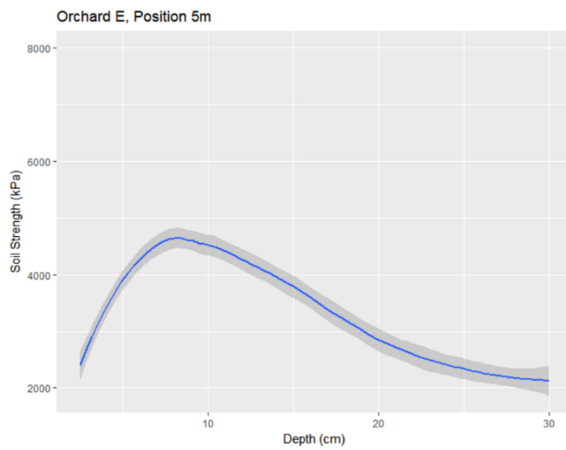
Soil strength by depth profiles for all sample positions in orchad D

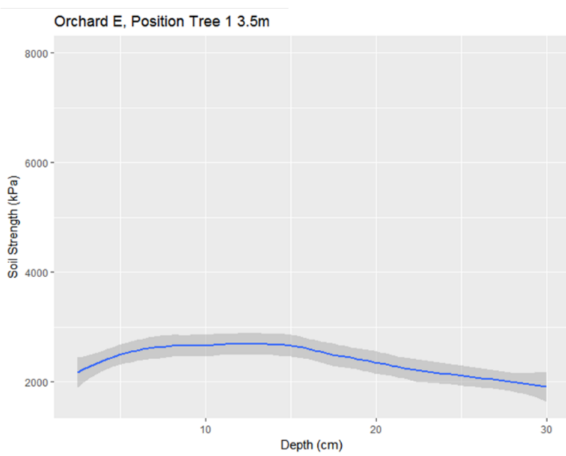


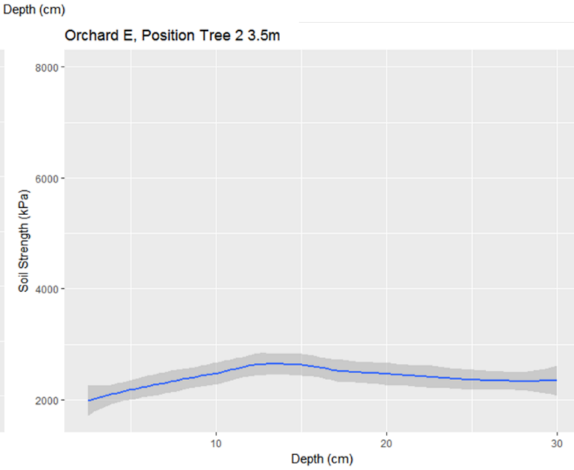
Soil strength by depth profiles for all sample positions in orchad E



## Appendix D

Predicted mean bulk density per orchard from the mean soil strength per orchard using the regression equation found.

| Orchard | Soil Strength | Moisture Content | Predicted Bulk Density |
|---|---:|---:|---:|
| **A** | 4122.95 | 9.7 | 1.47 |
| **B** | 3584.09 | 7.8 | 1.40 |
| **C** | 3099.71 | 13.7 | 1.39 |
| **D** | 3951.97 | 14 | 1.48 |
| **E** | 2772.55 | 26.2 | 1.43 |