ABSTRACT

NEWTON, MARSHALL MCNEILL. Evaluation of Soil Compaction Associated with Mechanized Harvest Operations and Multi-Species Cover Crops. (Under the direction of Dr. Mari S. Chinn).

United States cotton production faces many obstacles during a single growing season. From herbicide resistant weeds and root limiting compaction to multiple pieces of equipment needed at harvest, producers are constantly looking for ways to improve and overcome these pressing issues. These producers are rapidly adopting new picking technology of on board module building harvesters which have provided more efficient ways to harvest the crop. One machine is able to complete the job of what used to require three pieces of equipment and laborers; however, these machines weigh twice that of previous basket pickers. This raises some concern about implications for cotton root limiting compaction due to the harvest traffic. The objectives of this research focused on quantifying the changes in soil strength due to picker traffic at harvest along with utilizing a multi-species cover crop to assist in compaction alleviation as well as improving soil health.

Harvester effects were looked at over three farms using a John Deere 7760 round baler, a Case IH 625 Module Express, and a John Deere 9986 conventional basket harvester. Soil penetration resistance measurements were taken using a cone penetrometer and moisture content levels were obtained before and after traffic of each harvester over a single cotton harvest. Results showed no significant increase of soil penetration resistance from either harvester, suggesting that in Coastal Plain soils of North Carolina these harvesters are not negatively affecting the soil structure.

Multi-species cover crops were planted on four farms located in the Coastal Plains of North Carolina to identify compaction alleviation effects along with improvement of soil health by these cover species. The farms planted the covers in strips creating 3 plots of no cover and 3 plots with cover. Soil moisture, nutrients and penetration resistance measurements were taken just prior to cover crop planting and again just after the cover crop had been terminated to determine the effects of the multi-species covers. Biomass samples were obtained just after termination and a nutrient analysis was run. The results showed that after one season using the multi-species cover crop the soil strength was weakened suggesting compaction was alleviated to a certain degree. Not only did these cover crops help

in compaction alleviation they also provided a cover during harsh winter months preventing soil erosion and increasing organic matter.

It is well known that soil moisture has one of the largest impacts on soil penetration resistance levels. Replications from the four fields used in the cover crop study were done by removing soil from depths from 0 to 12” and 12 to 18” and brought back to the lab to be studied further. Soil cores were taken at each location in the field to determine accurate bulk densities at the different depths for each location. These bulk densities were then replicated in 5 gallon buckets of the specific soil from which the cores came from. The buckets of soil were used to measure soil penetration resistances at 0, 5, 10, 15, 20, 25, 30 and 40% moisture content (dry-basis) to identify a relationship between soil moisture and soil penetration resistance specific to our sites/soil types. It was found that an inverse relationship was consistent throughout each test unit. An empirical equation relating soil moisture to soil penetration resistance was determined by identifying the best trend line, linear, exponential or logarithmic and the highest R^2 values.

Evaluation of Soil Compaction Associated with Mechanized Harvest Operations and Multi-Species Cover Crops

by
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BIOGRAPHY

Marshall “Neill” Newton was born on June 2, 1989 in Pinehurst, North Carolina. He is the first born of Marshall and Allison Newton and the older brother to Mary Lawrence Newton. Neill grew up on a commercial farm in the big city of Raeford where they grew mostly cotton. He was exposed to the farm lifestyle and has been passionate about agriculture ever since. His father is a diehard Wolfpack fan graduating from NC State in Agronomy while his mother was a blue blooded Tar Heel graduating from Chapel Hill. With a passion for agriculture it was an easy decision for Neill to join the Wolfpack.

Neill graduated from Jack Britt High School in the spring of 2007 and started his college career at NC State in the Biological and Agricultural Engineering Department in the fall. Every summer he would return home to work on the farm and escape the city life. This was until his last summer as an undergraduate when he was given the opportunity to intern as an agricultural engineer at Cotton Incorporated in Cary, N.C. This position opened many doors, end eventually led to one great opportunity. He was approached by his supervisor at Cotton Incorporated about a master’s degree in Biological and Agricultural Engineering from NC State. This was something he had never considered until that point but was definitely something not to pass up.

After graduating with his undergraduate degree in the spring of 2012 he was eager to pursue graduate school in the Biological and Agricultural Engineering department. This was an opportunity for Neill to further his studies in areas of great interest and expand his knowledge on the crop he grew up on, cotton. His research focused on soil compaction in cotton due to the new harvesters and the use of multi-species cover crops to assist in compaction alleviation. After graduate school Neill plans to pursue a career in Agriculture focusing on precision agriculture, production or machine design.

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Literature Review

1.1 State of Global Cotton

Global cotton production is continuously evolving. Four countries alone produce nearly 80% of all the cotton produced in the world today. Together China and India produce nearly 50%, the United States produces about 15% and Pakistan is not far behind producing about 10% of the world's cotton. The U.S. is the world's leading exporter, exporting about 40% of all exported cotton globally, while China is the world's leading importer, importing an average of 17.5 million bales per year since 2010/2011 (Cotton Incorporated, 2014). China is not only the leading producer of cotton, but as a country they have the highest average yields for the current year, at over 1,200 lbs-/acre. The U.S. is expected to average around 800 lbs/acre, Pakistan just over 600 lbs/acre and India the lowest at 482 lbs/acre (Johnson et al., 2014). Mechanization is a huge contributor to improved production. China, India and Pakistan still have farms that are being harvested entirely by hand. For many farms the harvesting operations are outdated, and inputs and applications, whether it be fertilizer or some sort of pesticides, are still lacking the advanced technology that make precision application possible. A major contributor to increased yields and decreased inputs was so monumental it took only a few years to catch on. Bt cotton is a variety of cotton that contains *Bacillus thuringiensis* toxin that controls cotton boll worm, and other pests that was developed in 1996 (Huang and Fangbin 2001). China began planting Bt cotton in 1999, and India was soon to follow in 2002 (Manjunath, 2008). Bt cotton has drastically increased yields and profits for cotton farmers across the world by eliminating boll worm damage and pricy pesticide applications multiple times a year.

The Chinese government, beginning in 2011, began a massive buying effort of cotton, stockpiling it and not sending it to the mills. World prices were holding as if that cotton China had stockpiled was used up and no longer available for the mills to purchase; therefore, supply/demand forces were acting on a misleading tight world supply of cotton (Robinson, 2014). This kept producers around the world planting more cotton, due to stabile prices, that would not have otherwise been planted. This stockpile lasted until 2013 and there is now talk of stopping the stockpiling efforts and selling off the stock piled cotton. Depending on the condition of the stockpiled cotton and how they decide to sell it off, whether it be a little at a time or a large amount, this has the potential to negatively affect the world market prices in 2014 and years to follow (Robinson, 2014). In the past 10 years cotton prices have remained somewhat volatile with relatively little consistency, but have over all increased in price. Prices have been as low as 0.45 cents per pound to a record high of nearly $2.00 per pound around the time China began their stockpile. These high prices encouraged farmers to produce cotton; however, made it difficult for the mills to purchase and even forced the use of synthetics (Josephs, 2011). Cotton prices are now holding just under $1.00 per pound, and this has been the case for the past 2 to 3 years. The average increase in price is necessary to offset the increase in input costs (Index Mundi, 2014). Corn prices in the past 10 years have been extremely volatile ranging from $2.50 per bushel up to nearly $8.00 per bushel. Unlike cotton, corn prices are driven by livestock and alternative fuel industries. Cotton prices are driven more by available cotton or supply and more recently by Chinas' stockpile.

1.2 U.S. Cotton Production

The majority of U.S. cotton produced comes from two different species, Upland cotton which is grown in the southeast, mid-south, and some parts of the southwest and Pima cotton which is grown mostly in arid regions such as Arizona and California (National Cotton Council, 2014). Pima cotton is a more expensive fiber and has a much longer staple length or fiber length than Upland cotton. Cotton is grown in 17 of the southern states from Virginia to California. Because there is such a geographical difference in these states, management practices vary depending on region (USDA, 2014).

Cotton has one of the longest growing periods of crop commodities requiring 150 to 180 days from plant to harvest. Land preparation usually begins in late fall after harvest (National Cotton Council, 2014). There are many different management practices from conventional tilling to no-till operations. Conventionally tilled soils are usually completely cultivated with the topsoil and previous crop residue turned in and fresh soil left exposed on top. No-till practices leave all residue and topsoil as is and simply cut or shred the stalks and plant into that residue for the next spring leaving the land ultimately untouched. The southern states along the Gulf of Mexico and bordering Mexico can begin planting in February while, the northern states can plant as late as mid-June. Once the crop has been planted and a good stand established the battle begins with bugs, weeds and fungi trying to consume the cotton plant. A month to six weeks after these seedlings emerge blooms will begin to appear on the cotton plant which will hopefully fully develop into a cotton boll and open, unveiling the beautiful white fiber, about 50 to 60 days after bloom (Cotton Counts, 2014).

Cotton harvest has drastically become more advanced in the last 5 to 10 years. Between on-board yield monitoring and mapping to on-board module harvesters, these harvesters have drastically changed in size and price. Cotton can be harvested a few different ways in the U.S. Most of the cotton is harvested by a cotton picker that uses spindles to remove the seed cotton from the burr. The other type of harvester that is common in shorter irrigated cotton is called a cotton stripper. Strippers are used mostly in west Texas and other dry areas where cotton does not grow that tall. The stripper removes open and un-open bolls, leaves, sticks and other undesirable materials. The majority of harvesters used are the pickers, which consist of 1) a conventional basket picker that stores cotton in a large basket prior to transfer to a boll buggy for subsequent packing into large rectangular modules (~20,000 lbs) using a module builder; or 2) an onboard cotton module harvester that allows the farmer to harvest a field and have the cotton baled (round-bale, 5000 lbs or mini-module, 10,000 lbs) with one machine eliminating the need for a boll buggy or a module builder.

The ginning process is completed directly after harvest, usually by a community gin, where the farmer may pay a certain price per bale for the ginner to gin his cotton. This process begins with either the conventional rectangular module of cotton, round bales or mini -modules. These tightly packed modules are entered into the gin where they are loosened and separated and sent through various cleaners and dryers before actually entering the gin stand at which point the seeds and lint are separated. From here the clean seedless cotton is moved through a humidifier to add just a little bit of moisture and then to the bale press where it is pressed, packaged and sent out on trucks to a buyer or warehouse. The ginning process must be completed before the cotton is able to go onto the market to be sold.

1.3 Economic Impact of Cotton Production on Land and Wallet

Cotton production supports nearly 200 thousand jobs and generates direct business revenue of more than $27 billion in the United States (National Cotton Council of America, 2014). Practically every state in the U.S. houses processors and distributors of cotton fiber as well as downstream manufacturers of cotton apparel and home furnishings. Southeastern U.S. cotton, including Alabama, Florida, Georgia, North Carolina, South Carolina and Virginia, produces over $10 billion in revenue alone (National Cotton Council of America, 2014).

Cotton is a demanding crop requiring intensive management practices. Land prep before planting usually includes application of fertilizer and lime to get soil nutrients and pH levels where they should be. The majority of farmers use cotton seed that has been genetically modified, such as the Bt cotton, to resist certain pests and herbicides, and to increase tolerance to drought (Cotton Counts, 2014). This seed is very expensive simply because of all of the technology fees that go along with the genetic modifications. Once the cotton is planted and a good stand is established the work really begins. Pests from weeds to damaging insects are an early threat for small cotton that must be addressed immediately by pesticide/herbicide to limit the amount of damage these pests may cause to the cotton plant. Weeds are also pests in that they compete for soil resources, often starving the cotton plant from essential nutrients and water. Near the point of first bloom another dose of fertilizer may be applied to push it through the rest of the growing period and allow it to produce maximum fruit (Cotton Counts, 2014). Around this time a plant growth regulator is usually applied over top of the cotton to keep the cotton from shooting up and to limit the amount of rank growth, allowing for fill out and more fruit production. This plant growth regulator is usually applied 3 to 5 times throughout the rest of the growing season depending on the farmer. In some areas plant bugs are a big problem and must be eliminated to yield loss, using pesticides. At the cutout stage cotton is then sprayed again with a defoliant to remove all leaves and assist the bolls in opening in order to be harvested. Every farm has different management practices and may differ from what is described here as a general management practice (Cotton Council International, 2005).

Cotton production is becoming more sustainable, by tracking water, chemical and fertilizer usages. With the help of organizations like Cotton Incorporated and their sustainability initiatives, more farmers are becoming aware and making sure that management practices are environmentally friendly. Cotton has an elaborate rooting system that is very efficient in seeking moisture and nutrients from the soil. From an economic standpoint, cotton's water use efficiency allows cotton to generate more revenue per gallon of water than any other major field crop (Cotton Counts, 2014). According to the National Cotton Council of America (2014), U.S. Cotton from 2011 to 2013 had average total operating costs at $490.16 per planted acre, and an average allocated overhead of $296.10 per planted acre giving a total cost of $786.26 per planted acre. In comparison corn in the southeast in 2013 had a total operating cost of $398.74 per planted acre and an average allocated overhead of $262.25 per planted acre giving a total cost of $660.99 per acre. Soybeans in this region in 2013 had a total operating coast of $210.71 per planted acre and an overhead cost of $179.61 per acre resulting in a total cost to produce one acre of soybeans at $390.32 (USDA ERS, 2013).

1.4 Technological Advances in Machinery used for Cotton Production

As technology becomes more advanced, farm machinery has increased in size and weight (Kulkarni, Bajwa, and Huitink, 2010) and with the extensive weight on vulnerable soil types or soil conditions compaction can occur (Schafer, Bailey, Johnson, and Raper, 1991). The stress that machines exert on soils, whether tires or tracks, has been studied in both laboratory and field experiments (R. L. Raper and Kirby, 2006). Soil stress beneath dual and single wheeled machines proved to be similar, however; much greater than beneath tracked machines. Kirby and Blunden (1993) have shown compaction near the surface is dependent on ground contact pressure where at depths below the surface compaction is more dependent on axle load.

Both John Deere and Case IH have developed onboard cotton module harvesters. With these new machines, separate harvest, transport and module building operations are eliminated and the harvester does the job of all three at one time. The John Deere 7760 round bale harvester harvests the cotton and makes round bales on-board (carrying up to two at a time) weighing about 5,000 lbs each wraps them in a weather proof plastic and then places them on the ground for pick up (John Deere, 2012). The Case IH Module Express harvests the cotton and presses it into a small mini-module weighing about 10,000 lbs and unloads it off the back for delivery to the gin (Case IH, 2012).

The new harvesters offer several advantages over the conventional basket harvesters: a reduction of in–field labor, greater picking efficiency (Willcutt et al., 2009) and fewer pieces of equipment to break down and move between locations, all reducing the cost of production. There are, however, potentially negative aspects in that the Case IH on board cotton module harvester weighs over 5 tons more than the conventional basket harvester (Case, 2012), while the new John Deere machine outweighs the conventional basket picker by nearly 10 tons (Deere, 2012). Both of these machines have the ability to carry modules on the machine, either round bales or the Case IH mini module, adding an additional 5,000-10,000 lbs to the John Deere harvester (Deere, 2012) and nearly 10,000 lbs to the Case IH machine (Case IH, 2012). With these weights, these harvesters pose a risk in generating subsoil compaction especially if field conditions are "wet" during harvest. It has been reported that as little as 10 Mg (~2,200 lbs) of axle load, can cause bulk density to increase along soil penetration resistance (Voorhees et al., 1986). Research examining the effects of cotton harvest operations on soil compaction has been limited, either by these massive machines or with the traffic of the conventional methods, with no studies of the new harvesters reported for U.S. operations to date.

1.5 Compaction Issues in Cotton Production

Development of more technologically advanced and versatile agricultural equipment for different farm operations has led to larger and heavier vehicles; therefore, soil compaction has become a growing concern for both researchers and farmers alike. This is a topic that has been studied in depth for many years; and it has been shown that crop yield is reduced by soil compaction (Kulkarni et al., 2010). Cotton is particularly vulnerable with the extending tap root that takes advantage of maximum moisture and nutrient uptake (Grimes et al., 1975). When the tap root is unable to grow to an unrestricted depth, the soil is compacted and can lead to yield loss in the southeastern United States (Raper et al., 2009). With the need for mechanization, completely avoiding soil compaction is extremely difficult if not impossible (Schafer et al., 1991). Raper and Kirby (2006) explained soil compaction as the densification of the soil through the release of air caused by excessive weight on a weak soil or a soil that is moist and aerated. Schafer et al. (1991) went on to describe that different soil types have different strengths, and once the threshold of a soil is exceeded, compaction occurs. Moisture content of the soil is the most influential factor that effects compaction (Raper and Kirby, 2006). Several studies have reported, using a penetrometer, a cone index ≥ 2 MPa (~290 psi) will disrupt cotton tap root growth and result in a negative crop response (Raper et al., 1994; Kulkarni et al., 2010; Raper and Kirby, 2006).

Subsoiling, or tillage 35 cm below the soil surface, is the most popular form of tillage when trying to reduce compaction. It has been shown that various soil types respond well to subsoiling with an overall increase in crop yield (McConnell et al., 1989; Raper and Kirby, 2006; Raper et al., 2000). Raper et al. (1994) looked at various tillage methods which included: 1) conventional surface tillage, followed by 0.4m depth in-row strip-till at planting; 2) initial disruption of hardpan by subsoil tillage (without annual subsoiling thereafter) followed by conventional tillage and then planting; 3) conventional tillage and planting; and 4) strip-till at planting without conventional tillage.

These tillage treatments were paired with different trafficking patterns which were sampled throughout changes in soil condition during the season using a penetrometer. Soil samples were pulled to measure dry bulk density as well as gravimetric moisture content. It was concluded that the best method of tillage to reduce compaction, reduce bulk density, and increase or maintain soil moisture was the subsoiling at planting without surface tillage due to the greater disruption of the hard pan and minimal moisture losses at the surface through evaporation (Raper et al., 1994). In a similar experiment McConnell et al. (1989) found similar results concluding that the subsoiled plots in the experiment showed an increase in yield over plots that were not subsoiled. Raper et al. (2000) reported that sub-soiling was not necessary to increase yield if adequate water was available to the crop throughout the growing season, where roots do not have to grow deep in search of water if it is readily available. A study also done by Raper et al. (2000) investigated tillage depth, timing, and cover crop effects on cotton yield as well as tillage energy requirements. Subsoiling in fall in comparison to subsoiling in the spring before planting showed little to no variation in yield. The differences that did exist between the timing of the subsoiling operations were related to variations in the soil conditions due to weather. Additional effects were tied to a reduction in required energy by 50% when shallow tilling was used instead of deep tilling, yet shallow tilling did not disrupt the root limiting hardpan. High crop yields also resulted from conservation tillage by subsoiling at planting into a cover crop. These studies suggest the best tillage method for improved cotton yield is a conservative approach such as a strip-till method that does not disrupt the soil surface but breaks up compacted soil for maximum root growth and filtration. This type of tillage practice in combination with suitable water availability can overcome compaction challenges and enhance crop yields.

Traffic through the field is inevitable; it must be done to provide the necessary care the crop needs to thrive as well as to remove the crop from the field at harvest. This wheel traffic causes some level of compaction at every contact point between the soil and the tracks or tires (Raper and Kirby, 2006). Pressure from the contact point of tire and soil usually range from about 50 kPa (under tracks and dual tires), to 300 kPa or more (mostly narrow tires under heavy machinery like a cotton picker) (Kirby and Blunden, 1992). To reduce the effects of field traffic, equipment manufacturers have developed dual tires, tracks and extremely wide tires to displace ground pressure over a larger area. As the weight of the machine increases, tire width and or number of axles should increase, which in turn will increase contact area minimizing subsoil compaction (Håkansson and Reeder, 1994). Isolines of stress beneath a tire or track extend into the depths of the soil that is proportionate to the width of the tire or track (Raper and Kirby, 2006). Trafficking must be controlled to allow the crop to reap the full benefits of sub-soiling (Raper and Kirby, 2006).

The advancement of global positioning systems (GPS) has allowed the practice of controlled trafficking to be done with ease. The ability to continuously and consistently keep crop rows and trafficking lanes separate and in the same location year after year is another way of cutting down on soil compaction in the field. This allows the crop to be planted in the same row year after year without the soil ever being compacted by a piece of machinery

(Raper and Kirby, 2006). GPS guidance systems allow the farm manager to record traffic lanes and set up equipment to follow those trafficking lanes accordingly throughout the season. A study done by Williford, (1980) showed that a controlled traffic system resulted in an increase in crop yield as well as decrease in the need for deep tillage. Treatments with controlled traffic and non-controlled traffic in combination with various forms of subsoiling including one triplex subsoiler, two triplex subsoilers, and one no-till were investigated. Penetrometer readings showed that controlled traffic resulted in minimal compaction in both the double and single triplex subsoilers; whereas soil compaction was observed in the no-till treatment throughout the soil profile. Controlling the traffic in a field has also been shown to increase the soil moisture content throughout the soil profile (Raper et al., 1994). Other factors that go along with controlling traffic are methods such as decreasing axle loads where possible and spreading the load, whether it is over duals, tracks or increasing the number of axles. Research by Voorhees et al. (1986) has shown that axle loads in excess of 10 Mg can penetrate the subsoil causing compaction and a decrease in yield after consecutive years. Spreading out the axle loads over duals, tracks, or more axles could be potential solutions to limiting soil compaction, however, doing this usually changes tire spacing and makes it tougher to control the traffic patterns through the field (Raper and Kirby, 2006). Correlations between pressure on the soil and dual versus single axle equipment have been reported (Raper and Kirby, 2006). Duals reduced soil pressure by up to 50% through a soil profile of 50 cm when compared to a single axle. Rubber tracks replace tires on many tractors used today to increase traction and widen the footprint of rubber to soil contact. Studies show that tracks do not reduce pressure on the soil but actually exert pressures of the same magnitude as rubber tires therefore compacting the soil just as much as rubber tire machines (Raper and Kirby, 2006). Increasing the number of axles under a piece of machinery or an implement that is pulled through the field will indeed spread the load over more axles but actually increases the number of loadings on the soil which in fact can contribute to compaction Raper and Kirby, 2006).

A field that may be rotated between row crops and pasture during the off season may show signs of compaction as well as soil smearing at the soil surface. Because of the light weight of the animals this compaction and smearing is limited to the soil surface. Some farmland may have previously been a wooded area containing large trees that can cause deep compaction due to size as well as the extreme weight swaying back and forth (Raper and Kirby, 2006). Many studies have concluded that compaction from heavy trafficking, animals, and trees can result in yield loss, limited root growth, and erosion or excessive runoff (Raper and Kirby, 2006; Raper et al., 1994; Raper et al., 2000). With advancements in agriculture today, producers have several options to help reduce production challenges related to compaction in given soil conditions using a variety of tillage systems, controlled traffic practices, decreased axle loads, and planting cover crops (Williams and Weil, 2004; Raper and Kirby, 2006).

1.6 Soil Penetration Resistance Measurements

The most common way for scientists to assess soil strength or soil penetration resistance (SPR) is to use a cone penetrometer, which measures the force it takes to insert a cone of a specific size into the soil (Bradford, 1986). The cone penetrometer is a 30° circular stainless steel cone with a driving shaft attached to the base. According to ASAE Standards (1999) the soil cone penetrometer should be pushed into the soil at a uniform rate of approximately 30 mm/s (72 in/min). The surface reading is measured the instant the cone base is flush with the soil surface. Subsequent readings should be made continuously, while maintaining the 30 mm/s (72 in./min) insertion rate. Some apparatuses may have the ability to record both force per unit area (psi) and depth of the cone, supporting the ability to observe relationships between both variables. It has been reported that SPR data taken at random locations for agricultural applications will not provide statistically reliable estimates (Cassel 1982) and variations in SPR data may be highly dependent on tillage practices or traffic patterns through a particular field (ASAE, 1986).

There are many factors that affect SPR of the soil including bulk density, water content and matric potential, aggregation, cementation and soil type (Vaz and Hopmans, 2001). The two most influential factors that affect soil SPR are bulk density and water content at the time of sampling. SPR varies directly in function of bulk density and inversely in function of soil water content. Although wet soils are weaker, extremely wet soils technically do not compact. By definition, compaction is the densification of the soil through the expulsion of air, and therefore, by definition, a saturated soil cannot compact, it flows more like a fluid. SPR samples should be taken when the soil water content is at or below field capacity. Every effort should be taken to ensure that significant water content changes do not take place while multiple samples are being obtained to ensure accurate SPR levels are recorded (Ekwue and Stone, 1995).

1.7 Cover Crops

Deep tillage or subsoiling tends to be expensive, energy intensive and the effects can be considered short-lived (Williams and Weil, 2004). Adopting tillage methods in a no-till farming operation could potentially cause the soil to lose all developed soil health such as organic matter along with soil structure. Planting cover crops during the off season can increase soil health by incorporating nutrients back into the land, decreasing erosion and runoff, maintaining soil moisture from the biomass on the soil surface, and ultimately improving soil – plant interactions (Blanco-Canqui, et al, 2012; Raper et al., 2009; Williams and Weil, 2004). The biomass that is left over from cover crops will not only replenish nutrients and retain water, but also has the ability to act as a weed suppressant (Boquet et al., 2004). Cover crops are especially important for cotton since cotton has such little ground coverage/biomass after harvest, and a high percent of cotton acreage is composed of sandy soils that are susceptible to erosion (Boquet et al, 2004). There are many different factors that determine if a cover crop will be beneficial for the cash crop, including amount of water available, species of the cover crop, planting date of the cover crop, amount of biomass returned to the soil, type of tillage system used, and cover crop management (Blanco-Canqui et al., 2012). There has been some research conducted on the effects cover crops (e.g. Raper et al., (2009) , Bauer et al., (1995), Boquet et al., (2004)) have on cotton yield and soil health, however; there has been very little research done on the alleviation of soil compaction from cover crops. Williams and Weil (2004) studied the channels left behind by cover crops and how they effected the compaction of the soil on a soybean crop. Similar to the research conducted by Raper et al. (1994) soil core samples were taken to measure bulk density as well as soil water content. The four cover crops used in the study were canola, oilseed radish, forage radish, and cereal rye. The radishes have a large taproot that grows vertically through the soil profile and in theory provides channels in the soil for subsequent crops to root into (Williams and Weil, 2004); they were able to capture this phenomenon through minirhizotron images. The type of soil, level of compaction and availability of water also plays a factor in the effectiveness of a given cover. Williams and Weil (2004) found that a drier more compacted soil gained more benefit from a forage radish and its bulky long tap root while a soil that had the most water available resulted in higher yields from no-till planting into rye. It has been stated that cover crops planted in the winter are able to break through the hard pan because of the normally high soil moisture during that time, limiting soil compaction (Raper et al., 2000). Cover crops can be highly advantageous when used during the winter months of a cotton crop in terms of soil nutrient value as well as reduction in erosion. With further studies cover crops could potentially allow farmers to reduce tillage practices as a result of cover deep root development that may break up the soil hardpan (Boquet et al., 2004).

1.8 Objectives

As farm equipment changes, the need to produce high crop yields increases, and management practices become more intense requiring greater awareness of sustainability, , compaction may become a greater issue for farmers across the southeast. There is a need to quantify the effects equipment and cover crops can have on soil compaction and health in cotton production. The consequences of using larger machinery that operate on cotton farms today is unknown. While compaction presents challenges that can be addressed by tillage equipment, identifying methods to minimize compaction and reduce field operations that may be more sustainable is significant. The objectives of this research project were to:

1) Investigate the effects that the new John Deere 7760 Round Bale cotton harvester and the new Case IH Module Express cotton harvester have on soil compaction compared to the conventional basket harvesters that weigh nearly half that of the new models;

2) Evaluate the use of a mixed variety cover crop in cotton during the winter months to assist in alleviating existing compaction and improving soil nutrients; and

3) Establish a relationship between soil moisture content and mechanical penetrometer readings using soil matrices from farms across southeastern North Carolina in controlled lab experiments. Soil moisture is a major factor when measuring soil penetration resistance (SPR). With a well-known inverse relationship and no universal equation to adjust SPR readings, it is important to better understand how the soil moisture is affecting the recorded SPR readings.

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CHAPTER 2
Impact of Mechanized Harvesting Operations on Soil Compaction for North Carolina Cotton Farms

2.1 Introduction

Soil compaction and its consequences are well known throughout the agricultural community (Ekwue and Stone, 1995) and subsoil compaction has become a growing concern due to the drastic increase in agricultural machinery use and size (Horn et al., 2000). Cotton harvesters have evolved from a one row harvester that mounted onto a small low horsepower tractor to a single machine costing more than half of a million dollars that harvests cotton and packages it for delivery to the gin without having to stop (Deere, 2012). The technology has made farming much easier for farmers but it is unknown if these machines are affecting the soil in which the crops are grown. Both John Deere and Case IH have developed these onboard cotton module harvesters. With these new integrated features these machines have doubled the weight of the conventional basket harvester (Deere, 2012). With the excess weight, subsoil compaction has become a concern for many farmers and researchers (Horn et al., 2000).

The most common way for scientists to assess soil strength or soil penetration resistance (SPR) is to use a cone penetrometer, which measures the force it takes to insert a cone of a specific size into the soil (Bradford, 1986). A resistance of 2 MPa (~290 psi) has been reported as a measure of soil compaction that is limiting to root growth (Hazma and Anderson, 2005). Cotton grows best in well drained soils that do not hold an immense amount of water. Alluvial soils as well as sand loams are very good soil types for producing cotton (Boquet et al., 2004), unfortunately these soils are also very susceptible to compaction. Cotton producers in the southeast US have used various methods of tillage for years to assist in breaking up hard pans or concentrated areas of compaction (Schafer et al., 1991). A cotton tap root has the ability to grow up to 36 inches when looking for water and nutrients. In the southeast US the average tap root only reaches about 20 inches. This can be attributed to a number of different factors from compaction to aluminum toxicity to a raised water table. It is important to understand the impact root limiting compaction can add to soils that already have these problems of shallow rooting depths (Hazma and Anderson, 2005).

Braunack and Johnson (2013) looked at the changes in soil resistance due to cotton picker traffic during harvest operations on Australian cotton soils. Their research showed an increase in soil strength after picker traffic compared to before picker traffic down to 0.5 m in the soil profile. They also showed soil strength differences to be greater closer to the soil surface and increases with the heavier machine. The Braunack and Johnson (2013) study was able to make initial assessments of the John Deere 7760 Harvester on soil strength; however, to date a study does not exist that evaluates effects of the two available on-board cotton module harvesters on soil compaction during US cotton production. The objectives of this study were to quantify compaction levels resulting from conventional basket pickers and increased harvester equipment size, using the Case IH 625 and John Deere 7760, in the Coastal Plain region of North Carolina (southeast US)..

2.2 Materials and Methods

2.2.1 Site Characteristics and Management

This study was carried out on three different cooperative producers' fields in 2013/2014. The first was located on a Hoke County, NC farm (34°58'N, 79°15'W) which had a Norfolk loamy sand soil. This farm operated the new John Deere 7760 Round Bale harvester. A typical Norfolk loamy sand soil is a well-drained soil that has four horizons, an A, E, Bt and C. From 0 to 14 inches this soil is a loamy sand and below 14 inches it becomes a sandy clay loam. This soil has an average storage capacity of about 7.6 inches of water and low erosion susceptibility (NRCS, 2014). The second farm located in Halifax, NC (36°17'N, 77°40'W) had a Goldsboro sandy loam soil and operated the traditional basket style harvester. A typical Goldsboro sandy loam soil is a well-drained soil that has four horizons, an Ap, E, Bt and Btg. From 0 to 15 inches this soil is a sandy loam and below 15 inches it becomes a sandy clay loam. This soil has an average storage capacity of about 8 inches of water and low erosion susceptibility (NRCS, 2014). The third farm located in Sampson County, NC (35°12'N, 78°15'W) had a Rains sandy loam soil and operated the new Case IH

Module Express harvester. A typical Rains sandy loam soil is a poorly-drained soil that has five horizons an Ap, Eg, Btg1, Btg2 and Cg. From 0 to 12 inches this soil is a fine sandy loam, from 12 to 20 inches it is a sandy loam and below 20 inches it becomes a sandy clay loam. This soil has an average storage capacity of about 9.4 inches of water and is in a high Runoff class (NRCS, 2014).

Each of the farms has been in commercial agricultural production for the past 15 + years in rotation. The various crops previously grown consisted of cotton (*Gossypium hirsutum* L.), peanuts (*Arachis hypogaea*), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.) and soybeans (*Glycine max* L.).

The three farms, soil types, harvester equipment used and soil moisture contents before (1) and after (2) harvest are presented in Table 1. Each of the three farms operated three different harvesters, the John Deere 7760 Round Baler (69,660 lbs), the Case IH Module Express 625 (51,000 lbs) and the John Deere conventional basket harvester (36,300 lbs). Within each farm were 3 sampling plots that were identified based on soil type and geographic location in the field. The 6 rows the harvester would travel during harvest were determined at each of the 3 plots and marked using GPS. The initial 6 rows in each plot were designated to the experiment and used for initial (before harvest) as well as final (after harvest) sampling. Each plot generated 65 sampling positions, where the cone penetrometer samples were taken and a cone index (CI) was measured simultaneously, once every second, down to a depth of 18 inches. The soil penetrometer resistance (SPR) readings were analyzed in increments of 3inches (e.g. 0-3; 3-6; 6-9…) down to 18 inches, giving 6 depth measurements per sampling position. Sampling locations or SPR measurement positions were set up on a 13 x 5 sampling grid across the plot with 13 samples perpendicular to the cotton rows starting in a non-trafficked middle and ending in a non-trafficked middle and covering the entire 6 furrows and 7 middles with 5 positions along the row length. Once the 13 SPR measurements were taken across the 6 rows and 7 middles, while remaining on those same 6 rows the penetrometer was moved 10 meters down row and the 13 SPR measurements were repeated 4 more times giving the 13 x 5 sampling grid and 65 SPR measurement positions within each plot.

Table 2.1. Description of sites, soil types, machinery used and moisture content measured. Numbers following the site location represent before harvest (1) and after harvest (2) values.

Site	Soil Type	Machine	Average Moisture Content (%)
Halifax (1)	Goldsboro sandy loam	Basket (dual tires)	10.85
Halifax(2)			11.51
Hoke (1)	Norfolk loamy sand	JD Round Baler (dual tires)	9.05
Hoke (2)			8.65
Sampson (1)	Rains sandy loam	Case IH Module Express (dual tires)	11.3
Sampson (2)			13.3

These soil cone penetrometer readings were measured at two points in time; before and after picker traffic to ensure minimal change in profile soil moisture. The time between before and after sampling did not exceed a period of one week. Differences in sample time were tied to scheduling with the cooperators and could not be avoided. Effects of the harvesters on the soil profile strength were the primary focus of this experiment and all other field traffic prior to harvest was neglected.

2.2.2 Soil Cone Penetrometer Settings

The penetrometer consisted of a 24" linear actuator, an Omegadyne Inc. 1000 lb. load cell and a ¼" steel rod 20" long that screws into the load cell and has a steel 30° cone with a diameter of 0.5 inches (ASAE, 1999) attached to the bottom. These components work together by activating the electric drive linear actuator, forcing the cone and shaft into the soil at a rate of 1 inch per second. A potentiometer measures the distance that the shaft and cone travel by sending electronic signals to the same data acquisition card, once every second, which is then relayed to a LabView program that displays both the force per unit area (psi) and the distance traveled by the cone and shaft (in.). The program displays subsequent readings of both the force and the distance, or depth, once every second.

This system was mounted onto the backside of a common heavy duty hand truck taking advantage of the upright frame of the hand truck for easy mounting and maneuverability. Two garden tractor batteries were used to power the linear actuator, tablet, data acquisition card as well as a Trimble 372 GPS receiver that was used to record the location of each observation. Everything on the hand truck was then mounted onto the center of a common garden wagon for easier maneuverability, stability as well as an increased ability to add more down pressure. A ¾ inch steel plate was made to fit into the bottom of the wagon for extra weight and a solid surface to mount the hand truck securely. A 1 inch hole was drilled into the steel plate for the penetrometer cone and rod to travel through. The garden wagon was the best option for initial sampling because the cotton crop was still in the field and the initial sample was taken prior to harvest. The garden wagon fit between rows when traveling up and down rows to limit damage to the crop. Once the cotton was harvested the utilization of a small all-terrain vehicle (ATV) to mount the penetrometer made travel through the fields much more efficient. The hand truck with all components intact from the garden wagon was mounted onto the ATV. This ensured all components, other than the vehicle the instrument was mounted to, were identical in each sampling event. The hand truck was mounted on the driver side of the ATV to allow the operator of the ATV to operate the penetrometer simultaneously. The ATV provided adequate weight to ensure that the penetrometer entered the soil at a uniform rate. The GPS receiver was also mounted onto the ATV to again record each sampling location back to the tablet. Both the ATV penetrometer set up and the wagon set up were used to take SPR readings under identical conditions to determine whether differences in readings could be attributed to the vehicle the penetrometer was mounted to. The differences between readings from the wagon and readings from the ATV were minimal and treated as negligible differences (Figure 2.1).

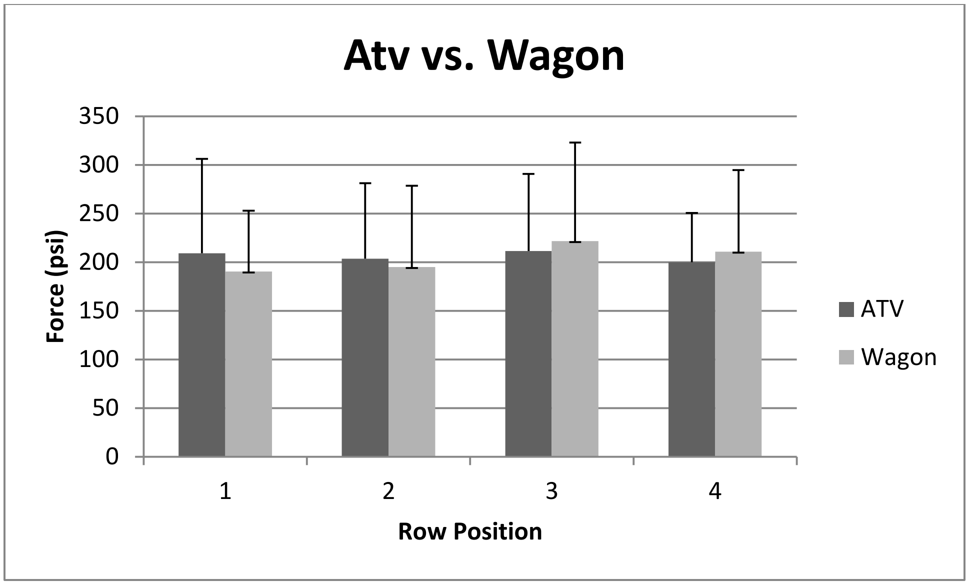

Figure 2.1 Force per unit area averages from both the garden wagon and ATV mounts.

2.2.3 Soil Nutrient and Moisture Content

Soil cores were pulled from each of the three plots in each field down to a depth of 6 inches using a 1 inch diameter probe. Core samples were taken during each penetrometer sampling event. Three cores were taken in each plot totaling 9 soil cores per farm. The core locations were chosen within the plot that would give the best representation of that plot. Each core was boxed and labeled to make sure there was no cross contamination between samples. The samples were oven dried at 45.5°C for 24 hours. Once the samples were completely dry they were ground in a soil grinder (Model Number, 5DPJ3, Humboldt Mfg.) prior to nutrient analysis. Soil nutrients measured were available Nitrogen, % Organic Matter, Sulfur, Phosphorus, Potassium and heavy metals. This analysis was completed using standard procedures in the NCDA&CS Soil Analysis Laboratories.

To determine moisture content of the soil at the time of SPR readings 1” diameter soil cores were taken down to an 18” depth. Five cores were pulled per plot that represented the moisture content of each of the 13 SPR readings. These cores were combined and weighed immediately to ensure minimal moisture loss due to evaporation and oven dried in a 45.5°C oven for 24 hours. Once the cores had been completely dried they were weighed again to record an oven dried weight and finally determined the percent moisture present in the soil at the time of SPR readings by using both the wet basis and dry basis moisture content equation, where W_w (g) is the wet weight of the soil and W_d (g) is the oven dried weight of the soil.

$$\%Moisture\ Content_{wet\ basis} = \frac{W_w - W_d}{W_w} \times 100$$

$$\%Moisture\ Content_{dry\ basis} = \frac{W_w - W_d}{W_d} \times 100$$

2.2.4 Statistical Analysis

The main and interaction effects of position on trafficked rows and non-trafficked rows, soil depth of measurement readings, time of measurement (before and after the harvester made a pass) and plot on SPR values were analyzed for each harvester type nested in site/location using PROC GLM in SAS (Version 9.3, Cary, NC). Measurements taken along a row length within a given plot for a specific row position were treated as replicates of SPR readings. Statistical comparisons of data values were determined using least square means and Tukey-Kramer Comparison tests. In addition to the penetrometer data, confidence intervals for the soil moisture from each soil type/site were compared to assess statistical significance.

2.3 Results and Discussion

Although this study only considered one picking season, the conditions were typical of those that are normally experienced during harvest as it relates to soil moisture content and the feasibility of using a mechanized harvester. Soil moisture ranged from 8-17% on a dry basis (8-14% wet-basis) across all farm sites and soil types. And within a specific farm moisture content measurements were within 5% of each other on a dry-basis, supporting more reliable penetrometer data. The three different farm sites represented three different soil type classifications and employed three different mechanized harvesters which varied by weight and in the case of the basket harvester, by overall function. Soil resistance data was not only affected by the variations in soil strength by type, but possibly the interaction with weights of the harvesters. As such, interpretation of the data was limited to differences observed within farm and overall comparisons of the three farm scenarios.

Five different locations along row length were averaged within both trafficked and non-trafficked rows within each plot to determine the effects each harvester may have had on row position. The trafficked and non-trafficked rows were identified based on harvester set up. On all three farms, at all locations within each farm the harvesters were 6 row harvesters and were equipped with dual tires in the front and a set of single tires in the rear. The trafficked rows were any row that was traveled over by a tire of the harvester, where for all three farms there were four trafficked rows per location. All trafficked and non-trafficked rows were analyzed statistically at each location within each farm to identify differences between the two for SPR measurements taken before and after the passing of the harvester.

For the Halifax County farm using the conventional basket harvester, the interaction of depth, location (plot), trafficked/non-trafficked and before/after harvest was statistically significant (p-value <0.001). Although the 3 plot locations on the farm showed enough variability that they were considered different, the trends in the data observed were very similar. The data from the conventional basket harvester used at the Halifax County farm at plot location 3 is presented in Table 2.2 and is a representation of the data observed in each plot for this farm. Analysis of the SPR values before and after for the different depth ranges showed a statistically significant increase in resistance with increases in depth. This was expected due to the change in soil texture as well as soil structure as depth increases. Hard pans or plow pans are developed over years of working the soil leading to subsoil compaction and are commonly found in loamy sands as well as sandy loams similar to the soils used for this study (Raper et al., 1994).

The SPR results found before and after harvest in trafficked and non-trafficked rows at each depth showed a decrease in resistance after the harvester passed. These results were not consistent with previous research conducted in Australia, where statistically significant increases in the compaction measurements were found as a result of a John Deere harvester.

Table 2.2 Soil penetration resistance (SPR) data averaged across samples taken along the row length for the conventional basket harvester at the Halifax County farm. SPR values shown are LS Means for each depth level down to 18 inches in 3 inch increments as interactions with trafficked and non-trafficked rows before and after harvest. The change in SPR value after harvest is also shown

					Harvester Type	**Depth**	**Before After**	**Trafficked**	**Force__psi_ LSMEAN**	**Change in SPR**
A					Basket	0 - 3"	Before	Yes	21.8958	-4.193
A					Basket	0 - 3"	After	Yes	17.7028	
A					Basket	0 - 3"	Before	No	17.5145	-6.1486
A					Basket	0 - 3"	After	No	11.3659	
A	B				Basket	3 -6"	Before	Yes	62.4244	-10.5691
A					Basket	3 - 6"	After	Yes	51.8553	
A					Basket	3 -6"	Before	No	47.5466	-15.9148
A					Basket	3 - 6"	After	No	31.6318	
		C			Basket	6 - 9"	Before	Yes	117.453	-22.9214
A		C			Basket	6 - 9"	After	Yes	94.5316	
A	B	C			Basket	6 - 9"	Before	No	83.5723	-22.0049
A					Basket	6 - 9"	After	No	61.5674	
	B	C			Basket	9 - 12"	Before	Yes	142.156	-9.792
	B	C			Basket	9 - 12"	After	Yes	132.364	
	B				Basket	9 - 12"	Before	No	132.47	-24.673
		C	D		Basket	9 - 12"	After	No	107.797	
A			D		Basket	12 - 15"	Before	Yes	200.11	-30.477
A	B		D		Basket	12 - 15"	After	Yes	169.633	
A	B	C	D		Basket	12 - 15"	Before	No	189.005	-28.001
				E	Basket	12 - 15"	After	No	161.004	
A				E	Basket	15 - 18"	Before	Yes	198.658	-63.208
	B			E	Basket	15 - 18"	After	Yes	135.45	
		C		E	Basket	15 - 18"	Before	No	155.875	18.549
A		C		E	Basket	15 - 18"	After	No	174.424	

Rows with different letters were statistically different as indicated by the letters A, B, C, D, and E (p-value < 0.05). Rows with similar letters were statistically similar.

The decrease in SPR value after the harvester that we observed was not expected and this statistically significant decrease in LS Means resistance values after the harvest was observed at nearly every sampling location. The change in force seemed to decrease with increase in depth, where the harvester had less effect on the SPR measurements from 12to 18”. The decrease in SPR values can be attributed to the time span between the before and after sample collection. Although the moisture content between the before and after samples was not statistically significant (p-value > 0.05), there were 12 days in between the sampling dates. This lapse in time likely allowed the soil time to transform its structure and distribute the forces from the harvester such that the data observed for this basket harvester indicated no negative effects on the soil. This finding was similar in plots at other locations as the lapse in time between sampling dates was as much as 14 days.

Table 2.3 shows the results from the Sampson County farm where the Case IH Module Express harvester was used. This table depicts data recorded from location (plot) 2 as a representation of the SPR data trends observed for all plots on the farm. Similar to the Halifax farm the interaction of depth, location (plot), trafficked/non-trafficked and before/after harvest was statistically significant (p-value <0.0001). The increase in average SPR values as depth increased were statistically significant. For the first 0-3” of soil depth the change in SPR increased and values were statistically higher as expected for both trafficked and non-trafficked rows as a result of the Case IH module builder. However the SPR values at depths beyond 3” decreased after the harvest for the majority of the depths and were statistically different (p-value < 0.05), similar to what was observed at the Halifax farm. The differences in the trafficked versus the non-trafficked rows proved to be statistically significant as well for a majority of the depths. The top three inches of soil varies extremely in structure and composition in that the soil may be very loose and easily shifted. The compaction observed here as indicated by the increase in SPR readings may be a result of the machine however, these results would be expected at depths up to 6” as well. In addition the results in the 0-3” depths were not consistent for the different plots on the farm, so the influence of the Case IH on compaction was inconclusive.

Table 2.3 Soil penetration resistance (SPR) data averaged across samples taken along the row length for the conventional basket harvester at the Sampson County farm. SPR values shown are LS Means for each depth level down to 18 inches in 3 inch increments as interactions with trafficked and non-trafficked rows before and after harvest. The change in SPR value after harvest is also shown.

					Harvester Type	**Depth**	**Before After**	**Trafficked**	**Force__psi_ LSMEAN**	**Change in SPR**
A	B				Case IH	0 - 3"	Before	Yes	24.7592	8.5531
A	B				Case IH	0 - 3"	After	Yes	33.3123	
A					Case IH	0 - 3"	Before	No	22.2916	12.2892
A	B				Case IH	0 - 3"	After	No	34.5808	
A		C			Case IH	3 -6"	Before	Yes	122.4668	-47.5062
A	B	C			Case IH	3 - 6"	After	Yes	74.9606	
		C			Case IH	3 -6"	Before	No	104.511	-23.76
A	B	C	D		Case IH	3 - 6"	After	No	80.751	
		C			Case IH	6 - 9"	Before	Yes	207.1253	-115.8757
A		C			Case IH	6 - 9"	After	Yes	91.2496	
			D		Case IH	6 - 9"	Before	No	184.3958	-87.4513
		C	D		Case IH	6 - 9"	After	No	96.9445	
	B		D		Case IH	9 - 12"	Before	Yes	216.1884	-127.4562
A	B		D	E	Case IH	9 - 12"	After	Yes	88.7322	
	B		D		Case IH	9 - 12"	Before	No	174.1	-85.9591
	B		D	E	Case IH	9 - 12"	After	No	88.1409	
A				E	Case IH	12 - 15"	Before	Yes	160.4521	-60.5113
	B			E	Case IH	12 - 15"	After	Yes	99.9408	
		C	D	E	Case IH	12 - 15"	Before	No	138.028	-48.3689
	B	C		E	Case IH	12 - 15"	After	No	89.6591	
A			D	E	Case IH	15 - 18"	Before	Yes	130.696	-23.4516
	B		D	E	Case IH	15 - 18"	After	Yes	107.2444	
A	B	C	D	E	Case IH	15 - 18"	Before	No	126.8036	-30.45
			D	E	Case IH	15 - 18"	After	No	96.3536	

Rows with different letters were statistically different as indicated by the letters A, B, C, D, and E (p-value < 0.05). Rows with similar letters were statistically similar.

It has been reported that soil moisture can influence soil penetrometer readings ((Ayers and Perumpral, 1982) see also chapter 4)). Depending on the soil type, differences in moisture can increase or decrease soil penetration resistance values observed. The moisture differences between the before and after harvest measurements within a given plot were not consistent. The Sampson County farm (Table 2.3) had a statistically significant increase in soil moisture from before harvest to after harvest. The magnitude of the change in SPR values measured as a result of a specific moisture content cannot be accurately quantified and varies with soil characteristics. This made it difficult to evaluate the SPR measurements and the true effect of the harvester. It may be that the moisture can have a greater effect on soil resistance than the harvester treatment, Since accounting for moisture in a manner that is easily quantifiable was not feasible, soil moisture was not considered a specific factor in the analysis but likely contributed to many of the differences observed (e.g decrease in SPR values after harvest).

The data for location (plot) 1 on the Hoke County farm where the John Deere round baler harvester was used is shown in Table 2.4 as a representation of the three different plots measured on farm. The interaction of depth, location (plot), trafficked/non-trafficked and before/after harvest was statistically significant on this farm as well (p-value <0.0001). The changes in average SPR values for each depth were statistically significant from one depth level to the next, where values increased with increase in depth. This soil showed greater compaction in comparison to the other farm sites based on the SPR values observed with a majority ranging from 200 to 300 psi. Again the increase in compaction with depth was an expected outcome based on the structure of the soil profile. The majority of the comparisons between the before and after SPR data were statistically significant, where the average SPR values decreased after the harvest for all depths except the 9 – 12” depth. This was not consistent in all locations (plots) on the farm. Both locations (plots) 2 and 3 showed a statistically significant decrease in the SPR values at these depths. In addition, the differences between SPR values before and after harvest were also statistically significant within trafficked and non-trafficked rows , where SPR values decreased for both row positions and resulted in no consistent pattern that would lead us to believe the trafficked rows

Table 2.4 Soil penetration resistance (SPR) data averaged across samples taken along the row length for the conventional basket harvester at the Hoke County farm. SPR values shown are LS Means for each depth level down to 18 inches in 3 inch increments as interactions with trafficked and non-trafficked rows before and after harvest. The change in SPR value after harvest is also shown.

					Harvester Type	**Depth**	**Before After**	**Trafficked**	**Force__psi_ LSMEAN**	**Change in SPR**
A	B	C			John Deere	0 - 3"	Before	Yes	50.6008	-3.0113
A	B				John Deere	0 - 3"	After	Yes	47.5895	
A					John Deere	0 - 3"	Before	No	42.276	-4.5022
A					John Deere	0 - 3"	After	No	37.7738	
A		C			John Deere	3 -6"	Before	Yes	234.1419	-64.9602
		C			John Deere	3 - 6"	After	Yes	169.1817	
	B	C			John Deere	3 -6"	Before	No	177.2622	-50.4619
			D		John Deere	3 - 6"	After	No	126.8003	
A			D		John Deere	6 - 9"	Before	Yes	319.4773	-39.9428
	B		D		John Deere	6 - 9"	After	Yes	279.5345	
		C	D		John Deere	6 - 9"	Before	No	240.7004	-36.1763
A	B		D		John Deere	6 - 9"	After	No	204.5241	
A		C	D		John Deere	9 - 12"	Before	Yes	285.7612	9.9254
A	B	C	D		John Deere	9 - 12"	After	Yes	295.6866	
		C	D		John Deere	9 - 12"	Before	No	236.8983	12.1971
A				E	John Deere	9 - 12"	After	No	249.0954	
			D	E	John Deere	12 - 15"	Before	Yes	227.8944	-10.2016
				E	John Deere	12 - 15"	After	Yes	217.6928	
		C	D	E	John Deere	12 - 15"	Before	No	226.1081	-32.8192
	B		D	E	John Deere	12 - 15"	After	No	193.2889	
	B			E	John Deere	15 - 18"	Before	Yes	218.6264	-50.289
A		C		E	John Deere	15 - 18"	After	Yes	168.3374	
A			D	E	John Deere	15 - 18"	Before	No	193.8765	-28.83
A	B	C	D	E	John Deere	15 - 18"	After	No	165.0465	

Rows with different letters were statistically different as indicated by the letters A, B, C, D, and E (p-value < 0.05). Rows with similar letters were statistically similar.

had a negative effect on the soil regardless of depth. The change in soil moisture was not significant on this farm; however there was a time lapse of about 10 days between samples. Similar to the other farms, this 10 day time period in addition to the slight change in soil moisture may have created enough difference in the soil structure that decreases in soil resistance were mostly observed across this farm.

Overall the decreases in soil penetration resistance measured after harvest for trafficked and non-trafficked rows for the different depths and locations were most likely heavily influenced by changes in soil moisture content and weather events in between sampling dates, where many have indicated that soil moisture has an inverse effect on soil strength (Ayers and Perumpral, 1982). The hypothesis that the new, much heavier harvesters that complete multiple operations in the field would have a large impact on soil penetration resistance was not demonstrated based on the results shown and the extent of data collected. Individual SPR values upwards of 350 psi (2.4 MPa) were observed on each of the three farms suggesting root limiting compaction was present both before and after harvest operations occurred within the 18" depth of interest. Resistance levels greater than 290 psi (2 MPa) are considered limiting to cotton root growth (Hamza and Anderson, 2005). Kulkarni et al. (2010) indicated that cotton growth can be affected by resistance as low as 233 psi (1.6 MPa); however, no yield loss was recorded at these SPR levels. The higher SPR values observed before harvest would suggest existing field compaction in those plots, potentially caused by previous field traffic or naturally occurring hardpans. The Australian study by Braunack and Johnston (2014) that looked at SPR readings before and after one single pass of the John Deere 7760 picker found increased compaction after harvest; however, differences in soil types may have contributed to the dissimilar results observed in this current study. Although it is claimed that Vertisol soils, like those in the Australian study, may be self-repairing due to the shrink-swell behavior, it may take up to 11 wet-dry cycles to repair structural degradation. In that case, clots of compressed soil may still remain between large cracks throughout the profile and especially in subsoil from over loading where immediate compaction effects can be observed (Sarmah et al., 1996). The clayey soils present in their study were much more susceptible to immediate compaction than the more coarse, sandier soils chosen for this work (Braunack and Johnston, 2014; Raper and Kirby, 2006). Larger plot sizes where the John Deere 7760 and Case IH 625 would have accumulated greater amounts of cotton material and produced multiple bales (up to 10,000 lb capacity) may have shown a greater soil compaction impact. Acquiring before and after SPR measurements using the cone penetrometer in the same day would have minimized variation in the soils as dynamic experimental units as it relates to structure and moisture interactions, possibly supporting more conclusive results on the effects of these harvesters on compaction.

2.4 Conclusions

Soil penetration resistance was statistically unaffected by one pass of the cotton harvesters suggesting that the machines regardless of type or weight did not cause harmful levels of compaction on these soil types in the Coastal Plains of North Carolina, with no significant increase in SPR values from before harvest to after harvest. Soil moisture seemed to affect the readings to a certain degree, however, no adjustment could be made to the force readings based on the soil moisture content. Further experiments over multiple years in the same field will be required to fully quantify the effects these new harvesters have on the soil strength as well as field maintenance leading up to harvest to prepare the soil for the extreme forces applied by these large machines long term.

Future management practices focusing on reducing compaction could start at controlling field traffic (Hulme et al. 1996). Controlling field traffic begins with designating rows in a field for equipment to travel on repeatedly to limit traffic on multiple rows. Being aware of field soil moisture and limiting field operations to only when the field has dried enough to support a machine will eliminate further and more severe compaction and fluidic movement and dispersion of the soils. Utilizing cover crops or rotating cash crops will allow the field to experience different covers, as well as rooting systems that could potentially help in compaction alleviation, minimizing potential long term effects of larger module harvesters.

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CHAPTER 3
Influence of Multi-Species Cover Crops on Soil Health Improvement for North Carolina Soils in Cotton Production

3.1 Introduction

Cotton production involves relatively intense management practices, to maintain nutrients, manage weeds (e.g. palmer amaranth, native broadleaf, native grasses) and address insects. As a result production of cotton requires many passes through the field to apply chemicals, fertilizers, and to harvest the crop. Cotton tap-roots have the ability to penetrate deep within the soil in search for moisture and nutrients requiring attention to compaction issues as it relates to soil health. With the new larger machinery used to produce cotton, soil compaction issues contributing to losses in yield are becoming a greater concern (Horn et al., 2000). In addition, cotton fields in the southeast US are especially prone to severe erosion as a result of the sandy, loamy soil types used for production, the low quantities of cotton residue remaining after harvest to serve as overwintering ground cover and the considerable winter rainfall levels. Interest in alleviating some of these production challenges has moved from fuel consuming tillage methods to the use of a cover crop that has multiple benefits.

Planting cover crops during the off season can increase soil health by incorporating nutrients back into the land, decreasing erosion and runoff, helping maintain soil moisture and ultimately improving the soil – crop relationship (Blanco-Canqui et al., 2012;. Raper et al., 2009; Williams and Weil, 2004). The biomass that is left over from a cover crop will not only replenish nutrients and retain water, but also has the ability to act as a weed suppressant (Boquet, Hutchinson, and Breitenbeck, 2004). Important factors that must be taken into consideration when determining the benefit of a cover crop include amount of water available, planting date of the cover crop, species of the cover crop, amount of biomass produced and termination date and method (Blanco-Canqui et al., 2012). Nitrogen fixing cover crops like hairy vetch, winter pea and crimson clover utilize atmospheric nitrogen and transform it into a form of nitrogen that can be taken up by plants. These cover crops grow quickly and break down quickly making the nitrogen available to the next crop that is planted. These cover crops have the potential to provide enough nitrogen to the main crop to allow the farmer to reduce fertilizer rates which could reduce overall production costs

(Boquet et al., 2004). Popular cover crop varieties planted in the southeast usually include a deep rooting grass such as rye oats or wheat, nitrogen fixating legumes such as crimson clover, vetch, or winter pea and/or tillage radishes, which have become more popular in helping break up existing hardpans or areas of compaction with the large tap roots (Surrency, 2000). A cover crop containing a mixture of these common varieties would have the potential to accomplish the entire spectrum of benefits from fixing nitrogen to establishing deep roots that disturb hardpans or areas of compaction. The objectives of this work were to investigate the advantages of using a multi-species cover in a cotton rotation to improve soil health as well as assist in compaction alleviation.

3.2 Materials and Methods

3.2.1 Site Characteristics and Management

This study was carried out on four different cooperative producers' fields in the Coastal Plains of North Carolina. The first was located on a Halifax County farm in the city of Halifax, NC (36°6'N, 77°24'W) that had a Goldsboro sandy loam soil. A typical Goldsboro sandy loam soil is a well-drained soil that has four horizons, an Ap, E, Bt and Btg. From 0 to 15 inches the soil is a sandy loam and below 15 inches it becomes a sandy clay loam. This soil has an average storage capacity of about 8 inches of water and is in a low Runoff class (NRCS, 2014). The second farm was also in Halifax County in the city of Scotland Neck, NC (36°17'N, 77°40'W) and had a Noboko fine sandy loam soil. A typical Noboko loamy sand soil is a well-drained soil that has three horizons, an Ap, E and Bt. The soil from 0 to 13 inches is a loamy sand and below 13 inches becomes a sandy clay loam. This soil has an average storage capacity of about 7.1 inches of water and is in a low Runoff class (NRCS, 2014). The third farm located in Sampson County, NC (35°7'N, 78°24'W) was a Norfolk sandy loam and the final farm was in Pitt County, NC (35°39'N, 77°14'W) which contained two different soil types an Ocilla loamy fine sand as well as a Goldsboro sandy loam. A typical Ocilla loamy fine sand is a somewhat poorly-drained soil that has six horizons, an Ap, E1, E2, Bt1, Bt2 and Bt3. From 0 to 28 inches this soil is a fine loamy sand

and below 28 inches it becomes a sandy clay loam. This soil has an average storage capacity of about 7.1 inches of water and is in a high Runoff class (NRCS, 2014).

Each of the farms has been in commercial agricultural production for the past 15 + years in rotation. The various crops previously grown consisted of cotton (*Gossypium hirsutum* L.), peanuts (Arachis hypogaea), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.) and soybeans (*Glycine max* L.). The four farms have practiced different tillage methods throughout the years. The farm located in Scotland Neck has been practicing conservation tillage for the past 8 to 10 years, operating a strip-till planter, enabling them to disrupt any hard pans with the deep ripper while minimizing surface tillage. The strip-till method was continued through the cover crop study. The Pitt County farm has been in no-till for the past 10 years, having no tillage to disrupt any hard pans, and this no-till practice was continued through this study. The farm located in Clinton has been in conventional tillage where the soil was completely disrupted and all surface residues were turned under. In this completion year the acreage was strip-tilled into the cover crop. The farm in the city of Halifax was the only farm that has been rotated with peanuts and therefore was disked under just before peanut planting; however, when other crops were grown on this farm strip tillage was the method used during planting.

Plots laid out on each farm were planted with a mixed species of cover crop following the 2013 harvest. The cover mixture included Daikon Radish (5 lbs/acre; 5.6 kg/ha), Dixie Crimson Clover (5 lbs/acre; 5.6 kg/ha), Wrens Abruzzi Rye (20 lbs/acre; 22.42 kg/ha), Tri 342 Triticale (20 lbs/acre; 22.42 kg/ha) and Hairy Vetch (15 lbs./acre, 18.13 kg/ha). The covers were planted either by drill or by spinner spreaders depending on the farmers' preference. On each farm there were strips that were left unplanted and fallow for the winter months to test the differences between plots with a cover crop and plots with no cover crop. In all, there were 6 plots per farm, three with cover and three with no cover. Each plot was approximately 50 meters in length and 5 meters wide. Cone penetrometer readings were taken just after the cover crop was planted in early winter and again just after the cover crop had been terminated in late spring. The last sample was taken just before planting so that the soil profile did not change much between sample date and plant date to ensure similar soil conditions to those encountered by the upcoming cotton crop. Penetrometer data were collected at 5 different row positions along the length of each plot. There was little to no management of the cover crop between plant date and termination. The termination of the cover crop on all farms except for the farm in Halifax was completed using an herbicide prior to planting the cash crop however the farmer saw fit. The cover established on the Halifax farm was tilled under in preparation for peanuts, limiting some of the data collection from this location.

3.2.2 Soil Cone Penetrometer Settings

The penetrometer was put together using a 24” linear actuator, an Omegadyne Inc. 1000 lb. load cell and a 20” long ¼” steel rod that screws into the load cell and has a steel 30° cone attached to the bottom. These three components worked together by activating the electric drive linear actuator forcing the cone and shaft into the soil at a rate of 1 inch per second. A potentiometer measured the distance that the shaft and cone traveled by sending electronic signals to the same data acquisition card which was then relayed to a LabView program that displayed both the force per unit area (psi) and the distance traveled by the cone and shaft (depth, inches). The program displayed subsequent readings of the force per unit area and distance every second.

This system was mounted onto the backside of a common heavy duty hand truck due feasibility of the upright frame of the hand truck for easy mounting and maneuverability and attached to a small all-terrain vehicle (ATV) to make travel through the fields much more efficient. This ensured all components, other than the vehicle the instrument was mounted to, were identical in each sampling event. The hand truck was mounted on the driver side of the ATV to allow the operator of the ATV to operate the penetrometer simultaneously. The ATV provided adequate weight to ensure that the penetrometer entered the soil at a uniform rate. A Trimble 372 GPS receiver was also mounted onto the ATV to record each sampling location back to a tablet. Cone index (CI) data or soil penetration resistance (SPR) values were collected at locations that were precisely determined based on the geography of each plot and measurements were set up on a 5 x 5 plot encompassing the entire plot. Five samples were taken with 0.5 meter spacing starting on one side of the strip plot and repeated down the length of the plot every 10 meters. The penetrometer data were recorded using a data acquisition card which saved to a tablet through a LabView program. The LabView program read in the force per unit area and depth data every second until the desired depth was reached. This method was repeated in each plot, both cover and no cover, giving a total of 25 observations within each plot.

3.2.3 Soil Nutrients, Moisture Content and Biomass

Soil cores were pulled from each of the six plots in each field down to a depth of 6 inches using a 1 inch diameter probe. Core samples were taken during each penetrometer sampling event. Three cores were taken in each plot totaling 18 soil cores per farm. The core locations were chosen within the plot that would give the best representation of that plot by utilization of aerial images of each farm to determine consistent elevations and to avoid areas near the end of the fields where equipment would travel most often. Each core was boxed and labeled to make sure there was no cross contamination between samples. The samples were oven dried at 45.5°C for 24 hours. Once the samples were completely dry they were ground in a soil grinder before further nutrient analysis testing. Nutrients quantified were % Organic Matter, Sulfur, Phosphorus, Potassium and any heavy metals that may have been present.

To determine moisture content of the soil at the time of SPR readings 1” diameter soil cores were taken down to an 18” depth. Five cores were pulled per plot that represented the moisture content of each of the 5 SPR reading locations. These cores were weighed in the field to record an accurate wet weight of the soil and oven dried in a 45.5°C oven for 24 hours. Once the cores had been completely dried they were weighed again to record an oven dried weight and finally determined the percent moisture present in the soil at the time of SPR readings on both a wet- and dry –basis.

Biomass samples were collected from each plot with cover from each farm. A green seeker (Trimble,Sunnyvale, CA) was used to determine an average Normalized Difference Vegetation Index (NDVI) across the entire plot containing the cover crop. Once the average was recorded, a location that was consistent with that average NDVI reading within the plot was selected and a 2’x 2’ square made of ¼” PVC pipe was placed flat on the soil and all standing cover crop was cut and removed from the 2'x 2' square. It was important to ensure that no residue from previous crops was obtained when collecting the biomass sample. Three biomass samples were removed from each of the three cover plots for each farm. These samples were removed in cloth bags and weighed immediately to get an accurate field wet weight of the cover. The samples were placed into an oven at 40.5°C for 36 hrs to ensure they were completely dried. After drying they were weighed to record an oven dried weight, and moisture content of the biomass was calculated. Biomass samples were also analyzed for nutrients.

3.2.4 Statistical Analysis

The main effects of soil type nested in site/location, row position and cover crop on initial SPR, final SPR and the change in SPR values were analyzed using PROC GLM in SAS (Version 9.3, Cary, NC). The SPR data were transformed using the natural log to improve the fit of the linear model and check for evidence of heteroskedasticity in the residuals. Statistical comparisons of data values were determined using least square means and paired t-tests. Levels of significance were determined at an α-level of 0.05. In addition to the penetrometer data, confidence intervals for the biomass dry weights from each soil type were compared to detect statistical significance.

3.3 Results and Discussion

3.3.1 Moisture Content and Row Position

Although only one season is considered, the growing season for these cover crops was very typical in terms of planting time, establishment, maturation and North Carolina weather patterns in the Coastal Plain. It is well documented that soil moisture effects soil penetration resistance where they are primarily inversely related (Busscher et al., 1997). Statistically it was determined that moisture content of the soils measured played a factor on initial force readings, where one unit increase in moisture resulted in a -.052 log unit decrease in force, across all soil types and all cover and no cover crop plots. The moisture contents measured ranged from 5 – 19% wet-basis (5-22% dry-basis) across all soil types. These effects were expected with changes in moisture content. Relationships between resistance and moisture content for the soils studied in this work were further quantified and described in Chapter 4.

Neither cover/no cover nor row position factors had significant effects on the initial force readings, substantiating the desired similarities within the field locations and plots selected prior to cover crop establishment. This was important to show there was a reasonably uniform starting point for the study. Cover/no cover and row position factors were also not statistically significant for the initial force measurements, supporting confidence in the data values collected. This also may indicate stabilization of the field at time of data collection with moisture levels ranging from 10 – 22% (wet-basis); however, the majority of the moisture readings fell between 13 – 18% (wet-basis).

3.3.2 Cover Crops

The effect of cover crop was statistically significant for the final forces measured after cover crop termination and just before planting of the new crop. The natural log of the final force means on plots with cover crops (4.42, 83.1 psi) was less than the natural log mean of forces on plots without cover crops (4.54,93.7 psi), across row position and all locations and soil types. This suggests that the soil strength was weakened in plots that were planted with the multi species cover, where compaction of the soil structure was alleviated to a certain degree. Williams and Weil (2004) looked at a mixed cover including a forage radish and rye before soybeans in an attempt to identify changes in yield, soil compaction and the ability for the soybean roots to utilize channels in the soil profile for root growth that were left behind from decaying cover crop roots. Throughout the winter growing season for the cover crops they experienced unusually dry conditions. The results revealed no significant difference in soil penetration resistance between areas with cover versus areas with no cover. These results are reported as an extremely conservative test of the cover crops ability to effectively alleviate the effects of soil compaction. This suggests that if the winter months in which the cover crops were grown had seen normal levels of precipitation compaction alleviation may have occurred. In our study we saw that similar mixed covers, the deep rooting grasses, have the potential to assist in compaction alleviation.

Raper et al.(2000) reported that the use of rye cover crop before cotton slightly decreased soil strength over the four years the experiment was carried out. This is similar to what we found in that the use of a deep rooting grass may have the ability to assist in compaction alleviation dependent on weather during the growing season. The use of the cover crop statistically increased cotton yields in three of the four years of the Raper et al. (2000) study, with the highest seed cotton yields consistently benefiting from the rye cover crop. This suggests that the use of a cover crop has benefits beyond compaction alleviation, supplementing the cash crop with essential nutrients even after the cover crop has been terminated. Both studies, Raper et al. (2000) and Williams and Weil (2004), were located on silt loams located in the eastern United States. These soils contain more clay percentages than the loamy sands and sandy loams this study was carried out in (Raper et al., 2000). Our similar findings with a multi-species cover indicate that different soil types can benefit from the use of a cover crop to assist in compaction alleviation

Table 3.1 presents a breakdown of the primary species observed in the cover plots as well as the NDVI numbers estimated using the green seeker. The dominant species in the cover crop plots were the deep rooting grasses. It was observed that the Wrens Abruzzi Rye and Triticale Tri 342 combined were the most prevalent types of biomass per plot suggesting a well- developed deep rooting system was established in the soil profile.

Table 3.1 Observed contents in each plot along with average NDVI readings per plot.

Soil type/Location	Abruzzi Wren Rye/ Triticale Tri 342	Crimson Clover	Hairy Vetch	NDVI
Goldsboro sandy loam/ Halifax				
Plot 1	60%	20%	20%	0.47
Plot 2	59%	10%	30%	0.55
Plot 3	20%	30%	50%	0.54
Noboko fine loamy sand/ Scotland Neck				
Plot 1	60%	20%	20%	0.17
Plot 2	40%	40%	20%	0.3

Plot 3	80%	10%	10%	0.19
Ocilla loamy fine sand/ Greenville				
Plot 1	40%	30%	30%	0.27
Plot 2	80%	10%	10%	0.2
Plot 3	95%	5%	0%	0.16
Norfolk sandy loam/ Clinton				
Plot 1	95%	5%	0%	0.09
Plot 2	80%	20%	0%	0.12
Plot 3	95%	5%	0%	0.08

In each plot that contained cover crop, root depths were examined and photographically documented. A representative image is shown in Figure 3.1 and additional images are presented in Appendix D.

Figure 3.1 Rooting system of the multi species cover

Each location/soil type had similar rooting depths varying from 8 to 13 inches where the soil profile at these depths most likely had been disturbed and the soil strength weakened resulting in the lower force readings observed on the penetrometer (Blanco-Canqui et al., 2012).

Calculation of the confidence intervals for biomass yields (dry weight) from the cover treatments at each location on the different soil types overlapped, indicating that the covers performed equally well across the experiment. The sample mean for biomass on the Goldsboro sandy loam was statistically higher than biomass on Ocilla loamy fine sand and on average, were higher than the other locations as shown in Table 3.2. Similar differences were found from NDVI numbers during biomass collection with the greenseeker (Table 3.1). The Goldsboro sandy loam was still green at the time of sampling, so the absence of herbicides and no termination date may have contributed to this result. However, the extent of maturation of the cover crops at the different locations did not seem to impact the overall effect on soil resistance.

Table 3.2 Biomass sample means per each soil type with 95% Confidence Intervals

Biomass Dry Weight				
Soil Type (Location)	**Number of Samples**	**Sample Mean (g)**	**Lower 95% CL for Mean (g)**	**Upper 95% CL for Mean (g)**
Goldsboro Sandy Loam (Halifax, NC)	2	249.50	243.15	255.85
Noboco Fine Sandy Loam (Scotland Neck, NC)	3	121.00	-7.82	249.82
Norfolk Sandy Loam (Clinton, NC)	3	194.33	61.24	327.42
Ocilla Loamy Fine Sand (Greenville, NC)	3	128.67	88.89	168.44

3.33 Soil Nutrients

The soil nutrient results revealed minimal changes throughout the cover crop growing season shown in Table 3.2 and 3.3. Cover crops are known to utilize available nutrients from the soil that may otherwise be leached out where we would expect soil nutrient levels to be a little lower at the time of the second sample. The Greenville and Scotland Neck farms showed no significant changes in the soil nutrient values for both cover and no cover plots. The Halifax farm on average showed a small increase in Ca values for the plots in cover and a decrease in Ca values for the plots without cover; however, statistically these changes do not seem to be significant. In plots without cover Ca levels may have decreased due to leaching effects and increased Ca levels in the cover plots may be a result of root and soil interactions such that additional Ca may have diffused through the soil profile. Halifax had a much more dense cover with increased populations of vetch and clover. The Clinton farm had similar results with an average increase in CEC levels along with increases in K and Mg. These increases were observed in the plots with cover crop while plots without cover had an average decrease in CEC, K and Mg. With the incorporation of the multi-species cover crop an increase in CEC was noticeable, which possibly affected the K and Mg levels that were also increased in the plots with cover.

Table 3.3 Soil properties and nutrient composition for plots with and without cover crops at Greeneville and Halifax

			Macronutrients					
	CEC*	**BS***	**Ac**	**pH**	**P**	**K**	**Ca**	**S**
Greenville	**meq/100 cm3**	**%**	**meq/100 cm3**		**ppm**	**ppm**	**ppm**	**ppm**
Cover (Initial)	7.2±1.5	67.3±7.0	2.1±0.3	5.6±0.3	126.7±10.0	117.3±41.0	660.0±165.1	18.7±5.6
Cover (Final)	9.0±3.7	78.0±4.7	1.9±0.8	5.8±0.1	168.0±117	171.0±63.7	956.0±375.6	16.3±1.7
No Cover (Initial)	6.2±0.9	71.0±4.6	1.7±0.3	5.5±0.3	123.7±115.5	87.3±37.1	604.3±106.4	20.7±2.3
No Cover (Final)	9.3±2.0	79.7±5.7	1.9 ±0.2	5.8±0.1	209.0±14.8	128.7±21.9	1054.3±326.7	16.3
Halifax								
Cover (Initial)	5.77±0.3	84.7±3.8	0.9±0.2	6.0±0.3	112.0±51.0	183.7±16.2	695.7±30.2	16.3±1.5
Cover (Final)	5.63±0.2	82.7±1.5	1.0±0.1	5.9±0.1	65.7±45.7	174.3±7.5	714.0±21.8	16.3±0.6
No Cover (Initial)	5.90±0.4	82.7±1.0	1.0±0.1	5.9±0.2	107.7±12.5	166.0±20.4	751.7±52.8	15.7±1.2
No Cover (Final)	5.87±1.6	80.0±7.8	1.1±0.1	5.6±0.5	90.3±21.9	163.7±26.9	708.0±242.5	19.7±2.1
			Micronutrients					
	HM*	**Density**	**Mn**	**Zn**	**Cu**	**Na**	**K**	**Mg**
Greenville	**g/100cc**	**g/cm^3**	**Ppm**	**ppm**	**ppm**	**meq/100 cm3**	**meq/100 cm3**	**meq/100 cm3**
Cover (Initial)	1.7±0.6	1.3±0.1	4.1±0.8	1.6±0.7	0.6±0.2	0	0.3±0.1	1.4±0.4
Cover (Final)	2.5±1.2	1.3±0.2	5.5±1.4	2.1±0.6	0.9±0.4	0.0±0.1	0.4±0.2	1.8±1.0
No Cover (Initial)	1.6±1.3	1.4	4.1±0.7	1.8±0.7	0.9±0.5	0	0.2±0.1	1.2±0.6
No Cover (Final)	3	1.2	6.1±1.2	2.1±0.4	0.9	0	0.3±0.1	1.9±0.5
Halifax								
Cover (Initial)	0.39±0.1	1.35	8.53±1.4	1.63±0.5	1.97±0.3	0.07±0.1	0.47	0.95±0.1
Cover (Final)	0.26±0.1	1.31	9.10±1.1	1.30±0.4	1.73±0.5	0.00±0.1	0.45	0.65±0.1
No Cover (Initial)	0.40±0.1	1.36	10.37±1.1	1.57±0.1	2.17±0.5	0.03	0.42±0.1	0.71±0.2
No Cover (Final)	0.38±0.2	1.31	7.33±0.5	1.43±0.2	1.73±0.1	0	0.42±0.1	0.80±0.4

*CEC – Cation Exchange Capacity; HM – Humic Matter; BS – Base Saturation; Ac - Acidity

Table 3.4 Soil properties and nutrient composition for plots with and without cover crops at Clinton and Scotland Neck

			Macronutrients					
	CEC*	**BS***	**Ac***	**pH**	**P**	**K**	**Mg**	**S**
Clinton	**meq/100 cm3**	**%**	**meq/100 cm3**		**ppm**	**ppm**	**ppm**	**ppm**
Cover (Initial)	6.9±0.9	79.3±0.6	1.5±0.1	5.6±0.2	310.7±35.8	84.0±31.8	113.3±12.9	20.3±4.9
Cover (Final)	10.0±2.8	84.0±6.9	1.5±0.3	5.9±0.2	295.3±49.5	163.7±52.2	230.3±105.5	20.7±10.1
No Cover (Initial)	9.6±4.2	80.0±4.6	1.8±0.2	5.6±0.2	302.7±5.1	125.0±89.5	192.3±166.3	28.0±6.5
No Cover (Final)	6.5±0.4	75.3±3.1	1.6±0.3	5.6±0.1	330.0±14.8	88.7±37.1	96.0±1.0	16.0±1.0
Scotland Neck								
Cover (Initial)	5.8±1.0	79.0±2.5	1.2±0.3	5.6±0.3	76.7±10.5	98.0±12.5	100.0±19.6	18.0±6.1
Cover (Final)	6.1±0.1	78.7±4.4	1.3±0.3	5.6±0.2	119.7±52.6	152.3±25.2	111.0±15.4	14.3±1.7
No Cover (Initial)	6.1±1.1	76.3±7.2	1.5±0.2	5.5±0.3	64.3±7.5	76.0±40.0	96.0±36.1	17.3±1.5
No Cover (Final)	6.4±0.5	81.7	1.2±0.1	5.9±0.1	91.7±15.6	118.3±8.5	112.7±2.1	13.3±2.1

			Micronutrients					
	HM*	**Density**	**Mn**	**Zn**	**Cu**	**Na**	**Ca**	**Mg**
Clinton	**g/100cc**	**g/cm^3**	**ppm**	**ppm**	**ppm**	**meq/100 cm3**	**meq/100 cm3**	**meq/100 cm3**
Cover (Initial)	0.7±0.2	1.5±0.1	19.3±1.4	10.7±1.1	3.2±0.3	0.0±0.1	4.4±0.6	0.9±0.1
Cover (Final)	1.8±0.9	1.4±0.1	15.0±5.8	10.5±1.6	4.0±0.2	0.1±0.1	6.2±1.8	1.9±0.9
No Cover (Initial)	1.6±1.0	1.4±0.2	16.3±4.6	11.2±3.7	3.8±0.9	0.1±0.1	5.92.4±	1.6±1.4
No Cover (Final)	0.8±0.2	1.5	18.5±3.9	10.6±0.8	3.3±0.3	0.1±0.1	3.9	0.8
Scotland Neck								
Cover (Initial)	0.4±0.1	1.4	8.8±2.1	1.4±0.6	1.8±0.2	0	3.5±0.6	0.8±0.2
Cover (Final)	0.5±0.1	1.4	10.6±1.9	1.3±0.4	1.7±0.2	0	3.5±0.1	0.9±0.1
No Cover (Initial)	0.5±0.1	1.4	6.2±1.7	0.8±0.7	1.5±0.6	0.0±0.1	3.7±0.9	0.8±0.3
No Cover (Final)	0.6±0.4	1.4	10.8±3.3	1.7±0.4	2.0±0.1	0	4.0±0.3	0.9

*CEC – Cation Exchange Capacity; HM – Humic Matter; BS – Base Saturation; Ac - Acidity

The ultimate question any producer wants to know is “Will I see returns on my investment in these multi-species cover crops?” The average cost of the mix of cover crop species used in this study was about $45 to $50 per acre. Depending on method of planting, aerial seeding averages about $15 per acre while drilling the cover in will depend on the set up but an average of around $8 per acre for fuel and maintenance costs should be expected. Alternatively, various tillage methods, multiple herbicide applications and erosion problems may cost a producer much more in money and labor when cover crops are not utilized. With the possibility of increasing nutrient levels, alleviating compaction, suppressing weed populations, increasing organic matter and limiting expensive tillage practices, the use of cover crops are becoming more popular (Bauer et al., 1995).

3.4 Conclusions

Incorporation of a mixed species cover crop on a sandy loam soil or loamy sand soil in the Coastal Plains of North Carolina can assist with compaction alleviation within a single cover crop establishment. Not only do these cover crops offer benefits to compaction issues, they also have the potential to increase soil health in terms of available organic nutrients from the terminated biomass and suppress weed emergence during growth of a subsequent crop (Bauer et al., 1995). The use of cover crops can also have benefits in reducing production costs and time often tied to tillage operations and herbicide applications. The overall impact through long term use as it relates subsequent crop yields, tillage and land management practices, alleopathic effects and soil condition will require additional seasonal data.

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CHAPTER 4
Quantification of Soil Penetration Resistance and Moisture Interactions in Various Soil Types from Coastal Plains North Carolina

4.1 Introduction

Soil penetration resistance is most often measured using a cone penetrometer. This method has a few advantages such as the simplicity and speed of collecting data, identification of compacted layers at various depths, and high correlation with plant root growth (Bengough et al., 2011). Field soil moisture can vary considerably in time and space where its effects might mask imposed treatment differences. The ability to quantify penetration resistance as a result of differences in soil moisture could provide an approach to correct for the moisture effect on measured penetrometer values. This can also provide a greater understanding of how data collection procedures can influence penetration resistance values.

There have been several researchers working on relationships between penetration resistance and soil water content. Asady et al. (1987) accounted for water content as a continuous covariate of the cone index readings in an analysis of variance (ANOVA). Ayers and Perumpral (1982) found a direct relationship between cone index and bulk density and an inverse relationship between cone index and soil moisture squared for various mixtures of sand and clay. Ohu et al. (1988) found an exponential relationship between cone index and soil moisture for loams and clays, while Ley et al. (1995) found a linear correlation between penetration resistance and soil moisture. All of these empirical and conceptual models that have been proposed to explain penetration resistance include water content as an independent variable. A mathematical equation that represents the dependence of soil penetration resistance on soil moisture at the time of sampling could greatly help in understanding the relationship between the two and how certain soils behave as viscoelastic materials. The ability to quantify the extent of deviation between moisture levels would in theory eliminate soil moisture as a factor and could be useful for simulations when soil strength and moisture content are used as inputs for predicting root growth (Henderson, 1989).

The objective of this study was to identify in the lab a generalized empirical relationship between cone index (soil penetration resistance) measurements and soil moisture to better understand the effects of moisture on penetrometer readings in Coastal Plains sandy loams and loamy sands in a controlled environment. This was done by replicating soil physical properties as best as possible in the lab with the ability to control and set bulk density as well as moisture content values.

4.2 Materials and Methods

4.2.1 Soil Sample Removal

The soil used in the lab analysis came from four farms in the Coastal Plains of North Carolina. The first was located on a Halifax County farm in the city of Halifax, NC (36°6'N, 77°24'W) and had a Noboko fine sandy loam. The second was from another Halifax County farm in the city of Scotland Neck, NC (36°17'N, 77°40'W) and had a Goldsboro sandy loam. The third farm located in Sampson County, NC(35°7'N, 78°24'W) was a Norfolk sandy loam and the final farm was in Pitt County, NC (35°39'N, 77°14'W) which contained two different soil types, an Ocilla loamy fine sand as well as a Goldsboro sandy loam. (71 United Sates Department of Agriculture - USDA, Natural Resource Conservation Society - NRCS 2014;). On these four farms 6 locations were randomly chosen per farm. At these 6 locations 2" diameter Soil cores were taken down to about 36" using an Amity Soil Core. This soil probe inserted a 2" diameter core, 48" long, along with a plastic tube with the same dimensions, into the soil and removed a fully intact core that remained inside the plastic tube. This tube protected the core as well as maintained soil moisture through the use of fitted rubber caps on each end, minimizing evaporation. Once the cores were packaged, varying sections of the cores were identified based on soil texture and appearance. For each core from the surface down to 12" was a solid uniform layer but for depths beyond 12" the texture and color changed drastically to either a large particle sand or clay. The observations made were consistent with the soil classification given by NRCS, 2014. These changes in soil texture and appearance determined the different depths necessary to remove from the field to use in the lab analysis and that coincided with root depths typical for the cotton crop grown on these farms. From each soil core location on each farm 2 five gallon buckets were filled full of soil from a depth of 0” to 12” and the other bucket full of soil from 12” to 18”. In addition to common root zone depths for a cotton crop, a final depth of 18” was chosen because previous experiments with the cone penetrometer only reached 18 inch depths. For each soil core, 2 five gallon buckets of soil were removed per farm, totaling 12 buckets of soil per farm. Unfortunately a rain storm only allowed us to remove 10 buckets of soil from the Halifax farm, so in all we had 46 five gallon buckets of soil and 24 soil cores, meticulously labeled and marked, for analysis at the lab. The time between core removal and lab analysis was never more than 6 hours. Soil cores were removed from the plastic tube without altering the core in any way. While the core laid flat on the table it was precisely cut into sections of 0” to 12” and 12” to 18”. After each section was separated, dimensions were noted and wet weights were taken before the cores were put into the oven. The oven was set on 45.5°C and the cores were allowed 24 hrs to completely dry. Once the cores were dried, dry weights were taken and dry bulk density, as well as wet bulk density were calculated based on the dimensions of the core and weights of both the dried and wet core.

4.2.2 Soil Preparations and Analysis

The soil in each of the 46 five gallon buckets were completely dried down using greenhouse space to spread each individual bucket out on a table and left to dry by the greenhouse fans and sun for nearly one week. The greenhouse fans and heat from the sun acted as an oven and dried the soils down to levels below 1% dry basis moisture content. Once these soils had been dried and sampled, to determine moisture content, they were placed back into the buckets for crushing. As the moist soils dried out in the greenhouse, large clods remained that had to be broken down to make a more uniform bucket of soil. To accomplish this, a small portable cement mixer was used with the addition of 3 medium size grinding rocks to assist in breaking these soils down into a more uniform state for testing. The soil was removed from the 5 gallon buckets into the cement mixer along with the three grinding rocks and mixed for about 10 minutes or until the soil was ground into a reasonable consistent texture. The soil from the mixer was not passed through a sieve because we wanted to retain some pore space when the soils were returned to the 5 gallon buckets. After all of the buckets had been ground down to the desired level, each bucket was packed down to the bulk density levels that were measured from the correlating soil cores collected from each farm site. Buckets were packed using a table top vibrating machine and the entire bucket was shaken to allow the particles to settle. Measurements were made to relate the soil core bulk density to the bucket bulk density and a required height was determined and marked on the outside of the bucket to ensure the soil height in the bucket would give the desired bulk density. Once the bucket had the correct measured bulk density cone penetrometer readings were taken from each bucket.

The penetrometer was put together using a 24" linear actuator, an Omegadyne Inc. 1000 lb. load cell and a 20" long , ¼" steel rod that screws into the load cell and has a steel 30° cone attached to the bottom. These three components worked together by activating the electric drive linear actuator forcing the cone and shaft into the soil at a rate of 1 inch per second. The program displayed subsequent readings of the force per unit area every second. The penetrometer apparatus was mounted onto the back side of a common hand truck to take advantage of the tall upright frame and improve ease of maneuverability. For this experiment the hand truck, with the penetrometer intact, was fastened to a stable platform that allowed the buckets to be easily placed underneath the cone for sampling. The penetrometer sampling pattern remained the same for each bucket. Each bucket was sampled 5 times in a star pattern as displayed in Figure 4.1.

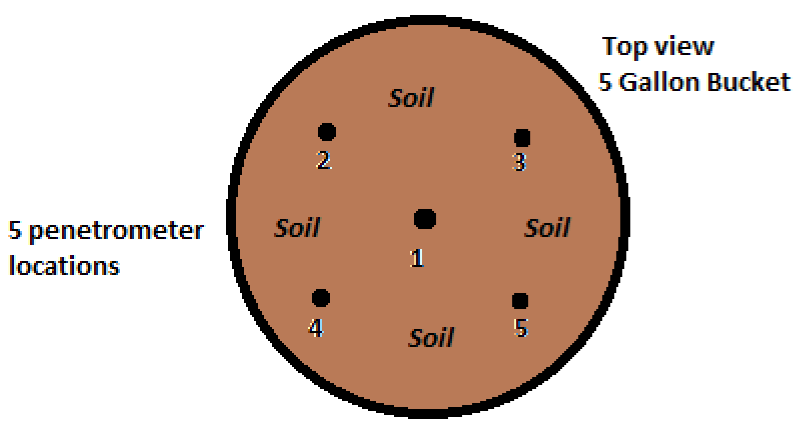

Figure 4.1 Penetrometer diagram for each 5 gallon bucket of soil

These five locations were spread out as evenly as possible to reduce the amount of pressure from previous sample locations as well as from the walls of the buckets. This process was repeated for each bucket at nearly 0% dry basis moisture content. A small sample was removed and labeled from each bucket following the penetrometer sampling and weighed. These samples were then oven-dried at 45.5°C for 24 hrs and oven dried weights were taken to verify the moisture content of the corresponding bucket at the time of sampling. After all 46 buckets had been sampled at “0%”, moisture was added to each bucket to increase the dry basis moisture content to 5%. The cone penetrometer sampling cycled with increasing moisture content was repeated for 5%, 10%, 15%, 20%, 25%, 30% and 40% dry-basis moisture content.

4.2.3 Increasing Moisture Content

Following previous penetrometer sampling events, oven dried samples were returned to their specific bucket and each bucket was again weighed to determine the amount of water to add to achieve the desired moisture content. The dry-basis moisture content equation was used by inserting the soil dry weight (W_d) (g) and the desired moisture content (%MC) to determine what the wet weight (W_w) (g) should be to reach the desired moisture content in each bucket.

$$\%Moisture\ Content_{dry\ basis} = \frac{W_w - W_d}{W_d} \times 100$$

The soil was transferred into a large mixing container (muck bucket) where it was hand mixed back to a uniform state for approximately 10 minutes. Water was carefully weighed out and sprayed into the mixing container until the desired moisture content was reached, and the soil was mixed thoroughly so that the moisture was evenly distributed through the soil. The soil was then returned to its original 5 gallon bucket where it was again packed down to the desired height to give the same initial bulk density (held constant). This process was repeated for each bucket at each level of moisture. Immediately after the buckets were at the desired bulk density levels the cone penetrometer sampling was done to prevent any surface evaporation as well as gravity from pulling moisture towards the bottom of the buckets.

4.2.4 Data Analysis

All farms but one had 6 buckets from 0 to 12 inch depth and 6 buckets from the 12 to 18 inch depth. The Halifax farm had only 5 buckets from 0 to 12 and 5 buckets from 12 to 18 inches. Because there was no observed difference between plots and all plots within farm had the same soil type, all of the 0 to 12 inch buckets were combined for each farm and all of the 12 to 18 inch buckets were combined to complete the lab tests and analysis. The soil penetration resistance from each bucket (average of 5 positions, 6 buckets per depth and soil type) was plotted against the measured moisture content for the corresponding bucket Trendlines were added to each plot to acquire an equation relating soil moisture and the soil penetration resistance (force per unit area).

4.3 Results and Discussion

It is well known that soil moisture has an inverse effect on soil penetration resistance (Ekwue and Stone, 1995). The point of this study was to identify how moisture affects a specific soil type in the Coastal Plains of North Carolina. As expected soil moisture had an inverse effect on soil penetration resistance however, some of the more coarse sandy soils reacted a differently than the others within specific moisture ranges. The method of adding moisture constantly without allowing the soil to dry after each sampling may have had an impact on the reaction to the increased water content. The soil was consistently becoming weaker with no opportunity to dry out and return to its original structure. If the test had been completed by drying to soil down after each sample and then reaching the desired moisture content, results may have been different. Natural variability and inherent nature of the soil itself was removed when the soil was taken from the field and put into the buckets, however the data presented give us a good idea of how these soils interact with water and behave as hygroscopic, viscoelastic materials.

Trend lines were fit to each farm data set to identify the best equation to quantify the relationship between SPR and moisture shown in Figure 4.1 and 4.2. The best empirical equations were determined based on the highest trends in the data and the highest R^2 value. The 0 to 12” soils from Halifax, Scotland Neck and Clinton had an exponential decay

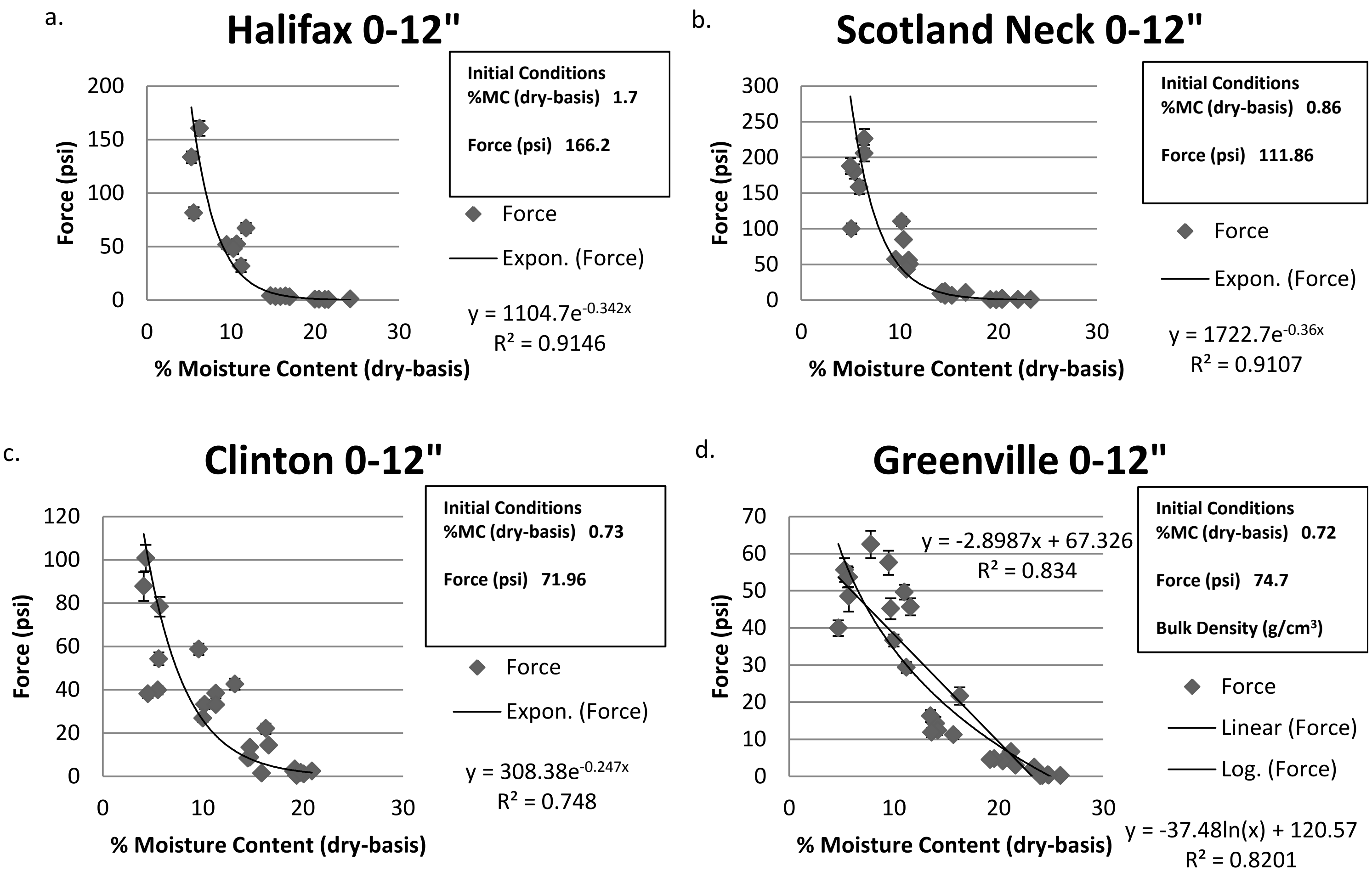

Figure 4.2 Soil penetration resistance (Force) and moisture relationship for depths 0 to 12”

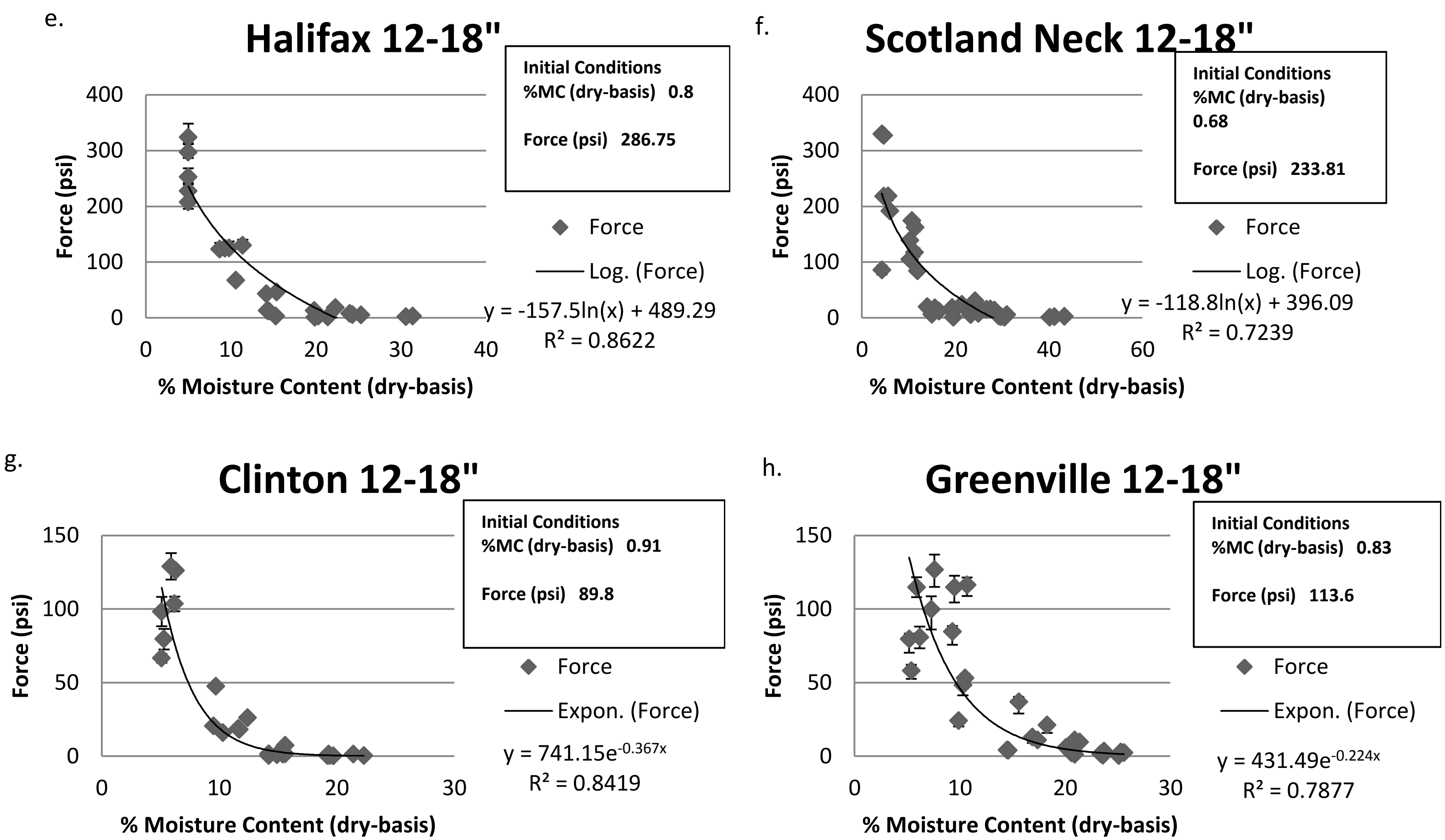

Figure 4.3 Soil penetration resistance (Force) and moisture relationship for depths 12 to 18”

relationship with soil moisture observations similar to the findings of Ohu et al. (1988) who looked at three different soil types, a sandy loam, clay loam and clay. The Greenville soil had a linear relationship with moisture giving an R^2 value of 0.834 which was similar to the findings of Ley et al. (1995) who looked at weak structure soils in Nigeria. The fine sandy loam in Greenville can be considered a weaker structure than the other locations examined in this experiment. There was greater variability in the data between 5% to 10% moisture content (dry-basis) for both depths analyzed at each farms, suggesting the equation fit to the data may be less accurate in those moisture ranges. This range of moisture content is regularly found in “normal” field conditions. Because of the variability, multiple comparative measurements may be necessary to ensure the measurements are a true representation of the soil moisture. Overall the observations from the 0 to 12” samples fit the trend lines better, giving R^2 values from 0.75 to 0.91, than the soil from 12’18”, giving R^2 values from 0.72 to 0.86. This could be a result of the change in texture from a more sandy non-plastic, non-sticky soil to a soil containing more clay content and having sticky, plastic characteristics at the greater depths. In addition, the uniformity of the soils decreased at the greater depths. These physical property differences influence soil-water interactions and matric potentials, thus impacting soil strength.

The different soil textures reacted differently to the added moisture. The more clayey soils held there structure much longer resulting in SPR values greater than 0 at higher moisture contents. The more coarse sandier soils lost structure around 15% moisture content (dry-basis) and resulted in SPR values near 0 at higher moisture contents. There was high variability noted in the moisture levels from 5 to 10% in all observations proving difficult to fit a regression line as well as determining an accurate empirical equation. As the moisture content increased the SPR readings became more consistent and the regression lines began to fit nicely. Unfortunately the moisture contents that resulted in high variability (5 to 10 % dry-basis) are moisture levels that occur under “normal” everyday field conditions. Thus it will be important to gather multiple comparative measurements to acquire a true representation of the field, and possible design an experiment that looked at data collection in the field with incremental changes in moisture. Because of the variability in the SPR values at the lower moisture contents and other variables that come along with replications of field scenarios in a lab, the empirical equations did not give enough confidence in the predictions to adjust SPR values based on known moisture content.

4.4 Conclusion

This study was initiated to identify relationships between soil moisture and soil penetration resistance, with the possibility of being able to establish predictive equations reasonable enough to estimate a correction factor that could be used to adjust SPR values to different moisture contents. Unfortunately both variability in the data and the un natural manipulation of the soil structure to accomplish a repeatable baseline in the material properties did not provide results with enough confidence to effectively use the empirical equations determined. This experiment did, however, show how different soil types/textures reacted to various moisture contents. Looking at these soils as engineering materials we may conclude that a more coarse, sandier soil loses its structure much faster than a tightly structured clayey soil. Future research will be necessary to accomplish an understanding of the soil – water interaction in a field scenario. A better representation of a field scenario must be set up in order to eliminate all factors that could possibly affect the SPR value besides moisture content.

4.5 References

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Appendices

Appendix A: SAS® Analysis for SPR effects due to Harvester Traffic

Appendix A.1 Basket Harvester Operated on the Halifax County Farm

Interaction Results:

1. Sums of Squares and ANOVA Table

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	84	29524646.36	351483.89	78.41	<.0001
Error	5862	26276814.03	4482.57		
Corrected Total	5946	55801460.39			

R-Square	Coeff Var	Root MSE	Force__psi_ Mean
0.529102	52.44261	66.95198	127.6671

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Observatio(Location)	12	510182.56	42515.21	9.48	<.0001
Before_After	1	590229.70	590229.70	131.67	<.0001
Depth	5	19062026.38	3812405.28	850.50	<.0001
Depth*Before_After	5	302736.80	60547.36	13.51	<.0001
Trafficked(Location)	3	750509.27	250169.76	55.81	<.0001
Befor*Traffi(Locati)	5	93953.75	18790.75	4.19	0.0008
Depth*Traffi(Locati)	25	731255.18	29250.21	6.53	<.0001
Dept*Befo*Traf(Loca)	25	520832.48	20833.30	4.65	<.0001
Location	2	228267.17	114133.58	25.46	<.0001
Moisture	1	962.40	962.40	0.21	0.6431

2. Least Squares Means Table

Tukey-Kramer Comparison Lines for Least Squares Means of Dept*Befo*Traf(Loca)												
LS-means with the same letter are not significantly different.												
							Force__psi_ LSMEAN	**Depth**	**Before_After**	**Trafficked**	**Location**	**LSMEAN Number**
			A				284.505	**5**	**Before**	**Yes**	**1**	20
			A									
	B		A				267.459	**5**	**Before**	**Yes**	**2**	44
	B		A									
	B		A		C		244.453	**5**	**Before**	**No**	**1**	19
	B				C							
	B		D		C		228.715	**5**	**Before**	**No**	**2**	43
	B		D		C							
	B		D		C		228.054	**6**	**Before**	**Yes**	**2**	48
	B		D		C							
	B	E	D		C		227.078	**6**	**Before**	**Yes**	**1**	24
	B	E	D		C							
	B	E	D		C		223.265	**6**	**Before**	**No**	**2**	47
	B	E	D		C							
F	B	E	D		C		216.34	**5**	**After**	**Yes**	**1**	18
F	B	E	D		C							
F	B	E	D		C		213.704	**5**	**After**	**Yes**	**2**	42
F		E	D		C							
F		E	D		C		209.531	**4**	**Before**	**Yes**	**1**	16
F		E	D									
F	G	E	D				200.11	**5**	**Before**	**Yes**	**3**	68
F	G	E	D									
F	G	E	D				198.658	**6**	**Before**	**Yes**	**3**	72
F	G	E	D									
F	G	E	D				195.903	**5**	**After**	**No**	**2**	41
F	G	E	D									
F	G	E	D		H		194.068	**4**	**Before**	**Yes**	**2**	40
F	G	E			H							
F	G	E			H		189.005	**5**	**Before**	**No**	**3**	67
F	G	E			H							

F	G	E	I		H		187.53	**5**	**After**	**No**	**1**	17
F	G		I		H							
F	G		I		H		186.501	**6**	**Before**	**No**	**1**	23
F	G		I		H							
F	G	J	I		H		174.424	**6**	**After**	**No**	**3**	69
F	G	J	I		H							
F	G	J	I		H		172.202	**6**	**After**	**No**	**1**	21
F	G	J	I		H							
F	G	J	I		H	K	170.962	**6**	**After**	**Yes**	**1**	22
F	G	J	I		H	K						
F	G	J	I	L	H	K	169.633	**5**	**After**	**Yes**	**3**	66
	G	J	I	L	H	K						
	G	J	I	L	H	K	161.004	**5**	**After**	**No**	**3**	65
	G	J	I	L	H	K						
M	G	J	I	L	H	K	156.082	**6**	**After**	**Yes**	**2**	46
M		J	I	L	H	K						
M		J	I	L	H	K	155.875	**6**	**Before**	**No**	**3**	71
M		J	I	L	H	K						
M		J	I	L	H	K	144.982	**6**	**After**	**No**	**2**	45
M		J	I	L	H	K						
M	N	J	I	L	H	K	142.622	**4**	**After**	**Yes**	**1**	14
M	N	J	I	L		K						
M	N	J	I	L		K	142.156	**4**	**Before**	**Yes**	**3**	64
M	N	J	I	L		K						
M	N	J	I	L		K	141.357	**4**	**After**	**Yes**	**2**	38
M	N	J		L		K						
M	N	J		L		K	135.45	**6**	**After**	**Yes**	**3**	70
M	N	J		L		K						
M	N	J		L		K	134.27	**3**	**Before**	**Yes**	**1**	12
M	N	J		L		K						
M	N	J		L		K	132.47	**4**	**Before**	**No**	**3**	63
M	N	J		L		K						
M	N	J		L		K	132.364	**4**	**After**	**Yes**	**3**	62
M	N			L		K						
M	N		O	L		K	123.885	**3**	**Before**	**Yes**	**2**	36
M	N		O	L								
M	N		O	L			122.853	**4**	**Before**	**No**	**1**	15
M	N		O	L								

M	N		O	L			119.021	**4**	**Before**	**No**	**2**	39
M	N		O	L								
M	N		O	L	P		117.997	**3**	**After**	**Yes**	**1**	10
M	N		O	L	P							
M	N		O	L	P		117.453	**3**	**Before**	**Yes**	**3**	60
M	N		O		P							
M	N	Q	O		P		107.797	**4**	**After**	**No**	**3**	61
M	N	Q	O		P							
M	N	Q	O		P	R	104.71	**3**	**After**	**Yes**	**2**	34
	N	Q	O		P	R						
	N	Q	O		P	R	97.7322	**4**	**After**	**No**	**2**	37
	N	Q	O		P	R						
	N	Q	O		P	R	94.5316	**3**	**After**	**Yes**	**3**	58
	N	Q	O		P	R						
	N	Q	O		P	R	92.8873	**4**	**After**	**No**	**1**	13
	N	Q	O		P	R						
	N	Q	O		P	R	88.019	**2**	**Before**	**Yes**	**1**	8
		Q	O		P	R						
		Q	O		P	R	83.5723	**3**	**Before**	**No**	**3**	59
		Q			P	R						
		Q			P	R	78.9314	**3**	**After**	**No**	**2**	33
		Q			P	R						
		Q			P	R	76.7823	**3**	**Before**	**No**	**2**	35
		Q			P	R						
		Q			P	R	62.4244	**2**	**Before**	**Yes**	**3**	56
		Q			P	R						
		Q			P	R	62.1827	**3**	**Before**	**No**	**1**	11
		Q			P	R						
		Q			P	R	61.849	**2**	**After**	**Yes**	**2**	30
		Q				R						
		Q				R	61.5955	**2**	**Before**	**Yes**	**2**	32
						R						
						R	61.5674	**3**	**After**	**No**	**3**	57
						R						
						R	59.7658	**3**	**After**	**No**	**1**	9
						R						
						R	57.419	**2**	**After**	**Yes**	**1**	6
						R						

						R	51.8553	**2**	**After**	**Yes**	**3**	54
						R						
						R	51.1291	**2**	**After**	**No**	**2**	29
						R						
						R	47.5466	**2**	**Before**	**No**	**3**	55
						R						
						R	43.668	**2**	**Before**	**No**	**1**	7
						R						
						R	38.0277	**2**	**Before**	**No**	**2**	31
						R						
						R	35.6001	**2**	**After**	**No**	**1**	5
						R						
						R	31.6318	**2**	**After**	**No**	**3**	53
						R						
						R	31.3211	**1**	**Before**	**Yes**	**1**	4
						R						
						R	21.8958	**1**	**Before**	**Yes**	**3**	52
						R						
						R	18.5896	**1**	**Before**	**Yes**	**2**	28
						R						
						R	18.0206	**1**	**Before**	**No**	**1**	3
						R						
						R	17.7028	**1**	**After**	**Yes**	**3**	50
						R						
						R	17.5145	**1**	**Before**	**No**	**3**	51
						R						
						R	15.3138	**1**	**After**	**Yes**	**2**	26
						R						
						R	12.7879	**1**	**After**	**No**	**2**	25
						R						
						R	12.672	**1**	**After**	**No**	**1**	1
						R						
						R	12.0709	**1**	**Before**	**No**	**2**	27
						R						
						R	11.3659	**1**	**After**	**No**	**3**	49
						R						
						R	6.60716	**1**	**After**	**Yes**	**1**	2

The LINES display does not reflect all significant comparisons. The following additional pairs are significantly different: (44,47) (24,67) (47,67) (47,17) (40,45) (67,71) (67,45) (17,45) (17,64) (23,71) (23,45) (23,64) (23,38) (69,63) (21,63) (66,39) (65,15) (65,39) (46,61) (71,39) (71,61) (71,34) (45,61) (14,13) (64,37) (64,13) (64,8) (38,13) (63,13) (15,59) (39,59) (10,56) (10,11) (60,56) (60,11) (60,30) (61,11) (34,29) (34,55) (34,7) (34,31) (34,5) (34,53) (34,4) (34,52) (34,28) (34,3) (34,51) (34,26) (34,25) (34,1) (34,27) (34,49) (37,9) (37,29) (37,55) (37,7) (37,31) (37,5) (37,53) (37,4) (37,52) (37,28) (37,3) (37,51) (37,26) (37,25) (37,1) (37,27) (37,49) (58,7) (58,31) (58,5) (58,53) (58,4) (58,52) (58,3) (58,51) (58,25) (58,1) (58,27) (58,49) (13,29) (13,55) (13,7) (13,31) (13,5) (13,53) (13,4) (13,52) (13,28) (13,3) (13,51) (13,26) (13,25) (13,1) (13,27) (13,49) (8,31) (8,5) (8,53) (8,52) (8,3) (8,51) (8,25) (8,1) (8,27) (8,49) (59,55) (59,7) (59,31) (59,5) (59,53) (59,52) (59,3) (59,51) (59,25) (59,1) (59,27) (59,49) (33,31) (33,5) (33,53) (33,3) (33,51) (33,25) (33,1) (33,27) (33,49) (35,31) (35,5) (35,53) (35,3) (35,51) (35,25) (35,1) (35,27) (35,49) (11,3) (11,51) (11,25) (11,27) (11,49) (57,3) (57,51)

Appendix A.2 Case IH Module Express Operated on the Sampson County Farm

1. Sums of Squares and ANOVA Table

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	84	10993500.43	130875.01	77.82	<.0001
Error	6038	10154247.22	1681.72		
Corrected Total	6122	21147747.65			

R-Square	Coeff Var	Root MSE	Force__psi_ Mean
0.519843	38.38847	41.00882	106.8259

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Observatio(Location)	12	107843.912	8986.993	5.34	<.0001
Before_After	1	383726.738	383726.738	228.17	<.0001
Depth	5	3816517.918	763303.584	453.88	<.0001
Depth*Before_After	5	955114.450	191022.890	113.59	<.0001
Trafficked(Location)	3	44989.797	14996.599	8.92	<.0001
Befor*Traffi(Locati)	5	117413.508	23482.702	13.96	<.0001
Depth*Traffi(Locati)	25	340681.828	13627.273	8.10	<.0001
Dept*Befo*Traf(Loca)	25	260046.566	10401.863	6.19	<.0001
Location	2	248758.485	124379.243	73.96	<.0001
Moisture	1	5643.446	5643.446	3.36	0.0670

2. Least Squares Means Table

Tukey-Kramer Comparison Lines for Least Squares Means of Dept*Befo*Traf(Loca)										
LS-means with the same letter are not significantly different.										
					Force__psi_ LSMEAN	Depth	Before_After	Trafficked	Location	LSMEAN Number
			A		216.1884	**4**	**Before**	**Yes**	**2**	40
			A							
			A		210.2818	**4**	**Before**	**No**	**1**	15
			A							
	B		A		207.1253	**3**	**Before**	**Yes**	**2**	36
	B		A							
	B		A	C	188.3660	**4**	**Before**	**Yes**	**1**	16
	B			C						
	B			C	184.3958	**3**	**Before**	**No**	**2**	35
				C						
			D	C	174.1000	**4**	**Before**	**No**	**2**	39
			D	C						
	E		D	C	162.1494	**3**	**Before**	**No**	**1**	11
	E		D	C						
	E	F	D	C	160.4521	**5**	**Before**	**Yes**	**2**	44
	E	F	D							
	E	F	D		159.6030	**5**	**Before**	**No**	**1**	19
	E	F	D							
	E	F	D	G	152.1895	**3**	**Before**	**Yes**	**1**	12
	E	F		G						
	E	F	H	G	142.3210	**4**	**Before**	**Yes**	**3**	64
	E	F	H	G						
	E	F	H	G	141.1043	**4**	**Before**	**No**	**3**	63
		F	H	G						
		F	H	G	138.0280	**5**	**Before**	**No**	**2**	43
		F	H	G						
		F	H	G	137.9315	**3**	**Before**	**No**	**3**	59
		F	H	G						
	I	F	H	G	134.9695	**3**	**Before**	**Yes**	**3**	60
	I	F	H	G						
J	I	F	H	G	131.5718	**5**	**Before**	**Yes**	**1**	20
J	I		H	G						
J	I		H	G	130.6960	**6**	**Before**	**Yes**	**2**	48
J	I		H	G						
J	I		H	G	126.8036	**6**	**Before**	**No**	**2**	47
J	I		H	G						

J	I	K	H	G	122.4668	**2**	**Before**	**Yes**	**2**	32
J	I	K	H	G						
J	I	K	H	G	121.4940	**5**	**Before**	**Yes**	**3**	68
J	I	K	H							
J	I	K	H		119.7727	**6**	**Before**	**Yes**	**3**	72
J	I	K	H							
J	I	K	H		119.7406	**6**	**Before**	**No**	**1**	23
J	I	K	H							
J	I	K	H		119.5923	**5**	**Before**	**No**	**3**	67
J	I	K								
J	I	K			114.9946	**6**	**Before**	**No**	**3**	71
J	I	K								
J	I	K	L		110.9887	**6**	**Before**	**Yes**	**1**	24
J	I	K	L							
J	I	K	L		107.2444	**6**	**After**	**Yes**	**2**	46
J	I	K	L							
J	I	K	L	M	104.5110	**2**	**Before**	**No**	**2**	31
J	I	K	L	M						
J	I	K	L	M	103.2204	**5**	**After**	**Yes**	**3**	66
J		K	L	M						
J		K	L	M	102.4597	**6**	**After**	**Yes**	**3**	70
J		K	L	M						
J		K	L	M	99.9408	**5**	**After**	**Yes**	**2**	42
J		K	L	M						
J		K	L	M	98.1971	**6**	**After**	**No**	**3**	69
J		K	L	M						
J		K	L	M	98.0824	**4**	**After**	**Yes**	**3**	62
J		K	L	M						
J		K	L	M	97.5603	**3**	**After**	**Yes**	**1**	10
		K	L	M						
		K	L	M	97.1603	**5**	**After**	**No**	**3**	65
		K	L	M						
		K	L	M	96.9445	**3**	**After**	**No**	**2**	33
		K	L	M						
		K	L	M	96.3536	**6**	**After**	**No**	**2**	45
		K	L	M						
		K	L	M	95.0105	**4**	**After**	**No**	**1**	13
		K	L	M						
		K	L	M	91.5133	**3**	**After**	**No**	**1**	9
		K	L	M						
		K	L	M	91.2496	**3**	**After**	**Yes**	**2**	34
		K	L	M						
		K	L	M	90.0776	**4**	**After**	**No**	**3**	61

		K	L	M						
		K	L	M	89.6591	**5**	**After**	**No**	**2**	41
		K	L	M						
	N	K	L	M	88.7322	**4**	**After**	**Yes**	**2**	38
	N	K	L	M						
	N	K	L	M	88.1409	**4**	**After**	**No**	**2**	37
	N	K	L	M						
	N	K	L	M	86.7873	**3**	**After**	**No**	**3**	57
	N	K	L	M						
O	N	K	L	M	86.4963	**4**	**After**	**Yes**	**1**	14
O	N		L	M						
O	N		L	M	86.1900	**2**	**Before**	**Yes**	**3**	56
O	N		L	M						
O	N		L	M	83.5892	**2**	**Before**	**No**	**1**	7
O	N		L	M						
O	N		L	M	82.2293	**2**	**Before**	**No**	**3**	55
O	N		L	M						
O	N	P	L	M	81.9423	**2**	**Before**	**Yes**	**1**	8
O	N	P		M						
O	N	P		M	80.7510	**2**	**After**	**No**	**2**	29
O	N	P		M						
O	N	P	Q	M	74.9606	**2**	**After**	**Yes**	**2**	30
O	N	P	Q	M						
O	N	P	Q	M	74.1775	**6**	**After**	**No**	**1**	21
O	N	P	Q	M						
O	N	P	Q	M	73.5694	**5**	**After**	**No**	**1**	17
O	N	P	Q	M						
O	N	P	Q	M	73.4325	**3**	**After**	**Yes**	**3**	58
O	N	P	Q	M						
O	N	P	Q	M	73.3763	**6**	**After**	**Yes**	**1**	22
O	N	P	Q	M						
O	N	P	Q	M	72.9931	**2**	**After**	**Yes**	**1**	6
O	N	P	Q	M						
O	N	P	Q	M	71.7052	**5**	**After**	**Yes**	**1**	18
O	N	P	Q							
O	N	P	Q		60.8966	**2**	**After**	**No**	**3**	53
O		P	Q							
O		P	Q		57.6920	**2**	**After**	**No**	**1**	5
O		P	Q							
O		P	Q		51.0468	**2**	**After**	**Yes**	**3**	54
		P	Q							
		P	Q		34.5808	**1**	**After**	**No**	**2**	25
		P	Q							

		P	Q		33.3123	**1**	**After**	**Yes**	**2**	26
		P	Q							
		P	Q		29.5829	**1**	**After**	**Yes**	**1**	2
		P	Q							
		P	Q		25.0721	**1**	**After**	**No**	**3**	49
		P	Q							
		P	Q		24.7592	**1**	**Before**	**Yes**	**2**	28
			Q							
			Q		24.0373	**1**	**After**	**No**	**1**	1
			Q							
			Q		22.2916	**1**	**Before**	**No**	**2**	27
			Q							
			Q		21.6618	**1**	**Before**	**No**	**1**	3
			Q							
			Q		20.9948	**1**	**After**	**Yes**	**3**	50
			Q							
			Q		19.9495	**1**	**Before**	**Yes**	**3**	52
			Q							
			Q		14.4475	**1**	**Before**	**No**	**3**	51
			Q							
			Q		11.7263	**1**	**Before**	**Yes**	**1**	4

The LINES display does not reflect all significant comparisons. The following additional pairs are significantly different: (35,11) (19,43) (19,20) (12,47) (63,23) (63,67) (60,31) (20,69) (48,31) (48,69) (48,62) (47,31) (47,69) (47,62) (32,61) (32,41) (32,37) (32,57) (68,9) (68,61) (68,41) (68,37) (68,57) (68,14) (72,9) (72,61) (72,41) (72,37) (72,57) (72,14) (23,45) (23,9) (23,61) (23,41) (23,38) (23,37) (23,57) (23,14) (67,69) (67,45) (67,13) (67,9) (67,61) (67,41) (67,38) (67,37) (67,57) (67,14) (71,9) (71,61) (71,41) (71,37) (71,57) (71,14) (24,7) (24,55) (31,21) (31,17) (31,58) (31,22) (70,21) (70,17) (69,21) (69,17) (65,21) (33,21) (45,21) (45,17) (37,53) (57,53) (14,5) (56,54) (7,54) (55,54) (8,25) (8,26) (8,2) (8,49) (29,25) (29,26) (29,2) (29,49) (29,28) (30,25) (30,26) (30,2) (30,49) (30,1) (30,27) (30,3) (30,50) (30,52) (30,51) (21,25) (21,26) (21,2) (21,49) (21,1) (21,27) (21,3) (21,50) (21,52) (21,51) (17,25) (17,26) (17,2) (17,49) (17,1) (17,27) (17,3) (17,50) (17,52) (17,51) (58,25) (58,26) (58,2) (58,49) (58,1) (58,27) (58,3) (58,50) (58,52) (58,51) (22,25) (22,26) (22,2) (22,49) (22,1) (22,27) (22,3) (22,50) (22,52) (22,51) (6,25) (6,26) (6,2) (6,49) (6,1) (6,27) (6,3) (6,50) (6,52) (6,51) (18,25) (18,26) (18,2) (18,49) (18,1) (18,27) (18,3) (18,50) (18,51) (53,25) (53,49) (53,1) (53,27) (53,3) (53,50) (53,51) (5,49) (5,1) (5,27) (5,50) (5,51)

Appendix A.3 John Deere Round Baler Operated on the Hoke County Farm

1. Sums of Squares and ANOVA Table

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	84	22451863.07	267284.08	41.80	<.0001
Error	6072	38831075.67	6395.10		
Corrected Total	6156	61282938.75			

R-Square	Coeff Var	Root MSE	Force__psi_ Mean
0.366364	47.11334	79.96940	169.7383

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Observatio(Location)	12	535722.48	44643.54	6.98	<.0001
Before_After	1	765505.93	765505.93	119.70	<.0001
Depth	5	10247842.25	2049568.45	320.49	<.0001
Depth*Before_After	5	228946.75	45789.35	7.16	<.0001
Trafficked(Location)	3	1954962.54	651654.18	101.90	<.0001
Befor*Traffi(Locati)	5	147806.18	29561.24	4.62	0.0003
Depth*Traffi(Locati)	25	2694708.29	107788.33	16.85	<.0001
Dept*Befo*Traf(Loca)	25	293377.87	11735.11	1.84	0.0068
Location	2	1596244.56	798122.28	124.80	<.0001
Moisture	1	9939.79	9939.79	1.55	0.2126

2. Least Squares Means Table

Tukey-Kramer Comparison Lines for Least Squares Means of Dept*Befo*Traf(Loca)														
LS-means with the same letter are not significantly different.														
									Force__psi_ LSMEAN	**Depth**	**Before_ After**	**Trafficked**	**Location**	**LSMEAN Number**
					A				319.4773	**3**	**Before**	**Yes**	**1**	12
					A									
	B				A				295.6866	**4**	**After**	**Yes**	**1**	14
	B				A									
	B				A		C		287.0265	**3**	**Before**	**Yes**	**3**	60
	B				A		C							
	B				A		C		285.7612	**4**	**Before**	**Yes**	**1**	16
	B				A		C							
	B		D		A		C		279.5345	**3**	**After**	**Yes**	**1**	10
	B		D		A		C							
	B		D		A		C		279.0629	**2**	**Before**	**Yes**	**3**	56
	B		D				C							
	B		D		E		C		249.0954	**4**	**After**	**No**	**1**	13
	B		D		E		C							
F	B		D		E		C		248.4977	**3**	**Before**	**Yes**	**2**	36
F	B		D		E		C							
F	B		D		E		C		246.5233	**4**	**Before**	**Yes**	**2**	40
F	B		D		E		C							
F	B		D		E		C	G	242.2223	**3**	**After**	**Yes**	**3**	58
F	B		D		E		C	G						
F	B		D		E		C	G	240.7004	**3**	**Before**	**No**	**1**	11
F	B		D		E		C	G						
F	B		D		E		C	G	240.4189	**4**	**Before**	**Yes**	**3**	64
F	B		D		E		C	G						
F	B		D		E		C	G	236.8983	**4**	**Before**	**No**	**1**	15
F	B		D		E		C	G						
F	B		D		E	H	C	G	234.1419	**2**	**Before**	**Yes**	**1**	8
F			D		E	H	C	G						
F	I		D		E	H	C	G	227.8944	**5**	**Before**	**Yes**	**1**	20
F	I		D		E	H		G						
F	I		D		E	H		G	226.1081	**5**	**Before**	**No**	**1**	19
F	I		D		E	H		G						
F	I		D		E	H	J	G	220.4879	**3**	**After**	**Yes**	**2**	34
F	I		D		E	H	J	G						
F	I		D		E	H	J	G	218.6264	**6**	**Before**	**Yes**	**1**	24
F	I		D		E	H	J	G						

F	I		D		E	H	J	G	217.6928	**5**	**After**	**Yes**	**1**	18
F	I				E	H	J	G						
F	I		K		E	H	J	G	207.1068	**4**	**After**	**Yes**	**3**	62
F	I		K		E	H	J	G						
F	I		K	L	E	H	J	G	205.4883	**4**	**After**	**Yes**	**2**	38
F	I		K	L		H	J	G						
F	I		K	L		H	J	G	204.5241	**3**	**After**	**No**	**1**	9
F	I		K	L		H	J	G						
F	I		K	L		H	J	G	193.8765	**6**	**Before**	**No**	**1**	23
F	I		K	L		H	J	G						
F	I		K	L		H	J	G	193.2889	**5**	**After**	**No**	**1**	17
F	I		K	L		H	J	G						
F	I		K	L	M	H	J	G	189.8343	**2**	**Before**	**Yes**	**2**	32
F	I		K	L	M	H	J	G						
F	I		K	L	M	H	J	G	188.8754	**5**	**Before**	**Yes**	**3**	68
	I		K	L	M	H	J	G						
	I		K	L	M	H	J	G	187.5432	**5**	**Before**	**No**	**3**	67
	I		K	L	M	H	J	G						
N	I		K	L	M	H	J	G	183.9056	**5**	**Before**	**Yes**	**2**	44
N	I		K	L	M	H	J							
N	I		K	L	M	H	J		177.2622	**2**	**Before**	**No**	**1**	7
N	I		K	L	M	H	J							
N	I		K	L	M	H	J	O	171.2196	**3**	**Before**	**No**	**3**	59
N	I		K	L	M	H	J	O						
N	I	P	K	L	M	H	J	O	169.1817	**2**	**After**	**Yes**	**1**	6
N	I	P	K	L	M		J	O						
N	I	P	K	L	M		J	O	168.3374	**6**	**After**	**Yes**	**1**	22
N	I	P	K	L	M		J	O						
N	I	P	K	L	M		J	O	168.3298	**6**	**Before**	**Yes**	**3**	72
N	I	P	K	L	M		J	O						
N	I	P	K	L	M		J	O	166.7245	**2**	**After**	**Yes**	**3**	54
N	I	P	K	L	M		J	O						
N	I	P	K	L	M		J	O	165.4623	**6**	**Before**	**No**	**3**	71
N	I	P	K	L	M		J	O						
N	I	P	K	L	M		J	O	165.0465	**6**	**After**	**No**	**1**	21
N	I	P	K	L	M		J	O						
N	I	P	K	L	M		J	O	164.8913	**5**	**After**	**Yes**	**3**	66
N		P	K	L	M		J	O						
N		P	K	L	M		J	O	164.6595	**4**	**Before**	**No**	**3**	63
N		P	K	L	M		J	O						
N		P	K	L	M		J	O	161.0042	**5**	**After**	**Yes**	**2**	42
N		P	K	L	M			O						
N		P	K	L	M			O	160.0168	**3**	**Before**	**No**	**2**	35

N		P	K	L	M			O						
N		P	K	L	M			O	159.9911	**2**	**Before**	**No**	**3**	55
N		P	K	L	M			O						
N		P	K	L	M			O	153.3375	**3**	**After**	**No**	**2**	33
N		P	K	L	M			O						
N	Q	P	K	L	M			O	153.1954	**6**	**Before**	**Yes**	**2**	48
N	Q	P		L	M			O						
N	Q	P		L	M			O	152.2338	**5**	**Before**	**No**	**2**	43
N	Q	P		L	M			O						
N	Q	P		L	M			O	152.1820	**6**	**Before**	**No**	**2**	47
N	Q	P		L	M			O						
N	Q	P		L	M			O	147.3030	**3**	**After**	**No**	**3**	57
N	Q	P		L	M			O						
N	Q	P		L	M			O	144.6840	**4**	**After**	**No**	**2**	37
N	Q	P		L	M			O						
N	Q	P		L	M			O	143.2417	**4**	**Before**	**No**	**2**	39
N	Q	P		L	M			O						
N	Q	P		L	M			O	139.8478	**6**	**After**	**No**	**2**	45
N	Q	P		L	M			O						
N	Q	P		L	M		R	O	138.3691	**2**	**After**	**Yes**	**2**	30
N	Q	P			M		R	O						
N	Q	P			M		R	O	136.2296	**6**	**After**	**Yes**	**3**	70
N	Q	P			M		R	O						
N	Q	P			M		R	O	136.1884	**5**	**After**	**No**	**3**	65
N	Q	P			M		R	O						
N	Q	P			M		R	O	135.5431	**6**	**After**	**Yes**	**2**	46
N	Q	P					R	O						
N	Q	P					R	O	132.0193	**6**	**After**	**No**	**3**	69
N	Q	P					R	O						
N	Q	P					R	O	130.2996	**4**	**After**	**No**	**3**	61
	Q	P					R	O						
	Q	P					R	O	129.2435	**2**	**Before**	**No**	**2**	31
	Q	P					R	O						
	Q	P			S		R	O	127.4159	**5**	**After**	**No**	**2**	41
	Q	P			S		R							
	Q	P			S		R		126.8003	**2**	**After**	**No**	**1**	5
	Q	P			S		R							
	Q	P	T		S		R		116.5684	**2**	**After**	**No**	**2**	29
	Q	P	T		S		R							
	Q	P	T		S		R		111.6670	**2**	**After**	**No**	**3**	53
	Q		T		S		R							
	Q		T		S		R		83.5833	**1**	**Before**	**Yes**	**3**	52
			T		S		R							

			T		S		R		67.8880	**1**	**Before**	**No**	**3**	51
			T		S		R							
			T		S		R		63.1457	**1**	**Before**	**No**	**2**	27
			T		S		R							
			T		S		R		57.4998	**1**	**Before**	**Yes**	**2**	28
			T		S		R							
			T		S		R		50.6008	**1**	**Before**	**Yes**	**1**	4
			T		S		R							
			T		S		R		48.2634	**1**	**After**	**Yes**	**2**	26
			T		S									
			T		S				47.5895	**1**	**After**	**Yes**	**1**	2
			T											
			T						44.4967	**1**	**After**	**No**	**2**	25
			T											
			T						42.2760	**1**	**Before**	**No**	**1**	3
			T											
			T						37.7738	**1**	**After**	**No**	**1**	1
			T											
			T						37.5077	**1**	**After**	**No**	**3**	49
			T											
			T						28.7764	**1**	**After**	**Yes**	**3**	50

The LINES display does not reflect all significant comparisons. The following additional pairs are significantly different: (14,11) (14,15) (16,15) (36,23) (36,17) (36,32) (40,23) (40,17) (11,23) (11,17) (11,67) (11,44) (64,67) (15,23) (15,67) (15,44) (8,7) (8,59) (20,59) (20,71) (20,21) (19,7) (19,59) (19,22) (19,72) (19,54) (19,71) (19,21) (19,66) (34,21) (24,21) (38,57) (38,37) (38,39) (38,45) (9,35) (9,55) (9,33) (9,43) (9,47) (9,57) (9,37) (9,39) (9,45) (9,30) (23,47) (23,57) (23,37) (23,39) (23,45) (17,37) (17,39) (17,45) (67,39) (67,45) (67,65) (7,69) (7,61) (59,31) (22,53) (71,29) (71,53) (21,29) (21,53) (63,29) (63,53) (35,29) (35,53) (43,52) (47,52) (30,51) (30,27) (30,28) (30,4) (70,51) (70,27) (70,28) (70,4) (65,51) (65,27) (65,28) (65,4) (46,51) (46,27) (46,28) (46,4) (69,51) (69,27) (69,28) (69,4) (61,51) (61,27) (61,28) (61,4) (31,51) (31,27) (31,28) (31,4) (41,51) (41,27) (41,28) (41,4) (5,51) (5,27) (5,28) (5,4) (29,27) (29,4) (29,25) (29,3) (29,1) (29,49) (53,25) (53,3) (53,1) (53,49)

Appendix B: SAS® Analysis for Cover Crop Interactions

Appendix B.1 Biomass and Soil Type Interactions

Confidence intervals for the biomass of each soil type were compared to detect statistical significance. The intervals are in the table below. Goldsboro Sandy Loam has significantly higher biomass than Ocilla Loamy Fine Sand. Otherwise, the confidence intervals overlap suggesting that the mean differences are not statistically significant. The sample sizes are small, though, so the power to detect small differences is low.

Biomass Dry Weight				
Soil Type	**Number of Samples**	**Sample Mean**	**Lower 95% CL for Mean**	**Upper 95% CL for Mean**
Goldsboro Sandy Loam	2	249.50	243.15	255.85
Noboco Fine Sandy Loam	3	121.00	-7.82	249.82
Norfolk Sandy Loam	3	194.33	61.24	327.42
Ocilla Loamy Fine Sand	3	128.67	88.89	168.44

Appendix B.2 SPR Analysis Just after Planting Cover Crop

Initial Force:

A linear model was fit to the initial force data using PROC GLM. Due to severe lack of fit, the raw data were transformed by taking natural logs. The fit was improved using the transformed data, but there is still evidence of heteroskedasticity in the residuals.

Cover crop and row position were not statistically significant ($p = 0.3203$ and $p = 0.7417$, respectively).

For each one unit increase in moisture content, initial force decreases by 0.052 log-units ($p = 0.0001$). The initial force means (log units) are 4.72 for soil with cover crops and 4.67 for soil without. These are not significantly different.

Appendix B.3 SPR Analysis Just Prior to Spring Cotton Planting

A linear model was fit to the final force data using PROC GLM. Due to lack of fit, the raw data were transformed by taking natural logs. The fit was improved using the transformed data, and there was no evidence of heteroskedasticity in the residuals.

Row position and final moisture content were not statistically significant ($p = 0.3867$ and $p = 0.1680$, respectively).

The final force means (log units) were 4.42 for soil with cover crops and 4.54 for soil without. These were significantly different.

Appendix C: Photos of the Three Harvesters Used

a.) John Deere 9996 Basket Harvester Identical to the Harvester Used on the Halifax County Farm

b.) John Deere 7760 Round Bale Harvester Used on the Hoke County Farm

c.) A Case IH Module Express 625 Identical to the Harvester Used on the Sampson County Farm

Appendix D: Cover Crop Rooting Depth Photos

a.) Halifax County Farm

b.) Sampson County Farm

c.) Pitt County Farm

d.) Scotland Neck Farm