Real-Time, Variable-Depth Tillage for Managing Soil Compaction in Cotton Production

Jonathan Fox
Clemson University

Follow this and additional works at: https://tigerprints.clemson.edu/all_theses

Recommended Citation

This Thesis is brought to you for free and open access by the Theses at TigerPrints. It has been accepted for inclusion in All Theses by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.
REAL-TIME, VARIABLE-DEPTH TILLAGE FOR MANAGING
SOIL COMPACTION IN COTTON PRODUCTION

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Plant and Environmental Science

by
Jonathan Fox
May 2018

Accepted by:
Dr. Young Han, Committee Co-Chair
Dr. Ahmad Khalilian, Committee Co-Chair
Dr. Joe Mari Maja
ABSTRACT

Cotton is one of the most important crops in the southern USA with an estimated production value of $6 billion. Cotton root growth is often hindered in the Southeastern U.S. due to the presence of root-restricting soil layers. Soils in this region have three distinct layers, the A horizon, the E horizon and the Bt horizon. The E horizon is often plagued with a hardpan layer that has a much higher bulk density than optimum for crop production. This limits the ability of the plant roots to penetrate into the Bt horizon for uptake of water and nutrients, therefore, reducing yields, limiting productivity, and making plants more susceptible to drought stress. Tillage must be used to temporarily remove this compacted soil layer to allow root growth to depths needed to sustain plants during periods of drought. However, due to significant variability in depth and thickness of hardpan layers in Coastal Plain soils, applying uniform-depth tillage over the entire field may be either too shallow to fracture the hardpan or deeper than required resulting in excess fuel consumption and inefficient use of energy. Therefore, significant savings in tillage energy could be achieved by adjusting tillage depth to match soil’s physical properties. However, there is currently no equipment commercially available to automatically control the tillage depth to match the soil physical properties. Therefore, the objective of this project was to develop and test equipment for controlling tillage depth “on-the-go” to match soil physical parameters, and plant responses in cotton production. The “Clemson Intelligent Plow” was developed by modifying an existing four-
row subsoiler into a variable depth tillage platform, which could change the tillage depth from zero to 45 cm (18 in) on-the-go. Site-specific tillage operations reduced fuel consumption by 45% compared to conventional constant-depth tillage. Only 20% of the test field required tillage at recommended depth for Coastal Plain regions (15 inches deep). Cotton taproots in the variable-depth tillage plots were 96% longer than those in the no-till plots (15.4 vs. 7.8 inches). Statistically, there were no differences in cotton lint yield between conventional and the variable-depth tillage. Deep tillage (conventional or variable-rate) increased cotton lint yields by 20% compared to no-till.
DEDICATION

I would like to dedicate this thesis to my parents, Cindy and Wayne Fox for their support throughout my college career and to my Fiancé, Stephanie Johnson for her continued support and motivation to work hard. I would also like to thank Dr. Young Han, Dr. Ahmad Khalilian, D. Joe Maja?, Dr. Ali Nafchi, and Phillip Williams for their knowledge and assistance that made this project possible.
TABLE OF CONTENTS

Page

TITLE PAGE ........................................................................................................................................... i
ABSTRACT ............................................................................................................................................... ii
DEDICATION........................................................................................................................................... iv
LIST OF TABLES...................................................................................................................................... vii
LIST OF FIGURES................................................................................................................................... viii

CHAPTER 1

1. INTRODUCTION............................................................................................................................... 1
   OBJECTIVES ...................................................................................................................................... 5

2. LITERATURE REVIEW ...................................................................................................................... 6
   Soil Compaction Management in Coastal Plain Soils ................................................................. 6
   Methods for Measuring Soil Compaction ...................................................................................... 8
   Effect of Soil Compaction on Root Growth and Yield .............................................................. 10
   On-the-Go Hardpan Detection and Variable Depth Tillage .................................................. 12

3. METHODS AND MATERIALS ......................................................................................................... 16
   Design Criteria ............................................................................................................................... 16
   Equipment Development .............................................................................................................. 16
   Instrumented Tractor .................................................................................................................. 27
   Data Logger and Control System .............................................................................................. 28
   Data Collection .......................................................................................................................... 33
   Test Field ...................................................................................................................................... 36
Table of Contents (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. RESULTS AND DISCUSSION</td>
<td>41</td>
</tr>
<tr>
<td>5. CONCLUSION</td>
<td>51</td>
</tr>
<tr>
<td>6. FUTURE STUDY</td>
<td>53</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>54</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3.3.1</td>
<td>Fuel flow meter accuracy test</td>
<td>28</td>
</tr>
<tr>
<td>1.3.5.1</td>
<td>Effects of different tillage treatments on cotton taproot length, plant height, and root weight, 2017</td>
<td>44</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.1</td>
<td>A typical soil profile of the Coastal Plain in the Southern USA</td>
<td>4</td>
</tr>
<tr>
<td>1.3.2.1.1</td>
<td>Design and components of the instrumented shank</td>
<td>17</td>
</tr>
<tr>
<td>1.3.2.1.2</td>
<td>Calibration apparatus for each instrumented shank section</td>
<td>19</td>
</tr>
<tr>
<td>1.3.2.1.3</td>
<td>Calibration equations for each instrumented shank section</td>
<td>20-22</td>
</tr>
<tr>
<td>1.3.2.2.1</td>
<td>Hydraulic proportional directional control valve calibration</td>
<td>25</td>
</tr>
<tr>
<td>1.3.2.3.1</td>
<td>Solid Works rendering of the Clemson Intelligent Plow</td>
<td>26</td>
</tr>
<tr>
<td>1.3.2.3.2</td>
<td>The Clemson Intelligent Plow</td>
<td>27</td>
</tr>
<tr>
<td>1.3.4.1.1</td>
<td>The Phidgets data logger and controller</td>
<td>30</td>
</tr>
<tr>
<td>1.3.4.2.1</td>
<td>Main page of the Edisto Variable Depth Tillage Program</td>
<td>31</td>
</tr>
<tr>
<td>1.3.4.2.2</td>
<td>Tillage depth control system flow chart</td>
<td>32</td>
</tr>
<tr>
<td>1.3.5.1</td>
<td>Schematic diagram of the soil compaction measurement system</td>
<td>34</td>
</tr>
<tr>
<td>1.3.5.2</td>
<td>The Clemson tractor-mounted soil compaction measurement System</td>
<td>35</td>
</tr>
<tr>
<td>1.3.5.3</td>
<td>Veris 3100 soil electrical conductivity measurement system used in the Study</td>
<td>36</td>
</tr>
<tr>
<td>1.3.6.1</td>
<td>2017 Variable depth tillage test plot plan</td>
<td>38</td>
</tr>
<tr>
<td>1.4.1</td>
<td>Required tillage depths for the one-hectare test field, 2017</td>
<td>41</td>
</tr>
</tbody>
</table>
List of Figures (Continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4.2</td>
<td>Effects of tillage depth on fuel consumption</td>
<td>43</td>
</tr>
<tr>
<td>1.4.3</td>
<td>Effects of tillage systems on root length</td>
<td>46</td>
</tr>
<tr>
<td>1.4.4</td>
<td>Effects of tillage systems on fuel consumption</td>
<td>47</td>
</tr>
<tr>
<td>1.4.5</td>
<td>Effects of tillage systems on cotton lint yields (2017)</td>
<td>48</td>
</tr>
<tr>
<td>1.4.6</td>
<td>Effects of tillage systems on soil compaction at cotton harvest</td>
<td>49</td>
</tr>
</tbody>
</table>
CHAPTER 1

1.1 INTRODUCTION

The soil profile of most of the Southeastern Coastal Plain region is comprised of three distinct textural layers: A horizon - sandy to loamy sand, E horizon - yellowish-brown sandy to sandy clay, and Bt horizon - sandy clay loam (Figure 1.1.1). The E horizon is often plagued with a hardpan layer that has a much higher bulk density than optimum for crop production. The hardpan layer exhibits a great amount of variability in depth and thickness in this region, and usually is present at 25 to 40 cm (10 to 16 in) deep and is typically 5 to 20 cm (2 to 8 in) thick (Gorucu et al., 2006). This compacted layer limits the ability of the plant roots to penetrate into the Bt horizon for uptake of water and nutrients, therefore, reducing yields, limiting productivity, and making plants more susceptible to drought stress. The E-horizon must be broken so that roots can grow into the subsoil or Bt-horizon, which contains a majority of moisture and nutrients in the soil profile. Soil compaction is managed in the Southeastern USA using of annual uniform-depth tillage before planting, to allow root growth to depths needed to sustain plants during periods of drought, which have been shown to improve yields (Garner et al., 1989; Khalilian et al., 1991; Khalilian et al., 2004, Marshall et al., 2016, Khalilian et al., 2017). The recommended tillage depth for Coastal Plain regions is usually about 35 to 40 cm (14 to 16 in.) deep (Garner et al., 1984; Reid, 1978; Campbell et al., 1974; Raper et al., 1994). Due to significant variability in depth and thickness of hardpan layers in Coastal Plain soils
(Raper et al., 2000; Gorucu et al., 2006), applying uniform-depth tillage over the entire field may be either too shallow to fracture the hardpan or deeper than required resulting in excess fuel consumption and an inefficient use of energy. Therefore, significant savings in tillage energy could be achieved by adjusting tillage depth to match soil’s physical properties. However, growers don’t know the depth and thickness of the hardpan or where the hardpan is located within a given field.

Ideally, depth and thickness of the hardpan layer need to be determined for the optimum tillage depth to remove the hardpan layer. Also, there is little to gain from tilling deeper than required to fracture the compacted layer and in some cases, penetration into the clay layer may be detrimental (Garner et al., 1986). Previous work at Clemson University showed that tilling 7.5 cm (3 in) deeper than the clay layer, increased draft requirements by 75% and fuel consumption by 50%, without increasing cotton yields (Garner et al., 1986). Also, using spatial cone index measurements to map the variability of the hardpan showed that approximately 75% of the field required a tillage depth less than 37.5 cm (15 in), the recommended tillage depth for coastal plains soils (Gorucu et al., 2001; Raper et al., 2002). Therefore, this variability leads us to believe that, by adjusting tillage depth on-the-go to match the depth and thickness of the hardpan layer, significant savings in tillage energy could be achieved.

Several researchers have attempted continuous measurement of soil strength at multiple depths (Glancey et al., 1996; Adamchuk et al. 2001; Andrade et al., 2001 and
2002; Alihamsyah et al., 1990; Alihamsyah and Humphries, 1991; Chukwu and Bowers, 1997; Raper and Hall, 2003; Chung et al., 2004; Khalilian et al., 2014). In addition, Khalilian et al. (2014) developed map-based equipment for determining optimum tillage depth on-the-go. However, currently, there is no equipment available to automatically control the tillage depth to match the soil physical properties.

Cotton is one of the most important crops in the southern USA with an estimated production value of $6 billion (USDA-NASS 2016). The crop is produced on over 5.5 million hectares (13-14 million acres) from California to the Carolinas. More than 440,000 jobs in the USA are directly associated with the cotton industry, generating revenue in excess of $120 billion (A.G. Jordan, 2004, National Cotton Council). Cotton root growth is often hindered in the Southeastern U.S. due to the presence of root-restricting soil layers. In this region, removal of the hardpan (by deep tillage, controlled traffic, etc.) has shown to enhance cotton plant performance and increase lint yields significantly (Garner et al., 1989; Khalilian et al., 1991; Khalilian et al., 2004, Marshall et al., 20016, Khalilian et al., 2017). However, the effects of site-specific tillage on cotton plant responses and yield cannot be found in published literature.

One of the main objectives of the experiment was to determine how Cotton (Gossypium hirsutum L.) was affected by utilizing this on the go variable depth tillage system. This experiment utilized a two-acre field at the Clemson’s Edisto Research and Education Center. This field was equipped with an overhead irrigation system to promote
optimal testing conditions. The field was divided into two soil texture zones using soil electrical conductivity (EC) data collected before planting.

Figure 1.1.1: A typical soil profile of the Coastal Plain in the Southern USA
1.1.1 OBJECTIVES

The overall objective of this study was to develop and test equipment for controlling tillage depth “on-the-go” to match soil physical parameters and to determine the effects of the new system on crop responses. To achieve this main objective, the following sub-objectives were outlined:

1) To combine the existing instrumented shank and the depth control systems to develop the “Clemson Intelligent Plow.”

2) To develop an electronic control system and custom software for this new system.

3) To determine the feasibility of using site-specific tillage to alleviate root-restrictions to improve profitability.

4) To evaluate the effects of The Clemson Intelligent Plow on soil properties and crop responses in cotton production.
1.2 LITERATURE REVIEW

This section is a review of the literature related to the study objectives, and it consists of four subheadings:

1) Soil compaction management in Coastal Plain soils,

2) Methods for measuring soil compaction,

3) Effect of soil compaction on root growth and yield, and

4) On-the-go hardpan detection and variable depth tillage.

1.2.1 Soil Compaction Management in Coastal Plain Soils

Nationwide farmers across the U.S. lose over $1 billion in crop revenues every year due to the effects of soil compaction (Clark et al., 1993). Reduction of losses due to soil compaction by one percent nationally could result in an additional $100 million in crop revenue. Chronic soil compaction is a significant problem among coastal plain soils in the Southern USA. Although reasons for compaction are not fully understood, it is assumed that low organic matter content and the nonexpanding clay predispose these soils to subsurface compaction (Siemens et al., 1993). The soil profile in this region is comprised of three distinct textural layers: A horizon - sandy to loamy sand, E horizon - yellowish-brown sandy to sandy clay, and Bt horizon - sandy clay loam (Figure 1.1). The E horizon has higher bulk density and a lower water holding capacity (less than 0.1 cm/cm) due to
predominantly sandy texture with very low organic matter content (less than 1%). This 
compacted zone or hardpan usually occurs at a depth of 25 to 40 cm in the soil profile 
and ranges from 5 to 20 cm in thickness (Gorucu et al., 2006). Typically, the hardpan layer 
limits root penetration below the plowing depth which reduces crop yield potential during 
drought stress conditions. For optimum crop productivity and yield, the E horizon must 
be broken using deep tillage so that roots can reach into the Bt horizon where water and 
nutrients are more plentiful (Khalilian et al., 1991). Soil compaction management in the 
Southern USA relies heavily on the use of annual deep tillage before planting, which have 
been shown to improve cotton lint yields (Garner et al., 1989; Khalilian et al., 1991; 
Khalilian et al., 2004, Marshall et al., 2016, Khalilian et al., 2017). The recommended 
tillage depth for Coastal Plain regions is usually about 35 to 40 cm (14 to 16 in.) deep 
(Garner et al., 1984; Reid, 1978; Campbell et al., 1974; Raper et al., 1994). Deep tillage on 
these soils can be accomplished with implements that have either straight or bent-leg 
shanks. Bent-leg implements, such as Paratill and Terra Max, are commercially available 
for crop production. Previous research in South Carolina has shown that bent-leg shanks 
loosened a greater volume of the compacted layer compared to the straight-legged 
shanks (Garner et al., 1989, Khalilian et al., 1991 and 2000). For example, conventional 
tillage cotton production systems in the coastal plain region of the Southern USA require 
a minimum of three to five field operations at the cost of approximately $90 per hectare 
(Marshall et al., 2016).
The effect of deep tillage on soil compaction has been quantified in other studies. According to Hall and Raper (2005), in-row subsoiling reduced or alleviated the problem of excessive soil strength. Khalilian et al., (2005), stated that the use of annual deep tillage drastically reduced the in-row soil compaction in Coastal plain soils.

Due to significant variability in depth and thickness of hardpan layers in Coastal Plain soils (Raper et al., 2000; Gorucu et al., 2006), applying uniform-depth tillage over the entire field may be either too shallow to fracture the hardpan or deeper than required resulting in excess fuel consumption and an inefficient use of energy. Therefore, significant savings in tillage energy could be achieved by adjusting tillage depth to match soil’s physical properties. However, growers don’t know the depth and thickness of the hardpan or where the hardpan is located within a given field.

1.2.2 Methods for Measuring Soil Compaction

The depth and thickness of the hardpan layer have been quantified by using ground penetrating radar, bulk density measurements, visual observations, soil cone penetrometer, and draft force. Within these methods, the soil cone penetrometer is perhaps the most accurate method for determining the depth and thickness of the compacted layers, but it has some limitations. A soil cone penetrometer (a stop-and-go procedure) provides discrete point measurements and provides a poor characterization of hardpan depth if the field is large, unless an impractically large number of samples are collected, which would be very costly when it comes to the amount of time and labor
requirements. The visual observation and bulk density methods also suffer from the same aspect, being costly and point specific rather than continuous measurements. Using these methods, one can interpolate between the point samples and create a relatively accurate map of compaction, but a true continuous soil map cannot be made. With the visual observation method, the accuracy is also limited by the perspective of the person who is inspecting the soil cores. This introduces more error and inaccuracy into the determination of the hardpan depth and thickness.

Utilizing ground penetrating radar is another method of detecting the compaction in the soil (Freeland et al., 1998; Petersen et al., 2006). This method uses short electromagnetic pulses radiated into the soil from an antenna that is mounted close to the soil surface. When the waves bounce back from the different density layers and objects in the soil, they are detected by a receiver. The signals then are processed to produce a continuous map of the soil profile. When using a 300-MHz antenna on the ground penetrating radars transmitter, crossing severely compacted soil produces a distorted signal from the upper profiles. At present, obtaining absolute quantitative compaction values by radar image alone is not feasible (Freeland et al., 1998). This method is likely uncommon due to the high cost of ground penetrating radar equipment.

Gorucu et al. (2006) utilized soil cone penetrometer readings to develop an algorithm to determine the optimal tillage depth. They proposed six different patterns of cone index profiles and that each pattern needed a unique tillage depth. Each pattern had a specific set of conditions to determine the optimal tillage depth. These sets of conditions
were based on the characteristics of graphical depictions of penetrometer samples. Specifically, the number of times in one sample that the pressure level detected by the penetrometer exceeded the limiting cone index value of 2.07 MPa (Taylor and Gardner, 1963) determined the condition number. This method proves to be accurate and very useful in research practices but is time-consuming. Also, using a penetrometer data for an on the go system proves impractical because of the need to stop to collect data.

1.2.3 Effect of Soil Compaction on Root Growth and Yield

Soil bulk density and soil strength are two of the most important factors in plant health. Soil strength is the ability of the soil to withstand external forces without failure. In other words, if the soil strength is too high, then the roots will not be able to grow deep enough to reach the more nutrient and water rich layers. On the other hand, if the soil is weak, then the plants will not be able to anchor themselves firmly into the soil and can easily be blown over or uprooted (Gorucu et al., 2006).

There have been many studies to determine the limiting soil strength that would prevent root penetration and also how this limitation affects crop yields. The effects of soil bulk density, moisture content, and soil strength on the penetration of cotton roots were evaluated by Taylor and Gardner (1963). They were able to find a strong negative correlation ($r = -0.96$) between soil strength and taproot penetration. Their findings showed that only 30 percent of the cotton taproots were able to penetrate into the soil when the soil strength exceeded 2 MPa or 290 psi. They also stated that moisture content
and bulk density had significant effects but that the main factor in tap root penetration was soil strength.

Khalilian et al., 2017 reported that cotton taproots measured six weeks after planting were significantly longer in all plots receiving subsoiling than in the no-till plots. This occurred in both the irrigated and the dry land experiments. Similar results were obtained with total root dry weight. Deep tillage significantly increased lint yields compared to no-till. Averaged over all treatments, irrigation increased lint yields by 77% compared to dry land in a dry year. There was no difference in lint yield between plots which had deep tillage operation in all three years (2002 to 2004) with those which had tillage operation only in the first year of the test. Therefore, with controlled traffic and planting directly into the previous year’s subsoiler furrow, the residual effect of deep tillage operations could extend for one or two additional years in coastal plain soils without causing farmers a loss of crop yield.

Marshall et al., 2016 reported that cool season cover crop significantly reduced soil compaction in the E-horizon (20-30 cm depth) without a deep tillage operation. Averaged over the entire field, the cone index values in the cool season cover crop plots were below the 2Mpa compaction threshold measured at the end of the production season. Reductions in soil compaction due to the cool season cover crop significantly increased cotton lint yield in the no-till plots (38%). There was also a strong linear correlation between cool season cover crop biomass and cotton lint yield increase.
Ehlers et al. (1983) studied the effect of soil strength in the root growth of oats in tilled and untilled soils. They also observed that soil strength was the limiting factor in root growth. They concluded that the limiting resistance for root growth was 3.6 MPa or 522 psi in tilled soil and 4.6 to 5.1 MPa or 667 to 740 psi in untilled soil. They also stated that the increased limiting resistance in untilled soils was the bio-pores created by earthworms or roots during the growing season.

Alimardani et al. (2007) stated that soil compaction is an important problem in the coastal plain region. Soil compaction restricts the root growth into the deeper layers that are rich in soil moisture and nutrients. It is also stated that the main soil properties that contribute to the energy requirements of deep tillage are moisture content, bulk density, cone index, and soil texture.

1.2.4 On-the-Go Hardpan Detection and Variable Depth Tillage

As mentioned earlier, growers in the Southeastern Coastal Plain region rely heavily on the use of annual uniform-depth deep tillage to manage soil compaction. However, farmers do not usually know if annual subsoiling is required, where it is required in a field, nor the required depth of subsoiling. Also, there is significant variability in depth and thickness of hardpan layers from field to field and also within a field (Raper et al., 2000a, 2000b; Clark, 1999; Gorucu et al., 2006). Therefore, applying uniform-depth tillage over the entire field may be either too shallow to fracture the hardpan or deeper than required resulting in excess fuel consumption (Khalilian et al., 2014). Gorucu et al., (2006) stated
that ideally both the depth and thickness of the hardpan needs to be known to accurately control a variable depth tillage system. Also, there is little to no gain from tilling deeper than required to fracture the compacted layer (Garner et al., 1986).

A number of researchers have attempted to develop equipment for continuous measurement of soil strength at multiple depths (Glancey et al., 1989; Alihamsyah et al., 1990; Adamchuk et al., 2001; Khalilian et al., 2002; Hall and Raper, 2005; Siefken et al., 2005; Chung et al., 2006; Khalilian et al., 2014). Although these systems have potential to significantly reduce the cost of data collection for research and production use, they are still in development stages, and more data are needed under various soils and operating conditions to increase their potential use by producers and researchers. Out of all the equipment for continuous measurement of soil strength (cited in literature) only one has been tested under Southeastern Coastal Plain sandy soils (Khalilian et al., 2014).

Glancey et al. (1989) designed, fabricated and tested a chisel to be used for force distribution and soil fracture mechanics investigations. They were able to develop a mathematical technique to determine the cutting force distribution over the depth of the chisel. The predicted force distribution to an operating depth of 15 cm was linear for both high and low operating speeds. On the other hand, the predicted force distribution over the chisel operating depth was found to be nonlinear when the chisel was operated at a depth of 30 cm (12 in). Therefore, they reported that the chisel method (used in their study) was inadequate at soil depths greater than approximately 15 cm (6 in).
Kostic et al. (2016) used a soil tillage resistance sensor that was only able to appropriately measure the compaction levels in the top 15 cm of the soil. Whereas the Instrumented shank utilized at Clemson was capable of accurately measuring the hardpan depth and thickness to a depth of 46 cm (Khalilian et al., 2014).

Hall and Raper (2005) developed an on-the-go soil strength sensor that acts similarly to a horizontal penetrometer. It has interchangeable tip sizes that are mounted on a steel shank. They reported the maximum depth reading for this system to be approximately 60 cm (24 in) which is better than most of the other systems. The system allows for manual adjustment of the sensing depth but can only measure the compaction levels at one set depth at a time. When looking at a graph of the shank measured vs penetrometer measured forces, the shank appears to be relatively accurate. Though this system appears to be capable of determining soil strength at a specified depth, it cannot sense the soil strength at a range of depths at one time. This limitation makes sensing the true depth and thickness of the hardpan a multi-step procedure. The shank would need to be run through the field at several different depths to create a profile of the top 45 cm of the soil. On the other hand, if the only information you need is the soil strength as a specified depth throughout a field, this is likely the most efficient method.

Real-time, sensor-based, site-specific tillage could achieve significant savings in tillage frequency and energy and increase crop yields in the Southeastern Coastal Plain region (Gorucu et al., 2001; Abbaspour et al., 2006). Spatial cone index measurements to
map the variability in root-restricting layers showed that about 75% of the field required shallower tillage depth than 37.5 cm (15 in), the recommended tillage depth for coastal plains soils (Gorucu et al., 2001; Raper et al., 2002). Therefore, this variability leads us to believe that, by adjusting tillage depth on-the-go to match the depth and thickness of the hardpan layer, significant savings in tillage energy could be achieved.

Khalilian et al. (2014) developed map-based equipment for determining the optimum tillage depth. However, there is currently no equipment available to automatically control the tillage depth to match the soil physical properties. Development of such a system is an essential step toward site-specific soil compaction management.
1.3 METHODS AND MATERIALS

1.3.1 Design Criteria

A variable-depth tillage system (the Clemson Intelligent Plow) was designed and constructed using the following criteria. The system should:

- Measure and record mechanical impedance of soil at multiple depths over the entire top 45-cm (18-in) of soil profile while moving through the soil.
- Calculate the depth and thickness of the hardpan layer, based on modified algorithm given by Gorucu et al., (2006).
- Control tillage depth on-the-go based on inputs from the instrumented shank, prescription maps, or manually from the tractors’ cab.
- Communicate with a GPS receiver.
- Measure and record fuel consumption, and tillage depth during the operation.
- Protect all of the instrumentation during operation.
- Incorporate user-friendly custom software and control system.

1.3.2 Equipment Development

1.3.2.1 Instrumented Shank: The instrumented shank developed at Clemson University (Khalilian et al., 2014) was modified for determining the mechanical impedance of soil at multiple depths over the entire top 45-cm (18-in) of soil profile while moving through the
soil. The instrumented subsoiler shank consisted of five 7.5-cm long sections attached to the subsoiler shank using load cells (Khalilian et al., 2002). The width of each section was 2.5 cm, and the face of each section was flat and perpendicular to the direction of travel. Two compression load cells (Model MSSP- COMP, 8896-N National Scale Technology, Huntsville, Ala.) were used in each 7.5-cm section to measure the horizontal force acting on the subsoiler shank (Figure 1.3.2.1.1).

Figure 1.3.2.1.1: Design and components of the instrumented shank

The sum of two load cells was used to calculate the total force acting on each section of the instrumented shank. By applying known forces and measuring output voltages for each section the shank was calibrated. Using a dynamometer, each section
on the instrumented shank was accurately loaded and then using the custom software (explained in the next sections), the output of each load cell was recorded and used to develop a calibration equation. Figure 1.3.2.1.2 shows the calibration apparatus used for this purpose and Figure 1.3.2.1.3 shows the calibration equations for each load cell pair. It should be noted that the shank thickness, shank position on the frame and sharpening angle of the subsoiler shank may affect the horizontal forces measured for field data. The gage wheels were used to control the depth of the subsoiler shank in a way that the lower part of the bottom instrumented section on the subsoiler shank would always be at a depth of 45-cm.
Figure 1.3.2.1.2: Calibration apparatus for each instrumented shank section.
The shank did not measure the mechanical impedance of the top 7.5-cm of the soil profile. Therefore, it measured only the force required to break through the soil surface between the 7.5 and 45 cm depth. The horizontal force on each load cell pair was collected at 100 Hz and averaged every one second for use in determining the optimum tillage depth. Averaging the force every second reduced the likelihood of the system changing its depth unnecessarily when hitting a rock or other object in the soil. Dividing the horizontal force by the area of the load cell plate 19-cm$^2$ (3-in$^2$) resulted in the amount of pressure acting on the plate, called the shank index. The horizontal pressure measured during tillage operation (the shank index) was then converted to cone index values using

Figure 1.3.2.1.3: Calibration equations for each instrumented shank section.
the equation published in Khalilian et al. (2014). The equation is as follows where CI stands for cone index and SI stands for shank index which was the sum of each load cell pair.

\[ CI = 1.5089 \times SI + 0.7801 \]

This conversion equation makes it possible to convert the shank index values to standard soil compaction measurement criteria, such as a cone penetrometer output (Cone index). Therefore, the maximum allowable level of compaction (2.07MPa or 300 PSI) for optimum crop performance could be used to determine the depth and thickness of the hardpan layer. Without converting the shank index into cone index there would be no available reference to use as a maximum allowable level of compaction.

The length of the instrumented was changed for use with the variable depth tillage system. A 2.5-cm thick by 15.3-cm wide flat bar was used for this purpose. The instrument shank and the flat bar was cut in “tongue and groove” pattern for a strong welded bond. Once the metal surfaces were prepared the two pieces were welded together using the shielded metal arc welding process (stick welder). Once welded the metal bond was hardened and tested for its structural integrity. The new shank length was 163-cm long.

1.3.2.2 Depth Control System: GPS-based equipment for controlling the tillage depth to match soil physical parameters was developed. The gage wheels on a four-row subsoiler were attached to an electro-hydraulic actuator (Parker Hannifin Co. model 03.25BB-HXLTS24A). The actuator moves the gage wheels upward or downward to
control the tillage depth on the go. The hydraulic cylinder is equipped with a dual element type linear potentiometer, which provides an analog feedback signal of the cylinder’s position. The spool of a proportional directional control valve (Parker series D1FX-CK) shifts in either direction in response to variable command signals, thus providing the desired length of extension of the hydraulic cylinder. Once the spool reaches the desired position, the internal potentiometer sends a feedback signal to the drive amplifier to maintain that position. The proportional directional control valve was controlled by a negative five volts to positive five volts direct current signal. When positive five volts was applied to the control system, the cylinder would retract to fully closed position, corresponding to 45-cm tillage depth. The opposite effect for negative five volts would fully extend the electro-hydraulic actuator correspondent to zero tillage depth. This system can extend the hydraulic cylinder to any length in-between zero and 45-cm using the calibration equation shown in Figure 1.3.2.2.1.
1.3.2.3 The Clemson Intelligent Plow: This project aimed to develop a system that will mount directly on the tractor and continuously measure the depth to the hardpan and adjust the tillage depth accordingly “intelligent Plow”. The new system was designed to measure soil compaction data, calculate the depth and thickness of the hardpan layer, and adjust tillage depth on-the-go for real-time, variable-depth, tillage operations for crop production. This was achieved by combining two systems “Instrumented Shank” and “Depth Control System” described above. The new “Clemson Intelligent Plow” was designed using SOLIDWORKS® software to allow for fabrication of all necessary components. Figure 1.3.2.3.1 the 3D sketch of the new design. With this
system, tillage depth can be changed from zero to 45 cm. Inputs for decision-making could be from the instrumented shank (real time) or controlled manually with a one-turn potentiometer located inside the tractor cab.

Figure 1.3.2.3.1: Solid Works rendering of the Clemson Intelligent Plow

The instrumented shank was attached to the system using two L-brackets bolted to the top bar of the gauge wheels. Also, the shank was supported using four L-brackets on the main beam of the four-row subsoiler. Teflon spacers were added between the brackets to ensure that the instrumented shank would not bind and have the ability to
move smoothly. A solid steel roller wheel (5 cm diameter) with a 1.25 cm sheer pin was used to protect the instrumented shank, to keep it perfectly vertical, and to ensure that it would freely move with respect to the remaining three subsoiler shanks. Once the final attachments were added and tested the system was painted to reduce the likelihood of corrosion. This is shown below in Figure 1.3.2.3.2.

![Figure 1.3.2.3.2: The Clemson Intelligent Plow](image)

1.3.3 Instrumented Tractor

An instrumented John Deere 7710 tractor (116 kW) was used to make in field measurements of tractor fuel consumption, and ground speed of the different tillage treatments. The instrumented tractor was equipped with a fuel flow meter (Model: Fuel
View DFM-50C-K), which produced 200 pulses per liter of fuel that passed through it. The fuel flow meter was tested to ensure its accuracy, and it was found that the factory calibration provided was very accurate with an error of less than 1% (Table 1.3.3.1).

<table>
<thead>
<tr>
<th>Metered Flow (LPM)</th>
<th>Metered Flow (GPM)</th>
<th>True (LPM)</th>
<th>True (GPM)</th>
<th>Absolute Percent Error[d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.513</td>
<td>0.136</td>
<td>0.505</td>
<td>0.133</td>
<td>2%</td>
</tr>
<tr>
<td>0.74</td>
<td>0.195</td>
<td>0.74</td>
<td>0.196</td>
<td>0%</td>
</tr>
<tr>
<td>0.407</td>
<td>0.108</td>
<td>0.404</td>
<td>0.107</td>
<td>1%</td>
</tr>
<tr>
<td>0.201</td>
<td>0.053</td>
<td>0.202</td>
<td>0.053</td>
<td>0%</td>
</tr>
<tr>
<td>0.678</td>
<td>0.179</td>
<td>0.673</td>
<td>0.178</td>
<td>1%</td>
</tr>
<tr>
<td>0.44</td>
<td>0.116</td>
<td>0.438</td>
<td>0.116</td>
<td>0%</td>
</tr>
<tr>
<td>0.468</td>
<td>0.124</td>
<td>0.471</td>
<td>0.124</td>
<td>1%</td>
</tr>
<tr>
<td>0.41</td>
<td>0.108</td>
<td>0.404</td>
<td>0.107</td>
<td>1%</td>
</tr>
<tr>
<td>0.373</td>
<td>0.099</td>
<td>0.37</td>
<td>0.098</td>
<td>1%</td>
</tr>
<tr>
<td>0.241</td>
<td>0.064</td>
<td>0.236</td>
<td>0.062</td>
<td>2%</td>
</tr>
<tr>
<td>0.205</td>
<td>0.054</td>
<td>0.202</td>
<td>0.053</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average Absolute Error</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.95982%</td>
</tr>
</tbody>
</table>

Table 1.3.3.1: Fuel flow meter accuracy test.

1.3.4 Data Logger and Control System

1.3.4.1 Data Logger: The Clemson instrumented shank originally used the LogBook/360 data logger (IOTech, Inc., Cleveland, OH) to log and read the compaction data. This system was updated with three Phidgets Wheatstone bridges to read the shank index data. Each of these bridges could read up to four load cells. The Phidgets Wheatstone bridge outputs five volts to the load cells and measures the return signal. The data is then transferred to an on-board computer via USB cable, where it is used to
calculate the pressure on each section of the instrumented shank. The program then converted the measured data into cone index to be utilized in calculating the optimal tillage depth. The optimal tillage depth was calculated on-the-go using an algorithm developed at Clemson (Gorucu et al., 2006).

The Phidgets analog output circuit board sends a plus or minus five-volt DC signal to the hydraulic cylinder control system for adjusting the tillage depth. The Phidgets analog output is also capable of sending negative to positive 10 volts DC if it was necessary for running other instrumentation. This allowed us to easily control the tillage depth using custom software described in the next section. A Phidgets frequency counter circuit board was used to read the output of the fuel flow meter (Fuel View DFM-50C-K) to enable us to measure real-time fuel consumption. The frequency counter was programmed to count the pulses that sent out by the fuel flow meter. With this system, every 200 pulses were equivalent to one liter of fuel. This also allowed us to measure the average fuel consumption for a given tillage depth for a specific tillage treatment. All of the Phidgets boards were wired into one quick disconnect box that was custom built for this application. This quick disconnect box allows for easy removal of the entire system from the tractor cab. The box is shown below in Figure 1.3.4.1.1.
1.2.4.2 Custom Software: Custom software was developed in Visual Basic to support the Clemson Intelligent-Plow. The software enables the user to visualize and log the data from all instrumentation in real time and control the tillage depth on-the-go. The main page of this program is shown in Figure 1.3.4.2.1. This program included the necessary requirements to read four Wheatstone bridges, a Phidgets analog output, a Phidgets frequency counter and to receive GPS position from any serial GPS receiver. In addition to allowing the user to control the Clemson Intelligent plow it also logs fuel consumption.
In the main page of the custom software, the raw data, as well as the calculated values, are displayed. The optimum tillage depth is calculated as shown in the flow chart below (Figure 1.3.4.2.2).
Figure 1.3.4.2.2: Tillage depth control system flow chart
The Program brings all the data in from the instrumented shank and sums each load cell pair. It then converts this raw bridge data to load using the calibration equations in Figure 1.3.2.1.3. Next, this load in pounds is converted to MPa and run through the shank index to cone index conversion equation. Then, it determines the optimum tillage depth based on the flow chart above. Lastly, the system sends the control voltage to the hydraulic depth adjustment system. The program is also equipped with GPS tracking to display the user’s current position in the field. In addition to the GPS tracking, the software also included the functionality to display a color-coded icon to enable the operator to visualize tillage depth at a given location in the field during the tillage operation.

1.3.5. DATA COLLECTION

To create a preseason map of the hardpan in the field, a microcomputer-based, tractor-mounted recording penetrometer, equipped with GPS system was used to quantify geo-referenced soil penetration resistance in the test field. Soil compaction values were calculated from the measured force required pushing a 3.23 cm$^2$ base area, 30-degree cone into the soil (ASABE Standards, R2013). The penetrometer was equipped with a hydraulic cylinder with a load cell and a penetrometer rod attached in that order. A flow control valve was used to achieve the ASABE recommended penetration rate of 3 cm/s (72 in./min). This allowed for relatively fast and highly accurate readings across the entire field compared to using a handheld penetrometer. The cylinder was controlled
with a flow control valve and a bidirectional valve. The depth of the penetrometer was measured using an instrumented guide rod with gear groves and an attached 10-turn potentiometer. The penetrometer system was hooked up to a Toughbook computer with software developed and calibrated at Clemson in 2016. The Penetrometers schematic drawing is shown in figure 1.3.5.1 followed by image of the actual mechanized penetrometer figure 1.3.5.2.

Figure 1.3.5.1: Schematic diagram of the soil compaction measurement system.

(1: cone tip, 2: load cell, 3: depth sensor, 4: ground surface detection switch, 5: GPS unit, 6: DGPS antenna, 7: computer and data acquisition system, 8: circuitry box)
Soil electrical conductivity was measured across the entire field to create a soil texture map. The soil electrical conductivity data were collected using a Veris 3100 electrical conductivity measurement system. The system can measure the electrical conductivity continuously across the field at two different depths (30 cm and 90 cm). This system also incorporated a GPS system so that all the data collected with this unit is geo-referenced. This allows the user to create a map based on the electro-conductivity data collected in the field. The implement can be operated at the travel speeds of 12 to 19 km/h. However, for this test, it was operated at 3.2 km/h to increase density of the data point within each plot. A swath width of 2.35 meters was used to cover each 4-row
cotton plots. The Veris 3100 electrical conductivity measurement system is shown below in figure 1.3.5.3.

Figure 1.3.5.3: Veris 3100 soil electrical conductivity measurement system used in the study.

1.3.6. Test Field

Replicated field tests were conducted to determine the performance of the Clemson Intelligent Plow. A one-hectare test field at the Edisto Research and Education Center of Clemson University near Blackville South Carolina (Latitude 33.359473° N, Longitude 81.332239° W), was mapped for variation in soil texture, using a soil electrical conductivity (EC) measurement system (Veris-3100). The test field was then divided into two management zones based on soil EC values, and 20 rectangular plots (4-row by 28 m) were assigned in each zone, for a total of 40 plots in the test field. The microcomputer-
based, tractor-mounted recording penetrometer was used to collect soil compaction data from each plot, before tillage operations and at cotton harvest. Three sets of penetrometer measurements were obtained from each plot. The optimum tillage depth in each plot was determined utilizing the penetrometer data, and an algorithm developed at Clemson (Gorucu et al., 2006).

The following four tillage treatments were applied at random to plots of each zone. A randomized complete block design with five replications was the statistical model selected for evaluating treatments.

1. Variable depth tillage based on real-time measurements of depth and thickness of the hardpan layer, using the intelligent plow (VDT);

2. Conventional tillage, constant depth, 38-cm (CON);

3. Tillage depth based on average penetrometer data (AP); and

4. No deep tillage operations (NT).

The plot plan for this experiment is shown below with low EC zones colored white and high EC zones highlighted red (Figure 1.3.6.1).
<table>
<thead>
<tr>
<th></th>
<th>Con</th>
<th>NT</th>
<th>VDT</th>
<th>Con</th>
<th>NT</th>
<th>AP</th>
<th>VDT</th>
<th>Con</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDT</td>
<td>NT</td>
<td>Con</td>
<td>AP</td>
<td>NT</td>
<td>VDT</td>
<td>NT</td>
<td>AP</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>NT</td>
<td>VDT</td>
<td>AP</td>
<td>VDT</td>
<td>AP</td>
<td>VDT</td>
<td>AP</td>
<td>Con</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Con</td>
<td>NT</td>
<td>AP</td>
<td>Con</td>
<td>VDT</td>
<td>NT</td>
<td>Con</td>
<td>NT</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>AP</td>
<td>VDT</td>
<td>Con</td>
<td>AP</td>
<td>NT</td>
<td>AP</td>
<td>Con</td>
<td>VDT</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

| 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |

**Figure 1.3.6.1:** 2017 Variable depth tillage test plot plan
Electrical conductivity data were collected on May 3rd, 2017 with a travel speed of 3.2 km/h to maximize the number of data points in each plot. Gramoxone was sprayed across the entire field on May 4th, 2017, to kill the volunteer peanuts and the weeds that had infested the field after harvest of the previous crops. Penetrometer data was collected on the May 16th, 2017. The following day, the test field was divided into plots, and four different tillage treatments were applied. Cotton (DP-1646-B2XF) was planted on May 18th, 2017 using a John Deer 1700 planter. Temik 15G, (5.6 kg/ha) was applied at planting for controlling nematodes and thrips. Following herbicides were applied for weed control: June 5th, 2017, Dicamba 1.6 l/ha and 2.3 l/ha of Roundup Max. In addition, on June 15th Liberty and Roundup Max were sprayed at 2.3 l/ha. The last round of herbicides (Dicamba and Roundup Max) was sprayed on July 7th at a rate of 1.6 l/ha. One week later, on July 14th 100 kg/ha liquid Nitrogen (S25) was applied to all plots. To slow the foliage growth of the cotton, 0.3 l/ha Pix was applied on July 20th along with 0.4 l/ha of Bidrin (insecticide) and 1.5 l/ha of Boron. Boron is commonly used to increase boll growth and health. Cotton was harvested on October 2017 using a 4-row cotton spindle type picker, equipped with weighting baskets. A second round of penetrometer data was collected post-harvest to determine the effects of the different tillage treatments on soil compaction.

To compare the root growth restrictions between the different treatments, 200 plants were carefully dug up, without breaking the tap root. Five plants per plot were bagged and labeled to keep them all in order. Next, the tap roots were cut off and tap
root length, and plant height were measured. All the roots were oven dried and weighed to determine root dry weight. All of the data was analyzed in the SAS software package (SAS v. 9.4, SAS Institute Inc., Cary, NC).
1.4 RESULTS AND DISCUSSION

Figure 1.4.1 shows the required tillage depth of the one-hectare test field based on the penetrometer data collected before any tillage operations using the Clemson optimal tillage depth algorithm. Based on average penetrometer data (AP), deep tillage was not needed in 52% of the test field (Figure 1.4.1). Only 20% of the field required tillage at recommended depth for Coastal Plain regions (38.1 cm deep).

![Required Tillage Depth](image)

Figure 1.4.1: Required tillage depths for the one-hectare test field, 2017.

This speaks volumes to the variability we have in coastal plain soils and the need for variable depth tillage. The result agrees with other researchers work on Coastal Plain soils (Gorucu et al., 2001; Raper et al., 2002; Abbaspour et al. 2006) they reported that, based on spatial cone index measurements the variability in root-restricting layers
showed that about 80% of the fields required shallower tillage depth than 37.5 cm (15 in), the recommended tillage depth for coastal plains soils. With conventional tillage practices, growers are unable to completely remove the hard pan layer, without tilling significantly deeper than required. Therefore, his conventional method waste significant amount of fuel.

As shown in Figure 1.4.2, the fuel requirement for “No-Tillage” (0 cm) was 8.7 l/hr. This amount of fuel was needed for just driving the JD-7710 (116 kW) tractor from one part of the field to another, without performing tillage operations. Therefore, in this field conventional deep tillage operations (38 cm deep) would have required 52% more fuel than site-specific tillage (based on penetrometer data). This provided confirmation that the fuel cost associated with deep tillage could be drastically reduced in Coastal Plain soils.
Cotton taproot length was determined by extracting five plants from each plot and measuring root length. To determine the total root weight for each sample in the data shown below, the roots were oven dried and then weighed (Table 1.4.1).
Table 1.4.1: Effects of different tillage treatments on cotton taproot length, plant height, and root weight, 2017.

<table>
<thead>
<tr>
<th>TRT</th>
<th>REP</th>
<th>ZONE</th>
<th>Plant/Plot ID</th>
<th>Plant Height</th>
<th>Root Length</th>
<th>Total Root weight</th>
<th>Root Weight/plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>1</td>
<td>1</td>
<td>A1</td>
<td>37</td>
<td>8.4</td>
<td>35.26</td>
<td>7.052</td>
</tr>
<tr>
<td>VDT</td>
<td>1</td>
<td>2</td>
<td>A2</td>
<td>50.6</td>
<td>13.8</td>
<td>52.36</td>
<td>10.472</td>
</tr>
<tr>
<td>CON</td>
<td>1</td>
<td>2</td>
<td>A3</td>
<td>52.8</td>
<td>17</td>
<td>58.7</td>
<td>11.74</td>
</tr>
<tr>
<td>NT</td>
<td>1</td>
<td>2</td>
<td>A4</td>
<td>44.4</td>
<td>5.1</td>
<td>70.2</td>
<td>14.04</td>
</tr>
<tr>
<td>AP</td>
<td>1</td>
<td>2</td>
<td>A5</td>
<td>48.8</td>
<td>11.8</td>
<td>57.42</td>
<td>11.484</td>
</tr>
<tr>
<td>AP</td>
<td>2</td>
<td>2</td>
<td>A6</td>
<td>46.8</td>
<td>8.7</td>
<td>58.9</td>
<td>11.78</td>
</tr>
<tr>
<td>CON</td>
<td>2</td>
<td>2</td>
<td>A7</td>
<td>53</td>
<td>10.8</td>
<td>48.08</td>
<td>9.616</td>
</tr>
<tr>
<td>VDT</td>
<td>2</td>
<td>2</td>
<td>A8</td>
<td>51</td>
<td>13.8</td>
<td>60.67</td>
<td>12.394</td>
</tr>
<tr>
<td>CON</td>
<td>1</td>
<td>1</td>
<td>B1</td>
<td>47.3</td>
<td>15.24</td>
<td>74.2</td>
<td>14.84</td>
</tr>
<tr>
<td>NT</td>
<td>2</td>
<td>2</td>
<td>B2</td>
<td>47</td>
<td>9.2</td>
<td>56.1</td>
<td>11.24</td>
</tr>
<tr>
<td>AP</td>
<td>3</td>
<td>2</td>
<td>B3</td>
<td>52.4</td>
<td>15.2</td>
<td>43.03</td>
<td>8.606</td>
</tr>
<tr>
<td>CON</td>
<td>3</td>
<td>2</td>
<td>B4</td>
<td>49.2</td>
<td>13.3</td>
<td>61.97</td>
<td>12.394</td>
</tr>
<tr>
<td>VDT</td>
<td>3</td>
<td>2</td>
<td>B5</td>
<td>52.4</td>
<td>17.2</td>
<td>61.87</td>
<td>12.394</td>
</tr>
<tr>
<td>NT</td>
<td>3</td>
<td>2</td>
<td>B6</td>
<td>50.2</td>
<td>10.2</td>
<td>84.71</td>
<td>16.942</td>
</tr>
<tr>
<td>CON</td>
<td>4</td>
<td>2</td>
<td>B7</td>
<td>52.2</td>
<td>13.9</td>
<td>50.47</td>
<td>10.094</td>
</tr>
<tr>
<td>NT</td>
<td>4</td>
<td>2</td>
<td>B8</td>
<td>48.4</td>
<td>7.8</td>
<td>53.27</td>
<td>10.654</td>
</tr>
<tr>
<td>NT</td>
<td>1</td>
<td>1</td>
<td>C1</td>
<td>42.8</td>
<td>4.3</td>
<td>76.61</td>
<td>15.322</td>
</tr>
<tr>
<td>VDT</td>
<td>4</td>
<td>2</td>
<td>C2</td>
<td>51.2</td>
<td>15.8</td>
<td>63.52</td>
<td>12.704</td>
</tr>
<tr>
<td>AP</td>
<td>4</td>
<td>2</td>
<td>C3</td>
<td>53.8</td>
<td>15.2</td>
<td>52.18</td>
<td>10.436</td>
</tr>
<tr>
<td>VDT</td>
<td>5</td>
<td>2</td>
<td>C4</td>
<td>51.4</td>
<td>12.7</td>
<td>52.08</td>
<td>10.436</td>
</tr>
<tr>
<td>AP</td>
<td>2</td>
<td>1</td>
<td>C6</td>
<td>54.4</td>
<td>16.9</td>
<td>50.47</td>
<td>10.094</td>
</tr>
<tr>
<td>VDT</td>
<td>2</td>
<td>1</td>
<td>C7</td>
<td>55.2</td>
<td>18</td>
<td>49.65</td>
<td>9.93</td>
</tr>
<tr>
<td>AP</td>
<td>5</td>
<td>2</td>
<td>C5</td>
<td>55.2</td>
<td>16.9</td>
<td>46.12</td>
<td>9.224</td>
</tr>
<tr>
<td>AP</td>
<td>2</td>
<td>1</td>
<td>C8</td>
<td>51.4</td>
<td>17.6</td>
<td>80.68</td>
<td>16.136</td>
</tr>
<tr>
<td>VDT</td>
<td>1</td>
<td>1</td>
<td>D1</td>
<td>43.6</td>
<td>9.8</td>
<td>83.16</td>
<td>16.632</td>
</tr>
<tr>
<td>NT</td>
<td>2</td>
<td>1</td>
<td>D2</td>
<td>43.6</td>
<td>9.8</td>
<td>36.12</td>
<td>7.224</td>
</tr>
<tr>
<td>CON</td>
<td>3</td>
<td>1</td>
<td>D3</td>
<td>47.4</td>
<td>11.5</td>
<td>56.21</td>
<td>11.242</td>
</tr>
<tr>
<td>AP</td>
<td>3</td>
<td>1</td>
<td>D4</td>
<td>47.6</td>
<td>16.3</td>
<td>56.41</td>
<td>11.282</td>
</tr>
<tr>
<td>NT</td>
<td>5</td>
<td>2</td>
<td>D5</td>
<td>47</td>
<td>10.1</td>
<td>39.4</td>
<td>7.88</td>
</tr>
<tr>
<td>VDT</td>
<td>3</td>
<td>1</td>
<td>D6</td>
<td>52.2</td>
<td>14</td>
<td>59.6</td>
<td>11.92</td>
</tr>
<tr>
<td>NT</td>
<td>3</td>
<td>1</td>
<td>D7</td>
<td>47</td>
<td>10.4</td>
<td>45.11</td>
<td>9.022</td>
</tr>
<tr>
<td>AP</td>
<td>4</td>
<td>1</td>
<td>D8</td>
<td>47</td>
<td>10.4</td>
<td>61.29</td>
<td>12.258</td>
</tr>
<tr>
<td>CON</td>
<td>4</td>
<td>1</td>
<td>E1</td>
<td>44.6</td>
<td>15</td>
<td>65.78</td>
<td>13.156</td>
</tr>
<tr>
<td>NT</td>
<td>4</td>
<td>1</td>
<td>E2</td>
<td>44</td>
<td>6.75</td>
<td>59.6</td>
<td>11.92</td>
</tr>
<tr>
<td>VDT</td>
<td>4</td>
<td>1</td>
<td>E3</td>
<td>52.2</td>
<td>18.7</td>
<td>61.42</td>
<td>12.284</td>
</tr>
<tr>
<td>CON</td>
<td>5</td>
<td>2</td>
<td>E4</td>
<td>48.2</td>
<td>13.7</td>
<td>64.86</td>
<td>16.972</td>
</tr>
<tr>
<td>NT</td>
<td>5</td>
<td>1</td>
<td>E5</td>
<td>41</td>
<td>4.6</td>
<td>26.43</td>
<td>5.286</td>
</tr>
<tr>
<td>AP</td>
<td>5</td>
<td>1</td>
<td>E6</td>
<td>45</td>
<td>11.4</td>
<td>49.08</td>
<td>9.816</td>
</tr>
<tr>
<td>VDT</td>
<td>5</td>
<td>1</td>
<td>E7</td>
<td>44.2</td>
<td>16</td>
<td>38.66</td>
<td>7.732</td>
</tr>
<tr>
<td>CON</td>
<td>5</td>
<td>1</td>
<td>E8</td>
<td>45.4</td>
<td>16.8</td>
<td>53.84</td>
<td>10.768</td>
</tr>
</tbody>
</table>
Statistically, there were no differences in taproot length between VDT, CON (conventional tillage), and AP (tillage depth calculated based on average penetrometer data). However, cotton taproots in the variable-depth tillage (VDT) plots were 64% longer than those in the no-till (NT) plots (Figure 1.4.3). Also, the measured plant heights in the no-till plots were 10.2 cm shorter than those in the variable depth tillage plots. Similar results were reported by Khalilian et al., 2004. There was no significant difference between the total cotton root weights based on the different tillage treatments. Due to the lack of statistical difference between the conventional and variable-depth tillage treatments we have proven that the tap root length is not negatively affected when using a variable-depth tillage system. Therefore, it is feasible to successfully use this technology in Coastal plain soils for crop production.
Figure 1.4.3: Effects of tillage systems on root length

Results also showed that, tillage operations based on either real-time sensor (VDT) or penetrometer data, reduced fuel consumption by 45% compared to conventional constant-depth tillage (Figure 1.4.4). This translates to an average saving of $2126.25 a year for a 404 hectare (1000 acre) field with only one deep tillage operation per year. Similar results were reported by Gorucu et al., 2001 and 2011. This significant increase in fuel efficiency further proves the ability of this tillage system to do the same task as conventional systems while decreasing the cost associated with the conventional
methods. This allows for farmers to increase profits without sacrificing yield potential. It also pushes forward the level of sustainability of tillage practices by only tilling where it is needed within a given field. This makes for better soil management practices and an overall better way to sustain the future of agriculture.

![Tillage System Fuel Consumption Chart](chart.png)

**Figure 1.4.4**: Effects of tillage systems on fuel consumption

Figure 1.4.5 shows the effects of tillage system on cotton lint yields. Statistically, there were no differences in cotton lint yields between conventional and the variable-depth tillage methods. However, as mentioned earlier the variable-depth tillage system required significantly less fuel during operation. Deep tillage (conventional or variable-
rate) increased cotton lint yields by 20% compared to no-till (NT). Once again, this system has proven to not negativity impact cotton plant performance or yield when compared to conventional practices. This leads to conclude that the new Clemson Intelligent Plow could be a wonderful innovation for managing soil compaction in production fields. This system has not only performed just as well as the existing methods but has drastically reduced the fuel consumption associated with deep tillage.

![Bar graph showing cotton lint yields by tillage system]

**Figure 1.4.5:** Effects of tillage systems on cotton lint yields (2017).

Figure 1.4.6 shows the effects of tillage systems on soil compaction at cotton harvest. Cone index values exceeding 2.07 MPa (300 psi), limits root penetration below
the compaction layer, reducing yields, and making plants more vulnerable to drought stress. Cone index values for both conventional and variable-depth tillage operations were below the limiting value of 2.07 MPa throughout the tillage depth (38 cm). both variable-depth and conventional tillage methods significantly reduced soil compaction compared to no-till. Results showed that, tillage operations based on average penetrometer data, did not remove the compacted layer (E horizon) in the test field completely. Cotton taproots were 14% shorter in these plots compared to variable-depth tillage plots. However, the difference was not statistically significant.

Figure 1.4.6: Effects of tillage systems on soil compaction at cotton harvest.
This graph also demonstrates that when using controlled traffic for all field operations both conventional and variable depth tillage methods have alleviated the hardpan problem for the entire growing season. Other research previously done at the Edisto Research and Education Center has suggested that deep tillage can alleviate the hardpan problem for two or in some cases three years when controlled traffic is employed (Khalilian et al., 2004 and 2017). In addition, they reported that there was no difference in lint yield between plots which were deep-tilled in all three years with those which had tillage operation only in the first year of the test.
1.5 CONCLUSION

Equipment was designed, developed and tested for controlling tillage depth “on-the-go” to match soil physical parameters. The new tillage system “Clemson Intelligent Plow” was constructed by combining an instrumented subsoiler shank and an on-the-go tillage depth controller. These two systems had to be combined both physically and electrically for the new plow to perform properly. Custom software was developed in Visual Basic to support the Clemson Intelligent-Plow. The software enabled the user to visualize and log the data from all instrumentation in real time and control the tillage depth on-the-go. The Clemson Intelligent plow closely followed the design specifications. It measured the mechanical impedance of soil at multiple depths over the entire top 45 cm of soil profile while moving through the soil. The gage wheels on the plow successfully controlled the tillage depth on-the-go, while maintaining the instrumented shank at a constant depth. With this system, tillage depth could be changed from zero to 45 cm. Inputs for decision-making could be from the instrumented shank (real time) or from soil compaction maps generated using a cone penetrometer measurement system. The tillage depth also could be controlled manually with a one-turn potentiometer located inside the tractor cab.

Replicated field tests were conducted to determine the performance of the Intelligent Plow. Site-specific tillage operations reduced fuel consumption by 45% compared to conventional constant-depth tillage. Only 20% of the test field required tillage at the commonly recommended depth for Coastal Plain regions (38-cm deep). Cotton taproots
in the variable-depth tillage plots were 96% longer than those in the no-till plots. Statistically, there were no differences in cotton lint yield between conventional and the variable-depth tillage. Deep tillage (conventional or variable-rate) increased cotton lint yields by 20% compared to no-till. Cone index values for both conventional and variable-depth tillage operations (measured at harvest) were below the limiting value of 2.07 MPa throughout the tillage depth (38 cm). Tillage significantly reduced soil compaction compared to no-till.
1.6 Future Study

To move this innovative technology (the Clemson Intelligent Plow) into farming communities, the system should be further tested on several Southeastern Coastal plain soils. This will help to determine the feasibility of utilizing this technology for managing soil compaction in this region.

Furthermore, to make adoption of this technology more attractive to growers, the system should be tested under actual farm conditions with different crops and soil types. In addition, the economic feasibility of utilizing this system and its component technologies needs to be determined and demonstrated to end users.

The new plow should be affordable, user friendly, and easy to operate. Therefore, other affordable ways to sense the soil compaction depth on-the-go, should be considered. This would eliminate the need for the instrumented shank and, therefore, further reducing the fuel consumption of this system.
REFERENCES


