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Locating the Variability of Soil Water Holding Capacity and Understanding Its Effects on Deficit Irrigation and Cotton Lint Yield

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I am submitting herewith a thesis written by Heath Adam Duncan entitled "Locating the Variability of Soil Water Holding Capacity and Understanding Its Effects on Deficit Irrigation and Cotton Lint Yield." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

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Locating the Variability of Soil Water Holding Capacity and Understanding Its Effects on Deficit Irrigation and Cotton Lint Yield

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ABSTRACT

Precision irrigation equipment such as variable-rate center pivots is readily available to Tennessee growers and producers; however, little research exists describing its application to cotton grown in Tennessee. In order to optimize the use of variable-rate irrigation equipment and water resources, two experiments were performed to determine (1) whether or not ground-penetrating radar (GPR) and electrical conductivity (EC) measurements can be used to delineate variable-rate irrigation zones and (2) examine the response of cotton lint yield to varying rates and duration of irrigation.

GPR and EC measurements were recorded, validated using soil cores, and used to identify the subsurface variability of soil texture, depth to a sandy layer (DTS), and soil available water holding capacity (AWHC) on a research location in Jackson, Tennessee. A strong, linear relationship between DTS and AWHC (R^2=0.92) indicated that a high resolution map of textural differences would provide a good approximation of AWHC variability. Both AWHC and DTS were related (R^2>70%) to both GPR and EC data. Variable-rate irrigation zones representing textural and AWHC variability were successfully partitioned using a combination of GPR and EC data.

Past cotton research regarding lint yield response to irrigation suggests that cotton irrigated on soils with a high AWHC might be negatively affected by the high irrigation rates required to maximize the yield of cotton grown on low

AWHC soils. Using three major soil blocks identified using GPR and EC data, varying levels of irrigation rate and duration were applied to cotton grown on soils with a low, moderate, and high AWHC. Statistical analysis shows that cotton grown on low AWHC soils responded differently (p=0.06) to irrigation treatments than cotton grown on moderate and high AWHC soils. In 2011, irrigating at 1.5 inches per week from first bloom until cracked boll resulted in approximately 1081 pounds of lint per acre increase in low AWHC soils but only 167 pounds of lint per acre increase in high AWHC soils. Also, this irrigation treatment resulted in a significant (alpha=0.10) lint yield decrease below maximum yield for high AWHC soils.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ATV	All-terrain vehicle
AWHC	Available water holding capacity
CMP	Common mid-point
DEC	Deep electrical conductivity
DTS	Depth to sand
EC	Electrical conductivity
F	Fahrenheit
GPR	Ground-penetrating radar
GPS	Global positioning system
MDTS	Measured depth to sand
MHz	Megahertz
mS/yd	milliSiemens per yard
psi	pounds per square inch
R	Reflection coefficient
RTK	Real-time kinematic
SEC	Shallow electrical conductivity
WTREC	West Tennessee Research and Education Center

INTRODUCTION

As precision irrigation equipment such as variable-rate center pivots becomes increasingly available to agricultural producers, research should be performed to determine how to best manage irrigation to optimize crop yield and water resources. The under-irrigation of crops leads to unnecessary water deficit stress, reduced yield, and an increased payback time for any loans used to purchase precision irrigation equipment. Over-irrigation of crops can lead to increased surface runoff of nutrients, fertilizers, and water as well as increasing the overall cost of irrigation and reducing profit. For cotton producers, over-irrigation has also been shown to reduce lint yield under certain circumstances.

The optimum amount of irrigation is closely related to the available water holding capacity (AWHC) of the soil. AWHC, a measure of the amount of water that can be held in the soil profile but still be available to the crop, must be accounted for when applying irrigation. A soil profile with a low AWHC will allow water to percolate through the soil profile quickly and will usually need to be irrigated at high rates or more frequently than soils with a high AWHC. A further complicating factor is that soil AWHC is closely related to soil texture, which is known to vary spatially in agricultural fields. Longwell et al. (1963) found soil AWHC to be consistently related to soil texture in soils throughout Tennessee. Fine sandy loams and silts tended to have the highest AWHC while an increase in either clay or sand content in the soil profile decreased the AWHC in a very predictable manner.

The formation of soils in the West Tennessee region has contributed to a high degree of spatial variability of soil texture and AWHC. Several layers of loess were deposited via glacial movement while erosion removed portions of loess deposits on slopes. Windblown deposits and alluvial soils can also be found throughout West Tennessee, and the effects of many years of conventional tillage have further increased the variability of soils due to erosion. In areas around West Tennessee, such as the research location used, low AWHC soil layers can be found at varying depths from the surface. When a large layer of sandy or other low AWHC texture is included into the soil profile of an otherwise high AWHC field, it alters the overall AWHC of the field and in turn affects the optimum irrigation rate.

Past research has shown that cotton, under the right conditions, can exhibit a strong, quadratic yield response to applied water (Gwathmey et al., 2011; Wanjura et al., 2002) while other research indicates that cotton on lower AWHC soils exhibits a more linear response to irrigation (DeTar, 2008; Bronson et al., 2006). Since Tennessee soils often exhibit a high degree of spatial variability of AWHC and it is possible that cotton irrigated on soils of variable AWHC will respond differently to irrigation, it is important to understand how the response of cotton grown on different soils might react to irrigation so that variable-rate irrigation equipment can be optimized to maximize yield and profit. Two experiments were performed in Jackson, Tennessee, to (1) use ground-penetrating radar and electrical conductivity to explore the variability of AWHC and partition appropriate variable-rate irrigation zones and (2) examine the response of cotton given varying rates and durations of supplemental irrigation on the previously determined variable-rate irrigation zones.

CHAPTER I

LOCATING AREAS OF VARYING WATER HOLDING CAPACITY

FOR VARIABLE-RATE IRRIGATION MANAGEMENT

Abstract

The number of producers and amount of acres irrigated in the state of Tennessee is steadily increasing. It is possible that variable-rate irrigation could be used to optimize irrigation and water resources; however, little research has been done to show how this equipment might benefit Tennessee cotton producers. Under-irrigation can cause unnecessary water deficit stress and yield loss, while over-irrigation is associated with increased surface runoff of water and nutrients, increased applied water cost, and loss of profit. Optimizing the use of variable-rate irrigation is especially important for a crop such as upland cotton, which can exhibit a quadratic yield response to applied water. The optimum amount of water needed irrigate cotton is closely related to the available water holding capacity (AWHC) of soil, which can exhibit a high degree of spatial variation as it is affected by soil characteristics such as bulk density and texture.

Ground-penetrating radar (GPR) and electrical conductivity (EC) measurements are two non-destructive methods of subsurface exploration that can quickly produce high resolution images of subsurface variability without the high cost and labor rate associated with soil sampling grids. Both of these technologies were used to examine the subsurface variability of a research field in Jackson, Tennessee that is known to contain significant amounts of soil texture and AWHC variability due to a layer of sandy, low AWHC soil at varying depths from the surface in an otherwise silt loam field. The goal of the

experiment was to determine whether or not these technologies can be used to determine the variability of AWHC and be used to identify and partition variable-rate irrigation zones.

GPR and EC data were recorded over cotton research plots and used to determine the average depth to the sandy layer (DTS) and EC measurement of each research plot, respectively. Soil cores were extracted and analyzed for soil texture and bulk density, which were used as inputs to the USDA ROSETTA model to calculate the average AWHC of each plot. DTS and AWHC were found to be strongly related (R^2 > 70%) to both GPR and EC measurements and DTS was very strongly (R^2 = 0.92) related to AWHC; however, the GPR and DEC datasets had to be combined to fully describe the variability found in the field. After combining the GPR and EC data to determine blocks of similar research plots, it was found that an irrigation experiment containing approximately seven irrigation treatments could be applied to the proposed irrigation zones.

Introduction

The 2008 Farm and Ranch Irrigation Survey found that the number of acres irrigated by U.S. farmers and ranchers increased by 4.6% to 54.9 million acres since 2003 (USDA NASS, 2009b). With precision irrigation equipment such as variable-rate center pivots becoming increasingly available to agricultural producers, emphasis should be placed on managing irrigation inputs in a fiscally and environmentally responsible manner. Crops that receive too little water from irrigation might not maximize either or both profit or yield on top of under-utilizing expensive irrigation inputs. Crops that receive too much water can result in wasted water resources, increased run-off and nutrient loss, reduced yield, and reduced profit. Even in fields subjected to the same crop, fertilization methods, and ambient conditions, the available water-holding capacity (AWHC) of the soil can affect the optimum irrigation rate. Proper and effective irrigation management, especially in areas of varying AWHC, plays a crucial role in optimizing the yield and profit potential of irrigation inputs.

AWHC is a measure of the amount of water that can be held in a soil profile but still be available to the crop. As plants draw water from the soil profile, irrigation is ideally used to replenish the soil profile with available water during times of inadequate rainfall. When the AWHC of soil is not appropriately accounted for, too much or too little irrigation may be applied. Too much irrigation can result in water being lost to runoff or deep percolation. Too little irrigation can induce unnecessary drought stress and disrupt the plants' ability to transport key nutrients and carbohydrates (Pettigrew, 2004). Soils with a low AWHC, such a sandy soils, allow water to percolate below the root zone of the plant quickly while soils with a high AWHC, such as silt loams, have a much stronger tendency to maintain water in the soil profile and require much less irrigation than low AWHC soils. The spatial variability of AWHC in agricultural fields has a tendency to complicate the balance between AWHC and optimum irrigation rates.

It is well recognized that soil texture is a controlling factor of many soil characteristics (Saxton and Rawls, 2006; Sadler et al., 2000). AWHC is affected by the attraction of soil particles to the polar charges of water molecules. Small soil particles, such as clay, have much more available surface area to attract and hold water (Hake and Grimes, 2010). Soil texture is defined by the distribution of particle sizes (sand, silt, and clay) within a soil and is directly related to the AWHC. Since soil texture is known to vary spatially within agricultural fields, soil AWHC is subject to the same degree of spatial variability found in soil texture. Work performed by Longwell et al. (1963) indicated a very consistent relationship between AWHC and soil texture. Longwell et al. (1963) showed that very fine sandy loams and silts tended to have the highest AWHC, while an increase in either clay or sand content decreased the AWHC in a very predictable manner.

The formation of soils in the West Tennessee region has been affected by a wide range of geological and anthropogenic factors. Much of the parent material for the soils around the research location (Jackson, Tennessee) is loess. Several layers of loess were deposited by glacial movement while erosion removed portions of the loess deposits on slopes. Windblown deposits can be found across much of the state, and many years of conventional tillage increased the variability of soils due to erosion. The soil at the research location mostly consists of a Lexington silt loam (Fine-silty, mixed, active, thermic Ultic Hapludalf) with a Dexter variant (more shallow than a typical Dexter) found in places. In some areas, a sandy soil layer with a very low AWHC can be found well within the root zone of crops. Low AWHC layers drop the average AWHC of the soil profile and in turn affect the optimum irrigation rate.

Given that optimum irrigation rates are affected by AWHC and AWHC is strongly related to soil texture, it is hypothesized that a map of either soil texture or soil AWHC with sufficient resolution can be used to effectively partition variable-rate irrigation zones. This paper investigates the use of ground-penetrating radar (GPR) and electrical conductivity (EC) measurements as methods of identifying and locating the spatial variability of AWHC caused by texturally inconsistent soil layers in order to identify, quantify, and locate precision irrigation management zones.

Objectives

The main objective of this research was to determine whether or not soil variability mapping can be used to identify, quantify, and partition variable-rate irrigation zones. Individual research objectives for this experiment were as follows:

- Locate a research site with known or expected variability of AWHC due to soil layer variation

- Generate geo-referenced map of GPR estimated depth to sand (DTS) within the research plots of a deficit irrigation cotton experiment and correlate with measured DTS and AWHC
- Generate geo-referenced map of soil EC values using a Veris EC 3100 within the research plots of a deficit irrigation cotton experiment and correlate with measured DTS and AWHC
- Perform soil texture analysis and measure the DTS on geo-referenced soil core samples from designated plots within the deficit irrigation cotton experiment
- Use soil texture to estimate soil AWHC in a profile depth of 48 inches from the surface to approximate the potential root zone of a cotton plant

Background

There is a wide variety of means available for subsurface exploration. Soil coring grids, ground-penetrating radar, electrical conductivity, and electromagnetic induction are all examples of established subsurface exploration methods. The methods used in this paper are by no means considered a comprehensive review of subsurface exploration. GPR was selected for use in this study because it is widely accepted as a very accurate method of estimating the depth to a buried target and because it was easily available for use for this project. EC measurements were included because the technology is more optimized for agricultural field use and again, the technology was readily available to the researchers. Traditional core sampling and texture analysis methods can very accurately identify AWHC variability; however, each core represents a very small volume of soil and the process can be very expensive and time consuming. GPR and EC measurements have the potential to greatly increase the efficiency of data collection by increasing map resolution and greatly reducing the number of cores needed for soil mapping.

Ground-penetrating Radar

GPR is a noninvasive method that sends electromagnetic energy into the ground and measures the time required for the wave to return to a receiving antenna. The delivered radar waves are reflected back to the receiving antenna when energy is reflected back by material with a dielectric constant different than that of the surrounding medium (Allred et al., 2005). The amount of energy that is reflected back to the receiver, the strength of the reflection, is determined by the difference in dielectric constant between the object or layer of interest and the surrounding medium. The dielectric constant of soil is very strongly tied to volumetric water content. Dry soil has a dielectric constant of about 5 to 15 while wet soil has a dielectric constant of approximately 30 to 40 (Allred et al., 2005). The difference in dielectric constant between dry and wet soil is mostly attributed to the high dielectric constant of water, which is about 80 (Allred et al., 2005). Allred et al. (2005) defined the ratio of the reflected radar pulse to the delivered radar pulse (in other words, the amount of energy returned to the receiving antenna) by the reflection coefficient, R. Equation [1] shows that R is directly related to the relationship between ε_1, the dielectric constant of the medium through which the radar pulse is currently traveling, and ε_2, the dielectric constant of the medium on the other side of a given subsurface discontinuity interface.

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}} \qquad \text{equation [1]}$$

Excluding extremely dry or very saturated soil water conditions, soil layers with a high AWHC should have higher water content than soil layers with a low AWHC and thus a higher dielectric constant. Truman et al. (1988) indicated that the argillic horizons studied had higher bulk densities and AWHC than the horizons above them. It was noted that the increased water content and increased bulk density raised the dielectric constant of the argillic horizons. By equation [1], this would create a situation where ε_2 is greater than ε_1 which would cause a positive radar reflection. Equation [1] shows that when a layer of soil with a low AWHC (which should exhibit a low dielectric constant) is beneath a layer with a higher AWHC, a negative radar reflection coefficient will occur. A negative R simply indicates that the polarity of the wave has been reversed (Allred et al., 2005). The accidental detection of soil layers rather than buried objects has been mentioned as a problem when the intention is to use GPR to detect the presence of underground objects such as clay pipes (Allred et al., 2005); however, the ability of GPR to detect soil layers is specifically what this research hopes to take advantage of.

Boll et al. (1996) performed a GPR survey of the same field in two different months to detect texturally finer layers in an otherwise sandy loam field. When the survey was performed in summer months, only the bottom of the fine-textured layers showed because water was trapped just below the layers while high levels of evaporation had dried the soil texture interface above the layers. After precipitation refilled the soil water profile, water perched on top of the soil layers in addition to the water trapped below the soil layers which allowed both the top and bottom of the soil layers to be visible for thickness estimation (Boll et al., 1996). Boll et al. (1996) noted that when simply assuming an average wave velocity, the depth of the soil layers could only be detected within 1.3 feet of accuracy on a depth scale of 6 feet; however, employing the Common Mid-Point, or CMP, technique for wave velocity estimation allowed for “more accurate” depth predictions. Freeland et al. (1998) used GPR to detect soil horizon interfaces and noted that GPR indicated water perched above layers such as fragipans, clay horizons, flat boulders, and even areas affected by high levels of compaction in agricultural fields. Doolittle and Collins (1995) tested GPR as a method to classify subsurface horizons to increase the resolution and accuracy of soil surveys and found that horizons can be classified because their physical characteristics, such as texture and bulk density, differ from overlying horizons.

Grote et al. (2003) noted that the spatial patterns of percent sand measurements were very similar to the GPR-derived water content patterns found while looking for a relationship between GPR readings and volumetric water content. Later research by Grote et al. (2010) found that water content near the soil surface (within 0.8 foot) is not related as closely to soil texture even when the site is not affected by significant topography or agricultural practices. However, water content of deeper readings was still closely related to soil texture variability and the coarse-grained fraction of soil texture (percent sand) correlated well with volumetric water content estimates made using GPR. GPR has been used to indicate the depth of clayey aquitards within 16% of the depth found using soil core sampling and the hydrometer method for particle size analysis (Szuch et al., 2006). Similar work shows a correlation of 0.94 between measured depth to argillic horizons found using particle size analysis and depth indicated by GPR (Truman et al., 1988). Perhaps the most promising research was performed by Simeoni et al. (2009) who used GPR images to visually estimate and record the depth to the texture contrast between the A and B horizons of duplex soils in Australia. The “picking” method described by Simeoni et al. (2009) is very similar to the method used for this research as described in the Materials and Methods section. A correlation coefficient of 0.90 was found between the measured depth to the B horizon from soil cores and the depth shown on the GPR profile (Simeoni et al., 2009).

It is worth noting that many factors can influence the success of a GPR study. "Reading" the output of a GPR can be very subjective as the image is not always free of ambiguity. Also, the frequency of the radar antenna as well as spatial and temporal changes in water content, clay content, salinity, and iron oxide content can all affect the GPR depth of penetration and wave velocity (Allred et al., 2005; Boll et al., 1996). Lower frequency antennas (10 to 300 MHz) increase the depth penetration of radar waves but reduce the image resolution relative to higher frequency antennas (400 to 900 MHz) and must be chosen accordingly (Doolittle et al., 2006; Allred et al., 2005). GPR measurements taken when a soil is near saturation can increase the effectiveness of GPR to detect soil textural differences (Grote et al., 2010) so long as the water table is not above the object or layer of interest. If the water table is above the subsurface discontinuity, the high water content of the water table can dissipate the GPR pulse and obscure anything that lies below it (Allred et al., 2005). The dielectric constant of soil, which determines the GPR reflectance, is affected by porosity, water saturation, amount and type of salts, clay content, and volume scattering (Doolittle and Collins, 1995). The use of methods such as Common Mid-Point estimation for wave velocity can greatly affect the accuracy of GPR surveys; thus, the methods used for GPR analysis must be carefully selected to provide optimum results. Like most technologies, a balance exists between the accuracy of the method and the associated cost.

GPR has the potential to greatly increase the data collection efficiency over traditional coring methods. Doolittle and Collins (1995) found that GPR could decrease the field cost by 70% while increasing productivity by 210% over conventional sampling methods, so long as the soil was well-suited for GPR. Inman et al. (2002) suggested using electromagnetic induction (a method used to collect information regarding electrical conductivity variability) as a precursor to GPR readings to narrow down the area that must be analyzed using GPR. This would reduce field and labor costs by using the less expensive measurement of soil EC to identify larger areas of variability where the accuracy and expense of GPR data is not necessary. Soil classifications made using visual interpretation of GPR compared well with classifications made using traditional techniques (Inman et al., 2002). Whether used by itself or in conjunction with other technologies, GPR appears to have the potential to provide high-speed, high-resolution data at a lower cost and increased efficiency compared to conventional methods.

Electrical Conductivity

Measurement of soil EC is a frequently used and very reliable method to indicate field variability in precision agriculture (Corwin and Lesch, 2003). Mobile EC measurement systems such as the Veris 3100 can provide geo-referenced maps of soil variability at faster speeds and higher resolution than traditional soil sampling (Mertens et al., 2008). Sand particles have a low electrical conductivity while clay particles have a high conductivity; therefore, finely textured soils should produce high EC values while coarse soils should produce low EC values (Lund et al., 1999; Sudduth et al., 2005). Unfortunately, this relationship can be complicated by other factors that change the conductivity of soil. Soil EC is affected by a variety of factors including soil salinity, water content, bulk density, and cation exchange capacity (Corwin and Lesch, 2003; Sudduth et al., 2005). Soil EC can be calibrated to any specific soil property so long as the soil property of interest dominates the other local soil properties that influence EC readings (Sudduth et al., 2005).

Cannon et al. (1994) used EC mapping to geo-reference soil salinity within 5% accuracy and indicated that EC mapping could be used to map soil texture provided the area in question was subject to a uniform distribution of salts. Doerge et al. (1999) suggested that EC could be successfully related to AWHC, which would be closely related to soil texture, so long as proper field verification is performed. Mertens et al. (2008) also recommended that ground truth verification be performed when using EC data because the regression of EC data versus clay percentage was found to vary from site to site. Doerge et al. (1999) noted that the relationship between EC and crop yield was strongest when AWHC was the main factor influencing yield differences; this suggests that EC should also be related to AWHC if other variables such as salinity are consistent. Field verification in combination with EC measurements has indeed led to significant correlation of EC to soil texture characteristics. Corwin et al. (2003) found a correlation coefficient of 0.76 for EC to percent clay. Similar work performed by Fulton et al. (2010) also showed correlation coefficients between EC and percent clay, sand, and silt of around 0.75; however, the correlation success varied throughout the field. McCutcheon et al. (2006) attempted to use soil EC as an indicator of soil texture in Eastern Colorado, but found that too much water content variability existed to generate a significant correlation between EC and percent clay. Mertens et al. (2008) used a mean weighted clay content rather than percent clay and found a high correlation (R^2=0.76) between EC and mean weighted clay content after adjusting for soil water and temperature differences. The exact values of soil EC are affected by soil temperature and especially soil water; however, the overall spatial patterns are consistent (Mertens et al., 2008). Sudduth et al. (2005) found that vastly different soil layers that mix within the range of the EC measurement device significantly affect the consistency of EC readings. Sudduth et al. (2010) later used these differences to estimate the depth of topsoil with root mean square errors of validation between 8.7 to 9.8 inches.

The relationship of AWHC to soil texture and structure should allow AWHC to be predicted using EC measurements. The success of the past research mentioned above that relates EC to soil texture characteristics such as percent clay and depth of topsoil suggests that EC has the potential to be strongly related to AWHC and thus would allow users to successfully identify precision management zones for irrigation management.

Materials and Methods

A research site located on the West Tennessee Research and Education Center in Jackson, Tennessee (35.624°N; 88.845°W) was selected for this project. Cotton lint yield variability and visual observations from the research site suggest that the field contains significant AWHC variability due to a layer of sandy soil in an otherwise silt loam field. Visual observations of the soil during sensor installation procedures revealed a very sandy layer of soil at varying depths from the surface. Differences in cotton growth and maturity rates indicate that some sections of the research site respond differently to rainfall and irrigation than others; the changes seem to be related to changes in the depth of the observed sandy layer. The observed field-scale variability ensures that testing occurs over the wide range of soil conditions that can be found in modern agriculture.

The field, approximately 0.75 acre in size, is currently being used for a deficit irrigation cotton experiment. Each spring, the field is planted to cotton using a no-tillage planter. Cotton plots are six rows by 30 feet, with a row spacing of 38 inches; different irrigation rates are applied to each plot using drip irrigation that is removed prior to harvest and not replaced until the following spring.

Both GPR and EC data are affected by soil water content. If either data set was collected during or shortly after irrigation, readings would be subject to the effects of the variable-rate irrigation. To eliminate this issue, the GPR and EC datasets were collected on December 9 and 8, 2010, respectively, after the soil water profile had been replenished by rainfall. Data collection of each method took place within 24 hours of each other with moist, but not saturated, soil conditions.

GPR Data Collection

A GPR system integrated with real-time, RTK-corrected GPS was used for this study. The system utilized a GSSI SIR-20 data acquisition unit (Geophysical Survey Systems, Inc.) connected to a 200-MHz antenna (GSSI Model 5106). The 200-MHz antenna was selected based on the recommendation from an experienced GPR user in this region based on past experience and the estimated depth and size of the soil layer that needed to be identified. The antenna sits on top of a fiberglass skid and is pulled by an ATV to take data at approximate planting speeds without damaging the GPR antenna (Freeland et al., 2002). RADAN 6.6 software was run via a laptop computer and used to integrate GPR data with GPS coordinates provided by the Topcon antenna (Topcon Positioning Systems, Inc., PG-A1) mounted directly above the GPR antenna via a fiberglass mounting bracket.

Because the research field was planted in a pattern of six row cotton research plots for the on-going irrigation study, it was desirable to collect data in a manner that allowed researchers to calculate a plot-averaged value. To accomplish this, data were recorded in between the most central three row middles of each plot to minimize the influence of border differences. For clarity, the GPR path through a single plot is represented graphically in Figure 1.

Following data acquisition, the radar images were viewed using RADAN 6.6 software. The “Pick” tool was used to select a series of points along the texture horizon detected by the GPR reflections. This tool generates a database of the latitude, longitude, and estimated depth (based on the time of radar wave travel in nanoseconds and the velocity of the wave through the soil) of each point selected. Points were selected along the top of the radar reflection generated by the difference in dielectric constant between the two soil layers to estimate the DTS. All files were processed by the same person for consistency. The results of the “Pick” tool database were imported into an ArcGIS shapefile. ArcGIS Krigging was then used to generate a surface to represent the estimated DTS; values of the interpolated surface were shaded to provide a visual interpretation of the estimated DTS.

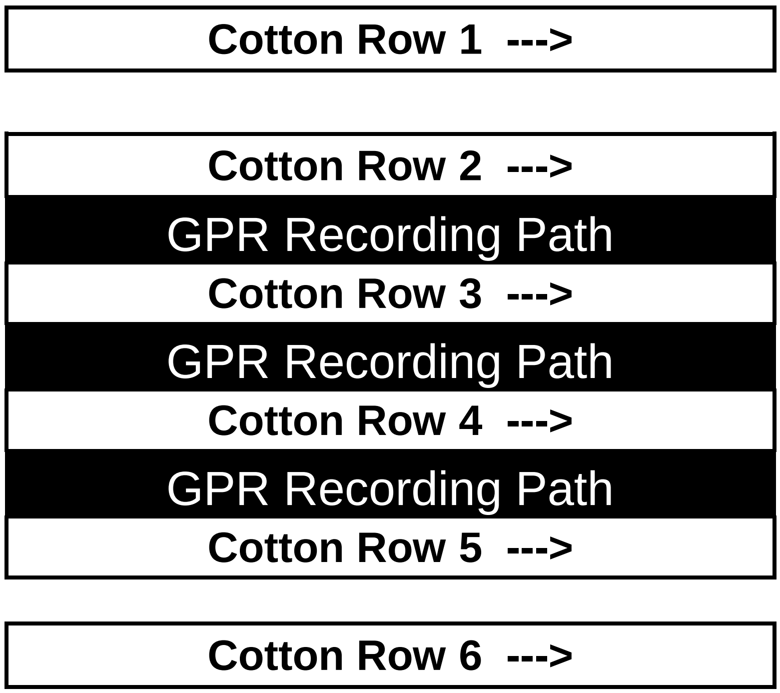

Figure 1: GPR data were recorded in each of the three center-most rows of each six row cotton plot

Veris EC Data Collection

A Veris Soil EC 3100 (Veris Technologies) was also used for this study. The Veris 3100 utilizes two sets of coulters; one for deep readings and one for shallow readings. The coulter spacing was set to generate average readings of a volume of soil with a depth from 0 to 36 inches below the surface for the deep coulters and from 0 to 12 inches below the surface for the shallow coulters. The output produces one deep electrical conductivity (DEC) and one shallow electrical conductivity (SEC) measurement simultaneously, and each reading is averaged over the total volume of soil measured each time. This reading is sometimes referred to as bulk or average electrical conductivity. Since no other forms of EC were measured in this study, the simple term EC is used for brevity.

The width of the widest (DEC) coulters covers 88 inches of field per swath. When centered within the cotton research plots, the Veris EC 3100 coulters approximately covered the four center rows (those of the most interest as the four center rows are harvested for analysis) of each cotton plot. Since it was again desirable to focus data collection in a manner that allowed researchers to calculate a plot averaged EC value, the Veris EC 3100 was centered on the plot and a single pass of data were collected for each plot. The location of each EC reading was recorded using a John Deere StarFire 3000 receiver utilizing the John Deere SF2 correction signal (www.deere.com).

EC data were recorded and stored on a portable hard drive. After data collection, the soil EC data were plotted using the recorded GPS location of each point in ArcGIS. Data were exported to an ArcGIS shapefile and Krigging was again used to generate an interpolated surface representing the field EC variation. Two separate maps were generated, one for DEC and one for SEC. Values of the interpolated surface were shaded to provide a visual interpretation of the EC variation.

EC data were taken only in research plots that were used during the 2010 field layout. Because not all research plots were used, a few areas of the field were not directly measured using the EC 3100. A semivariogram of the EC data performed using the ArcGIS Geostatistical Wizard indicated that the spatial variability of EC data would allow the Krigging method to interpolate within all of the unmeasured areas. Regardless, any further analysis or validation of EC data took place using only plots that were directly measured using both GPR and EC.

Variable-rate Irrigation Zone Layout

Initial analysis of the GPR and EC variability maps indicated that no single dataset adequately described all of the observed field variability. The 200-MHz GPR antenna detected differences more strongly in areas of the field with a relatively deep DTS than in areas with a relatively shallow DTS. Contrarily, DEC data corresponded best with areas observed to have a relatively shallow DTS but corresponded poorly to areas with a relatively deep DTS. This could most likely be accounted for by taking multiple GPR datasets at once using varying antenna frequencies or by taking multiple EC datasets with the coulters set at varying widths (and therefore sampling depths) in the future; however, neither of these approaches were utilized for this research. Rather than increase the amount of data collection, a combined method of plot classification using both the GPR and DEC datasets was used.

Research plots were grouped based on similarities of both GPR and DEC measurements. Blocks were initially created by grouping research plots with similar GPR measurements, creating classification blocks ranging from a relatively shallow to a relatively deep DTS. Initial blocks were further refined based on their DEC measurement. The DEC measurements contributed to a better division of plots with a relatively shallow DTS and isolated several deep DTS plots that had unusually low DEC values.

The combined block classification method resulted in six soil classification blocks, each containing at least six similar research plots. Further discussion of the six soil classification blocks occurs in the Results section. After classifying all of the research plots that were measured by both GPR and DEC, soil coring was used to validate the results.

Soil Coring

Soil core samples were pulled from the research location to validate the results of the irrigation zone classification. Seven plots each were chosen from three classification blocks to represent the scale of variability that is encountered in the research location. The first seven plots were chosen from the first block. The first block contains plots with the shallowest GPR and lowest DEC measurements. Since only six research plots are contained in this block, a seventh research plot was added from the second block that contains the next shallowest GPR measurements. An additional seven plots were chosen from the fifth block, which represents the deepest GPR and highest DEC measurements. The final seven plots were chosen from the fourth block, which contains plots with an average GPR and DEC reading in between that of the deepest and shallowest GPR measurements. Further details regarding the selection of plots for soil coring are shown in the Results section.

One soil core was extracted from each research plot for a total of 21 soil core samples. Each 2.5 inch diameter core was extracted using a truck-mounted, hydraulic soil probe. Where possible, core length reached 48 inches below the surface. In some places, the sandy layer of soil would not remain together long enough to extract the soil core. In these areas, the actual length of the soil core that was successfully extracted was recorded and used as the basis for calculations. For areas that did not allow a full 48 inch soil core, it is likely that everything below the end of the extractable core is a continuation of the sandy layer; otherwise, a full core would have been extracted successfully. However, the actual core length was used for further calculations because the soil characteristics below the extracted soil core could not be verified. After the core was extracted, the depth from the ground surface to the sand layer was visually located, measured, and recorded as the measured DTS (MDTS). Each soil core was broken into approximately six inch increments—slight adjustments were made to accommodate texture horizon interfaces—and then stored in sealed, plastic bags for transportation back to the lab. This provided samples with a volume of approximately 30 cubic inches. The location of each soil core was recorded using differentially-corrected GPS from a Trimble GeoXH (www.trimble.com) handheld receiver.

In the lab, each sample was first weighed at its current water content. After mixing the soil samples to ensure a representative sample would be taken, an approximately 1.8 ounce (50 gram) sub-sample was taken from each sample to be weighed wet and then oven-dried at 221°F for 24 hours. The water content was calculated using the difference between the wet and dry soil weights divided by the dry sub-sample weight. Each sample was then adjusted for water content and the calculated dry weight of the full sample was divided by the total volume to determine bulk density.

Approximately 0.2 ounce (6 gram) sub-sub-samples were then taken from each sub-sample for texture analysis. For any sub-sub-samples containing soil that was within six inches of the soil surface, hydrogen peroxide was used to eliminate organic matter. For soil particle dispersion, a solution of 1.8 ounces (50 grams) of sodium-hexametaphosphate per 1.1 quarts (1 liter) of water was added in a quantity of 0.5 fluid ounces(15 mL) to each sub-sub-sample along with 1.0 fluid ounce (30 mL) of distilled water and left to sit for 24 hours. All sub-sub-samples were then shaken overnight on a horizontal shaker (Gee and Bauder, 1986). An ASTM Number 270 sieve was used to filter out any sand particles. The sand portion was dried at 221°F for 24 hours and then weighed. The remaining silt and clay mixture was kept in solution and analyzed using a Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyzer (BeckMan Coulter, Inc.). The results from the laser analyzer combined with the known dry weight of sand in the sub-sub-sample allowed calculation of the percent sand, silt, and clay particles in each sample.

The calculated bulk density and texture analysis were used as inputs to the USDA ROSETTA hydraulic function model to predict the van Genuchten water retention curve (Schaap et al, 2001). The ROSETTA model output the coefficients needed to model the van Genuchten water retention curve as well as the USDA soil texture class of each sample. The inputs and outputs from the modeling process can be found in Table 8, located in the Appendix. The predicted water retention curve was used to calculate the predicted water content at field capacity and wilting point. Field capacity and wilting point were assumed to be 5 psi (33 kPa) and 220 psi (1500 kPa) of matric potential, respectively. The difference in water content between those two points was calculated as the available water-holding capacity (AWHC) of each sample. Finally, a weighted average of the AWHC per sample multiplied by the length of each sample and then divided by the overall core length was calculated and defined as the core-average AWHC. For soil cores that were not extracted to the full 48 inch depth, the average AWHC calculated is based only on the actual, extracted soil core length. A database was generated that combined the measured DTS, soil texture class above and below the measured DTS, and core-average AWHC with the GPS location of each soil core.

Correlation Analysis

After obtaining the GPR and EC data, a layer was created in ArcGIS consisting of a series of polygons to represent the appropriate size and location of each research plot. A spatial join was used to calculate the plot-averaged value of the GPR, SEC, and DEC readings for each research plot. The results of the spatial join were exported and then opened in Microsoft Excel 2007 for any further analysis. After block classification and soil core validation, the regression portion of the Data Analysis add-in for Excel was used to perform linear regressions to determine the relationships between the variables of interest: GPR, SEC, DEC, DTS, and AWHC.

Results and Discussion

Because the effect of AWHC variability on cotton lint yield in this research location is so distinct that it is easily visible on a satellite image, the variability patterns visible in the aerial image were first compared to the variability patterns indicated by the interpolated surface maps. Figures 2, 3, and 4 represent the aerial image of the research area, the GPR variability map, and the DEC variability map, respectively. It is important to note that the GPR values reported in this paper contain no adjustment or calibration. The depth values from GPR are simply estimated using an arbitrarily assigned dielectric constant of the soil to estimate wave velocity. A calibration method such as common mid-point, or CMP, calibration would provide more realistic values of GPR measurements compared to DTS than what is portrayed; however, relative differences in the GPR values as well as the correlation of GPR to other factors will remain consistent given any calibration that assumes a constant dielectric constant of the soil. Overall, the soil texture patterns indicated by the GPR and DEC variability maps resemble the variation noted in the aerial image. This suggests that AWHC differences do affect cotton growth and response to irrigation and that the mapping techniques used here correspond to that variability; however, the correspondence is not without error.

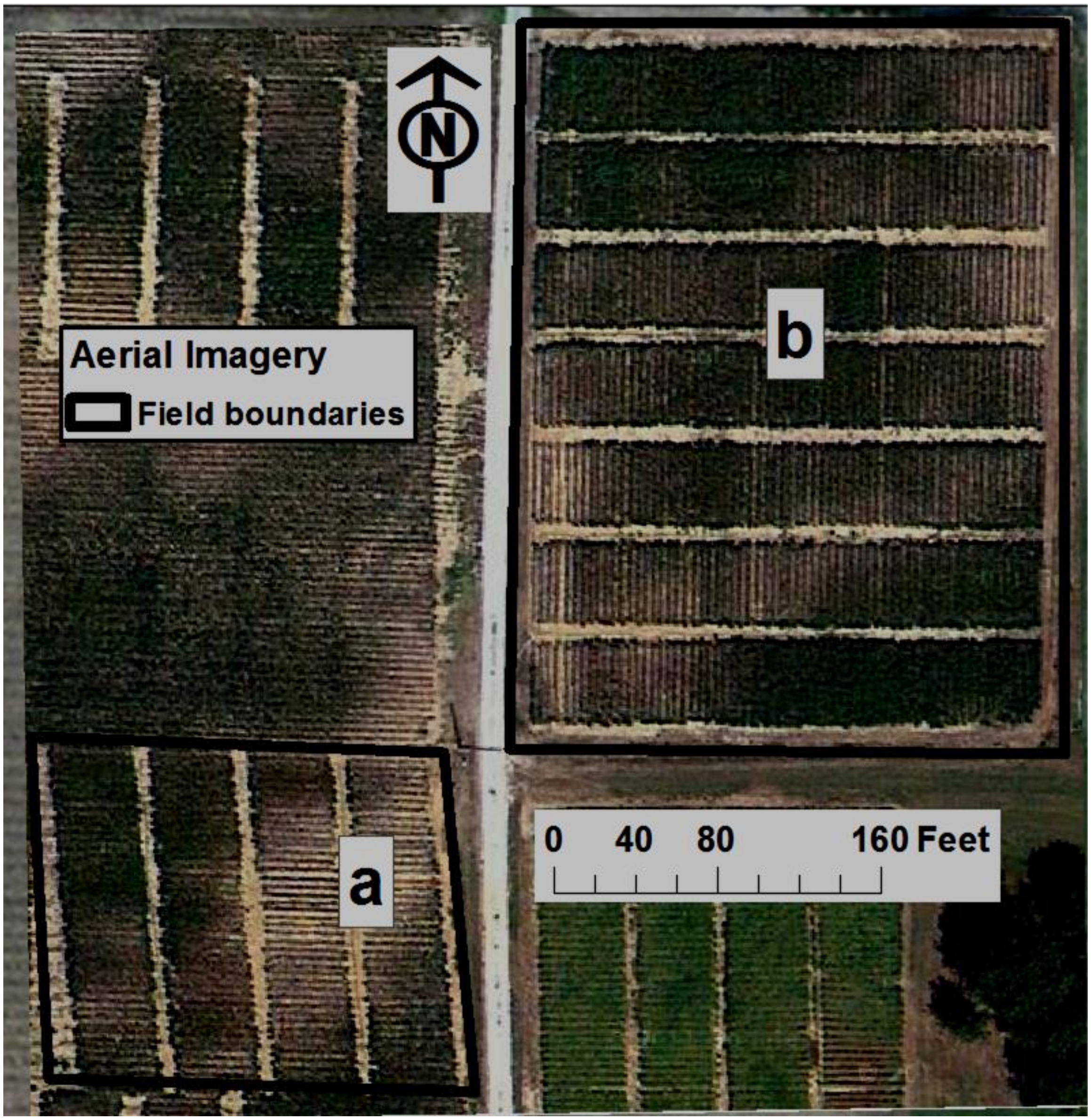

Figure 2: Cotton growth variability indicated by an aerial image of the research location (obtained via Google Maps)

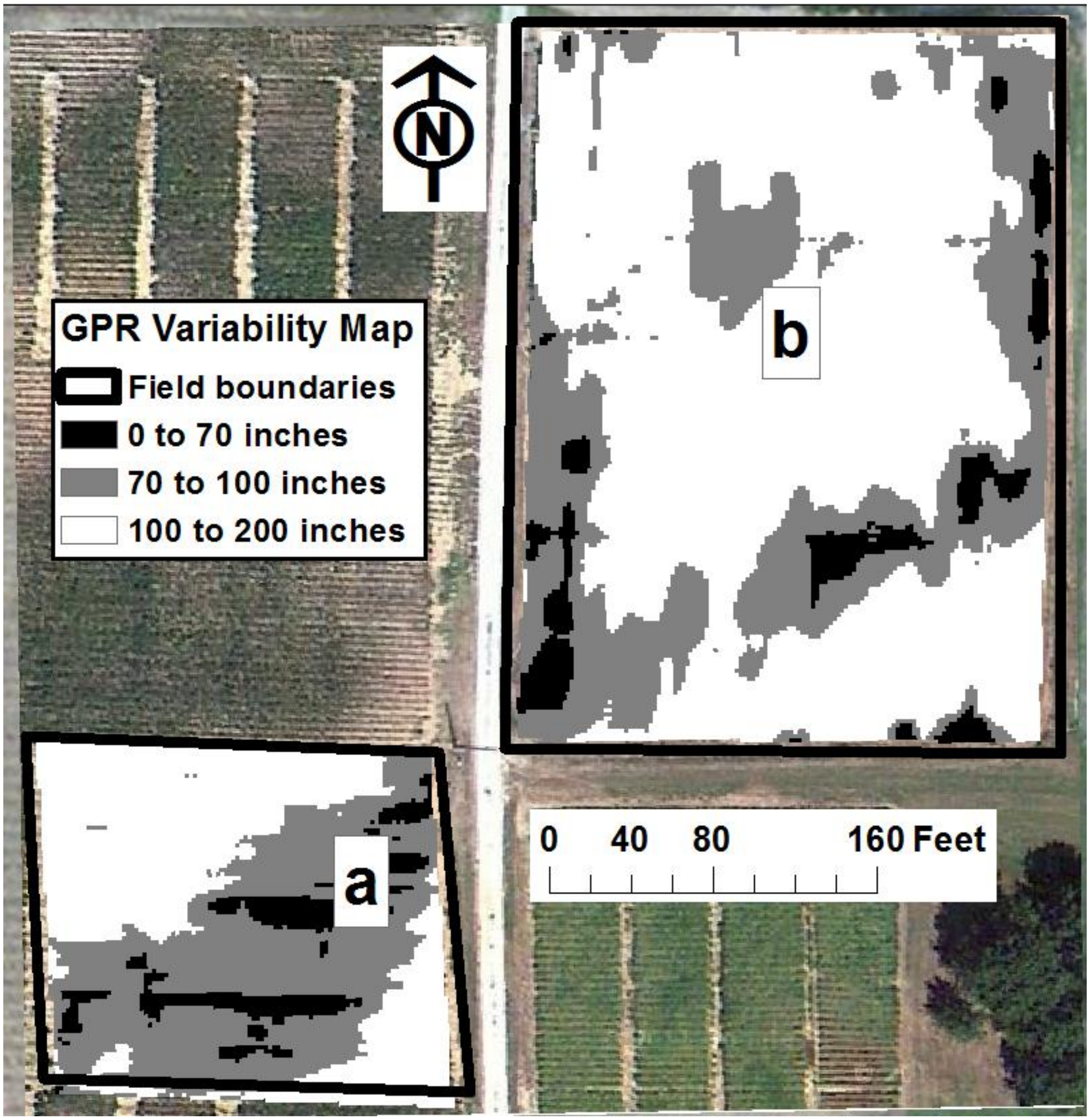

Figure 3: Depth to sand variability indicated by GPR data

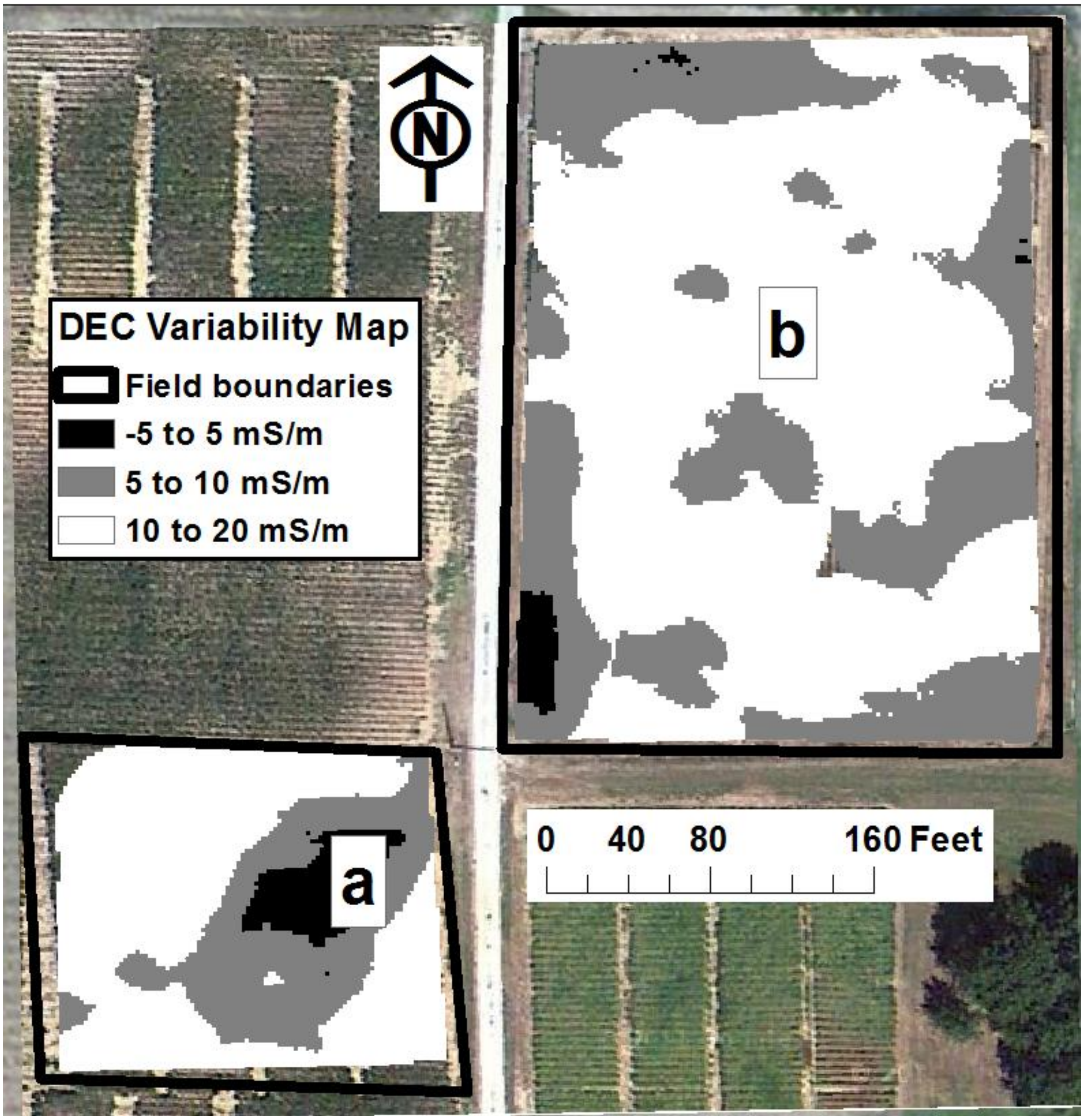

Figure 4: Electrical conductivity variability indicated by DEC data

In Figures 2, 3, and 4, marker “a” indicates an area that was found to be very sandy (shallow DTS) and have a relatively low AWHC, consistently resulting in very stunted cotton growth with little canopy. The shape of this sandy area from Figure 2 corresponds more strongly with the shape portrayed by the DEC map in Figure 4 than it does with the GPR map in Figure 3. Marker “b”, also indicated in Figures 2, 3, and 4, indicates an area that was consistently noted as being very silty (deep DTS) with a very high AWHC, which contributed to very large cotton plants with a thick canopy. The shape of the area denoted by marker “b” corresponds more strongly with the shape portrayed by the GPR map in Figure 3 than with the shape suggested by the DEC map in Figure 4. In multiple areas of the field, the DEC map corresponded more strongly with noted variability in shallow DTS areas while the GPR map corresponded more strongly with variability seen in deeper DTS areas. This suggests that neither the GPR nor the DEC map corresponded to the full range of variability contained in this field.

As mentioned previously, this situation could most likely be remedied by obtaining and calibrating multiple GPR datasets of varying antenna frequency or by obtaining and calibrating multiple DEC datasets with varying coulter spacing. Either of these solutions has the potential to increase the accuracy of these mapping technologies at varying depths which would increase the overall accuracy of the map. For this research, the alternative method used was to combine the information from the GPR and DEC maps and use both in the grouping of research plots. SEC data were not used for plot grouping because the majority of DTS changes in this field occurred at greater than 12 inches below the surface, which is outside the range of SEC measurements.

Using an ArcGIS layer with individual polygons to represent each research plot, a DEC and GPR value was calculated for each plot. Research blocks were formed by first grouping plots with a similar GPR value and then blocks were further refined by grouping plots that also contained a similar DEC value. The results are shown in Table 1.

Some amount of overlap in the range of GPR and DEC vales can be noted. For example, in areas of shallow GPR readings and known shallow DTS areas such as Block 1, the DEC value was treated as a more important factor than the GPR reading because of the observed correspondence noted from Figures 2, 3, and 4. Blocks 5 and 6 contain very similar GPR readings, but much different DEC readings. It is unclear what caused these differences as no validation was performed in this area; however, it provides an interesting example of conflicting information provided by GPR and DEC.

Using the blocks indicated in Table 1, three areas were selected for field validation. Block 1 was chosen to represent the shallowest DTS areas, Block 5 was chosen to represent deep DTS areas, and Block 4 was chosen as an approximate medium between the shallowest and deepest DTS areas.

Table 1: Variability of research plots after combined blocking method

Block	Number of Plots	Average GPR Measurement (in)	Range of GPR Measurements (in)	Average DEC Measurement (mS/yd)	Range of DEC Measurements (mS/yd)
1	6	71	67 to 75	-1	-4 to 3
2	7	79	71 to 91	8	5 to 9
3	7	87	79 to 98	11	9 to 12
4	18	106	98 to 114	12	9 to 12
5	21	126	118 to 138	12	11 to 15
6	9	126	118 to 134	9	7 to 11

Shaded areas indicate blocks chosen for validation

From each block chosen, 1 core was extracted from each of seven research plots contained in that block. Since Block 1 contained only six plots, one plot from Block 2 that was most similar to Block 1 plots was chosen as the seventh plot. Results from the validation process are shown in Table 2. The strong transition between texture horizons noted in many of the soil cores can be seen in Figure 5. Figure 5 indicates an extracted soil core. At approximately 12 inches below the ground surface, marked by the measuring tape below the soil core, the dark silt loam transitions to a sandy layer denoted by its much lighter color and larger particle size.

In general, plots with the lowest AWHC were characterized by having sand introduced into the soil profile at less than 30 inches below the ground surface. The highest AWHC plots remained a deep silt loam for almost the entire 48 inch soil core profile. Those plots residing in the moderate AWHC range contained a sandier soil horizon within 30 to 48 inches of the ground surface. The depths of the textural classification changes noted were very consistent with the measured DTS, suggesting that DTS does indeed have a strong relationship with AWHC. Regression was used to determine the strength of the relationship between AWHC and DTS. The relationship is linear and the two variables are very strongly related (R^2=0.92), as shown in Figure 6.

It should be noted that five of the high AWHC soil cores did not contain any observable soil horizons in the 48 inch soil core. Because sand was never

Table 2: Soil coring results

Block	Core	GPR (in)	SEC (mS/yd)	DEC (mS/yd)	DTS (in)	AWHC (in/in)	Texture
1	**1**	67	8	-2	17	0.04	sandy loam/sand
	2	71	7	-4	14	0.05	sandy loam/sand
	3	71	6	-4	11	0.04	loam/loamy sand
	4	71	7	-2	12	0.03	loam/sand
	5	71	10	3	26	0.09	silty loam/loamy sand
	6	75	9	3	29	0.07	silty loam/sand
	7	75	12	8	23	0.06	silty loam/sand
4	**8**	98	15	11	36	0.13	silty loam/loamy sand
	9	98	16	11	40	0.13	silty loam/sandy loam
	10	98	15	12	40	0.10	loam/sandy loam
	11	102	12	11	24	0.07	silty loam/sand
	12	102	12	12	47	0.15	silty loam/sandy loam
	13	106	13	12	40	0.12	silty loam/loamy sand
	14	106	12	12	47	0.16	silty loam/loam
5	**15**	118	13	11	42	0.14	silty loam/sandy loam
	16	122	11	12	>48	0.17	silty loam
	17	126	11	13	>48	0.16	silty loam
	18	126	13	13	42	0.15	silty loam/sandy loam
	19	134	13	14	>48	0.16	silty loam
	20	138	10	11	>48	0.16	silty loam
	21	138	12	12	>48	0.19	silty loam

Figure 5: Transition between soil texture horizons from soil cores

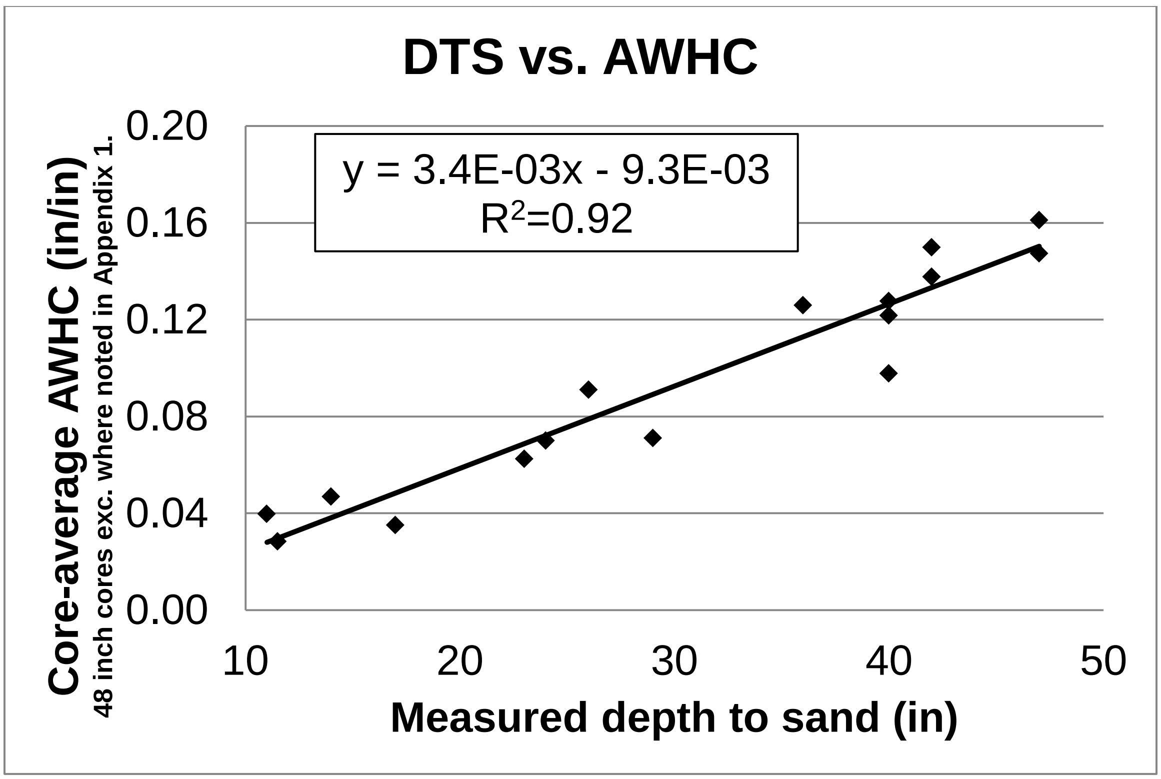

Figure 6: Relationship between measured DTS and AWHC. AWHC was calculated using ROSETTA model output.

officially observed, a measured DTS could not be accurately reported for these cores. Consequently, the five cores without an observable DTS were left out of any correlation analysis that utilized measured DTS. Given the strong relationship between AWHC and DTS, any tool that provides an accurate prediction of DTS should also provide an accurate prediction of AWHC.

Linear regression was then used to examine the relationship between GPR, DEC, and SEC versus AWHC and DTS. The results are shown in Figures 7 through 12, but are first summarized in Table 3.

SEC, as predicted, did not have an adequate sampling depth to obtain a strong correlation with AWHC, although a mild correlation was obtained with SEC versus DTS. It is not surprising that a mapping method designed to reach only approximately 12 inches below the surface was unable to detect changes that generally happen deeper than 12 inches below the surface.

The texture analysis results shown in Table 2 indicates that the shallow DTS area (Block 1) did have a different soil texture than Blocks 4 and 5 at the surface, which generated a relationship with DTS using SEC. The ability of SEC to detect only shallow changes, as expected, is confirmed by a visual analysis of the above mentioned regressions, shown in Figures 9 and 10.

GPR and DEC appear to be much better overall predictors of DTS and AWHC both in theory and in practice. Both GPR and DEC were able to explain approximately 75% of the variability in AWHC (R^2 = 0.82 and 0.74, respectively).

Table 3: Regression of each mapping method versus DTS and AWHC

Method	Prediction of DTS		Prediction of AWHC	
	R^2	Standard error (in)	R^2	Standard error (in/in)
GPR	0.70	7	0.82	0.02
SEC	0.65	8	0.32	0.04
DEC	0.81	6	0.74	0.03

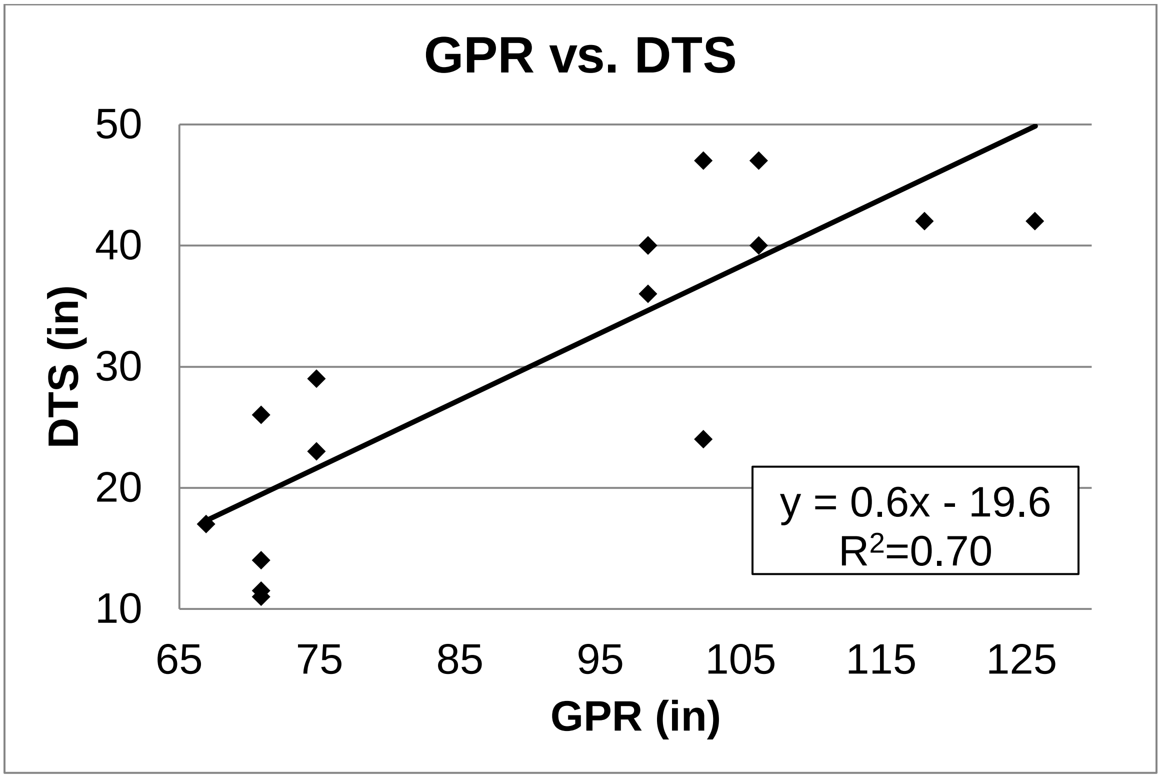

Figure 7: Relationship between GPR output and measured DTS

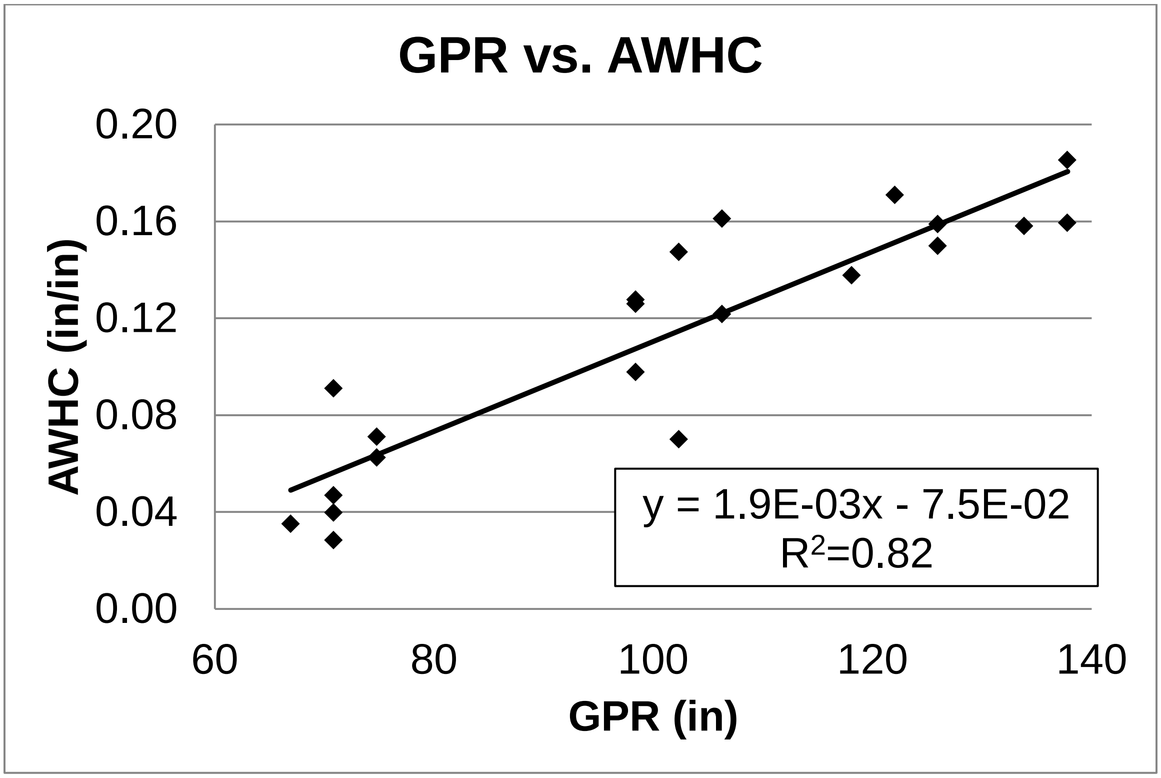

Figure 8: Relationship between GPR output and AWHC. AWHC was calculated using ROSETTA model output.

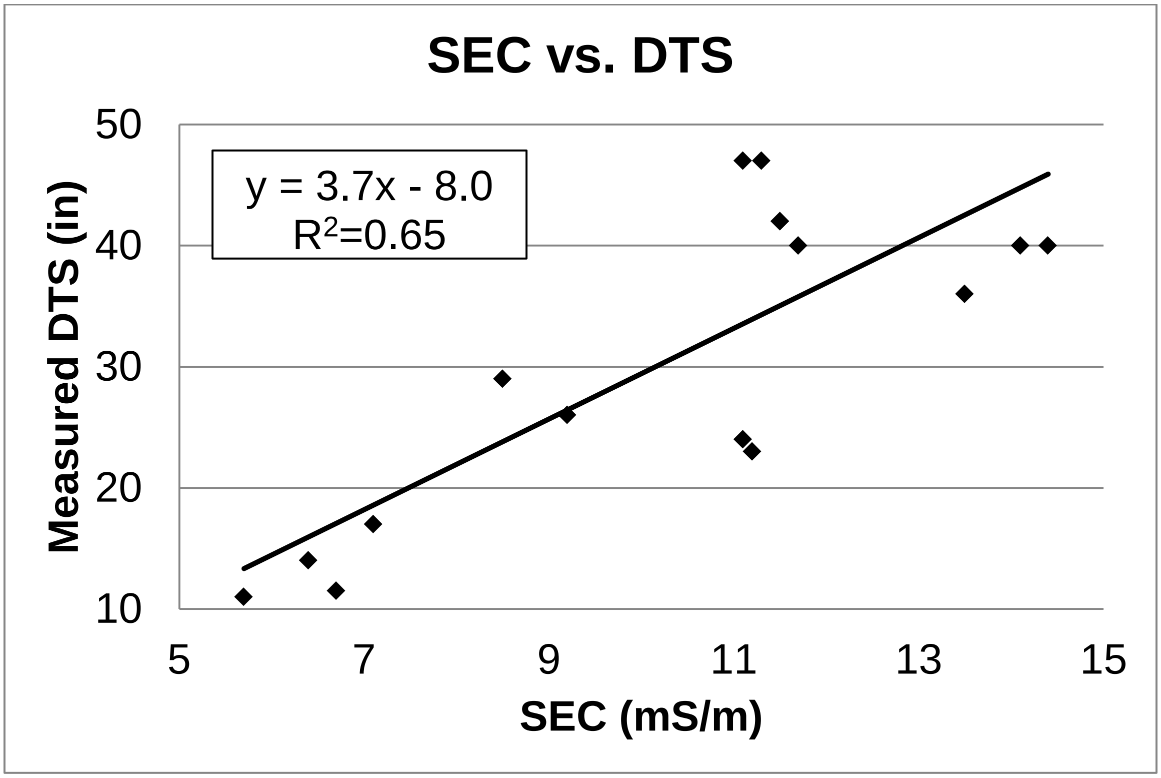

Figure 9: Relationship between shallow EC and measured DTS

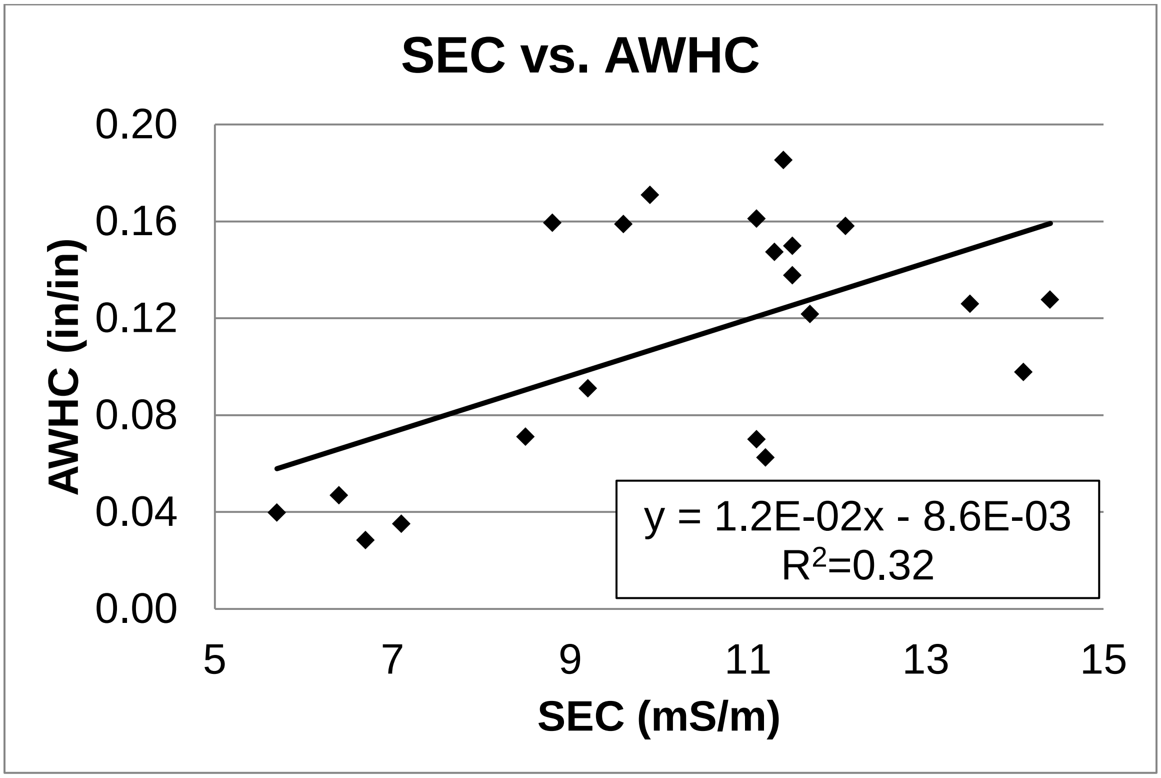

Figure 10: Relationship between shallow EC and AWHC. AWHC was calculated using ROSETTA model output.

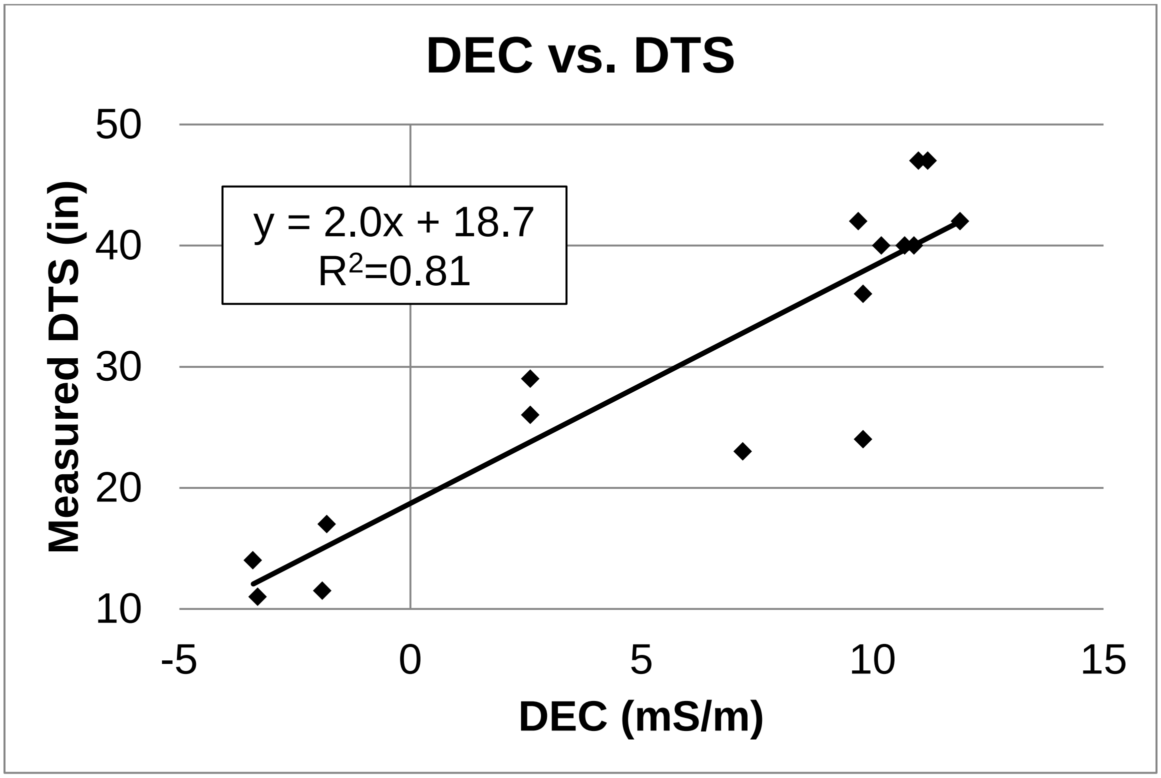

Figure 11: Relationship between deep EC and measured DTS

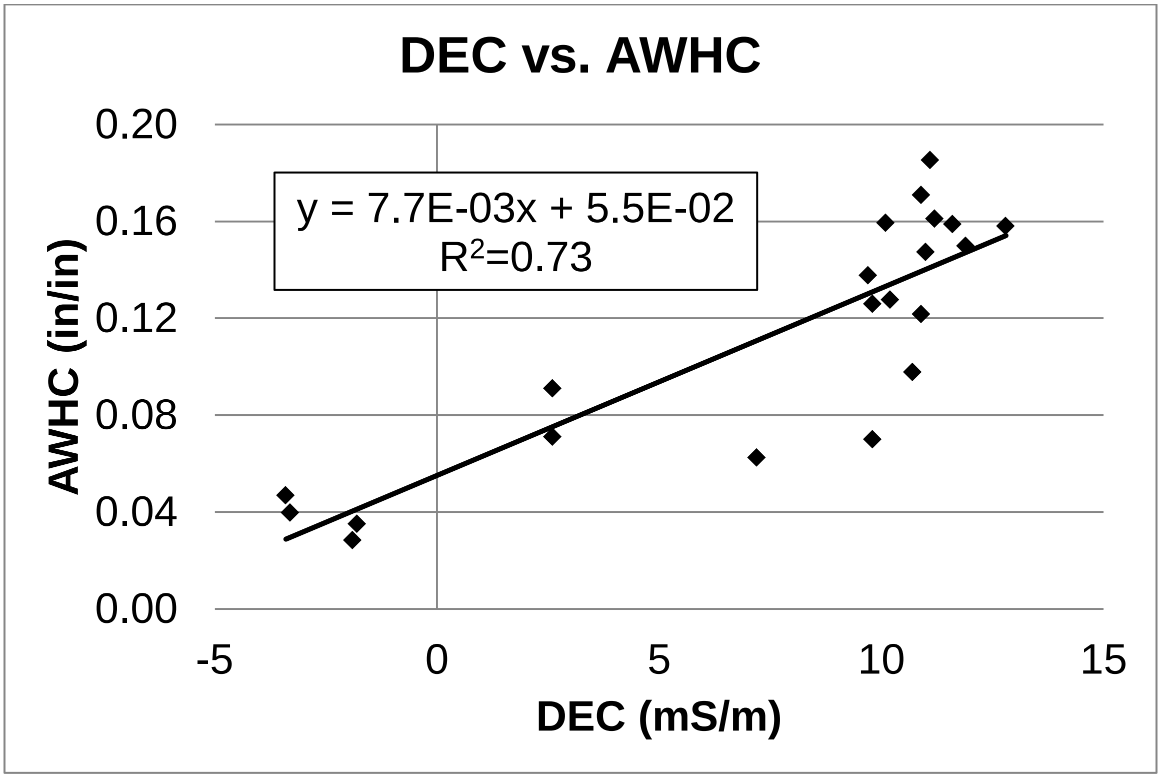

Figure 12: Relationship between deep EC and AWHC. AWHC was calculated using ROSETTA model output.

This is probably more accurate than simply using an aerial image such as Figure 2 or past crop experience to estimate the delineation of variable-rate irrigation zones, and could lead to a substantial increase in irrigation optimization. The six to eight inches of standard error found amongst all mapping methods is fairly significant over the estimated 48 inch root zone of the cotton. This could be a result of a highly variable surface of the sandy layer compared to relatively large sampling area of plot-average measurements. If the difference in AWHC was very large between two layers and full irrigation was being used to replenish the soil profile to its field capacity on each cycle, the standard errors shown in Table 3 could prove problematic. However, under deficit irrigation techniques, enough flexibility would most likely exist in the soil profile that the error would cause little harm to irrigation optimization. It is interesting that each mapping method produced much different correlations with DTS than AWHC. A possible explanation is the limited number of soil cores obtained for validation. If the resolution of soil cores used to validate these mapping methods were increased, one might see a more similar correlation of each method versus both DTS and AWHC. While a high-resolution of soil coring would be extremely useful for this research, the high cost of soil coring and analysis must be considered when this technology is used by producers.

The variations between Figures 2, 3, and 4 as well as the relatively high standard errors of the mapping methods suggest that a single dataset of either technology does not describe the full range of variability in this location. The error shown in the R^2 values of the regression of GPR and DEC versus both DTS and AWHC indicate that a significant amount of variability of both DTS and AWHC is not being explained by these mapping methods. Figure 12 indicates that DEC correlated much more strongly to low AWHC plots than moderate to high AWHC plots. Figure 8 shows a significant cluster of plots with a low AWHC that were not predicted as well by GPR as higher AWHC plots were. Although a higher resolution validation should be used to confirm this, it is possible that future uses of this technology would benefit from a more structured combined method of GPR and EC measurements, multiple frequencies of GPR data, or multiple sampling depths of DEC measurement. Any of these approaches would add considerable complexity, however, to the classification of irrigation zones because a simple linear model would probably not suffice. A more complex analysis of multiple datasets would require multiple linear models used individually at certain depths or a single modeling method more suited for the use of multiple inputs, such as a neural network.

Conclusion

Both GPR and DEC measurements showed good correlation with DTS and AWHC variability. The results from the GPR and DEC datasets were combined to partition several variable-rate irrigation zones that corresponded well with observed field variability. Ground-truth validation of these mapping methods indicated that GPR and DEC can predict approximately 75% of the variability in AWHC (R^2 = 0.82 and 0.74, respectively), which has the potential to substantially increase irrigation optimization. A very strong, linear relationship (R^2 = 0.92) was confirmed between DTS and AWHC, indicating that soil texture was very strongly related to AWHC and that DTS variability was a strong indicator of AWHC variability. Analysis of the DEC mapping results and regression versus AWHC shows that DEC data corresponded most strongly to plots with an AWHC of less than 0.05 in/in. Contrarily, GPR data corresponded more strongly to AWHC variability in plots with an AWHC greater than 0.15 in/in. These results suggest that optimizing GPR, DEC, or a combination of the two for different depths of interest could produce a more complex, but more accurate, model of AWHC variability. An in-depth study of the effects of AWHC variability and variable-rate irrigation on the growth and yield of cotton would provide insight into whether or not a more accurate method of delineating variable-rate irrigation zones is cost effective.

CHAPTER II

DETERMINING THE EFFECTS OF VARYING WATER HOLDING CAPACITY AND DEFICIT IRRIGATION ON COTTON LINT YIELD

Abstract

It is possible that precision irrigation equipment such as variable-rate center pivots could be used to maximize the effectiveness of water resources for Tennessee cotton producers, but we first must understand the response of cotton lint yield to applied water. Past research has indicated that cotton irrigated on high available water holding capacity (AWHC) soils responds differently than cotton grown on low AWHC soils. Many fields in Tennessee contain significant levels of AWHC variability due to the formation of soils and effects of erosion in this region. It is possible that variable-rate irrigation could optimize the irrigation of cotton grown in such fields.

Previously recorded ground-penetrating radar (GPR) and electrical conductivity (EC) data were used to identify and quantify three major soil blocks in a research field in Jackson, Tennessee, that represent soils of low, moderate, and high AWHC. Surface drip tape was used in 2010 and 2011 to apply irrigation rates ranging from 0.5 to 1.5 inches per week starting at pinhead square, first bloom, or two weeks post bloom and ending at either cracked boll or physiological cutout.

Least significant difference (LSD) mean separation as well as a quadratic regression of lint yield versus applied water was used to examine the response of cotton lint yield within each soil block. Cotton grown on low AWHC soils generally required higher rates of irrigation applied starting around the

emergence of pinhead square to maximize yields and exhibited a more linear response to applied water. Cotton grown on high AWHC soils exhibited a more quadratic response to applied water and responded best to lower rates of irrigation applied at first bloom or later. Cotton grown on moderate AWHC soils did produce a quadratic yield response to irrigation, but were not as sensitive to changes in irrigation rate and duration as low and high AWHC soils. Cotton grown on low to moderate AWHC soils showed a significant increase to lint yield compared to rainfed yields in both years at the 90% level of confidence. The maximum increase in lint yield for cotton grown on low AWHC soils was 1080 pounds of lint per acre, compared to an increase of only 380 pounds of lint per acre on high AWHC soils. Also, different irrigation regimes were required to achieve maximum lint yield in different soils. Results show that the lint yield of cotton grown on fields containing a significant degree of variability cannot be maximized by a single irrigation decision in all years.

Introduction

Irrigation management is a particularly important aspect for many agricultural producers. The amount of acres irrigated by U.S. farmers and ranchers increased by 4.6% from 2003 to 2007 (USDA NASS, 2009). The same source indicates that producers spent $2.1 billion on irrigation related equipment in 2007; furthermore, 15% of that expenditure was spent towards water conservation (USDA NASS, 2009). The amount of money spent by producers to conserve water indicates that a substantial market exists for methods or equipment, such variable-rate irrigation, that have the potential to optimize both water use and yield return. Cotton producers must remain especially mindful of their irrigation management because cotton can exhibit a quadratic yield response to irrigation; thus, cotton lint yield can be negatively affected by both water deficit and water excess (Balkcom et al., 2006; Geerts and Raes, 2009; Gwathmey et al., 2011; Wanjura et al., 2002). The quadratic yield response of cotton to applied water is complicated by the fact that the optimum irrigation amount is not consistent between soil type, location, and cultivar. These complicating factors sometimes lead to a more linear response of cotton lint yield to irrigation (Bronson et al., 2006; DeTar, 2008; Leib et al., 2010).

The optimum amount of water needed for effective irrigation should be related to the available water holding capacity (AWHC) of the soil. Water applied by either rainfall or irrigation is stored in the soil profile until it is used by the crop, lost to evaporation, or percolates through the soil profile past the root zone of the crop. The amount of water that can be stored in the soil profile and made available to the crop, the available water holding capacity, will affect how much applied water is needed to satisfy crop demand. In soils with a very low AWHC, water can percolate quickly through the soil profile past the root zone and should require higher irrigation rates to maximize yields. Soils with a high AWHC should be able to produce maximum yields with much less irrigation. Because cotton can exhibit a quadratic yield response to applied water, irrigating an entire field based on the needs of cotton grown on the lowest AWHC soils has the potential to decrease yield in soils with a high AWHC. Likewise, irrigating an entire field based on the needs of cotton grown on the highest AWHC will likely decrease the yields in soils of low AWHC.

The AWHC capacity is directly related to soil texture (Longwell et al., 1963) and soil texture is known to vary spatially in agricultural fields. The spatial variability of soil texture, and therefore soil AWHC, suggests that a single irrigation regime cannot maximize the yield across an entire field that contains significant soil variability. Precision irrigation equipment, which is becoming increasingly available to producers, has the potential to optimize the irrigation regime, and thus yield, of areas affected by low AWHC without an unnecessary reduction of yield in areas of high AWHC. While precision irrigation equipment has the potential to optimize both water use and lint yield, it is unclear the extent to which cotton lint yield will vary under irrigation when planted on soils with a varying AWHC. The goal of this research is to perform a deficit irrigation study on areas of varying AWHC to determine the relationship between cotton lint yield and applied water when affected by AWHC differences.

Objectives

The objective of this experiment is to determine the relationship between cotton lint yield and variations of irrigation rates, irrigation timings, and the available water holding capacity of soil. Individual research objectives are as follows:

- Utilize a research site with previously identified variability of AWHC due to soil layers
- Implement varying rates of irrigation at several different initiation timings to appropriate soil variability blocks based on AWHC variability
- Perform statistical analysis to determine the relationship of cotton lint yield to AWHC, irrigation timing, and irrigation rate

Background

This experiment is an expansion and continuation of previous work performed by Gwathmey et al. (2011) and Leib et al. (2010) who indicated a strong, quadratic response of cotton lint yield to irrigation in deep silt loam soils in West Tennessee. Other research described by Bronson et al. (2006) and DeTar (2008) indicates a more linear response of cotton grown on lower AWHC soils such as sandy loams in Texas and California, respectively, except for years of above-average rainfall. Because AWHC can vary within a field and cotton lint yield can be negatively affected by both over and under irrigation, it is important to adjust irrigation according to variations in AWHC for crops grown under either full or deficit irrigation.

Full Versus Deficit Irrigation

Irrigation is applied to replenish the soil water profile by replacing all or some of the consumptive water use of the crop. When all of the consumptive water use of the crop is replenished, it is generally referred to as full irrigation. Replacing only part of the consumptive water use of the crop is referred to as deficit irrigation. Deficit irrigation relies on the amount of water stored in the soil profile to balance the difference between irrigation applied and the consumptive water use of the crop. Additionally, reducing the amount of soil water in the profile can reduce the consumptive water use of the crop. Ideally, deficit irrigation prevents yield loss while reducing the amount of applied irrigation water and irrigation cost (Fereres and Auxiliadora, 2007). The reduction of water use has the potential to benefit both individual producers and society as a whole; however, the amount of optimum deficit can vary greatly between different areas and crops as well as availability of water (English et al., 2002). Deficit irrigation is sometimes associated with purposefully sacrificing crop yield to reduce water use; however, when a crop such as cotton exhibits a quadratic yield response to applied water, deficit irrigation can be used to both reduce water use and maximize yield. For the purposes of this experiment, deficit irrigation is referred to as reducing applied irrigation water while still producing maximum yield.

Quadratic Yield Response of Cotton

The quadratic response of cotton lint yield to applied water has been consistently reported for irrigated cotton on silt loam soils (Balkcom et al., 2006; Gwathmey et al., 2011; Wanjura et al., 2002). Gwathmey et al. (2011) studied the effects of several supplemental irrigation rates on a Memphis silt loam at the West Tennessee Research and Education Center from 2006 to 2009. Supplemental irrigation rates were varied from rainfed to 1.5 inches per week from the appearance of pinhead square until cracked boll. A positive, quadratic yield response to irrigation was found in 3 of 4 years. Wanjura et al. (2002) reported similar results when irrigating cotton grown on an Olton clay loam in Texas. Irrigation generally occurred from the appearance of pinhead square until early September each year, and a quadratic yield response was again caused by a yield decrease at the highest irrigation rates. Balkcom et al. (2006) performed cotton irrigation on Decatur silt loam soils in Alabama using a daily irrigation frequency from first bloom until one month prior to the expected harvest. Irrigation rates ranged from rainfed up to 0.3 inches per day. Despite the delayed irrigation start compared to that described by Gwathmey et al. (2011), the results from Balkcom et al. (2006) noted that a quadratic yield response to irrigation was caused by a yield decrease at the highest level of irrigation. In other cases, delaying the start of irrigation past the appearance of pinhead square generates a linear response to irrigation even at high irrigation rates. The work of Leib et al. (2010) described the results of the same irrigation experiment as the work performed by Gwathmey et al. (2011) in addition to results that occurred when delaying the start of irrigation until the appearance of first bloom and two weeks after first bloom. Leib et al. (2010) found that starting irrigation at the later growth stages of first bloom and two weeks after first bloom on silt loams soils generated a linear response to irrigation even at the 1.5 inches per week rate. Delaying the start of irrigation is a form of deficit irrigation as a soil water deficit is created before irrigation is applied. Because delaying the start of irrigation caused irrigation to start with a drier soil water profile, the results of Leib et al. (2010) suggest that irrigation of cotton performed on lower AWHC soils might also generate a linear, rather than quadratic, yield response.

Indeed, the results of cotton irrigation on lower AWHC soils are generally more linear than the yield response of irrigated cotton on the high AWHC silt loams described previously. DeTar (2008) irrigated cotton on a sandy loam in California from day of year (DOY) 135 until DOY 243. Since the cotton was planted around the middle of April, these irrigation dates probably correspond to starting irrigation prior to the appearance of first bloom. DeTar (2008) reported that a quadratic yield response was seen only in one year of four and the yield decrease occurred only at the highest irrigation rate. The other three years did respond positively to irrigation, but the response was linear. Similar results were found by Bronson et al. (2006) when irrigating cotton on a fine, sandy loam in

Texas. Irrigation occurred at a base rate of 75% of the measured evapotranspiration as well as rates of plus and minus 10% of the base rate. Although the start and duration of irrigation is not mentioned, a linear response of lint yield to irrigation was noted in two of three years and the quadratic response to irrigation occurred due to a year of above-average rainfall.

The results of current research regarding the irrigation of cotton on high and low AWHC soils suggest that the AWHC of the soil affects the response of cotton lint yield to supplemental irrigation. The quadratic yield response of cotton lint yield to irrigation is much more prevalent in the studies performed on high AWHC soils by Gwathmey et al. (2011), Wanjura et al. (2002), and Balkcom et al. (2006) than it is in the studies performed on low AWHC soils by DeTar (2008) and Bronson et al. (2006). The linear response of cotton when irrigated on lower AWHC soils, except in years of above-average rainfall, conflicts with the generally quadratic response of cotton when irrigated on high AWHC soils. When irrigation occurs in fields of variable AWHC, this discrepancy could contribute to a significant amount of over or under irrigation. Site-specific, or variable-rate, irrigation would allow the optimization of management for both areas to prevent unnecessary yield loss and a waste of water resources.

Site-specific Irrigation

Managing irrigation based on site-specific crop needs can allow producers to minimize the amount of crop that is over or under-irrigated (Sadler et al., 2000). This can reduce water use, irrigation cost, harmful run-off of sediment and fertilizers, and potentially increase yield. Academic literature regarding the actual practice of variable-rate irrigation is not yet abundant. Bronson et al. (2006) used a variable-rate center pivot to apply varying irrigation rates to cotton grown on sideslopes versus bottom slopes, but found that the same rate was required on all soils despite measuring EC differences between the sideslopes and bottomslopes. Booker et al. (2006) also used a variable-rate center pivot to apply multiple irrigation rates to cotton grown on an Olton clay loam in Texas, but did not mention generating any particular irrigation zones based off of soil variability. Booker et al. (2006) also indicated that growing an indeterminate crop in a highly variable area such as the Texas High Plains might be too unpredictable to benefit from variable-rate irrigation. King et al. (2006) used a soil sampling grid to determine the percentages of sand, silt, and clay of approximately 88 samples covering a 36 acre field. The texture analysis results were used to predict the field capacity and permanent wilting point of the soil cores and then calculate the AWHC. Irrigation management zones were generated based on AWHC variability, and variable-rate irrigation was compared to consistent rates of irrigation. King et al. (2006) found that site-specific irrigation increased potato yield around 5% and generated a gross income increase of about $65 per acre, but noted that no noticeable water savings were achieved and that AWHC alone may not be the only factor needed to fully utilize variable-rate irrigation. Based on the small number of studies that have been conducted utilizing site-specific irrigation for cotton production, it is difficult to determine the full potential of this technology. Certainly, more specific studies of variable-rate irrigation are needed to determine whether or not this technology can be used to optimize cotton lint yield given the conflicting results of lint yield response to irrigation on soils of varying AWHC. In order for site-specific irrigation to be an effective means of correcting this conflict, areas of AWHC variability must be accurately identified.

Identifying Areas of AWHC Variability

Identifying AWHC variability in agricultural fields can be done in a variety of ways. Traditional core sampling provides very accurate information, but induces very serious labor costs to generate high-resolution data. Technologies such as ground-penetrating radar, electrical conductivity measurements, or electromagnetic induction have the potential to produce high-resolution data while reducing field costs and increasing efficiency. A combination of ground-penetrating radar (GPR) and deep electrical conductivity measurements (DEC) was used for this study due to their observed success at producing accurate predictions of subsurface variability. The AWHC variability in the research location used for this project is caused by a sandy, low AWHC layer that is found at varying depths throughout an otherwise silt loam field. Different amounts of water can be held by soil layers with a different AWHC, which causes a difference in dielectric constant between the layers and can be detected using GPR. This technique has been used very successfully to accurately identify the depth to buried features such as soil layers (Freeland et al., 1998; Grote et al., 2003; Truman et al., 1988; Simeoni et al., 2009). Likewise, DEC readings are a measurement of bulk electrical conductivity taken from the ground surface to approximately 36 inches below the surface. Different amounts of soil water and varying soil texture influence the DEC measurements, which can be calibrated to AWHC variability. This technique has also been used successfully in the past the indicate subsurface variability such as soil layers and textural differences (Corwin et al., 2003; Fulton et al., 2010; Mertens et al., 2008; Sudduth et al., 2010). Once the areas of AWHC variability have been accurately identified, varying rates of supplemental irrigation can be used to determine whether or not these areas differ in their response to irrigation.

Materials and Methods

The research site, located on the West Tennessee Research and Education Center in Jackson, Tennessee (35.624^{O}N; 88.845^{O}W), was selected for this project because cotton lint yield variability and visual observations from the research site indicated significant AWHC variability due to a layer of sandy soil in an otherwise silt loam field. Visual observations of the soil during sensor installation procedures revealed a very sandy layer of soil at varying depths from the surface. Variations in cotton growth and maturity rates indicate that some sections of the research site respond differently to rainfall and irrigation than others; the changes seem to be related to changes in the depth of the observed sandy layer. The observed field-scale variability ensured that testing occurs over the wide range of soil conditions that are found in modern agriculture.

The field, approximately 0.75 acre in size, was used to implement an experiment to determine the effects of varying rates of deficit irrigation on cotton lint yield for a variety of soil types. In the spring of the 2010 and 2011 growing seasons, the field was planted to PHY 375 WRF cotton on May 5 and May 12, respectively, using a no-tillage planter into existing crop residue. After plant population establishment, the field was divided into cotton plots that are six rows wide by 30 feet long, with a row spacing of 38 inches. The experiment was designed as a Randomized Complete Block and each combination of an irrigation rate and timing was considered a single treatment. A combination of ground-penetrating radar (GPR) and deep electrical conductivity (DEC) data were used to predict the AWHC and soil texture classification of each research plot and create three major soil blocks. Research plots were first grouped according to similar GPR measurements, and blocks were further refined by grouping those with similar DEC measurements. Soil cores were extracted from the field for validation of the GPR and DEC data. Texture analysis was performed on the soil cores and used, along with bulk density, as inputs into the USDA ROSETTA model (Schaap et al., 2001) to predict the textural class and

AWHC of each soil core increment. Using this validation, the GPR and DEC data were interpolated using ArcGIS Krigging to predict the AWHC variability of the entire field. Texture analysis indicated that three major soils blocks existed within the field. The three blocks, ranging from low to high AWHC, were labeled according to their general soil texture classifications. Shallow loam over sand, silty loam over loamy sand, and deep silt loam represent the blocks from lowest to highest AWHC. The field layout can be seen in Figure 13. The characteristics of each of the three blocks are described in Table 4.

Irrigation rates were applied to each plot using surface drip irrigation that was removed prior to harvest and not replaced until the following spring. Different sizes of surface drip tape (T-tape by John Deere Water, www.deere.com) with rated flow rates of 0.220, 0.450, and 0.670 gallons per minute per 100 feet for 2010 and nominal flow rates of 0.110, 0.220, and 0.340 gallons per minute per 100 feet for 2011 were used to apply irrigation at nominal rates of 0 inch, 0.5 inch, 1.0 inch, and 1.5 inches per week. Flow rates were adjusted for the 2011 growing season because the higher flow rates used in 2010, combined with the slope of the research location, contributed to surface runoff during irrigation. The surface runoff was contained within plots using trenching; however, using a lower flow rate of drip tape and running for a longer period of time required much less maintenance. Line pressure was regulated and maintained at 10 psi during irrigation. Irrigation was generally applied on

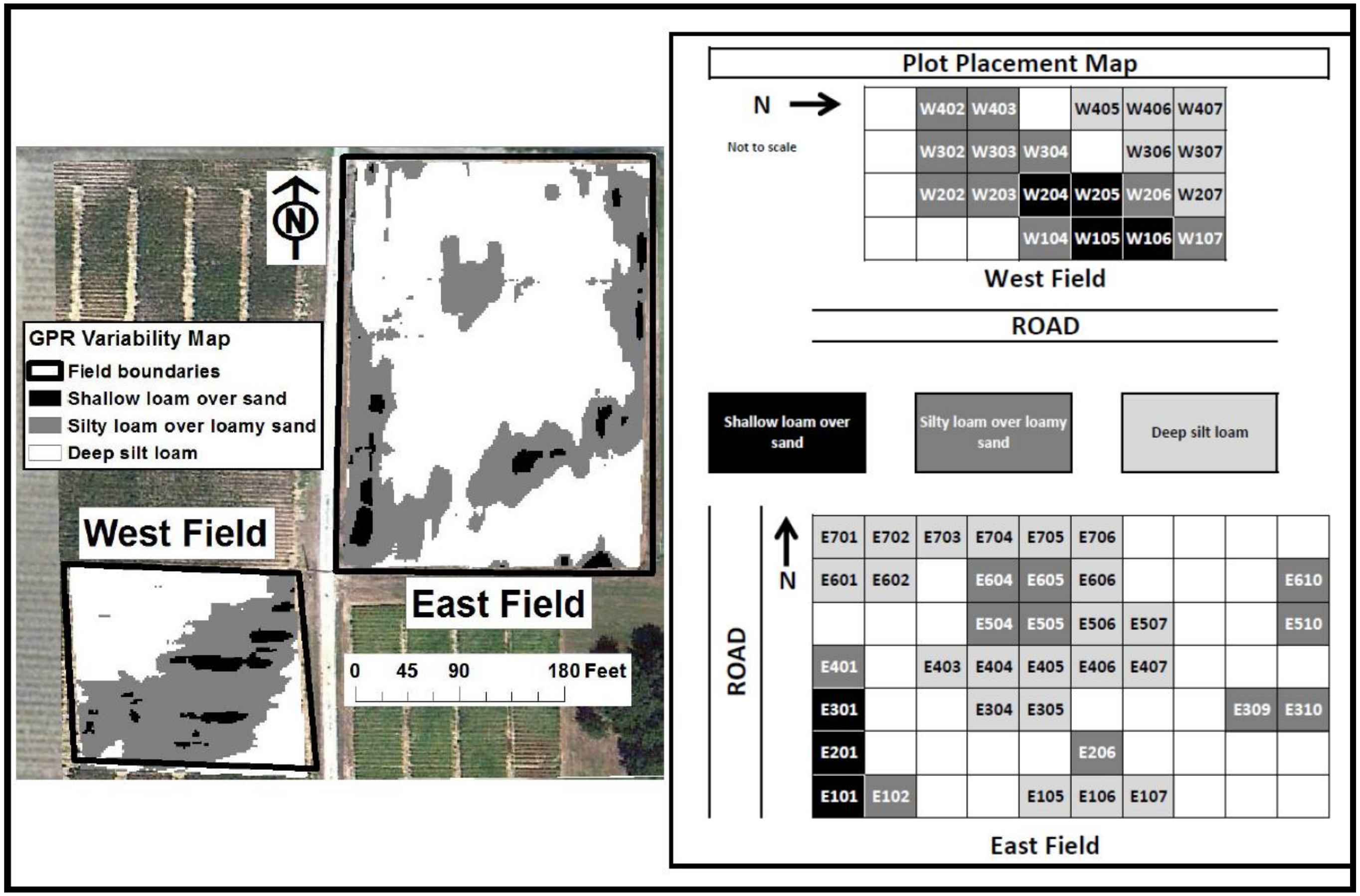

Figure 13: An example of the GPR variability map (left) used in combination with a similar DEC variability map to generate the plot placement map shown to the right

Table 4: Summary of research block characteristics

	Number of plots	Average DTS (in)	Average AWHC (in/in)
Shallow loam over sand	7	20	0.057
Silty loam over loamy sand	21	30	0.091
Deep silt loam	30	50	0.158

Mondays, Wednesdays, and Fridays of each week, but was adjusted proportionally on each day according to rainfall over the previous seven day period. If less than one inch of rainfall occurred over any seven-day period, all irrigation rates were adjusted proportionally. For example, if 0.5 inch of rainfall occurred over a seven day period, irrigation rates would be adjusted such that all treatments were run for one half of their allotted normal time. This resulted in 0.5 inch per week treatments receiving 0.25 inch of irrigation, the 1.0 inch per week treatments receiving 0.5 inch of irrigation, and 1.5 inches per week treatments receiving 0.75 inch irrigation. If greater than one inch of rainfall plus irrigation occurred over a seven day period, no further irrigation was applied for that seven day period.

For 2010, each of the non-zero irrigation rates was initiated at one of three growth stages (at pinhead square, at first bloom, and at 2 weeks post-bloom) and continued until at least half of the plants in irrigated plots contained at least one open, or cracked, boll. The 2010 treatment design was a continuation of the work performed by Gwathmey et al. (2011) and Leib et al. (2010); however, the current work was expanded to include soils with multiple levels of AWHC rather than high AWHC soils only. The 2010 experiment was put into place based on observations made during soil sensor installations and limited GPR data. GPR data were initially taken in the spring of 2010; unfortunately, heavy rainfall prior to the spring GPR data collection prevented a full dataset from being collected and analyzed before the 2010 experiment began. After a full GPR and DEC dataset was collected and analyzed in December of 2010, the 2010 blocks were found to be inconsistent with predicted AWHC variability. Because of this problem, the experimental units from 2010 were re-classified according to the blocking scheme as shown in Figure 13.

A main objective of this research is to determine whether or not cotton grown and irrigated on low AWHC soils reacts differently than high AWHC soils. After re-classifying soil blocks for 2011, soil classification indicated that very few research plots satisfied the conditions necessary to be considered very low AWHC. The lack of experimental units allowed for only one replication of seven irrigation treatments to be applied in the shallow loam over sand block, three replications of seven treatments in the silty loam over loamy sand block, and three replications of nine treatments in the deep silt loam block. In order to accommodate the lower number of experimental units, treatments were adjusted for the 2011 growing season. Low AWHC soils are not likely to retain enough water in the soil profile to satisfy crop demand from the planting date until two weeks post bloom without incurring a high amount of water deficit stress. Since it was unrealistic to delay the start of irrigation until two weeks after first bloom on low AWHC soils and the available number of treatments was limited for both the shallow loam over sand block and the silty loam over loamy sand block, all treatments that delayed the start of irrigation until two weeks after bloom were removed for 2011. Several years of data regarding the effects of the removed treatments on high AWHC soils already exist from the research performed Leib et al. (2010).

For 2011 in the deep silt loam block only, the two weeks post-bloom treatments were replaced with two treatments consisting of irrigation rates of 1.0 inch and 1.5 inches per week initiated at pinhead square but ceasing at the plant's physiological cutoff. Physiological cutoff was assumed when at least half of the plants in these plots had decreased to only three nodes above white flower, which occurred around the first day of August. It was hypothesized that cotton grown on high AWHC soils could withdraw enough water from the previously irrigated soil profile to maintain the crop after physiological cutout. All other treatments remained the same for 2011. Also, at least one non-irrigated control treatment was applied in each block for comparison. Table 5 summarizes the treatments used for 2010 and 2011.

Application of fertilizer, growth regulator, and other cotton maintenance was performed by the WTREC staff according to University of Tennessee

Table 5: Summary of treatments used for 2010 and 2011 growing seasons

Treatment Number	Irrigation Rate (in/wk)	Irrigation begins…	Irrigation ends…	Year
1	1.5	First square	Cracked boll	2010
2	1.0	First square	Cracked boll	
3	0.5	First square	Cracked boll	
4	1.5	First bloom	Cracked boll	
5	1.0	First bloom	Cracked boll	
6	0.5	First bloom	Cracked boll	
7	0.0	n/a	n/a	
10	1.5	Two weeks after first bloom	Cracked boll	
11	1.0	Two weeks after first bloom	Cracked boll	
12	0.5	Two weeks after first bloom	Cracked boll	
1	1.5	First square	Cracked boll	2011
2	1.0	First square	Cracked boll	
3	0.5	First square	Cracked boll	
4	1.5	First bloom	Cracked boll	
5	1.0	First bloom	Cracked boll	
6	0.5	First bloom	Cracked boll	
7	0.0	n/a	n/a	
8*	1.5	First square	Cutout	
9*	1.0	First square	Cutout	

*** =Treatment only applied to deep silt loam block**

Extension Service recommendations for cotton production. The center four rows of each six row plot were harvested using a spindle cotton picker adapted for harvesting small plots. A sample from each plot was used to determine lint percentage, and the lint yield of each plot was converted to a pounds per acre basis for comparison.

Analysis of Variance as performed by PROC MIXED in SAS 9.3 (www.sas.com) was used to analyze lint yield differences between treatments and regression analysis was used to determine the relationship between lint yield and applied water. Data from each year was analyzed separately due to major differences in rainfall amount and distribution between years; this is discussed in more detail below. Also, the reclassification of 2010 research plots after correcting for full GPR and DEC datasets required that the 2010 experiment be analyzed as an incomplete block design while the 2011 experiment remained a randomized complete block. Because Tukey's Single Degree of Freedom Test detected a block by treatment interaction at the 90% significance level ($\alpha=0.10$), mean separation and regression analysis was performed separately within each of the three major soil blocks. Mean separation was analyzed using Fishers protected LSD mean separation at the 90% significance level and regression analysis of polynomial and linear trends was performed using the Data Analysis add-in for Microsoft Excel 2007.

Results and Discussion

Adequate heat units were received in both the 2010 and 2011 growing seasons to produce the full yield potential of the cotton crop. It should be noted, however, that rainfall distribution and amount did vary greatly between years. Figure 14 shows that the 2010 growing season was provided with an above-average amount of rainfall, especially towards the end of the growing season. Contrarily, the 2011 growing season received a below-average amount of rainfall, including a lengthy drought towards the end of the growing season. The 30 year average is estimated using monthly average data from 1971 to 2000 as reported by the National Climatic Data Center (www.ncdc.noaa.gov). Due to the difference in rainfall pattern between the 2010 and 2011 growing seasons, results from each year were analyzed separately. For comparison, Gwathmey et al. (2011) discussed the general rainfall pattern of this area and its effect on cotton lint yield in more detail. Tables 9 and 10, located in the Appendix, show the daily climatic data for the 2010 and 2011 growing season, respectively.

RBD analysis of 2011 treatment means showed a significant (p=0.06) interaction of treatments between soil blocks using Tukey's Single DF test. The extent of the block by treatment interaction is shown in Figure 15. Figure 15 shows that when irrigation occurred on shallow loam over sand soils (very low AWHC), a very large increase in yield occurred under Treatment 1. Treatment 1 is the highest rate of water applied from pinhead square to cracked boll. These

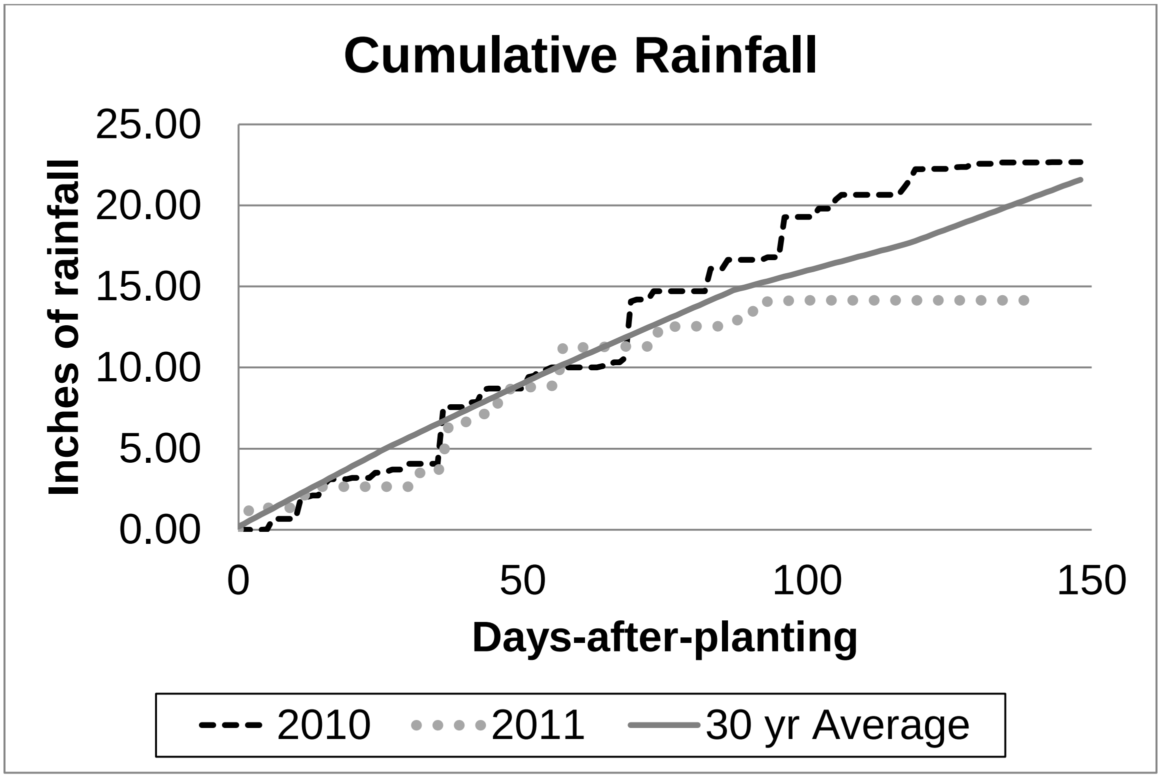

Figure 14: Cumulative rainfall differences between the 2010 and 2011 growing seasons

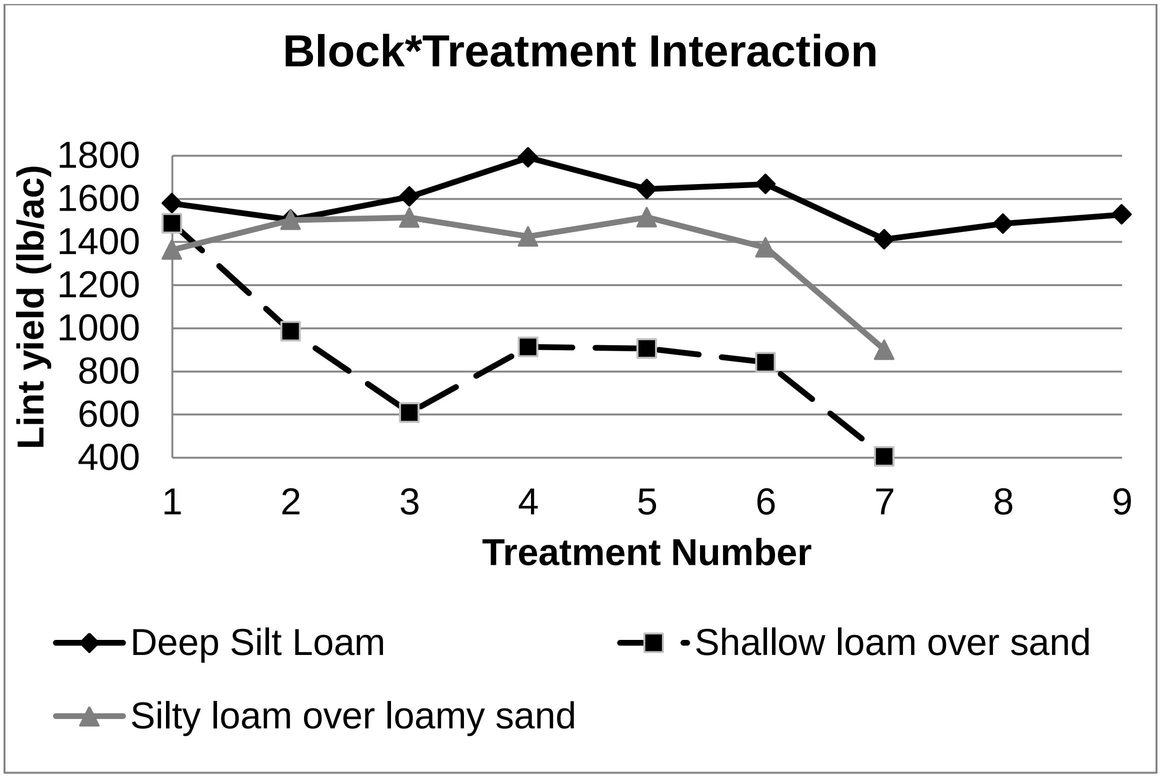

Figure 15: A significant soil block by treatment interaction was noted in 2011 (p=0.06)

results are very inconsistent with the results of Treatment 1 in the deep silt loam and silty loam over loamy sand blocks. The same interaction was not found to be significant in 2010; however, this is most likely due to a very low number of observations in the shallow loam over sand block due to the re-classification of soil plots.

The 2011 interaction is consistent with the hypothesis that low AWHC soils will require a higher rate of water applied earlier in the growing season to maximize lint yield, while high rates of water applied to cotton grown on higher AWHC soils will result in little to no increase, if not a decrease, in lint yield. Because the block by treatment interaction was found to be significant, cotton lint yield differences were analyzed within each block separately for both years. The treatment means from the 2010 and 2011 experiments are reported by soil block in Tables 6 and 7, respectively.

Lint yields were generally higher in the drier growing season of 2011 than in 2010, especially in the deep silt loam block where the maximum irrigated yield was 1790 pounds per acre in 2011 compared to 1510 pounds per acre in 2010. The highest amount of applied water (irrigation plus rainfall) for 2011 was barely greater than the amount of water received by rainfall only in 2010. The heavy rainfall in 2010 contributed to overall cooler temperatures and cloudy days, as well as producing over 11 inches of rainfall between 40 and 120 days after planting. Gwathmey et al. (2011) predicted that, for high AWHC soils, a lint yield.

Table 6: Treatment means from the 2010 growing season, by block

2010 Treatment Means
α=0.10

Irrigation treatment			Shallow loam over sand		Silty loam over loamy sand			Deep silt loam			
Duration	**Rate (in/wk)**		**Lint yield (lb/ac)**								**Rainfall* + irrigation (in)**
Pinhead square to cracked boll	1.5		900		1320	abc		1110	d		31.0
	1.0				1300	abc		1260	cd		28.2
	0.5				1370	ab		1450	ab		25.4
First bloom to cracked boll	1.5		1060		1170	bc		1300	bc		29.9
	1.0		740		1430	a		1370	abc		27.5
	0.5		880		1450	a		1380	abc		25.1
2 weeks post bloom to cracked boll	1.5				1390	ab		1260	c		28.5
	1.0				1150	c		1510	a		26.6
	0.5				1300	abc		1480	a		24.6
Rainfed	0.0		520		790	d		1380	abc		22.7

***=Rainfall amount for 2010 was 22.7 inches**

Table 7: Treatment means from the 2011 growing season, by block

2011 Treatment Means α=0.10												
Irrigation treatment			Shallow loam over sand		Silty loam over loamy sand			Deep silt loam				
Duration	Rate (in/wk)		Lint yield (lb/ac)									Rainfall* + irrigation (in)
Pinhead square to cracked boll	1.5		1490		1360	a		1580	bcd			23.0
	1.0		990		1500	a		1500	cde			20.3
	0.5		610		1510	a		1610	bcd			17.6
First bloom to cracked boll	1.5		910		1430	a		1790	a			21.5
	1.0		910		1510	a		1650	abc			19.3
	0.5		840		1370	a		1670	ab			17.0
Pinhead square to plant cutout	1.5							1490	de			19.3
	1.0							1530	bcde			17.8
Rainfed	0.0		400		900	b		1410	e			14.8

***=Total rainfall amount for 2011 was 14.8 inches**

response to irrigation may not be seen at all in years that produced more than 11 inches of rainfall between 40 and 120 days after planting. This is consistent with the lack of significant yield increase due to irrigation in deep silt loam soils for 2010; however, at least one irrigation regime resulted in a significant increase in lint yield for soils of lower AWHC.

In both years, the yield of rainfed plots is very consistent. Also, rainfed yield is consistent with blocked AWHC differences; this is a strong indication that the blocking method was effective. The lowest AWHC soils had the lowest rainfed yields, the highest AWHC soils had the highest rainfed yields, and the moderate AWHC soils produced lint yields in between the lowest and highest. The fact that this trend is not consistent through all irrigation treatments is further indication that each block reacts differently to irrigation due to AWHC differences.

Further analysis of Tables 6 and 7 shows that maximum yields were not always created using the same irrigation decision in a single soil type. For the very low AWHC soils found in the shallow loam over sand block, 1.5 inches of water per week applied from pinhead square to cracked boll generated the maximum lint yield in 2011. In a wetter year such as 2010, maximum lint yield was achieved by waiting to apply irrigation later in the growing season despite the very low AWHC. High irrigation levels were required to maximize lint yield in low AWHC soils for 2011, but caused a decrease in lint yield in 2010.

Results differed for the very high AWHC soils found in the deep silt loam block, where the highest level of irrigation was never required to maximize yield. In the wet growing season of 2010, yields generally increased as the irrigation rate decreased and was initiated later in the year. The highest increase in lint yields for 2010 in the deep silt loam block was less than 200 pounds per acre and was not significantly different than rainfed yields. The quadratic yield response of cotton lint yield to irrigation is noted by a significant decrease in cotton lint yields when 1.5 inches of water per week from pinhead square to cracked boll is applied to the deep silt loam block in 2010. In 2011, 1.5 inches of water per week applied from first bloom to cracked boll resulted in over 300 pounds of lint per acre increase relative to rainfed cotton. The drier growing season of 2011 required more irrigation applied earlier in the growing season to maximize lint yields. Much of the dry period of 2011 occurred late in the growing season and caused treatments that ended at plant cutout rather than at cracked boll to receive very little water after irrigation ceased. The lack of rainfall in this part of the growing season combined with an already dry year may have harmed boll development, thus explaining why these treatments did not produce a significant increase over rainfed yields.

The moderate AWHC soils of the silty loam over loamy sand block allowed much more flexibility in irrigation regimes. Lint yields show much less change across regimes in 2010 and 2011 for these soils, although a significant increase in lint yield relative to rainfed cotton was seen in both years. Low to medium rates of water applied from either pinhead square or first bloom appear to produce equally high lint yields in these soils as little to no mean separation was noted.

Results from Tables 6 and 7 are consistent with the quadratic yield response of cotton when irrigated on silty, high AWHC soils as discussed throughout academic literature as well as the hypotheses of this research. In high AWHC soils, high amounts of irrigation combined with high levels of water already held in the soil profile provided too much water to the plant, which can result in a yield decrease. For moderate AWHC soils, more flexibility is noted in irrigation regimes because the soil profile holds enough water to contribute to crop growth for fairly long periods of time, but does not hold enough water to produce major lint decreases unless subjected to very high rates of irrigation. In very low AWHC soils, very little water can be held by the sandy soil profile; thus, higher rates of irrigation are necessary to produce maximum yields except for years producing above-average rainfall. These results indicate that a single irrigation decision cannot maximize cotton lint yields on all soil types in all years. Irrigation scheduling and application must remain as dynamic and flexible as possible to optimize the needs of cotton grown on different soil types and rainfall patterns.

Further evidence that lint yield response to irrigation varies depending on AWHC is shown by regression analysis of lint yield versus applied water. Polynomial regression of lint yield response versus total applied water indicated a significant (α=0.10) quadratic response in all cases except in the 2011 deep silt loam. The lack of a significant, quadratic response to applied water in the 2011 deep silt loam appears to be more from small yield increases, due to already high yields from the high AWHC soil, combined with a fair amount of plot variability. The regression results are shown in Figures 16 through 21. The vertical error bars shown in Figures 18 through 21 represent the standard deviation of yield measured on replicates; no replication occurred in the low AWHC block (Figures 16 and 17) due to a lack of experimental units.

The regression analysis of low AWHC soils shown in Figures 16 and 17 represent a quadratic response for both years. However, Figure 17 shows that the quadratic response of lint yield to applied water in 2011 on low AWHC soils is inverted. The lack of vertical error bars on these figures indicates the lack of replications due to a limited number of low AWHC experimental units. If replications were included for this analysis and the number of observations was increased, the response of lint yield to applied water in 2011 on low AWHC soils would most likely be linear. Indeed, an equally strong (R^2=0.81) linear regression can be fitted to this data, suggesting that in drier years, the lint yield of cotton

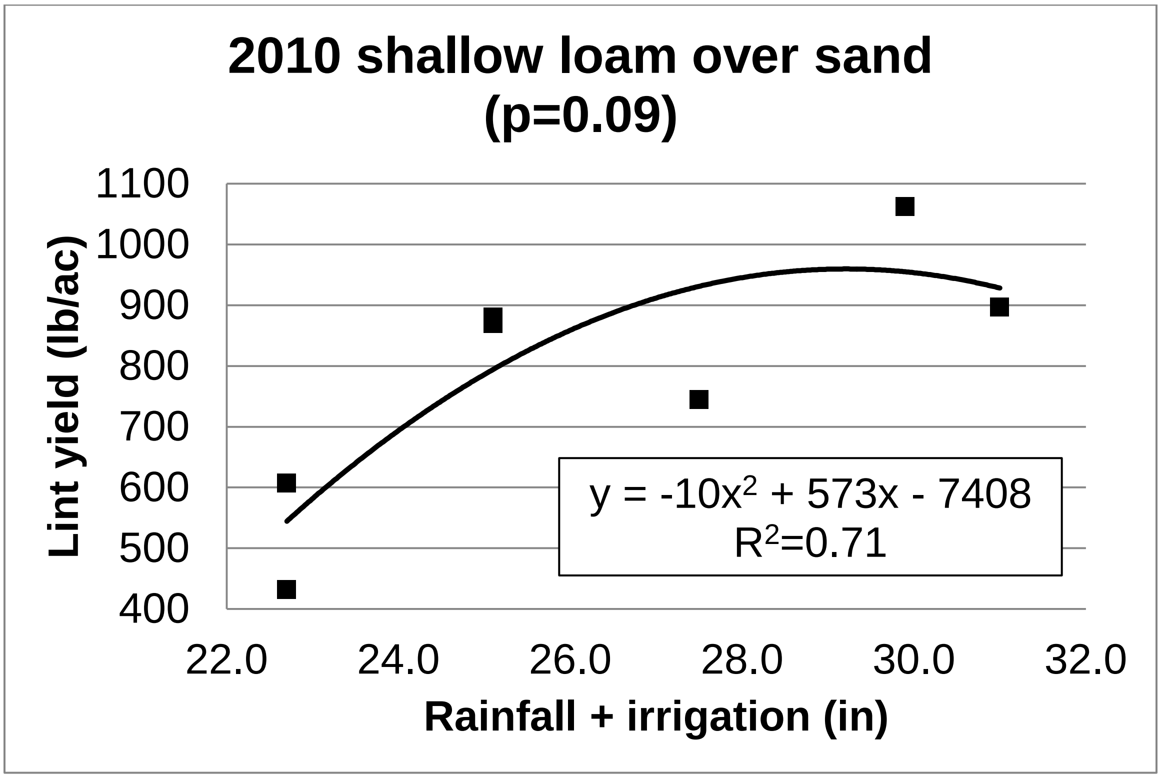

Figure 16: Polynomial regression of lint yield response to applied water for 2010, low AWHC soils

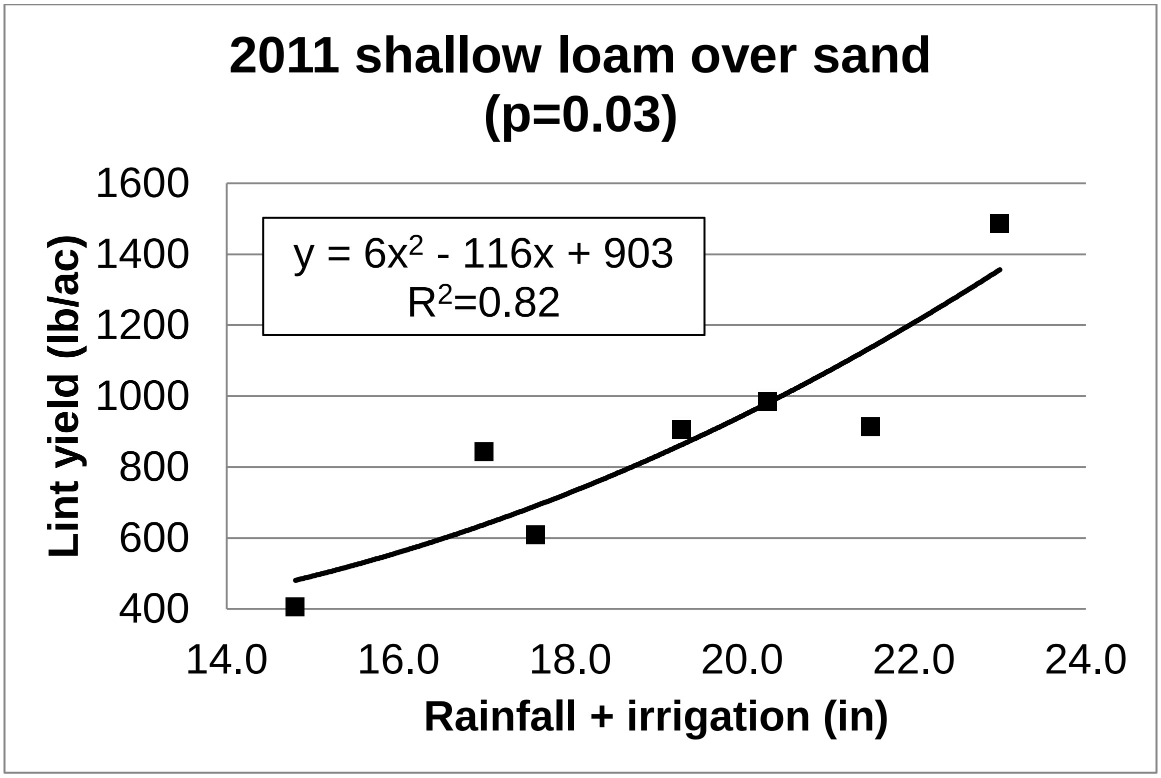

Figure 17: Polynomial regression of lint yield response to applied water for 2011, low AWHC soils

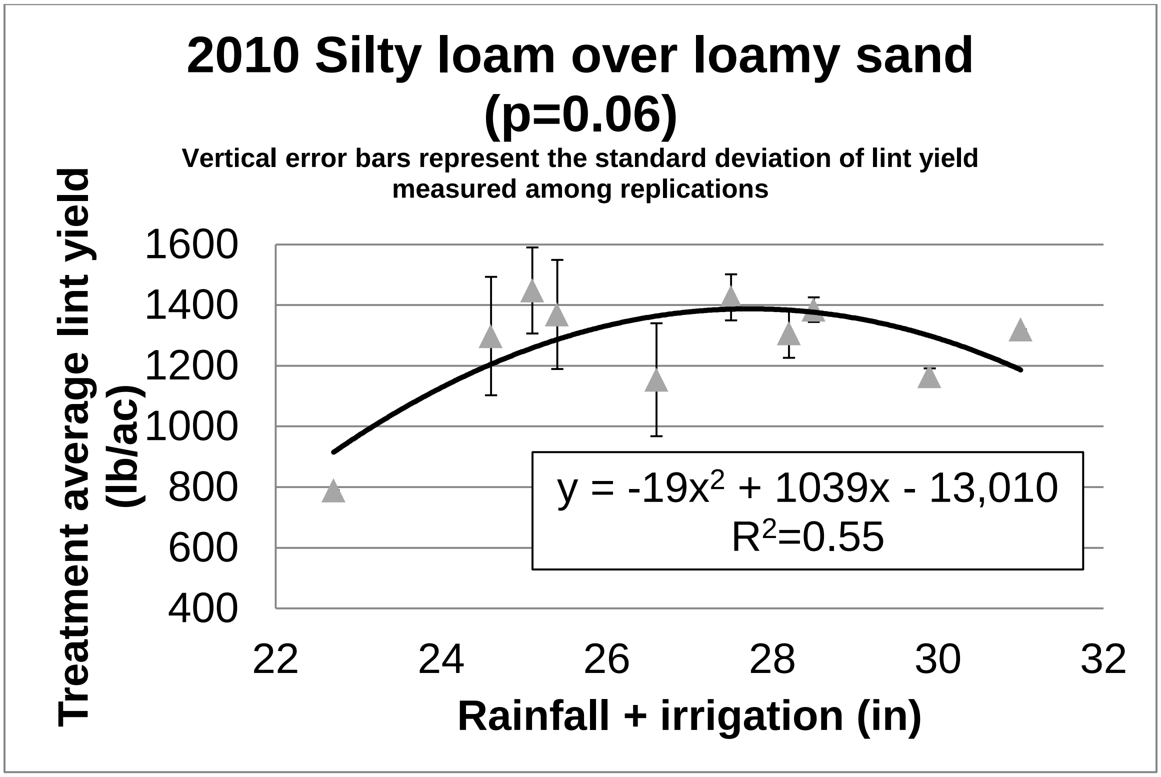

Figure 18: Polynomial regression of lint yield response to applied water for 2010, moderate AWHC soils

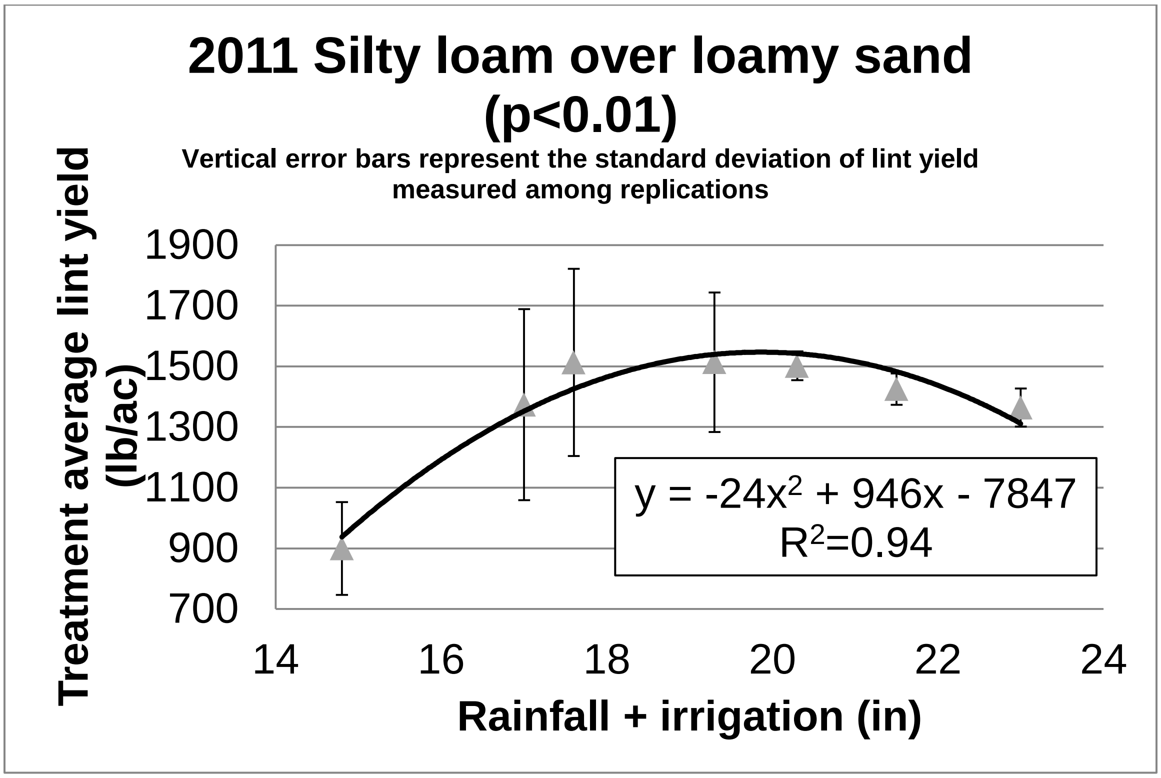

Figure 19: Polynomial regression of lint yield response to applied water for 2011, moderate AWHC soils

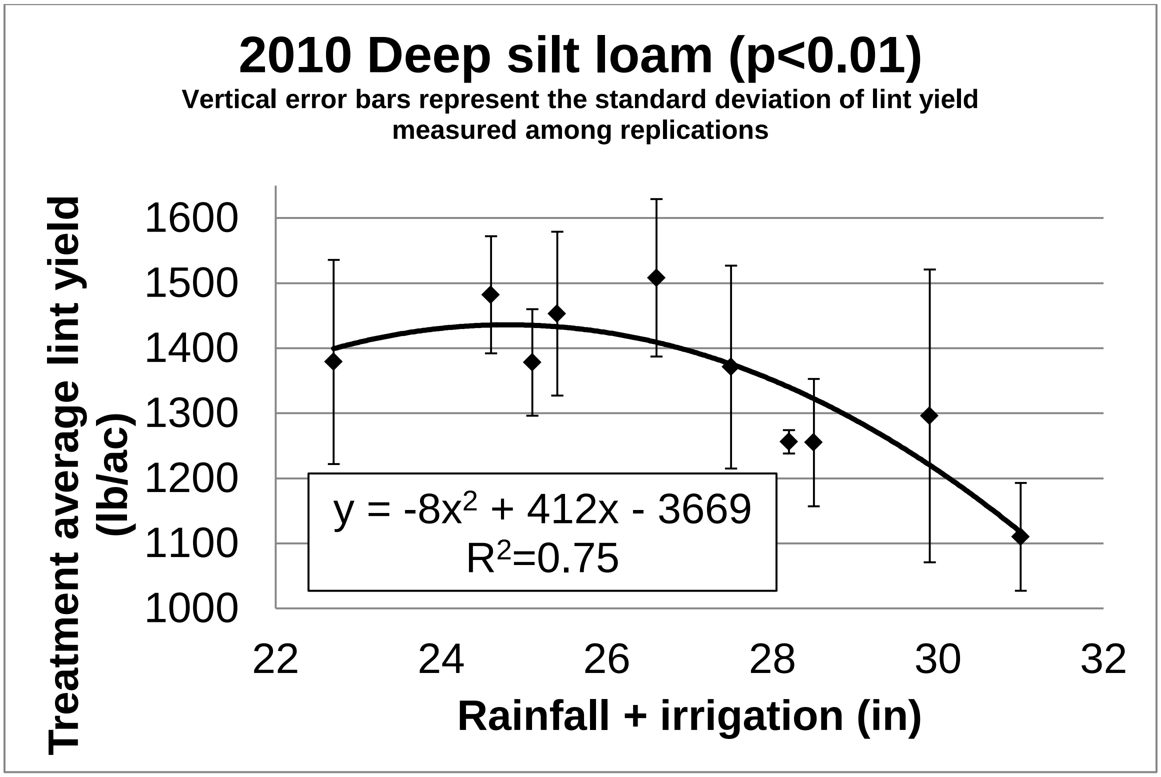

Figure 20: Polynomial regression of lint yield response to applied water for 2010, high AWHC soils

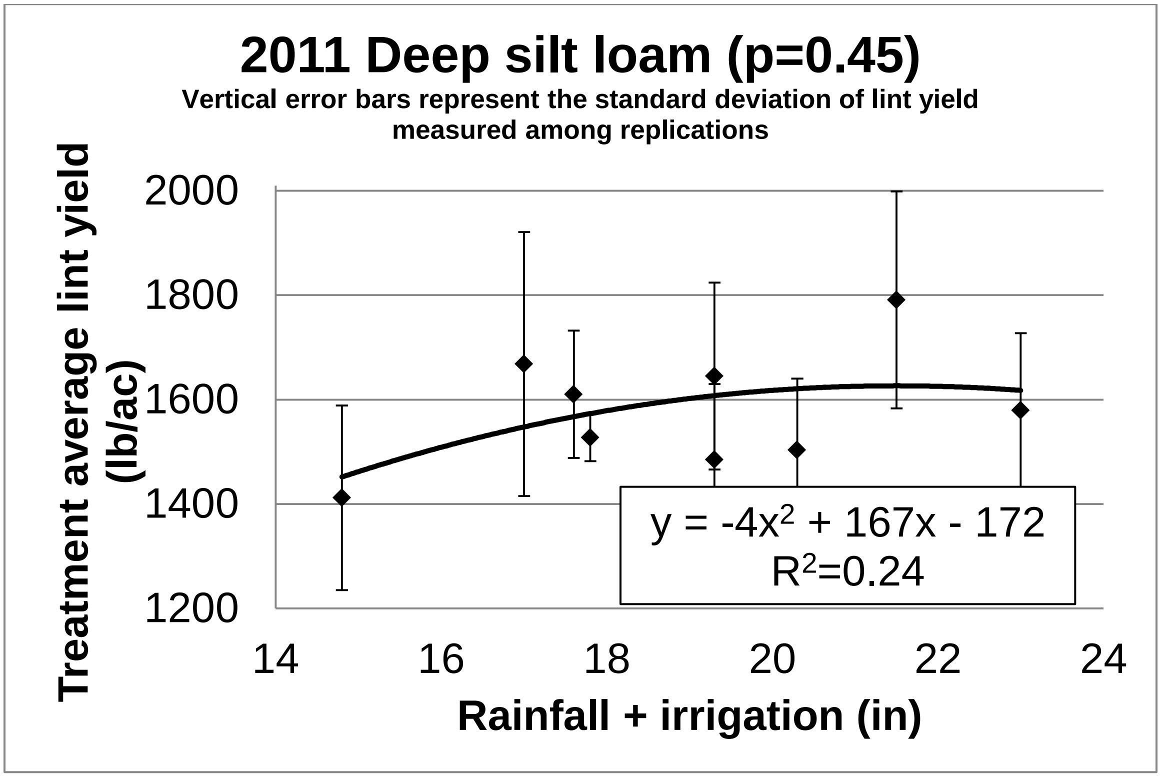

Figure 21: Polynomial regression of lint yield response to applied water for 2011, high AWHC soils

irrigated on low AWHC soils is still limited by water. Whether quadratic or linear, the response is much different from the response indicated by other soil types. Figures 16 and 17 show that yield increased with higher amounts of applied water on low AWHC soils. In Figures 18 and 19, the peak of the quadratic response tends to occur more near the center of the irrigation treatments. In Figure 20, which represents the response of high AWHC soils in 2010, the peak of the quadratic response occurs with a very low amount of applied water. Furthermore, Figure 20 shows the significant yield loss associated with over-irrigation of high AWHC soils. In 2011, the response is relatively flat and the quadratic response was not significant. The flatter response to irrigation in Figure 21 indicates that in a drier year such as 2011, it is less likely to over-irrigate cotton on high AWHC soils to the same degree of yield loss seen in 2010.

Mean separation of lint yield and regression analysis both indicate that a single irrigation regime cannot optimize yield on all soil types in all years. The differences in lint yield and regression response to applied water between blocks shows that (1) GPR and DEC data were effectively used to identify soil AWHC variability and that (2) lint yield response to irrigation is related to variations in AWHC. In general, as soil AWHC increases, the optimum amount of irrigation decreases and should be applied later in the growing season. The data indicates that, especially in wet years, applying too much irrigation can result in a significant decrease in lint yield; thus, always irrigating to meet the needs of cotton grown on low AWHC soils might not be an effective irrigation decision because that can result in profit loss from both wasted water resources and yield loss. Furthermore, the optimum irrigation regime required on a consistent soil type can vary greatly from year to year depending on available heat units as well as rainfall amount and distribution. Variable-rate irrigation could be a very effective means of managing the conflicting needs of cotton grown on variable AWHC soils by allowing producers to apply little to no irrigation to high AWHC soils early in the growing season while still applying water to low AWHC soils.

Future research should continue to examine the response of lint yield to varying irrigation regimes over several years of data due to the changes in response caused by temperature and rainfall pattern variability. It is important for producers to know how to react to changes in rainfall distribution and amount between years. Also, this work as well as the work of Gwathmey et al. (2011) focuses on applying the same rate of water throughout the application of irrigation. Given the current state of irrigation technology, there is no reason that the rate must remain constant. Perhaps it would be beneficial to increase the irrigation rate later in the year as temperatures tend to rise and rainfall tends to decrease. Likewise, in years without a long absence of rainfall at the end of the growing season, treatments that cease irrigation at plant cutoff rather than cracked boll may prove beneficial. Also, research should be conducted to understand the effects of a fragipan on AWHC and cotton response to irrigation.

Furthermore, textural variability is not the sole variability that causes AWHC variability. In Tennessee, nearly 55% of loessially derived, upland soils contain a fragipan layer at varying depths from the surface (Graveel et al., 2002). Fragipan horizons typically have a low or very low permeability (Lindbo et la., 1995) that can cause significant decreases in yield due to a decrease in AWHC relative to overlying horizons (Graveel et al., 2002). Crop yield tends to decrease as the depth from the surface to the fragipan decreases (Graveel et al., 2002). Similarly, the yield results in this paper indicated that yield tends to decrease as the DTS decreased. A fundamental difference between this research and fragipan soils, however, is that water applied to sandy soils tends to percolate quickly through the soil profile while water applied to a fragipan would have a much greater tendency to perch on top of the layer due to the low permeability of the fragipan. While cotton irrigated on fragipan soils could benefit from variable rate irrigation, it will likely need to be managed differently than cotton that is irrigated on soils with low AWHC caused by sandy layers.

Conclusion

Deficit irrigation of cotton took place on soils of varying levels of AWHC in the 2010 and 2011 growing seasons in Jackson, Tennessee. GPR and DEC measurements were used to group similar soil research plots and provide three blocks consisting of shallow loam over sand, silty loam over loamy sand, and deep silt loam soils. These soil textures correspond to a low, moderate, and high

AWHC, respectively. The 2010 and 2011 growing seasons each provided very different rainfall conditions. In 2010, an above-average rainfall year was experienced while 2011 resulted in below-average rainfall, including a long period of very little precipitation in the last month of the growing season. Mean separation and quadratic regression were used to examine the response of lint yield to varying amounts of applied water of each soil type in each year.

As the AWHC of the soil decreased, more irrigation was necessary to maximize yield. Furthermore, cotton grown on high AWHC soils indicated decreased yield relative to rainfed yield when provided with high levels of irrigation, especially under above-average rainfall conditions. Cotton grown on high AWHC soils generally responded better to low amounts of irrigation applied beginning at first bloom or later and ceasing at the first sign of an open boll. Contrarily, cotton grown on low AWHC soils required higher amounts of irrigation with application beginning earlier in the growing season. In years of below-average rainfall, cotton grown on low AWHC soils exhibited a more linear, rather than quadratic response to applied water. Applying 1.5 inches of water per week from pinhead square to cracked boll in 2011 resulted in 1080 pounds of lint per acre increase for cotton grown on soils with a low AWHC. Applying the same irrigation regime to cotton grown on high AWHC soils resulted in only 170 pounds of lint per acre increase relative to rainfed. This is approximately half of the maximum lint yield increase achieved in high AWHC soils, indicating that a single irrigation decision cannot maximize lint yield on soils with significantly different AWHC in all years.

CONCLUSION

Two experiments were performed in West Tennessee to determine the effectiveness of subsurface exploration for partitioning variable-rate irrigation zones and to examine the response of cotton lint yield to varying rates and durations of irrigation when grown on soils of varying AWHC. GPR and EC measurements were used to identify and quantify several variable-rate irrigation zones based on soil texture and AWHC variability. The identified irrigation zones were used to implement a deficit irrigation cotton experiment to examine lint yield response to variable-rate irrigation.

Shallow EC (SEC) readings were an inadequate means of determining subsurface variability in this location because the sampling depth reached only 12 inches below the surface, which is shallower than the majority of the observed variability. Both GPR and deep EC (DEC) showed good correlation with observed field variability; however, neither dataset seemed to describe the full amount of variability in the field on its own. Variable-rate irrigation zones were created by combining research plots that contained both similar GPR and DEC measurements; differences were then validated using a series of soil cores. Texture analysis of soil cores was used to predict AWHC of the cores as well as physically measure the observed depth to the sandy layer contained in the research field (DTS). Validation showed that GPR and DEC can predict approximately 75% of the variability in AWHC (R^2 = 0.82 and 0.74, respectively).

A very strong, linear relationship was found between DTS and AWHC (R^2 = 0.92) which indicates that an accurate model of either DTS or AWHC can likely be used to differentiate variable-rate irrigation zones. GPR and DEC were successfully combined to generate variable-rate irrigation zones based on AWHC variability. In the future, it might be possible to increase the accuracy of the relationship between mapping methods and AWHC variability by optimizing the combination of GPR and DEC data or by recording and combining GPR or DEC data that is optimized for several different sampling depths.

Using the previously recorded GPR and DEC data, a deficit irrigation cotton experiment was applied to the same research location in the 2010 and 2011 growing seasons. Three variable-rate irrigation zones consisted of soil textures best described as shallow loam over sand, silty loam over loamy sand, and deep silt loam. These textural differences corresponded to AWHC of low, moderate, and high, respectively. Statistical analysis of lint yield differences showed that cotton grown on low AWHC soils reacted differently to irrigation treatments than cotton grown on moderate and high AWHC soils ($p=0.06$). Because of the soil block by treatment interaction as well as distinct rainfall differences, results were analyzed separately within each year and each soil block using mean separation at the 90% level of confidence and quadratic regression analysis.

A significant increase in cotton lint yield due to irrigation was found in all blocks except for the deep silt loam block in 2010. In 2011, a significant increase in cotton lint yield due to irrigation was found in all blocks; however, the same irrigation treatment did not maximize yield in the same block in both years. As the AWHC of the soil decreased, irrigation was required in higher amounts and at longer durations to maximize yield. Cotton grown on soils with a low AWHC exhibited a much more linear response than cotton grown on soils with a moderate to high AWHC and responded best to high levels of irrigation beginning around the emergence of first square. Cotton grown on high AWHC soils generally showed a significant, quadratic response to irrigation and generally responded best to low amounts of irrigation applied beginning at first bloom or later and ceasing at the first cracked boll. In 2011, applying 1.5 inches of water per week from first square to cracked boll resulted in a 1080 pounds of lint per acre increase in cotton grown on low AWHC soils. The same irrigation regime resulted in only 170 pounds of lint per acre increase in high AWHC soils, which was significantly less than the maximum lint yield increase achieved by applying water starting at first bloom rather than pinhead square. Results indicate that irrigating an entire field based on the needs of the lowest or highest AWHC soils will likely result in a significant over or under irrigation of some of the crop. A single irrigation decision did not maximize yield on all soil types in both years;

however, variable-rate irrigation could be used to optimize the irrigation on all soil types.

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APPENDICES

Appendix 1: ROSETTA Input and Output Parameters

Table 8: ROSETTA model input and output parameters

Core number	Depth from surface (inches)	% sand	% silt	% clay	Bulk density (lb/ft^3)	θ_r*	θ_s*	α*	n*
1	0 - 6	52	42	7	99	0.03	0.33	-1.21	0.15
1	6 - 12	53	41	7	118	0.03	0.27	-0.83	0.09
1	12 - 18	72	23	5	118	0.03	0.28	-0.80	0.14
1	18 - 24	92	7	1	80	0.05	0.44	-0.98	0.42
1	24 - 30	98	2	0	108	0.05	0.32	-1.08	0.59
1	30 - 36	99	0	0	91	0.05	0.39	-1.11	0.65
1	36 - 40	99	1	0	77	0.05	0.48	-0.98	0.51
2	0 - 6	58	37	6	84	0.04	0.39	-1.33	0.17
2	6 - 12	67	28	5	119	0.03	0.27	-0.76	0.11
2	12 - 18	86	11	3	105	0.04	0.33	-0.97	0.33
2	18 - 24	98	2	0	98	0.05	0.35	-1.09	0.62
2	24 - 30	97	3	0	51	0.05	0.61	-0.72	0.27
3	0 - 6	51	42	7	115	0.03	0.29	-0.96	0.10
3	6 - 11	63	32	5	131	0.03	0.24	-0.70	0.10
3	11-18	100	0	0	83	0.04	0.44	-0.96	0.29
3	18 - 24	85	13	3	97	0.04	0.35	-0.98	0.34
4	0 - 6	42	49	9	119	0.03	0.27	-1.00	0.09
4	6 - 12	75	21	4	113	0.03	0.30	-0.83	0.17
4	12 - 18	93	6	1	120	0.04	0.28	-1.04	0.46
4	18 - 24	96	3	1	146	0.05	0.22	-1.15	0.60
4	24-27	97	2	0	121	0.05	0.28	-1.09	0.54
5	0 - 6	40	52	8	68	0.05	0.43	-1.87	0.22
5	6 - 12	47	45	8	115	0.03	0.29	-1.04	0.10
5	12 - 18	32	57	11	105	0.04	0.32	-1.50	0.15
5	18 - 24	49	43	8	111	0.03	0.29	-1.01	0.10
5	24 - 30	72	23	4	91	0.04	0.37	-0.96	0.19
5	30 - 36	92	7	1	114	0.04	0.30	-1.02	0.45

Table 8: ROSETTA model input and output parameters (continued)

Core number	Depth from surface (inches)	% sand	% silt	% clay	Bulk density (lb/ft^3)	θ_r*	θ_s*	α*	n*
5	36 - 40	85	12	3	67	0.04	0.50	-0.91	0.22
6	0 - 6	39	52	9	94	0.04	0.35	-1.60	0.18
6	6 - 12	23	65	12	97	0.05	0.35	-1.73	0.19
6	12 - 18	34	56	10	85	0.05	0.37	-1.78	0.21
6	18 - 24	41	50	9	112	0.03	0.29	-1.17	0.11
6	24 - 30	80	17	3	119	0.04	0.28	-0.87	0.22
6	30 - 36	92	7	1	114	0.04	0.30	-1.02	0.45
6	36 - 42	96	4	1	113	0.05	0.30	-1.07	0.53
6	42 - 48	95	5	1	92	0.05	0.38	-1.07	0.56
7	0 - 6	36	55	9	112	0.03	0.29	-1.26	0.12
7	6 - 12	39	52	9	104	0.03	0.31	-1.35	0.14
7	12 - 18	57	36	7	96	0.03	0.36	-1.20	0.15
7	18 - 24	79	17	4	101	0.04	0.35	-0.94	0.24
7	24 - 33	92	7	1	92	0.05	0.38	-1.04	0.49
8	0 - 6	37	55	9	85	0.04	0.36	-1.73	0.21
8	6 - 12	24	65	11	105	0.04	0.33	-1.61	0.17
8	12 - 18	20	68	12	103	0.05	0.36	-1.75	0.20
8	18 - 24	20	68	12	92	0.05	0.38	-1.83	0.21
8	24 - 30	28	62	11	99	0.04	0.34	-1.68	0.19
8	30 - 36	49	42	8	104	0.03	0.31	-1.13	0.12
8	36 - 42	69	26	5	114	0.03	0.30	-0.81	0.13
8	42-43	82	15	3	137	0.04	0.23	-0.96	0.32
9	0 - 6	24	65	10	125	0.03	0.27	-1.20	0.10
9	6 - 12	25	63	12	107	0.04	0.33	-1.61	0.17
9	12 - 18	9	78	13	95	0.06	0.41	-1.83	0.21
9	18 - 24	21	66	13	112	0.04	0.31	-1.53	0.15
9	24 - 30	21	68	11	104	0.04	0.33	-1.63	0.17
9	30 - 36	31	59	11	88	0.05	0.37	-1.83	0.22
9	36 - 42	57	36	7	86	0.04	0.38	-1.28	0.16

Table 8: ROSETTA model input and output parameters (continued)

Core number	Depth from surface (inches)	% sand	% silt	% clay	Bulk density (lb/ft^3)	θ_r*	θ_s*	α*	n*
9	42 - 46	64	30	6	98	0.03	0.34	-0.99	0.15
10	0 - 6	47	47	7	114	0.03	0.29	-1.03	0.11
10	6 - 12	18	69	13	88	0.06	0.40	-1.90	0.23
10	12 - 18	17	70	13	107	0.05	0.34	-1.68	0.18
10	18 - 24	22	66	12	134	0.03	0.26	-1.15	0.09
10	24 - 30	27	62	11	133	0.03	0.25	-1.06	0.08
10	30 - 36	49	43	8	129	0.02	0.24	-0.72	0.07
10	36 - 42	64	31	6	115	0.03	0.29	-0.83	0.12
10	42 - 48	64	31	5	91	0.03	0.36	-1.05	0.16
11	0 - 6	25	65	10	83	0.05	0.40	-1.93	0.23
11	6 - 12	26	63	12	99	0.05	0.34	-1.71	0.20
11	12 - 18	39	50	11	111	0.03	0.29	-1.23	0.11
11	18 - 24	67	27	6	105	0.03	0.32	-0.89	0.14
11	24 - 30	81	15	4	107	0.04	0.33	-0.92	0.25
11	30 - 36	95	4	1	123	0.05	0.26	-1.09	0.51
11	36 - 42	94	5	1	101	0.05	0.35	-1.06	0.53
11	42 - 48	94	5	1	69	0.05	0.51	-0.89	0.35
12	0 - 6	28	63	9	85	0.05	0.38	-1.84	0.22
12	6 - 12	26	64	10	96	0.05	0.36	-1.78	0.21
12	12 - 18	14	73	14	98	0.06	0.37	-1.78	0.21
12	18 - 24	20	67	12	101	0.05	0.36	-1.75	0.19
12	24 - 30	23	66	11	82	0.06	0.41	-1.94	0.23
12	30 - 36	26	63	11	97	0.05	0.34	-1.70	0.19
12	36 - 42	39	50	10	105	0.04	0.31	-1.36	0.14
12	42 - 48	59	35	7	106	0.03	0.31	-0.98	0.13
13	0 - 6	25	65	9	78	0.05	0.43	-1.97	0.24
13	6 - 12	28	62	11	109	0.04	0.30	-1.43	0.14
13	12 - 18	13	72	15	113	0.05	0.33	-1.62	0.16
13	18 - 24	16	70	14	123	0.04	0.28	-1.37	0.11

Table 8: ROSETTA model input and output parameters (continued)

Core number	Depth from surface (inches)	% sand	% silt	% clay	Bulk density (lb/ft^3)	θ_r*	θ_s*	α*	n*
13	24 - 30	25	65	10	101	0.04	0.34	-1.70	0.19
13	30 - 36	33	57	10	91	0.04	0.35	-1.70	0.20
13	36 - 42	56	37	7	104	0.03	0.31	-1.01	0.12
13	42 - 48	77	19	4	100	0.04	0.35	-0.93	0.22
14	0 - 6	23	67	10	79	0.05	0.41	-1.93	0.23
14	6 - 12	19	68	13	105	0.05	0.34	-1.67	0.18
14	12 - 18	6	77	17	92	0.07	0.42	-1.82	0.21
14	18 - 24	8	79	14	94	0.06	0.41	-1.82	0.22
14	24 - 30	12	74	14	98	0.06	0.38	-1.78	0.20
14	30 - 36	14	73	12	91	0.06	0.39	-1.84	0.21
14	36 - 42	28	61	11	99	0.04	0.34	-1.68	0.19
14	42 - 48	47	45	8	100	0.03	0.33	-1.31	0.15
15	0 - 6	27	63	10	113	0.04	0.30	-1.42	0.14
15	6 - 12	16	71	12	79	0.06	0.43	-1.94	0.23
15	12 - 18	11	75	14	95	0.06	0.40	-1.84	0.22
15	18 - 24	12	75	13	114	0.05	0.33	-1.61	0.16
15	24 - 30	25	64	11	88	0.05	0.38	-1.87	0.22
15	30 - 36	31	59	11	98	0.04	0.34	-1.65	0.19
15	36 - 42	52	41	7	103	0.03	0.33	-1.20	0.14
15	42 - 48	73	23	5	105	0.03	0.32	-0.88	0.18
16	0 - 6	17	72	12	107	0.05	0.34	-1.67	0.18
16	6 - 12	17	70	14	99	0.05	0.36	-1.78	0.20
16	12 - 18	7	77	16	95	0.07	0.41	-1.83	0.21
16	18 - 24	11	73	16	79	0.07	0.45	-1.91	0.23
16	24 - 30	6	80	14	82	0.07	0.46	-1.88	0.22
16	30 - 36	9	77	14	86	0.07	0.43	-1.87	0.22
16	36 - 42	14	74	13	99	0.05	0.37	-1.77	0.21
16	42 - 48	19	69	12	121	0.04	0.30	-1.42	0.13
17	0 - 6	8	78	14	96	0.06	0.41	-1.83	0.21

Table 8: ROSETTA model input and output parameters (continued)

Core number	Depth from surface (inches)	% sand	% silt	% clay	Bulk density (lb/ft^3)	θ_r*	θ_s*	α*	n*
17	6 - 12	5	75	20	97	0.07	0.40	-1.78	0.20
17	12 - 18	7	74	19	108	0.06	0.37	-1.73	0.18
17	18 - 24	13	70	18	91	0.07	0.40	-1.84	0.22
17	24 - 30	13	72	16	99	0.06	0.38	-1.79	0.21
17	30 - 36	9	74	16	90	0.07	0.43	-1.88	0.22
17	36 - 42	9	77	14	103	0.05	0.36	-1.71	0.18
17	42 - 48	8	79	12	136	0.04	0.27	-1.16	0.10
18	0 - 6	25	65	10	95	0.05	0.36	-1.79	0.21
18	6 - 12	15	73	12	82	0.06	0.43	-1.93	0.23
18	12 - 18	12	73	15	92	0.06	0.40	-1.84	0.22
18	18 - 24	6	79	15	77	0.07	0.49	-1.90	0.23
18	24 - 30	15	72	13	111	0.04	0.32	-1.59	0.16
18	30 - 36	29	60	11	98	0.04	0.34	-1.67	0.18
18	36 - 42	41	49	9	93	0.04	0.35	-1.55	0.17
18	42 - 48	63	30	7	157	0.03	0.20	-0.85	0.22
19	0 - 6	26	64	10	105	0.04	0.32	-1.57	0.17
19	6 - 12	27	62	11	113	0.04	0.30	-1.44	0.14
19	12 - 18	11	73	16	80	0.07	0.45	-1.91	0.23
19	18 - 24	12	72	15	89	0.07	0.42	-1.89	0.22
19	24 - 30	12	74	14	107	0.05	0.35	-1.71	0.18
19	30 - 36	7	79	14	90	0.07	0.44	-1.86	0.22
19	36 - 42	11	75	13	85	0.06	0.42	-1.88	0.22
19	42 - 48	11	76	13	136	0.03	0.26	-1.16	0.10
20	0 - 6	28	60	11	94	0.05	0.36	-1.77	0.20
20	6 - 12	18	66	16	99	0.06	0.36	-1.78	0.20
20	12 - 18	11	73	16	92	0.06	0.40	-1.84	0.21
20	18 - 24	12	72	16	90	0.07	0.42	-1.89	0.22
20	24 - 30	11	74	15	92	0.06	0.40	-1.84	0.22
20	30 - 36	13	73	14	96	0.06	0.40	-1.84	0.22

Table 8: ROSETTA model input and output parameters (continued)

Core number	Depth from surface (inches)	% sand	% silt	% clay	Bulk density (lb/ft^3)	θ_r*	θ_s*	α*	n*
20	36 - 42	17	70	13	101	0.05	0.36	-1.77	0.20
20	42 - 48	20	69	11	140	0.03	0.25	-1.04	0.09
21	0 - 6	27	64	9	91	0.04	0.36	-1.76	0.21
21	6 - 12	17	71	12	95	0.05	0.38	-1.84	0.22
21	12 - 18	10	77	13	92	0.06	0.40	-1.83	0.21
21	18 - 24	11	75	14	87	0.06	0.42	-1.88	0.22
21	24 - 30	9	76	14	89	0.07	0.43	-1.88	0.22
21	30 - 36	8	77	15	72	0.07	0.48	-1.91	0.23
21	36 - 42	8	80	12	78	0.07	0.48	-1.92	0.23
21	42 - 48	15	73	13	120	0.04	0.30	-1.48	0.14

*Coefficients are consistent with those described in Schaap et al. (2001)

Appendix 2: Climatic Data for 2010 Growing Season

Table 9: Recorded climate information for 2010

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
5/5/2010	0	86	61	13	13	0.0	0.21
5/6/2010	1	88	63	15	29	0.0	0.40
5/7/2010	2	88	68	18	47	0.0	0.35
5/8/2010	3	89	54	12	58	0.0	0.51
5/9/2010	4	67	46	-4	55	0.0	0.30
5/10/2010	5	67	47	-3	52	0.0	0.19
5/11/2010	6	63	53	-2	50	0.6	0.08
5/12/2010	7	77	60	9	58	0.0	0.06
5/13/2010	8	86	70	18	76	0.0	0.24
5/14/2010	9	86	72	19	95	0.0	0.24
5/15/2010	10	88	66	17	112	0.0	0.36
5/16/2010	11	85	67	16	128	1.3	-
5/17/2010	12	81	61	11	139	0.0	0.07
5/18/2010	13	79	58	8	148	0.1	0.28
5/19/2010	14	69	51	0	148	0.0	0.18
5/20/2010	15	78	56	7	155	0.7	0.21
5/21/2010	16	75	59	7	162	0.3	0.21
5/22/2010	17	82	67	14	176	0.0	0.25
5/23/2010	18	87	70	19	195	0.0	0.26
5/24/2010	19	92	71	22	216	0.0	0.00
5/25/2010	20	89	64	17	233	0.1	0.45
5/26/2010	21	86	67	16	249	0.0	0.14
5/27/2010	22	88	66	17	266	0.0	0.31
5/28/2010	23	89	67	18	284	0.0	0.30
5/29/2010	24	88	67	17	302	0.3	0.39
5/30/2010	25	85	68	16	318	0.0	0.23
5/31/2010	26	85	66	15	334	0.1	0.08

Table 9: Recorded climate information for 2010 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
6/1/2010	27	86	67	16	350	0.1	0.15
6/2/2010	28	93	71	22	372	0.0	0.31
6/3/2010	29	92	70	21	393	0.0	0.29
6/4/2010	30	90	69	20	413	0.4	0.41
6/5/2010	31	87	70	19	431	0.0	0.22
6/6/2010	32	89	73	21	452	0.0	0.25
6/7/2010	33	88	61	14	467	0.0	0.31
6/8/2010	34	88	63	15	482	0.0	0.18
6/9/2010	35	90	72	21	503	0.0	0.33
6/10/2010	36	92	70	21	524	3.5	-
6/11/2010	37	88	72	20	544	0.0	0.13
6/12/2010	38	88	75	22	566	0.0	0.35
6/13/2010	39	93	74	23	589	0.0	0.31
6/14/2010	40	94	74	24	613	0.0	0.19
6/15/2010	41	94	69	22	635	0.3	0.48
6/16/2010	42	94	71	22	657	0.0	0.40
6/17/2010	43	93	72	22	680	0.8	0.35
6/18/2010	44	96	72	24	704	0.1	0.25
6/19/2010	45	95	74	24	728	0.0	0.29
6/20/2010	46	94	73	23	751	0.0	0.42
6/21/2010	47	95	72	23	775	0.0	0.31
6/22/2010	48	96	73	25	800	0.0	0.26
6/23/2010	49	97	73	25	825	0.0	0.34
6/24/2010	50	94	77	25	850	0.0	0.29
6/25/2010	51	95	74	24	874	0.7	0.63
6/26/2010	52	93	72	22	897	0.1	0.32
6/27/2010	53	92	73	22	919	0.4	0.34
6/28/2010	54	94	75	24	944	0.0	0.33
6/29/2010	55	93	72	22	966	0.1	0.32

Table 9: Recorded climate information for 2010 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
6/30/2010	56	89	70	20	986	0.0	0.28
7/1/2010	57	88	66	17	1003	0.0	0.41
7/2/2010	58	88	65	16	1019	0.0	0.38
7/3/2010	59	88	67	17	1037	0.0	0.31
7/4/2010	60	91	70	21	1057	0.0	0.32
7/5/2010	61	90	69	20	1077	0.0	0.35
7/6/2010	62	91	72	22	1098	0.0	0.20
7/7/2010	63	94	73	23	1122	0.0	0.43
7/8/2010	64	92	72	22	1144	0.1	0.13
7/9/2010	65	96	73	25	1168	0.0	0.33
7/10/2010	66	91	74	22	1191	0.2	-
7/11/2010	67	92	72	22	1213	0.0	0.38
7/12/2010	68	92	72	22	1235	0.3	0.30
7/13/2010	69	87	70	19	1253	3.4	-
7/14/2010	70	88	71	20	1273	0.1	0.28
7/15/2010	71	96	76	26	1299	0.0	0.26
7/16/2010	72	97	77	27	1326	0.0	0.32
7/17/2010	73	93	72	22	1348	0.5	0.32
7/18/2010	74	89	74	22	1370	0.0	0.26
7/19/2010	75	90	73	22	1391	0.0	0.25
7/20/2010	76	94	73	23	1415	0.0	0.24
7/21/2010	77	92	76	24	1439	0.0	0.37
7/22/2010	78	95	77	26	1465	0.0	0.31
7/23/2010	79	95	75	25	1490	0.0	0.24
7/24/2010	80	94	74	24	1514	0.0	0.47
7/25/2010	81	96	77	27	1540	0.0	0.31
7/26/2010	82	95	78	27	1567	0.0	0.14
7/27/2010	83	95	72	23	1590	1.4	0.41
7/28/2010	84	89	72	21	1611	0.0	0.27

Table 9: Recorded climate information for 2010 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
7/29/2010	85	91	74	22	1633	0.0	0.34
7/30/2010	86	94	74	24	1657	0.6	0.22
7/31/2010	87	94	75	24	1682	0.0	0.44
8/1/2010	88	95	78	27	1708	0.0	0.24
8/2/2010	89	93	71	22	1730	0.0	0.24
8/3/2010	90	96	75	26	1756	0.0	0.24
8/4/2010	91	101	75	28	1784	0.0	0.28
8/5/2010	92	101	78	30	1813	0.0	0.23
8/6/2010	93	96	74	25	1838	0.2	0.41
8/7/2010	94	90	71	21	1859	0.0	0.31
8/8/2010	95	94	70	22	1881	0.0	0.29
8/9/2010	96	96	72	24	1905	2.5	0.40
8/10/2010	97	97	76	26	1931	0.0	-
8/11/2010	98	96	76	26	1957	0.0	0.22
8/12/2010	99	97	77	27	1984	0.0	0.20
8/13/2010	100	98	74	26	2010	0.0	0.34
8/14/2010	101	98	74	26	2036	0.0	0.27
8/15/2010	102	98	75	27	2063	0.5	0.45
8/16/2010	103	97	71	24	2087	0.0	0.25
8/17/2010	104	91	71	21	2108	0.0	0.37
8/18/2010	105	93	72	22	2130	0.6	0.50
8/19/2010	106	87	73	20	2150	0.3	0.30
8/20/2010	107	94	72	23	2173	0.0	0.15
8/21/2010	108	94	73	23	2197	0.0	0.30
8/22/2010	109	97	72	24	2221	0.0	0.36
8/23/2010	110	96	73	25	2246	0.0	0.29
8/24/2010	111	93	64	19	2264	0.0	0.24
8/25/2010	112	90	64	17	2281	0.0	0.37
8/26/2010	113	88	63	15	2297	0.0	0.22

Table 9: Recorded climate information for 2010 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
8/27/2010	114	87	58	13	2309	0.0	0.30
8/28/2010	115	90	59	14	2324	0.0	0.44
8/29/2010	116	92	69	21	2344	0.0	0.19
8/30/2010	117	81	72	16	2361	0.5	0.19
8/31/2010	118	85	66	15	2376	0.4	0.15
9/1/2010	119	89	65	17	2393	0.7	-
9/2/2010	120	90	67	18	2412	0.0	0.27
9/3/2010	121	93	68	21	2432	0.0	0.40
9/4/2010	122	83	53	8	2440	0.0	0.31
9/5/2010	123	81	50	5	2446	0.0	0.25
9/6/2010	124	84	51	8	2453	0.0	0.25
9/7/2010	125	92	58	15	2468	0.0	0.17
9/8/2010	126	89	69	19	2487	0.1	0.19
9/9/2010	127	84	69	17	2504	0.0	0.09
9/10/2010	128	85	69	17	2521	0.0	0.08
9/11/2010	129	94	71	22	2543	0.2	0.42
9/12/2010	130	84	65	14	2558	0.0	0.14
9/13/2010	131	85	52	8	2566	0.0	0.14
9/14/2010	132	90	52	11	2577	0.0	0.36
9/15/2010	133	92	56	14	2591	0.0	0.19
9/16/2010	134	94	62	18	2609	0.1	0.29
9/17/2010	135	92	65	18	2627	0.0	0.24
9/18/2010	136	90	57	13	2641	0.0	0.25
9/19/2010	137	94	55	14	2655	0.0	0.25
9/20/2010	138	97	57	17	2672	0.0	0.20
9/21/2010	139	97	62	20	2692	0.0	0.27
9/22/2010	140	97	65	21	2713	0.0	0.36
9/23/2010	141	95	64	20	2732	0.0	0.24
9/24/2010	142	94	66	20	2752	0.0	0.32

Table 9: Recorded climate information for 2010 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
9/25/2010	143	93	67	20	2772	0.0	0.30
9/26/2010	144	82	55	9	2781	0.0	0.39
9/27/2010	145	76	54	5	2786	0.0	0.05
9/28/2010	146	77	47	2	2788	0.0	0.21
9/29/2010	147	76	45	0	2788	0.0	0.05
9/30/2010	148	82	46	4	2792	0.0	0.22

Weather data as reported by the National Climatic Data Center from the Jackson Experiment Station (www.ncdc.com) as of July 2012.

Appendix 3: Climatic Data for 2011 Growing Season

Table 10: Recorded climate information for 2011

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
5/12/2011	0	89	69	19	19	0.0	0.26
5/13/2011	1	89	64	17	36	0.6	0.30
5/14/2011	2	79	58	8	44	0.8	0.50
5/15/2011	3	60	54	-3	41	0.0	0.10
5/16/2011	4	60	48	-6	35	0.0	0.03
5/17/2011	5	63	41	-8	27	0.0	0.09
5/18/2011	6	66	43	-6	22	0.0	0.30
5/19/2011	7	73	48	1	22	0.0	0.21
5/20/2011	8	80	58	9	31	0.0	0.15
5/21/2011	9	87	64	16	47	0.0	0.46
5/22/2011	10	87	66	17	63	0.0	0.27
5/23/2011	11	79	62	11	74	0.6	0.06
5/24/2011	12	83	62	13	86	0.4	0.33
5/25/2011	13	87	66	17	103	0.0	0.13
5/26/2011	14	88	56	12	115	0.4	0.35
5/27/2011	15	76	55	5	120	0.0	0.32
5/28/2011	16	73	57	5	125	0.0	0.18
5/29/2011	17	89	64	17	142	0.0	0.33
5/30/2011	18	91	70	21	162	0.0	0.38
5/31/2011	19	93	71	22	184	0.0	0.30
6/1/2011	20	93	69	21	205	0.0	0.28
6/2/2011	21	95	68	22	227	0.0	0.33
6/3/2011	22	94	71	22	249	0.0	0.30
6/4/2011	23	96	74	25	274	0.0	0.33
6/5/2011	24	97	70	23	298	0.0	0.33
6/6/2011	25	96	69	23	321	0.0	0.15
6/7/2011	26	94	69	22	342	0.0	0.30

Table 10: Recorded climate information for 2011 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
6/8/2011	27	95	73	24	366	0.0	0.34
6/9/2011	28	94	71	22	389	0.0	0.27
6/10/2011	29	93	69	21	410	0.0	0.36
6/11/2011	30	94	70	22	432	0.0	0.52
6/12/2011	31	94	65	19	451	0.9	0.57
6/13/2011	32	87	67	17	468	0.0	0.08
6/14/2011	33	94	69	22	489	0.0	0.07
6/15/2011	34	89	65	17	506	0.0	0.31
6/16/2011	35	94	60	17	523	0.0	0.30
6/17/2011	36	93	53	13	536	1.0	0.39
6/18/2011	37	85	65	15	551	2.0	-
6/19/2011	38	85	68	16	568	0.1	0.23
6/20/2011	39	92	76	24	592	0.0	0.23
6/21/2011	40	92	64	18	610	0.0	0.30
6/22/2011	41	85	69	17	627	0.4	0.26
6/23/2011	42	84	70	17	644	0.1	0.11
6/24/2011	43	92	62	17	661	0.0	-
6/25/2011	44	82	69	16	676	0.0	0.57
6/26/2011	45	92	70	21	697	0.0	0.24
6/27/2011	46	85	68	16	714	1.1	0.24
6/28/2011	47	91	74	22	736	0.0	0.31
6/29/2011	48	82	69	16	752	0.5	0.18
6/30/2011	49	88	64	16	768	0.0	0.30
7/1/2011	50	90	64	17	785	0.0	0.30
7/2/2011	51	91	66	19	803	0.0	0.43
7/3/2011	52	93	71	22	825	0.0	0.30
7/4/2011	53	94	73	23	849	0.0	0.32
7/5/2011	54	92	63	17	866	0.1	0.21
7/6/2011	55	91	69	20	886	0.0	0.24

Table 10: Recorded climate information for 2011 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
7/7/2011	56	94	73	23	910	0.0	0.21
7/8/2011	57	91	69	20	930	2.4	-
7/9/2011	58	88	72	20	950	0.0	-
7/10/2011	59	93	76	24	974	0.0	0.32
7/11/2011	60	97	78	28	1002	0.0	0.20
7/12/2011	61	99	77	28	1030	0.0	0.31
7/13/2011	62	99	73	26	1056	0.0	0.41
7/14/2011	63	95	75	25	1081	0.0	0.31
7/15/2011	64	95	72	23	1104	0.0	0.28
7/16/2011	65	92	74	23	1127	0.0	0.44
7/17/2011	66	87	74	21	1148	0.0	0.23
7/18/2011	67	89	71	20	1168	0.0	0.22
7/19/2011	68	93	71	22	1190	0.0	0.22
7/20/2011	69	94	74	24	1214	0.0	0.27
7/21/2011	70	95	74	24	1238	0.0	0.43
7/22/2011	71	97	73	25	1263	0.0	0.42
7/23/2011	72	93	74	23	1287	0.0	0.42
7/24/2011	73	92	75	23	1310	0.0	0.30
7/25/2011	74	95	72	23	1334	1.2	0.36
7/26/2011	75	92	73	22	1356	0.0	0.26
7/27/2011	76	95	73	24	1380	0.0	0.23
7/28/2011	77	97	73	25	1405	0.0	0.32
7/29/2011	78	93	75	24	1429	0.0	-
7/30/2011	79	88	75	22	1451	0.0	0.15
7/31/2011	80	93	73	23	1474	0.0	0.29
8/1/2011	81	97	75	26	1500	0.0	0.29
8/2/2011	82	98	69	24	1523	0.0	0.23
8/3/2011	83	98	73	26	1549	0.0	0.45
8/4/2011	84	104	73	29	1577	0.0	0.39

Table 10: Recorded climate information for 2011 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
8/5/2011	85	96	73	25	1602	0.0	0.44
8/6/2011	86	83	74	18	1620	0.2	0.14
8/7/2011	87	91	74	22	1643	0.0	0.10
8/8/2011	88	97	72	24	1667	0.2	0.33
8/9/2011	89	93	73	23	1690	0.0	0.29
8/10/2011	90	93	67	20	1710	0.0	0.30
8/11/2011	91	89	70	20	1730	1.1	0.36
8/12/2011	92	88	66	17	1747	0.0	0.24
8/13/2011	93	91	66	19	1765	0.0	0.47
8/14/2011	94	88	70	19	1784	0.0	0.06
8/15/2011	95	85	59	12	1796	0.0	0.19
8/16/2011	96	84	59	12	1808	0.0	0.27
8/17/2011	97	89	59	14	1822	0.1	0.29
8/18/2011	98	92	69	21	1842	0.0	0.32
8/19/2011	99	91	66	19	1861	0.0	0.19
8/20/2011	100	92	67	19	1880	0.0	0.19
8/21/2011	101	93	72	22	1903	0.0	0.34
8/22/2011	102	92	71	22	1924	0.1	0.10
8/23/2011	103	96	70	23	1947	0.0	0.31
8/24/2011	104	98	71	25	1972	0.0	0.39
8/25/2011	105	94	63	18	1990	0.0	0.16
8/26/2011	106	96	63	20	2010	0.0	0.41
8/27/2011	107	93	63	18	2028	0.0	0.45
8/28/2011	108	92	65	18	2046	0.0	0.33
8/29/2011	109	91	59	15	2061	0.0	0.14
8/30/2011	110	92	59	15	2077	0.0	0.40
8/31/2011	111	96	61	19	2095	0.0	0.49
9/1/2011	112	99	69	24	2119	0.0	0.28
9/2/2011	113	100	72	26	2145	0.0	0.30

Table 10: Recorded climate information for 2011 (continued)

Date (m/d/y)	Days since planting	High temp-rature (°F)	Low Temp-rature (°F)	Number of DD60	Cumu-lative DD60	Daily precip-itation (in)	Pan evapo-ration (in)
9/3/2011	114	99	69	24	2169	0.0	0.36
9/4/2011	115	100	73	27	2196	0.0	0.32
9/5/2011	116	80	65	13	2209	0.3	0.09
9/6/2011	117	68	54	1	2209	0.0	0.03
9/7/2011	118	74	52	3	2212	0.0	0.20
9/8/2011	119	77	48	3	2215	0.0	0.37
9/9/2011	120	74	47	0	2215	0.0	0.31
9/10/2011	121	83	53	8	2223	0.0	0.31
9/11/2011	122	88	56	12	2235	0.0	0.08
9/12/2011	123	87	57	12	2247	0.2	0.25
9/13/2011	124	89	56	13	2260	0.0	0.34

Weather data as reported by the National Climatic Data Center from the Jackson Experiment Station (www.ncdc.com) as of July 2012.

VITA

Heath Adam Duncan was born in Albany, Georgia in 1988. After living in Smiths Station, Alabama and then Eufaula, Alabama, he moved to Knoxville, Tennessee where he graduated from Bearden High School in 2006. Following his passion for engineering design, he graduated from the University of Tennessee in 2010 with a Bachelor of Science in Biosystems Engineering with a minor in Environmental Engineering. He then earned his Master of Science degree in Biosystems Engineering in August 2012.